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DESKTOP TECHNIQUES FOR ANALYZING SURFACE-GROUND WATER INTERACTIONS

The Reelfoot Lake Case Study

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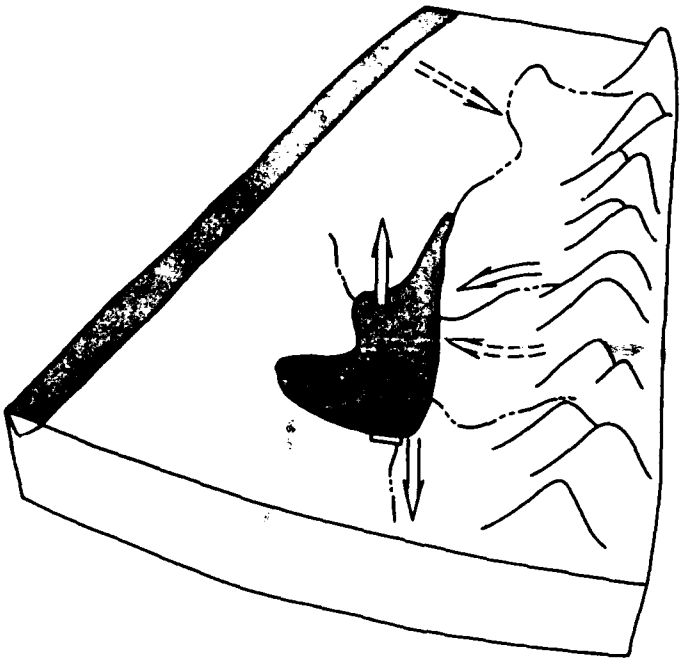

Research Document No. 28

May 1988

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DESKTOP TECHNIQUES FOR ANALYZING SURFACE-GROUND WATER INTERACTIONS

The Reelfoot Lake Case Study

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Prepared for
The Hydrologic Engineering Center
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Davis, California

May 1988

FOREWORD

This report is the second in a series of case studies prepared for the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) in order to illustrate the importance of "desk-top" analyses in hydrologic investigations. The first report in this series (McLaughlin, 1984) suggested that such analyses may be the most cost-effective way to analyze certain environmental problems. An opportunity to pursue this topic further arose when the Memphis District of the Corps of Engineers became involved in a study of Reelfoot Lake, a large natural lake in northwestern Tennessee. Although modeling studies of the lake and its watershed had been carried out and further studies were in progress, the District wanted to sponsor a small-scale desk-top analysis of its own. HEC agreed to provide partial support for this study, primarily because of its potential interest to a broader audience of engineers and hydrologists. This report, which documents the Reelfoot Lake case study, is an attempt to satisfy both the project-oriented objectives of the district and the tutorial objectives of HEC. We hope that the result provides a realistic picture of the issues and problems which arise in a typical hydrologic investigation.

The author wishes to express his appreciation for the support and encouragement of Bill Johnson of the Hydrologic Engineering Center, and of Mike Gatewood, John Monroe, and Larry Sharpe of the Memphis District. Report preparation was funded under Contract No. DACW05-86-P-3202 from the U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA, 95616.

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SYNPOSIS

This report is intended to illustrate how simple "desktop" analyses can be used to investigate complex hydrologic systems. Our discussion focuses on a case study of Reelfoot Lake, Tennessee, a shallow eutrophic lake which is plagued by a number of water quality problems. These problems are related, at least in part, to activities in the tributary watershed. The Reelfoot Lake watershed extends from an upland region which supplies most of the runoff, and probably most of the nutrients, entering the lake to a lowland region which was historically part of the Mississippi River flood plain. Levees, drainage projects, and spillways have altered the watershed's hydrology and have complicated the lake's management. Since hydrologic data are limited and generally not very reliable, the processes which control the flow of water to and from the lake are not well understood. Some major questions about the region's hydrology need to be resolved before the agencies responsible for the lake can develop effective long-term management plans.

The Reelfoot Lake case study offers a good opportunity to explore the advantages and disadvantages of simple desktop approaches to hydrologic analysis. We are particularly interested here in the way that desktop methods help reveal data gaps and uncertainties which tend to be obscured in more elaborate computer modeling studies. We are also interested in the qualitative conceptual issues that must be addressed in the beginning of any real-world hydrologic study, desktop or computerized. These are issues that are not always discussed in traditional project reports but which are, nevertheless, quite familiar to practicing hydrologists.

Our analysis starts with a conceptual description of the regional hydrologic cycle. This description is formalized in a set of mass balance equations which form the basis for subsequent water budget computations. Inflows and outflows identified in the mass balance equations are estimated from available data sources, primarily rain and stream gage records, well hydrographs, and qualitative geological observations. All inflow and outflow estimates are assembled in water budget tables which resemble financial spreadsheets. The water budgets provide an compact and informative hydrologic summary which can be used both to understand historic patterns and to predict future trends.

The most important surface water inflows to Reelfoot Lake can be estimated reasonably accurately from recorded flows in major tributaries. Subsurface inflows to the lake are much more difficult to estimate. In fact, there is some controversy about the hydrogeology of the alluvial formation which lies below most of the region. A review of geological data and a groundwater flow net analysis indicate that the subsurface system behaves like a leaky confined aquifer which is recharged both from river seepage and from infiltrating precipitation. The quantity of

groundwater flowing from this aquifer to the lake is quite small compared to the amount of surface water entering from upland tributaries. The lake's water budget is dominated by these upland inflows and by outflows through the controlled spillway. This suggests that drainage projects in the lowlands lying to the west and north (e.g. the Lake No. 9 project) have little effect on the lake's water level.

A simple analysis of available sedimentation studies indicates that Reelfoot Lake could disappear in 200 to 400 years if sediment inflows continue at present rates. It seems unlikely that sedimentation has contributed significantly to the general impression that the lake is shrinking in size. Stage-volume curves compiled over the last several decades appear to support this conclusion. It is true, however, that encroaching aquatic vegatation has reduced the accessible area of the lake in many places. Also, the spillway which essentially controls the lake's water level is leaking badly and not well maintained. This may have caused undesirable depth fluctuations and unnecessary losses of water during dry periods.

The Reelfoot Lake desktop analysis reveals a number of major data deficiencies which could be eliminated with a carefully planned long-term monitoring program. This program would include continuous monitoring of flows in Running Reelfoot Bayou and Running Slough and much more extensive long-term monitoring of ground water levels around the lake, particularly on the east side where subsurface flows are the greatest. Pump tests are needed to provide a better description of effective (large scale) aquifer properties. An expanded ground water data collection program could help clarify ambiguities about the geohydrology of the Reelfoot Lake aquifer and could provide better estimates of subsurface fluxes from the aquifer into the lake.

The case study indicates that simple desktop analyses can, in fact, reveal much about the relative importance of the various hydrologic factors which affect the water budget of Reelfoot Lake. It also shows that the early stages of problem formulation have a significant impact on the outcome of a hydrologic analysis. The relevant issues actually seem to be easier to identify in a desk-top analysis than in a modeling study, where a computer code stands, in a sense, between the modeler and reality. This is not to say that computer models are undesirable. Rather, they should be viewed as logical extensions of a lengthy thought process which starts with a few simple pictures and calculations sketched out on a sheet of paper. If this exploratory process is done properly, subsequent modeling efforts are much more likely to be successful.

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1. INTRODUCTION

Conflicts over the use of limited water resources have preoccupied both farmer and city dweller throughout recorded history and are just as important today as they ever were. Now, however, we have at our disposal more information and a greater range of technical abilities than at any time in the past. Environmental disputes are more esoteric, requiring the intervention of specialists who, as often as not, disagree in their interpretations and diagnoses. Computer-based simulation and prediction techniques are part of this trend towards the specialization of environmental analysis. Computer methods undoubtedly give us new predictive capabilities, but they can also widen the gap between the informed layman and the specialist.

An earlier report in this series (McLaughlin, 1984) examined the role of computer modeling in New Mexico's San Andres-Glorieta ground water basin. This report focused on some of the more judgemental aspects of modeling and made the case that simple "desk-top" analyses can often give answers just as good as sophisticated models, particularly when field data are limited and ambiguous. Since desk-top techniques are less likely to obscure critical assumptions and are more accessible to laymen, they provide a tempting alternative to the somewhat forbidding world of computer models. Ideally, desk-top and computer analyses should be viewed as complementary tools which work best when combined. This was, in fact, the position taken in the above report, which suggested that desk-top methods should provide the foundation for more detailed modeling studies.

Here we examine desk-top techniques in more detail than was possible in the San Andres-Glorieta study. As before, we take a case study approach and illustrate most of the basic concepts by example. Our focus is on Reelfoot Lake, a large natural lake which lies in a primarily agricultural watershed in northwestern Tennessee. The conflicts in this case study involve agricultural and recreational interests, as well as a number of state and federal agencies with differing objectives and responsibilities. The management issues being debated involve aspects of surface and ground water hydrology, terrestrial and aquatic biology, land use and wildlife management, and resource economics. In this multidisciplinary context, it is particularly important that specialized studies of the lake be both easy to understand and credible. Otherwise, these studies will have little or no impact on practical policy decisions.

The Reelfoot Lake case study provides an excellent opportunity to use desk-top techniques to examine a number of unresolved questions about the management of the lake. We concentrate primarily on hydrologic issues in order to limit the length and scope of the discussion. Our overall objectives are to identify the sources and pathways of water moving through the lake and to construct a set of long-term average water budgets. These water budgets provide a way to assess the relative importance of the various

hydrologic processes which affect the lake. They also indicate where further research efforts should be directed.

Before we begin, we should probably attempt to define the term "desk-top analysis". It seems reasonable to expect that a desk-top analysis could be performed relatively quickly and easily by an investigator using a pencil and paper and perhaps a hand calculator. But it could be argued that most hand calculators are really computers (especially programmable ones). Or that personal computers are commonly found on engineers' desk tops. Since such semantic distinctions are unproductive, let us just say that desk-top analyses lie on one end of a spectrum which varies from back-of-the envelope calculations to highly sophisticated supercomputer simulations. We are interested in exploring the simpler end of this spectrum, but with an awareness that some of the problems we encounter will require more complicated techniques.

Although the emphasis here is on a particular case study, we believe that many of the concepts presented in our discussion are relevant to a broad range of applications. Since this report is intended to serve a tutorial function, basic concepts are discussed in more detail than in a typical project report. Readers interested in more background information are encouraged to investigate some of the cited textbooks. Our discussion begins, in Chapter 2, with a brief review of the Reelfoot lake case study. Chapter 3 describes several important desk-top techniques and indicates how they can be applied to the case study. Chapter 4 discusses some of the management implications of our analysis. Finally, Chapter 5 reviews the major points of the report and provides some comments and recommendations regarding the application of desk-top techniques.

2. THE REELFOOT LAKE CASE STUDY

2.1 PHYSICAL SETTING

General Information

Reelfoot Lake, the largest natural lake in Tennessee, is an important regional resource which has received considerable attention in recent years. It is located east of the Mississippi River, near the Tennessee-Kentucky border and about 120 miles north of Memphis, TN (see Figure 2-1). Reelfoot is an oxbow lake formed from the Mississippi during the New Madrid earthquakes of 1811-1812. Published estimates of the current open water area of the lake vary between 13,000 and 18,000 acres at a normal pool elevation of 282.2 feet above mean sea level (MSL). The average water depth is about 5.2 feet, but nearly half the lake is less than 3.0 feet deep (Robbins, 1985). Much of the open water area is bordered by an additional 10,000 acres of cypress swamps, saw grass, and water lilies.

The Reelfoot Lake drainage basin covers around 240 mi^2 which includes uplands rising to the east as well as lowlands in the historic Mississippi River flood plain lying between the lake and the river. The uplands area consists of rolling hills and ridges with an average elevation of about 500 feet MSL. The lowlands area is nearly flat with an average elevation of about 285 feet MSL. The lake's major tributaries enter from the east and north, although a number of small sloughs on the west side can carry significant amounts of water during wet periods. The major outlet is through a controlled spillway at the southern end of the lake. Important surface features of the Reelfoot Lake region are indicated in Figure 2-2.

The area surrounding Reelfoot Lake was originally heavily forested but is now primarily agricultural, with a concentration of recreational development along the shoreline. The lake and its adjoining wetlands include several state and federal wildlife management areas which protect local fisheries as well as indigenous and migratory bird populations. Although fish productivity in Reelfoot Lake is six times the national average, catches appear to be declining due to hypereutrophic conditions caused by excessive nutrient inputs. The general perception of residents and most researchers is that siltation and vegetation encroachment have been steadily reducing the accessible area of the lake (Tennessee Wildlife Resources Agency, 1985). This would , of course, have detrimental effects on most of the activities that make Reelfoot Lake a popular recreational area.

Surface Hydrology

Long-term precipitation records for the Reelfoot Lake region are available from National Weather Service gages at Hickman, KY and Samburg,

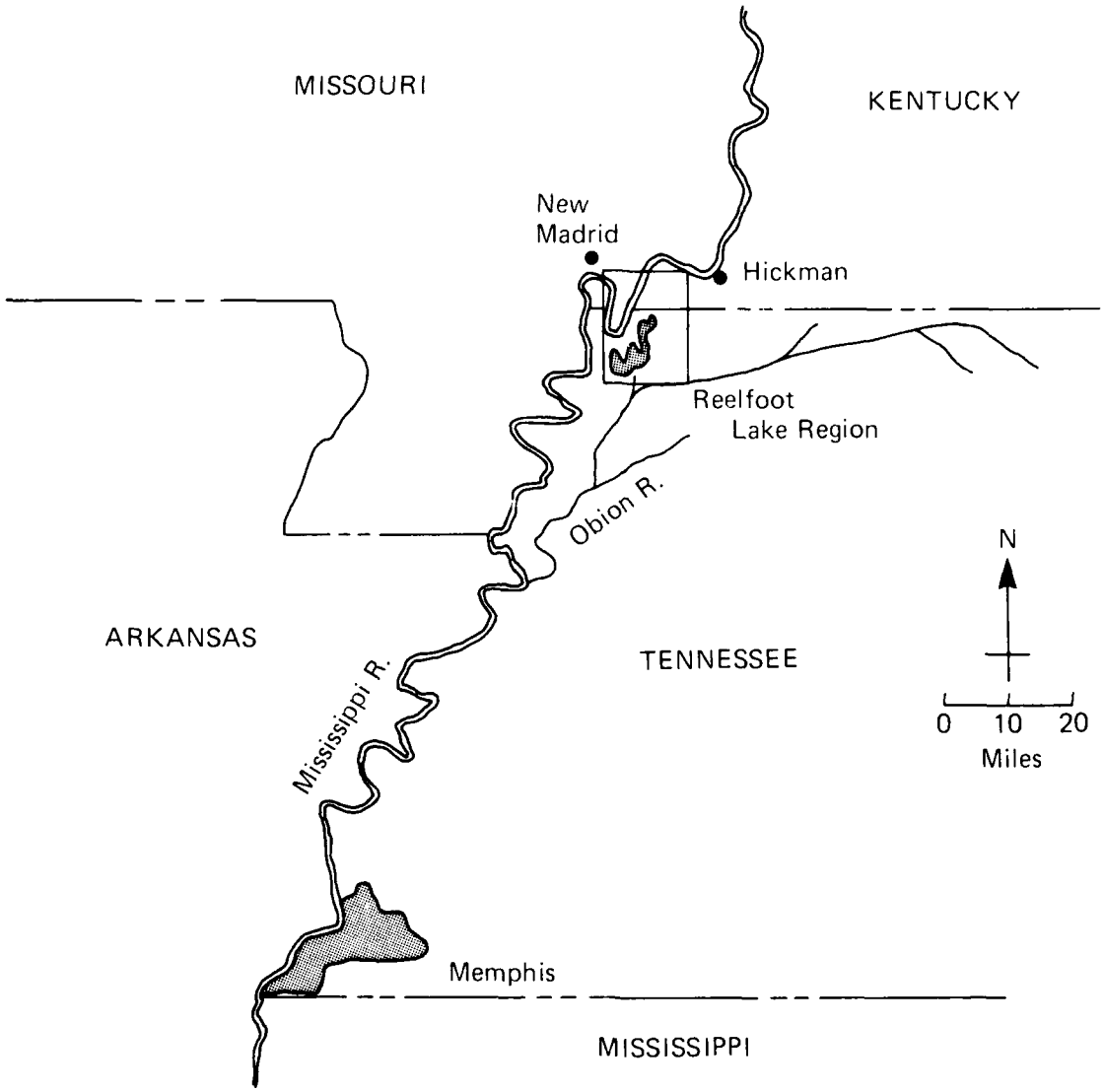


Figure 2-1

Location of the Reelfoot Lake Region

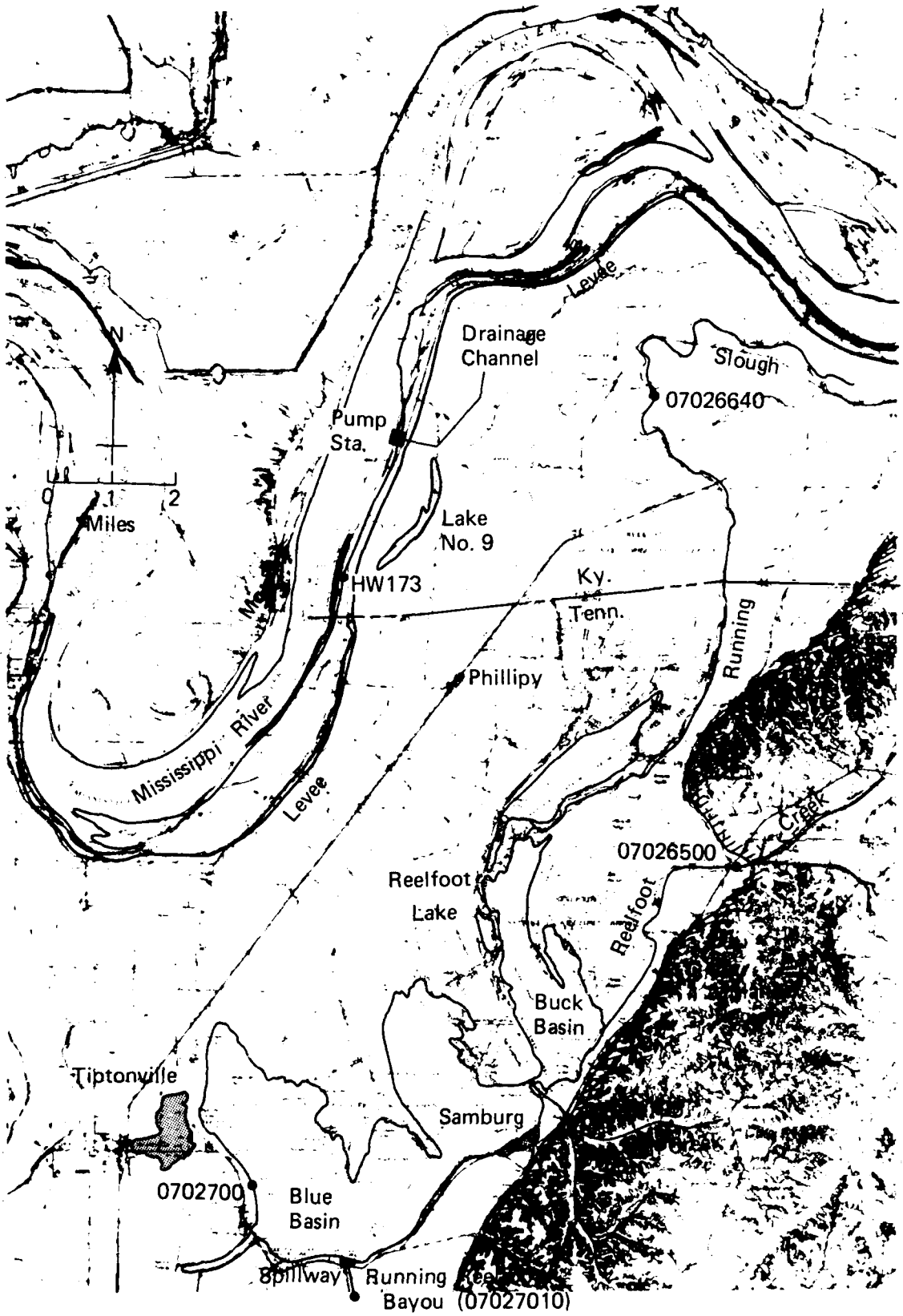


Figure 2-2

Important Surface Features of the Reelfoot Lake Region

TN. These gages indicate that annual precipitation varies over a range from 31.5 to 72.2 inches (U.S Army Corps of Engineers, 1974). Normal monthly rainfall averages 4.0 inches and varies from 3.07 inches to 5.39 inches, with the heaviest amounts recorded during the period December through April. The stages of Reelfoot Lake and the Mississippi River exhibit long-term seasonal variations which are roughly correlated with long-term rainfall. This is illustrated in Figure 2-3, which compares average monthly precipitation at the Samburg, TN raingage to the Reelfoot Lake stage measured at gage 07027000 (located near Tiptonville, TN) and the Mississippi River stage measured at HW gage 173 (see Figure 2-2 for gage locations). All three curves are based on data collected over the period 1954-1985. It should be noted that river and rainfall conditions at any particular time may depart significantly from these long-term averages. In particular, the river stage may be unusually high (or low) when rainfall is unusually low (or high). The lake stage is, on the other hand, relatively stable, generally remaining within a fraction of a foot of the long-term average.

There is very little quantitative information on evapotranspiration and soil moisture in the Reelfoot Lake region. For the most part, evapotranspiration estimates must be inferred from measurements taken in other areas where land use and climatic conditions are similar. Robbins (1985) presents estimates of the average monthly evaporation from the surface of Reelfoot Lake. These estimates, which are plotted in Figure 2-4, are based on pan evaporation data collected over the period 1977-1984 from the National Weather Service station at Martin, TN. Although pan evaporation measurements probably do not accurately describe actual evaporative loss from the surface of a large lake, they provide the best information currently available for estimating this portion of the regional water budget.

The major tributaries of Reelfoot Lake are streams flowing from the uplands to the east (primarily Reelfoot and Indian Creeks) and from the lowlands to the north (Running Slough). The gaged portions of these three streams account for about 60% of the total drainage area of the lake. The only one of the gaged streams with a record long enough to provide reliable monthly average flow estimates is Reelfoot Creek. Figure 2-5 compares the average monthly flow measured at Reelfoot Creek gage 07026500 for the period 1951-1973 to the long term Samburg, TN rainfall record plotted in Figure 2-3. Note that the volumetric flow has been divided by the drainage area of 110 mi^2 and reported in units of inches/month. Figure 2-5 indicates that the apparent runoff coefficient (ratio of streamflow to total precipitation) for the upland watershed drained by Reelfoot Creek varies from a low of about 0.10 in the summer to a high of about 0.55 in mid-winter. The low coefficients observed at the end of the dry season probably reflect the combined effect of low soil moisture, low water tables, and increased vegetative cover and evapotranspiration. All of these factors act to decrease runoff. Runoff coefficients for the alluvial lowland region to the north and east of the lake are probably different but are difficult to estimate from the small amount of discharge data available.

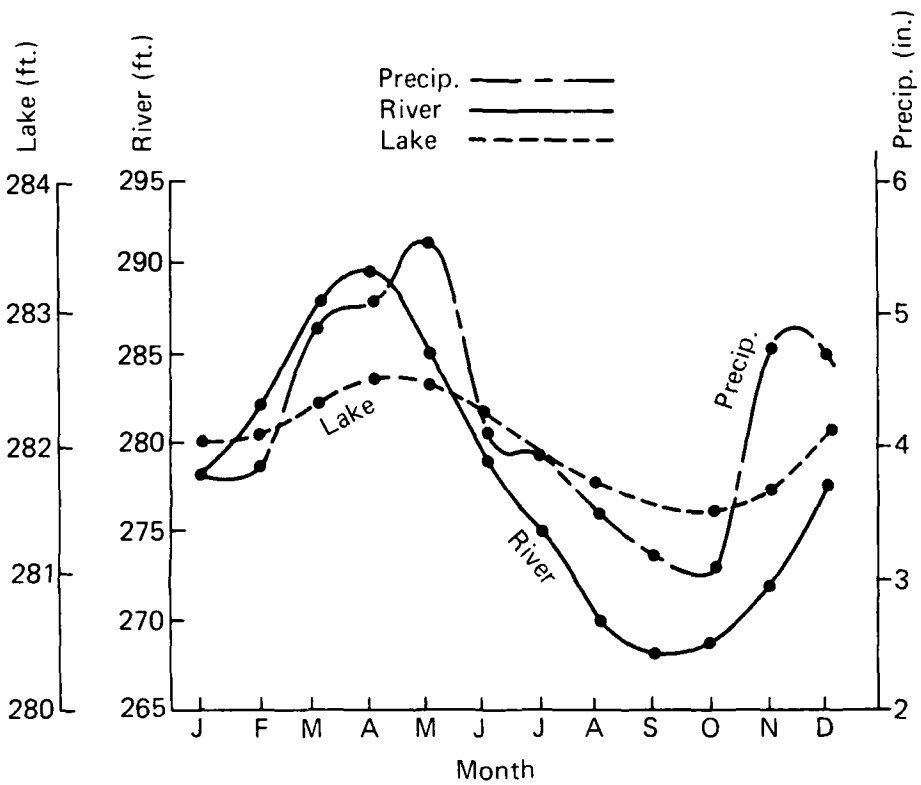


Figure 2-3

Long-term Average Precipitation, Lake Elevation, and River Elevation for the Reelfoot Region

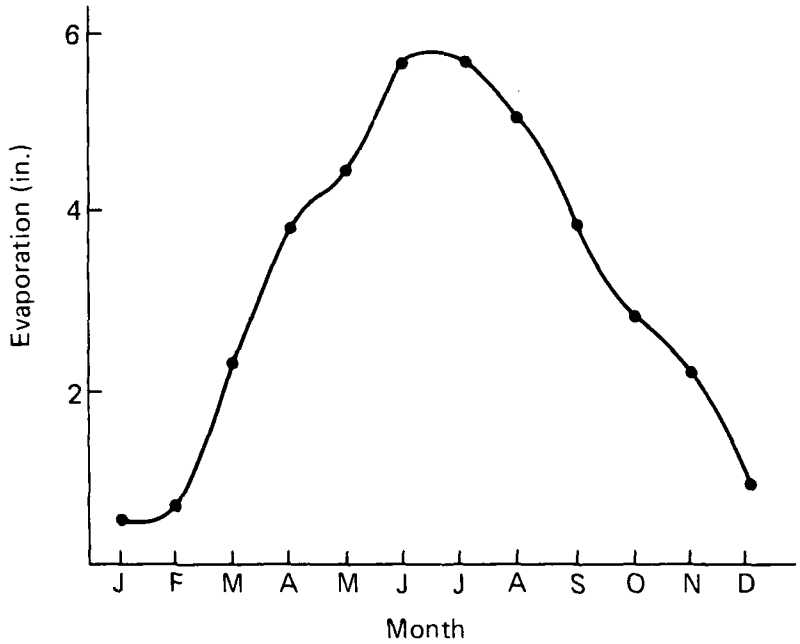


Figure 2-4

Long-term Average Evaporation for the Reelfoot Region

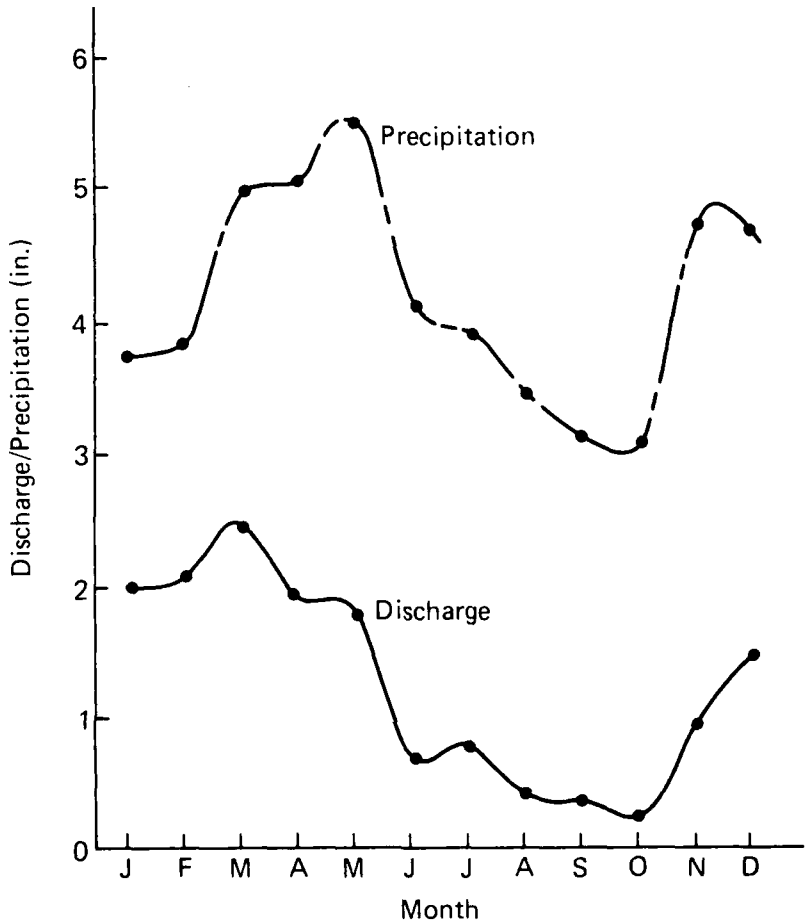


Figure 2-5

Long-term Average Discharge in Reelfoot Creek

Surface outflows from Reelfoot Lake discharge into Running Reelfoot Bayou through a flashboard gated spillway and radial arm gate located at the extreme southern end of the lake. The improved channel downstream of the spillway runs south to the Obion River and then to the Mississippi. The top of the fixed portion of the spillway sets a limit of 282.2 feet MSL on the maximum stage at the lower end of the lake. Although detailed information on the operation of this structure is not available, about 30 months of flow measurements (during the period 1982 through 1985) have been collected on Running Reelfoot Bayou less than a mile downstream. These measurements show, as expected, that the largest flows occur during the late spring months and the smallest flows occur during the late summer and early fall.

Geology and Geohydrology

Reviews of the geology of the Reelfoot Lake region are provided in a number of publications, including Strausberg and Schreurs (1958), Robbins (1985), and U.S. Army Corps of Engineers (1974). Geological maps and an extensive set of borehole soil samples for the section of the Mississippi River levee in the northwestern portion of the Reelfoot region are presented in U.S. Army Corps of Engineers (1980). Figure 2-6 shows two representative geological cross-sections through the Reelfoot region. The approximate locations of these cross-sections are indicated in Figure 2-7.

Available evidence indicates that the uppermost formation in the lowland region is composed of between 50 and 200 feet of Mississippi River alluvium. The clay content of the alluvial material is highest at the top, where there is evidence of recently deposited point bar deposits and abandoned river channels (U.S. Army Corps of Engineers, 1974). The sand content of the alluvium generally increases with depth. The clay layer (or "overburden") at the top of the alluvial formation is generally between 10 and 20 feet thick, although it appears to be as thick as 50 feet in places. This overburden apparently underlies much of the Reelfoot Lake drainage basin, including a significant fraction of the lake itself (see Figure 2-6). Ground water levels in the alluvial lowland region are generally within 15 feet of the surface.

The uppermost formation in the uplands to the east of Reelfoot lake is composed of undifferentiated Pleistocene deposits which are sometimes overlain by loess (windblown soils). The alluvial lowland aquifer and the upland Pleistocene deposits are both underlain by from 70 to 250 feet of relatively impermeable Tertiary clay and fine sand (U.S. Army Corps of Engineers, 1974; 1980). The Tertiary, in turn, lies above about 600 feet of highly permeable Memphis Sand (Strausberg and Schreuers, 1958).

The investigators cited above give significantly different geohydrologic interpretations of available information on the alluvial aquifer system. Robbins (1985) states that the alluvial ground water system is "generally under water-table conditions; localized artesian conditions may exist where

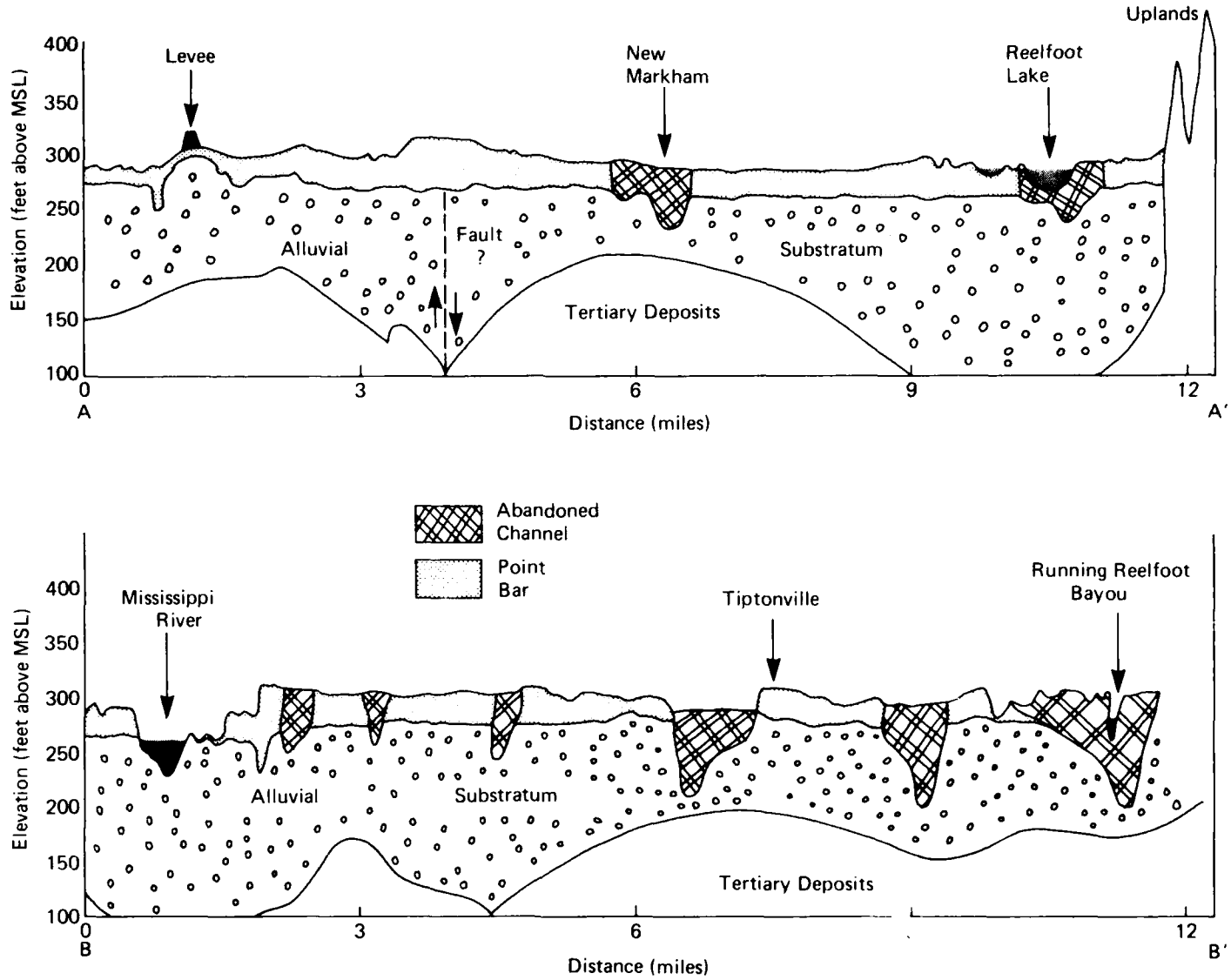


Figure 2-6 Geological Cross-sections through the Reelfoot Region

Figure 2-7

Locations of Selected USGS Wells

the upper unit contains significant amounts of clay". This conclusion appears to be based primarily on data compiled by Strausberg and Schreuers (1958). More recent data compiled by the U.S. Army Corps of Engineers (1974; 1980) suggest that high clay abandoned river channel deposits are more extensive than reported in Strausberg and Schreuers (1958). Consequently, most geohydrologic and geotechnical analyses performed by the Corps (e.g. U.S. Army Corps of Engineers, 1980) have assumed that the alluvial system is a leaky confined aquifer.

Information on ground water conditions in the Reelfoot Lake region was very limited until recent years when public concern about the lake prompted a significant increase in monitoring, primarily by the U.S. Geological Survey (USGS). Most of the geohydrologic data available today was collected by the USGS over the period 1984-1986 (Robbins, 1985; United States Geological Survey, 1986). This includes a set of water level measurements taken at approximately one month intervals at about 30 wells scattered around the Reelfoot Lake region. The locations of these wells are indicated in Figure 2-7. These measurements indicate that ground water levels in the region are high (within 10 or 15 feet of the surface) and that head gradients are generally small. The major exceptions occur near the Mississippi River when the river stage is either much higher or much lower than the lake level and near the bluffs at the eastern upland boundary. Localized ground water mounds have been observed in the lowland area between the river and lake after periods of high precipitation. These do not appear to have a significant effect on regional ground water flow or on gradients near the lake.

Sedimentation and Water Quality

The impacts of sediment inflow and deposition have been addressed in several studies of Reelfoot Lake, including reports by the Soil Conservation Service (1956) and McIntyre and McHenry (1984). These studies agree that the easily eroded but fertile loess soil in the uplands portion of the Reelfoot region is the major source of sediment entering the lake. The Soil Conservation Service (1956) estimated that 161.3 acre feet (AF) of sediment were entering Reelfoot Lake annually before construction of sediment detention facilities began in 1967. This rate, which is probably larger than present-day values, is small compared to the lake's estimated normal pool volume of 80,300 AF (Robbins, 1985). The historical surface area and volume vs. stage curves plotted in Figure 2-8 confirm that sedimentation has probably had a minor impact on the total size of the Reelfoot Lake during the period 1931 through 1984 (Tennessee Wildlife Resources Agency, 1985; Mike Gatewood, Memphis District, U.S. Army Corps of Engineers, personal communication). Nevertheless, it is possible that sedimentation has significantly reduced lake depths in localized areas. This may, in part, explain the common perception that the lake's depth is consistently decreasing.

Water quality in Reelfoot is typical of a shallow hypereutrophic lake

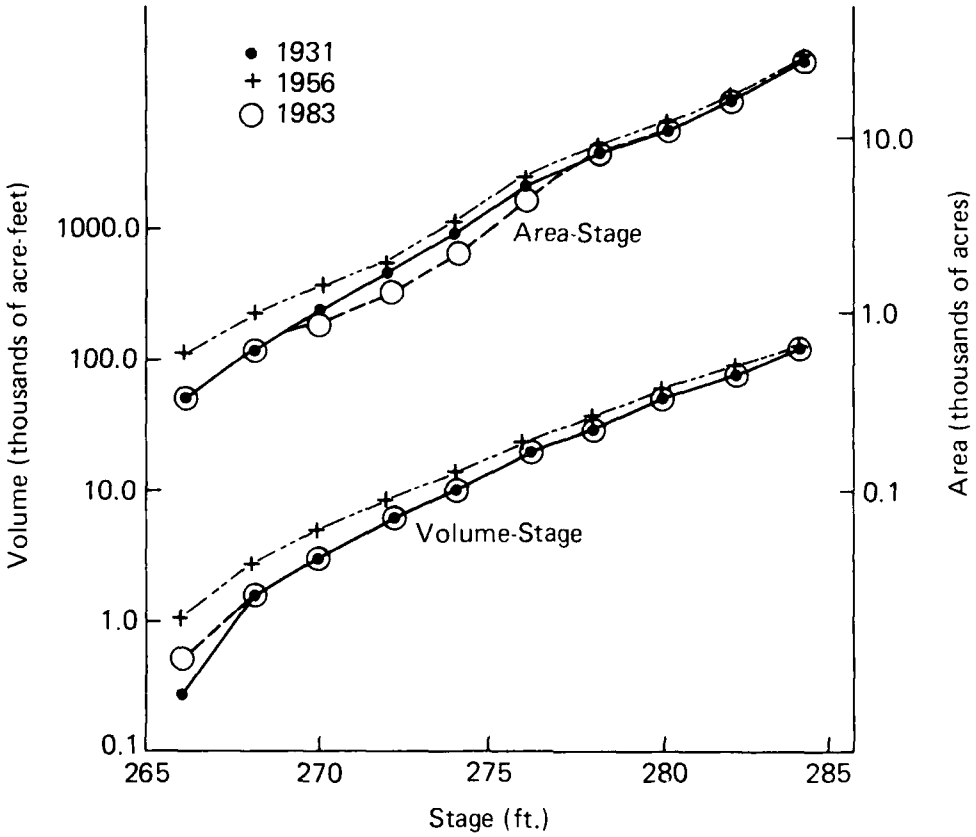


Figure 2-8

Area-stage and Volume-stage Curves for Reelfoot Lake

(Smith and Pitts, 1982). Measured nutrient levels are high and occassional fish kills indicate that dissolved oxygen levels may be low during the summer months (Tennessee Department of Health and Environment, 1984). Conditions generally favor the growth of aquatic plants which restrict access to the lake, reduce circulation, and increase the accumulation of dead organic matter on the bottom. One of the consequences has been a noticeable decline in the abundance of sportfish. Eutrophication problems have been aggravated by the influx of fertilizers and pesticides carried in sediments from upland erosion. Degrading water quality conditions have been responsible for a marked decline in swimming and a gradual shift in recreational use from the summer to the winter. Additional information on the water quality and ecology of Reelfoot Lake is provided in reports issued by Tennessee Wildlife Resources Agency (1985; 1986) and the Tennessee Department of Health and Environment (1984). These references discuss the origins of many of the lake's current problems.

2.2 MANAGEMENT ISSUES

Management History

The resource management questions which have received the most attention in the Reelfoot Lake region have traditionally been flood control and preservation of the lake and its wildlife. Flood control activities have focused primarily on the lowland regions to the north of the lake, where property and agricultural operations are periodically threatened by flooding from high river stages and/or high surface runoff. The most conspicuous measures taken to preserve the lake have been the establishment of wildlife management areas and the construction of sediment detention facilities in eastern uplands. Although flood control and preservation activities have traditionally proceeded independently, the trend among agencies responsible for the region's natural resources has been to devote increased attention to possible connections between these activities. The following historical review provides background information for the more extensive discussion of management issues presented later in thi- n.

During the period between 1811-1812, when Reelfoot Lake was formed, and 1940, when the Hickman Ky. to Cates Tenn. section of the Mississippi River Levee was completed, the Mississippi periodically flooded the Reelfoot region, providing an important surface connection between the river and lake. The lake was, for all practical purposes, a part of the river system. Lake levels closely followed the river stage and fish and nutrients from the river replenished the lake. When the levee was completed surface flows from the river to the lake were eliminated for all but the most extreme flood conditions. The levee project flood attains a stage of 313 ft. at river mile 908.5, near HW gage 173. This stage has not been exceeded during the historical period of record and has a recurrence interval of well over one hundred years (U.S. Army Corps of Engineers, 1974).

Additional controls on Reelfoot Lake were established over the period

from 1917 through 1959 as a result of a series of construction and dredging projects at the lake's southern end. The first of several spillways was constucted at the outlet to Running Reelfoot Bayou in 1917. The current spillway was built in 1931 and improved by the addition of a radial arm control gate in 1959. These controls stabilized the lake level and further reduced natural flushing of the lake's waters (Tennessee Wildlife Resources Agency, 1985).

An agreement between the State of Tennessee and the U.S. Department of the Interior created the Reelfoot Lake National Wildlife Refuge in 1941. Later, in 1984, the state legislature designated the Tennessee Wildlife Resources Agency (TWRA) to be Tennessee's lead management agency for Reelfoot Lake. In recent years the U.S. Fish and Wildlife Service has operated the spillway to maintain the lake level in a relatively narrow range between 281 and 283 ft. MSL. The spillway is, however, in poor repair and the lake outflow is becoming increasingly difficult to regulate.

Recurrent property and crop damage caused by runoff impounded during flood periods prompted the U.S. Army Corps of Engineers to propose, in 1974, a flood control and drainage project for the northern portion of the Reelfoot Lake watershed (U.S. Army Corps of Engineers, 1974). The original project included 15.8 miles of channel construction, enlargement, and realignment; diversion and control structures; and a gated culvert and 500 cubic feet per second (CFS) pumping station on the Mississippi River levee near Lake No. 9. The improved channel was designed to divert flood waters to the levee facility where flow would be released or pumped to the Mississippi, depending on the river stage. Right-of-way problems prevented completion of the entire project but the gated culvert, pumping station, and 3.3 miles of improved channel were built. The original and as-built projects are described in Figure 2-9. Although there are no records of the amount of water actually diverted by the Lake No. 9 project, the area drained is about 12 mi^2 (about 5% of the 240 mi^2 tributary to Reelfoot Lake). The pump station has only been operated sporadically since it was first used in 1978. Pumpage over the period 1978 through 1986 averaged about 2200 AF per year.

In 1967 the State of Tennessee began acquiring land in the Reelfoot and Indian Creek watersheds for construction of facilities to trap sediment flowing into Reelfoot Lake. As of 1985, the Soil Conservation Service had built 6 of 15 proposed detention structures. Preliminary studies indicate that these structures have reduced local sediment inflows to about 30% of pre-project levels (Mike Gatewood, Memphis District, U.S. Army Corps of Engineers, personal communication). It is likely that efforts to control sediment inflows into the lake will continue in the future, particularly if existing facilities prove to be effective.

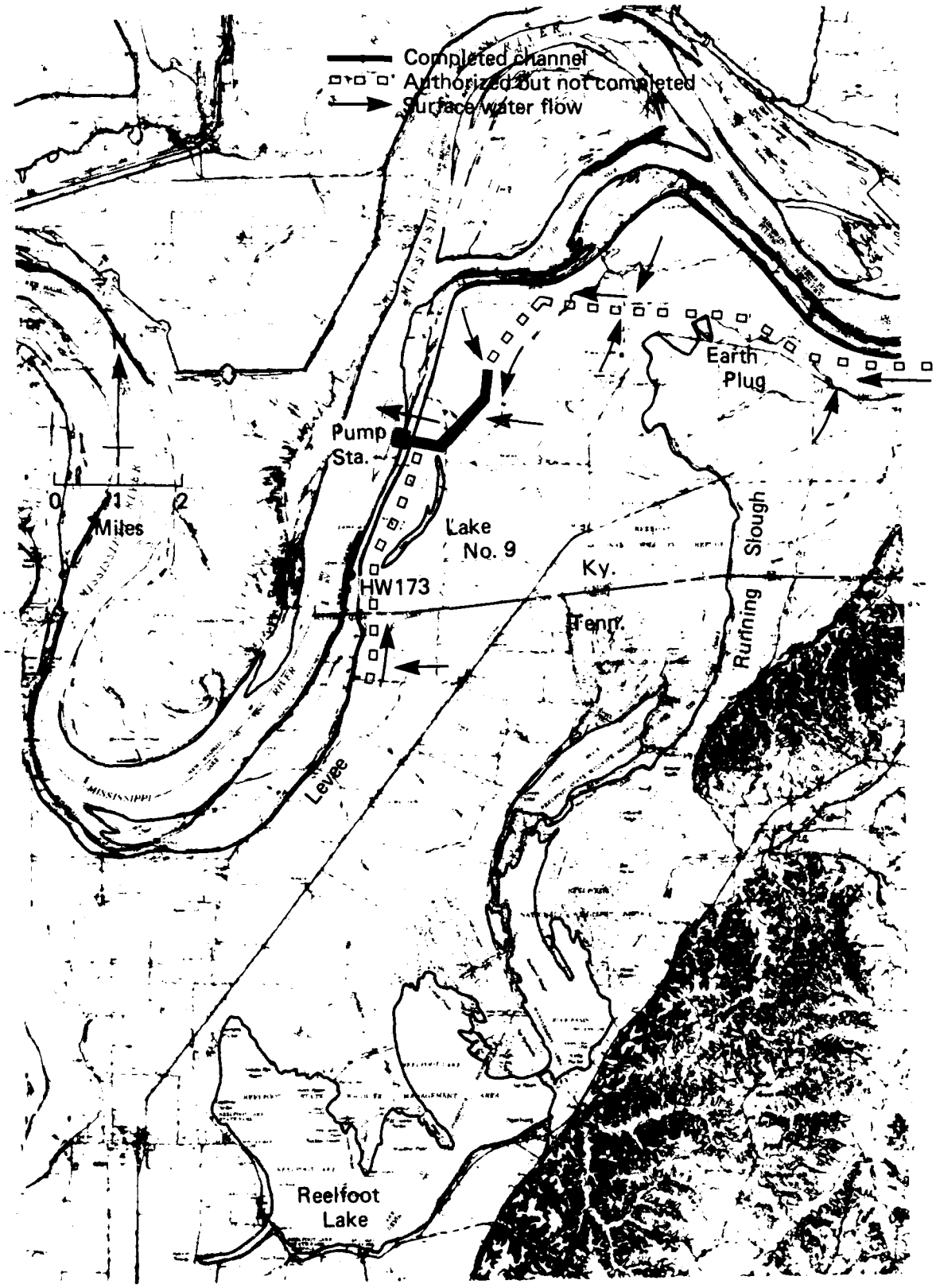


Figure 2-9

Major Features of the Lake No. 9 Project

Issues of Current Interest

Although the management measures described above have alleviated flooding and decreased sediment loads to Reelfoot Lake, they have not, by any means, solved all of the region's natural resource problems. The levee system has isolated Reelfoot Lake from the Mississippi and probably accelerated the natural eutrophication process. The as-built Lake No. 9 drainage project has had little or no impact on potential flood risks in the Hickman, KY area since channel improvements do not extend to the affected watershed. Reduced sediment inflows have not had a marked impact on the water quality of the lake or on the continuing encroachment of vegetation. For these reasons, there is an ongoing search for a comprehensive and effective approach for managing the region's resources.

There currently appears to be relatively little interest in completing the authorized Lake No. 9 drainage project, partly because local agencies do not have the financial resources to support construction, operation, and maintenance of an expanded project. Nevertheless, there is considerable support among farming interests in the area for preserving the project's existing features. This support is based primarily on the desire to maximize the amount of land under cultivation during wet years. The existing project has tended to limit shoreline flooding from rising waters in Lake No. 9 and other small ponds in the immediate vicinity. The total amount of cropland affected is, however, quite small; probably less than a few hundred acres.

The future of the Lake No. 9 project is complicated by recent claims that this project diverts water from the Reelfoot Lake drainage and, by implication, has an adverse impact on Reelfoot water levels. Concern about the impacts of the as-built project helped motivate a study of the regional ground water system which is currently being conducted by the Tennessee District of the USGS in cooperation with the State of Tennessee (United States Geological Survey, 1986a). This study includes a field data collection program as well as computer modeling of flow in the alluvial aquifer. One of the study's objectives is an evaluation of the impact of the Lake No. 9 project on subsurface inflows to Reelfoot Lake (United States Geological Survey, 1986a).

A study completed by TWRA in 1985 proposed a plan for dealing with some of the water quality and vegetation problems which plague Reelfoot Lake (Tennessee Wildlife Resources Agency, 1985). The basic idea is to periodically (perhaps every ten years) draw Reelfoot Lake down during the mid-summer to a level of 276.4 feet MSL (about 5.8 feet below normal pool of 282.2 feet MSL) and then to gradually refill the lake during the late fall (Tennessee Wildlife Resources Agency, 1985; Robbins, 1985). The purpose of this manipulation of the lake's water level is to expose and dry extensive areas of unconsolidated bottom sediments which have high organic contents and impose large oxygen demands. Advocates of the plan hope that the drying process will oxygenate and compact these sediments so that bottom conditions

will improve and eutrophication will be slowed down (Tennessee Wildlife Resources Agency, 1985). Some of the hydrologic implications of the proposed drawdown are examined in Robbins (1985).

An initial attempt to carry out the Reelfoot Lake drawdown plan in the summer of 1985 was halted by local opposition. TWRA has just completed a comprehensive fifty-year management plan which again proposes manipulation of the lake level. This plan also includes replacement of the existing spillway with a more reliable structure (Tennessee Wildlife Resources Agency, 1986) . Although the new spillway will give TWRA better control of outflows from the lake, it is not clear, given differing attitudes in the region, how this control will actually be used.

3. DESKTOP ANALYSIS OF THE REELFOOT LAKE CASE STUDY

3.1 INTRODUCTION

The summary of management issues presented in the preceding chapter suggests that there is a real need for a better understanding of many of the natural processes which affect Reelfoot Lake and its tributary watersheds. This understanding must be based on a judicious combination of field observations, scientific principles, and common sense. Since field observations of many important variables are limited, any description of natural processes in the Reelfoot region is necessarily speculative and uncertain. Given this, detailed predictions of the effects of management actions can be misleading. A more realistic, and ultimately more useful, approach is to explicitly acknowledge the sources and possible implications of uncertainty. This type of analysis provides a good basis for an informed discussion of the benefits and risks of proposed management alternatives.

It is useful to begin an analysis of a complex environmental system such as Reelfoot Lake with an assessment of the relative importance of the various physical processes which appear to be relevant. Such an assessment need not be elaborate or time-consuming since it is intended primarily to provide the basis for more detailed studies. In this chapter we illustrate how a preliminary environmental assessment might be carried out in practice. Although our focus is on the hydrology of the Reelfoot Lake region, many of the concepts presented here could also be used to study regional ecology or land use.

One of the best ways to assess the relative importance of the different hydrologic processes affecting Reelfoot Lake is to develop "water budgets" which give a complete accounting of all water entering and leaving the lake. The lake's water balance changes over time, reflecting the influence of droughts, wet periods, and normal seasonal variations in climate. Water budgets are therefore presented either as "snapshots" taken at particular times or, more often, as averages taken over particular periods. The type of water budget we can hope to develop is, of course, highly dependent on the type and amount of data available. Here we are interested both in long-term averages and in possible deviations from these averages. Taken together, these provide a reasonably good picture of the local hydrologic cycle.

Our analysis is divided into three phases which progressively lead to a set of long-term water budgets for Reelfoot Lake. These phases can be summarized as follows:

1. <u>Identify Hydrologic Pathways</u> -- The objective of this initial phase of the analysis is to develop a qualitative description of the hydrologic cycle in the region of interest. This includes

identification of the source and ultimate fate of water moving through the system and the location and relative importance of alternative surface and subsurface pathways. It also includes an assessment of the role of temporal and spatial variability. A number of graphical techniques, including flow nets, may be used to display the results of the pathway analysis.

2. Estimate Hydrologic Fluxes -- The objective of the next phase of the analysis is to develop estimates of the fluxes of water moving through each hydrologic pathway at various times. The spatial and temporal resolution used in the analysis depends both on the study's objectives and on the availability of data.

3. Construct Water Budgets -- The final phase of the analysis provides a complete accounting of all water moving through the hydrologic system. This is done with water budgets which list estimated fluxes for all hydrologic pathways. Depending on the application, these water budgets can be used to reveal data gaps, identify problem areas, or even predict the likely effects of proposed management strategies.

Each of these aspects of the analysis is discussed in more detail in one of the following sections.

3.2 HYDROLOGIC PATHWAYS

The Hydrologic Cycle

The general features of the hydrologic cycle of the Reelfoot Lake region are relatively easy to identify. As indicated in Figure 3-1, water enters the region either as precipitation or as river seepage. Most of the precipitation falls on the watershed, where it either runs off into the lake's tributary streams or infiltrates into the ground water system. Some of the infiltrated water may later appear in these streams as baseflow (exfiltration). The influence of the river is felt mostly through its interactions with the ground water system. Some of the river seepage entering the alluvial aquifer may later exfiltrate into small streams and sloughs. Water leaves the region through evaporation, subsurface outflow, and the spillway discharge to Running Reelfoot Bayou. Although precipitation, evaporation, and some streamflow records are available for the Reelfoot region, many of the fluxes identified in Figure 3-1 have not been measured and are, consequently, highly uncertain. One of the primary objectives of the hydrologic analysis presented here is to estimate these fluxes.

The problem of estimating hydrologic fluxes and related water budgets can be simplified if we concentrate specifically on the inflows and outflows crossing the boundaries of Reelfoot Lake. This focuses attention on the variables identified schematically in Figure 3-2. Note that the lake and

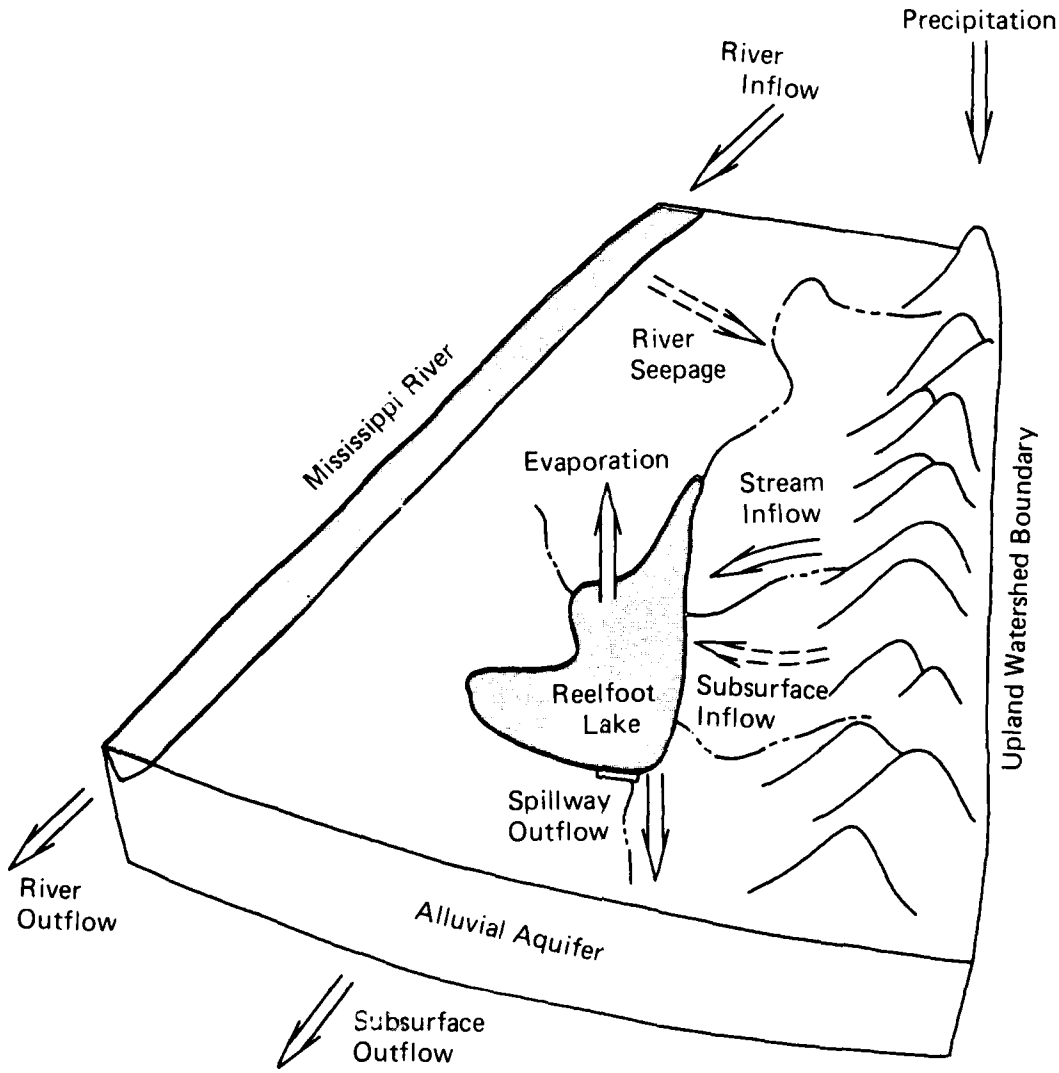


Figure 3-1

Hydrologic Cycle in the Reelfoot Region

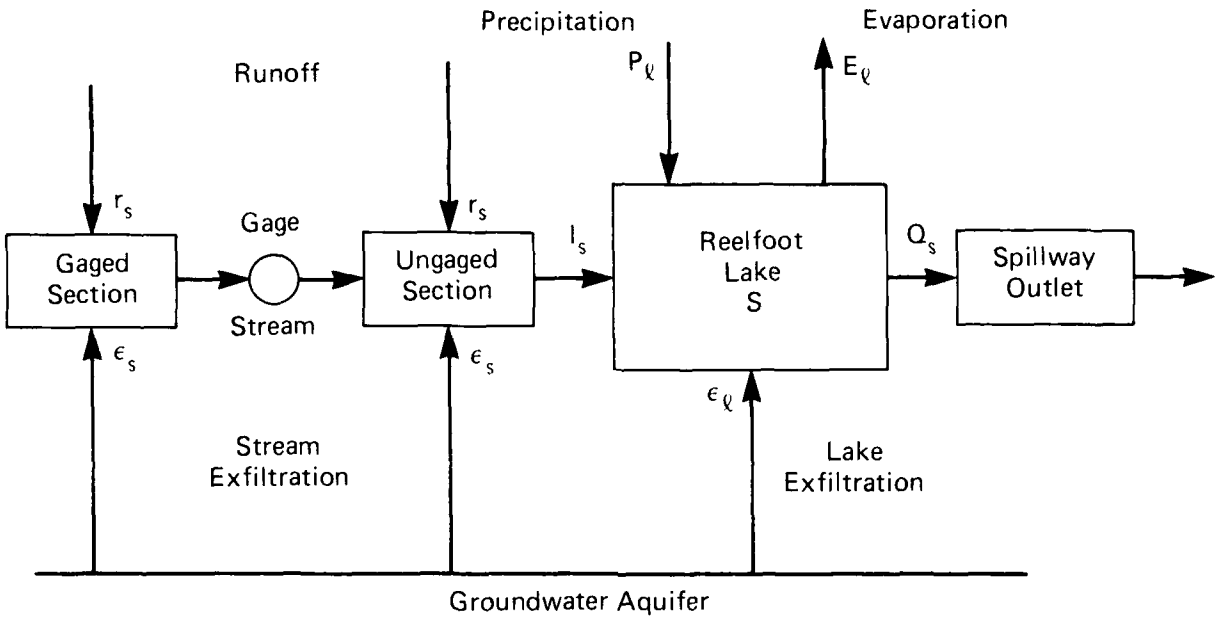


Figure 3-2

Elements of the Reelfoot Lake Water Budget

its tributary streams are both assumed to interact with the underlying ground water aquifer. Surface-subsurface interactions are defined in terms of net exfiltration from the aquifer to the surface. If the flow of water is in the opposite direction (infiltration), the exfiltration flux is negative. Tributary inflows are divided into two components, direct runoff and exfiltration, which may be treated separately or lumped together, depending on the situation.

The relationships illustrated in Figure 3-2 are conveniently summarized by the following lake and tributary mass balance equations, which are understood to apply at a particular time t:

<u>Lake mass balance equation (instantaneous)</u>

$$\frac{dS}{dt} = P_\ell + I_s + \epsilon_\ell - E_\ell - Q_s \tag{3-1}$$

<u>Tributary mass balance equation (instantaneous)</u>

$$I_s = r_s + \epsilon_s \tag{3-2}$$

where:

S = volume of water stored in the lake (L^3)

t = time (T)

P_ℓ = total precipitation falling on the surface of the lake (L^3T^{-1})

I_s = total tributary streamflow into the lake (L^3T^{-1})

ϵ_ℓ = net exfiltration from the aquifer into the lake (L^3T^{-1})

E_ℓ = total evaporation from the surface of the lake (L^3T^{-1})

Q_s = total stream outflow from the lake (L^3T^{-1})

r_s = total surface runoff into ungaged portions of streams (L^3T^{-1})

ϵ_s = net exfiltration from the aquifer into ungaged portions of streams

(L^3T^{-1})

Note that all variables appearing in equations are assumed to be expressed in terms of consistent length (L), time (T), and mass (M) units. This simplifies subsequent notation since it eliminates the conversion coefficients needed to reconcile commonly used, but inconsistent, hydrologic units.

The instantaneous fluxes appearing in Equations (3-1) and (3-2) are difficult to estimate even when extensive field measurements are available. It is, consequently, convenient to express these mass balance equations in terms of long-term averages. This is accomplished by integrating each equation over a specified averaging interval $T = t_{n-1} - t_n$. The resulting discretized expressions may be written as:

<u>Lake mass balance equation (averaged)</u>

$$S_{n+1} - S_n = P_{\ell n} + I_{sn} + \epsilon_{\ell n} - E_{\ell n} - Q_{sn} \quad ; \quad n = 1,\ldots,N \qquad (3\text{-}3)$$

<u>Tributary mass balance equation (averaged)</u>

$$I_{sn} = r_{sn} + \epsilon_{sn} \quad ; \quad n = 1,\ldots,N \qquad (3\text{-}4)$$

where:

S_n = volume of water in storage at time t_n (L^3)

$P_{\ell n} = \int_{t_n}^{t_{n+1}} P_\ell(t)\, dt$ = total precipitation over the period between t_n and t_{n+1} (L^3)

Equation (3-3) relates the lake storage at some discrete time t_{n+1} to the storage at the previous time t_n and sum of the time-integrated fluxes entering over the interval between t_n and t_{n+1}. The various integrated fluxes appearing in both Equations (3-3) and (3-4) are all defined in the same way as the total precipitation P_n.

The time-averaged mass balanced equations provide a way to develop either historical or future water budgets for Reelfoot Lake. If a historical water budget is of interest, the variables appearing in these

equations are estimated from available hydrologic and meteorologic records for the period of interest. If the two equalities are satisfied, the estimates are said to give a mass balance. Otherwise, the difference between the left and right-hand sides of each equation is defined to be a mass balance error. This error is a readily computed measure of the accuracy of the estimation process. Historical water budgets are useful partly because they reveal how important various hydrologic fluxes have been in the past. They also give us, through the mass balance error, some indication of the uncertainty inherent in our analysis.

If a future water budget is of interest, we generally postulate likely values for all but one of the terms appearing in Equation (3-3) and then assume that the remaining term has the value needed to achieve a mass balance. The most common alternatives are:

1. Derive the outflow (Q_s) that maintains a constant storage (i.e. gives $S_{n+1} - S_n = 0$).

2. Derive the storage change ($S_{n+1} - S_n$) obtained with a specified outflow (Q_s).

In either case, it is often instructive to evaluate the sensitivity of the derived variable to specified inputs such as stream inflow, groundwater infiltration, etc. The nominal values for these inputs may be obtained from a historical water budget or may be based on an analysis of the effects of some proposed management action (e.g. diversion of inflows).

In this case study we develop historic and future water budgets for Reelfoot Lake using data obtained, for the most part, from published reports. Such water budgets are needed to formulate intelligent long-term management plans and to evaluate the feasibility of more detailed modeling studies. The process of constructing water budgets helps to reveal just how much (or little) we actually know about the processes affecting the lake. It also suggests where additional field work and data collection might be most beneficial.

It is convenient to divide our discussion of hydrologic pathways into two parts dealing, respectively, with surface water movement and surface-subsurface interactions. The first category includes all of the variables represented with upper-case symbols in Figure 3-2 and Equations (3-3) and (3-4). The second category includes the variables represented with lower-case symbols. In this section we examine some of the physical processes which influence water movement in the Reelfoot region and then present conceptual models that can be used to estimate long-term hydrologic fluxes. Flux estimates for particular scenarios and time periods are developed in Section 3.2.

Surface Water Movement

The surface water fluxes which appear in the Reelfoot Lake water budget equation (Equation (3-3)) are:

1. Precipitation ($P_{\ell n}$)

2. Total stream inflow (I_{sn})

4. Evaporation ($E_{\ell n}$)

5. Total stream outflow (Q_{sn})

The numbers included here refer to the position of each variable in the water budgets presented later in this chapter

Although spatial and temporal variability tend to complicate estimation of the precipitation and evaporation fluxes, the available database for these two variables is probably adequate for the development of long-term water budgets. Stream discharge records for the region are, on the other hand, too limited to provide all of the stream inflow and outflow information needed for a water budget analysis. Instead, indirect water balance computations based on Equation (3-4) must be used to estimate long-term inflows from ungaged or partially gaged tributaries. Other indirect techniques must be used to estimate long-term outflows through the Reelfoot Lake spillway. The following subsections briefly review some of the hydrologic factors which should be considered in such indirect streamflow analyses.

General Description of the Reelfoot Lake Watershed

As mentioned earlier, most of the surface flow entering Reelfoot Lake comes from three tributaries -- Reelfoot and Indian Creeks to the east and Running Slough to the north. The gaged portions of these tributaries account for about 60 percent of the total runoff producing area. Table 3-1 indicates how the total Reelfoot Lake drainage area of 240 mi^2 can be subdivided into upland and lowland and gaged and ungaged components. The area allocation presented in this table deserves further explanation since it differs somewhat from results presented in other studies of the region. These differences are important because they affect estimates of long-term average surface runoff into Reelfoot Lake.

Robbins (1985) and the U.S. Army Corps of Engineers (1974) both state that the total area tributary to Reelfoot Lake is about 240 mi^2, of which 24 mi^2 is normally covered by the lake. We assume here that the remaining 216 mi^2 figure includes areas which normally drain into small lakes and ponds located between the Mississippi River and Reelfoot Lake, although neither of

the above references is clear on this point. These small surface water bodies effectively impound runoff until their water levels reach an elevation of around 283.5 feet. Infiltration of the impounded water into the subsurface flow system is probably small since the confining layer has a particularly high clay content beneath the lowland ponds.

When the pond elevations reach the 283.5 foot level, the excess runs off into small sloughs and channels which flow into Reelfoot Lake. Lake No. 9, the largest pond in the area, drains about 12 mi^2 and the remaining ponds in the area drain no more than one or two square miles. This suggests that the drainage area of Reelfoot Lake is actually 204 mi^2 during most of the year. It increases to 216 mi^2 only when either the Mississippi River stage or local runoff is unusually high. In this case, a portion of the increased runoff contributed by Lake No. 9 and nearby ponds probably flows through the Lake No. 9 drainage system into the Mississippi River (see Section 2.2).

The values given in Table 3-1 for the gaged areas of the Reelfoot Creek, Indian Creek, and Running Slough catchments are consistent with those reported by Robbins (1985) and the U.S. Army Corps of Engineers (1974). All of the gaged areas of the Reelfoot and Indian Creek catchments lie in the upland area east of Reelfoot Lake. About 2 mi^2 of the gaged area of the Running Slough catchment lies in the upland region in the southwestern section of Hickman Ky. The rest of the gaged area drains lowlands which are also tributary to Running Slough.

Several ungaged small streams flow from the uplands into the east side of Reelfoot Lake. The total ungaged area associated with these streams is approximately 10 mi^2. The remaining ungaged portions of the basin cover 74 mi^2 of lowlands extending around the other three sides of the lake. Approximately 19 mi^2 of this area lie in the north, below the gage on Running Slough. Another 8 mi^2 lie in the small lowland area draining into the lake from the south. The remaining 38 mi^2 is drained by the many small sloughs flowing into the western side of the lake.

With this general description in mind, we can now consider the particular factors influencing streamflow in the tributaries of Reelfoot Lake. It is convenient to divide the discussion into sections dealing with upland inflows, lowland inflows, and outflows to Running Reelfoot Bayou.

Upland Inflows

Most of the upland drainage area identified in Table 3-1 (110 mi^2 out of a total of 130 mi^2) is tributary to Reelfoot Creek gage 07026500. The topography, soils, vegetation, and rainfall of the remaining 20 mi^2 of ungaged upland area are similar to those found in the Reelfoot Creek watershed. Since many of the tributaries in the upland area are perennial streams, it is likely that they receive water both from direct surface runoff and from slower acting ground water exfiltration. These sources of surface water are both related to antecedent precipitation and are

TABLE 3-1

DRAINAGE AREA ALLOCATION FOR THE REELFOOT LAKE BASIN

Region	Area (mi^2)
Uplands	
Gaged areas:	
Reelfoot Creek (Gage 07026500)	110
Indian Creek (Gage 07026795)	8
Running Slough (Gage 07026640)	2
Ungaged areas:	
Small streams on the east side of Reelfoot Lake	10
Upland subtotal:	130
Lowlands	
Gaged areas:	
Running Slough (Gage 07026640)	9
Ungaged areas:	
Running Slough	19
Small sloughs on the south side of Reelfoot Lake	8
Small sloughs on the west side of Reelfoot Lake	38
Lowland subtotal	74
Lake No. 9 drainage	12
Maximum total drainage area	216
Reelfoot Lake surface area	24
Maximum total basin area	240

essentially indistinguishable in terms of their effect on long-term (monthly or seasonal) streamflows. Consequently, it is reasonable to assume that long-term average discharge from the upland watershed is proportional to long-term average precipitation. The proportionality constant (or runoff coefficient) can be estimated directly from available precipitation and discharge data. The details are discussed in Section 3.3

Lowland Inflows

The situation is more complicated in the lowland area where much of the exfiltration from the alluvial aquifer appears to be the result of high river stages rather than antecedent precipitation. This type of exfiltration cannot be lumped into a runoff coefficient computation which assumes that discharge is proportional to precipitation. Instead, we must divide the total discharge into two components, a runoff component which is proportional to precipitation and an exfiltration component which depends on interactions between the aquifer and surface water system. Figure 3-2 provides the conceptual basis for this approach.

The most important lowland tributary of Reelfoot Lake is Running Slough, which drains a small amount of upland watershed and about 28 mi^2 in the northern portion of the lowland watershed. A few years of discharge measurements are available at the Running Slough gage (07026640), which covers about 9 mi^2 out of the total lowland drainage area of 74 mi^2. The measured discharges vary greatly with season and appear to be weakly correlated with antecedent precipitation and with the stage of the Mississippi River, supporting our hypothesis that precipitation-related runoff and seepage-related exfiltration both contribute to local streamflow. Available geohydrologic data suggest that net exfiltration increases when the river stage is high, particularly in the northern lowland region above the Running Slough stream gage (U.S. Army Corps of Engineers, 1974). Flow net techniques described later in this section may be used to estimate exfiltration into Running Slough. Runoff coefficients may be derived by combining these estimates with available discharge and precipitation data. The details are discussed in Section 3.3.

Field observations indicate that most of the lowland tributaries on the western and southern sides of Reelfoot Lake are small ephemeral streams and sloughs that only flow during storms or when the Mississippi River stage is unusually high. Although runoff and ground water exfiltration may both contribute to streamflow in this region during certain periods, flow net computations indicate that the long-term impact of the exfiltration component is minor. Given this, it seems reasonable to neglect exfiltration in the western and southern sections, at least for a preliminary analysis. Discharge in local streams can then be derived from the Running Slough runoff coefficients.

Outflows to Running Reelfoot Bayou

The only surface outflow from Reelfoot Lake is the spillway discharge to Running Reelfoot Bayou, which leaves the lake at its southern end. This outflow deserves special consideration since it is the only component of the lake water budget that can be directly controlled. Depending on our objectives, we may wish to estimate historic spillway discharges or derive a policy for determining discharges in the future. In either case, it is convenient to identify an operating rule which expresses daily discharge as a function of lake stage. This approach reflects the observation that spillway releases are most commonly adjusted in response to reservoir water levels. If historical discharges are of interest, an operating rule can be estimated from a relatively small number of historical stage and discharge measurements. If future operation is of interest, the effects of different operating rules can be evaluated and the best one selected. Some typical operating rules are illustrated in Figure 3-3.

Once a spillway operating rule is selected, long-term discharges may be estimated by integrating the daily discharge over a specified time-period. Since daily discharge is assumed to depend on daily lake stage, this requires that the stage be expressed as an explicit function of time. Although there are many possibilities, the long-term average plot of lake stage shown in Figure 2-3 suggests that a plausible choice for a historical analysis of Reelfoot Lake is a sinusoidal function with a period of one year. This function implies that the lake stage varies seasonally, rising during periods of high inflow and falling during periods of low inflow. Section 3.3 presents a detailed analysis of the spillway outflows obtained when this sinusoidal stage function is combined with a simple quadratic operating rule.

Surface-subsurface Interactions

The only subsurface flow included in the water budget for Reelfoot Lake proper is the following interaction term:

3. Exfiltration from the ground water aquifer to the lake ($\epsilon_{\ell n}$)

It should be noted, however, that exfiltration from the aquifer to the lake (ϵ_{sn}) has an indirect role in the lake water budget since it contributes to stream inflow. Since we have no direct measurements of either of these fluxes, we must infer them indirectly from geohydrologic measurements, primarily water level observations. This requires a detailed analysis of the regional ground water system.

The portion of the regional ground water system which is most likely to be connected to Reelfoot Lake is the alluvial aquifer which extends from the ground surface to a depth of between 50 and 200 feet and which covers the

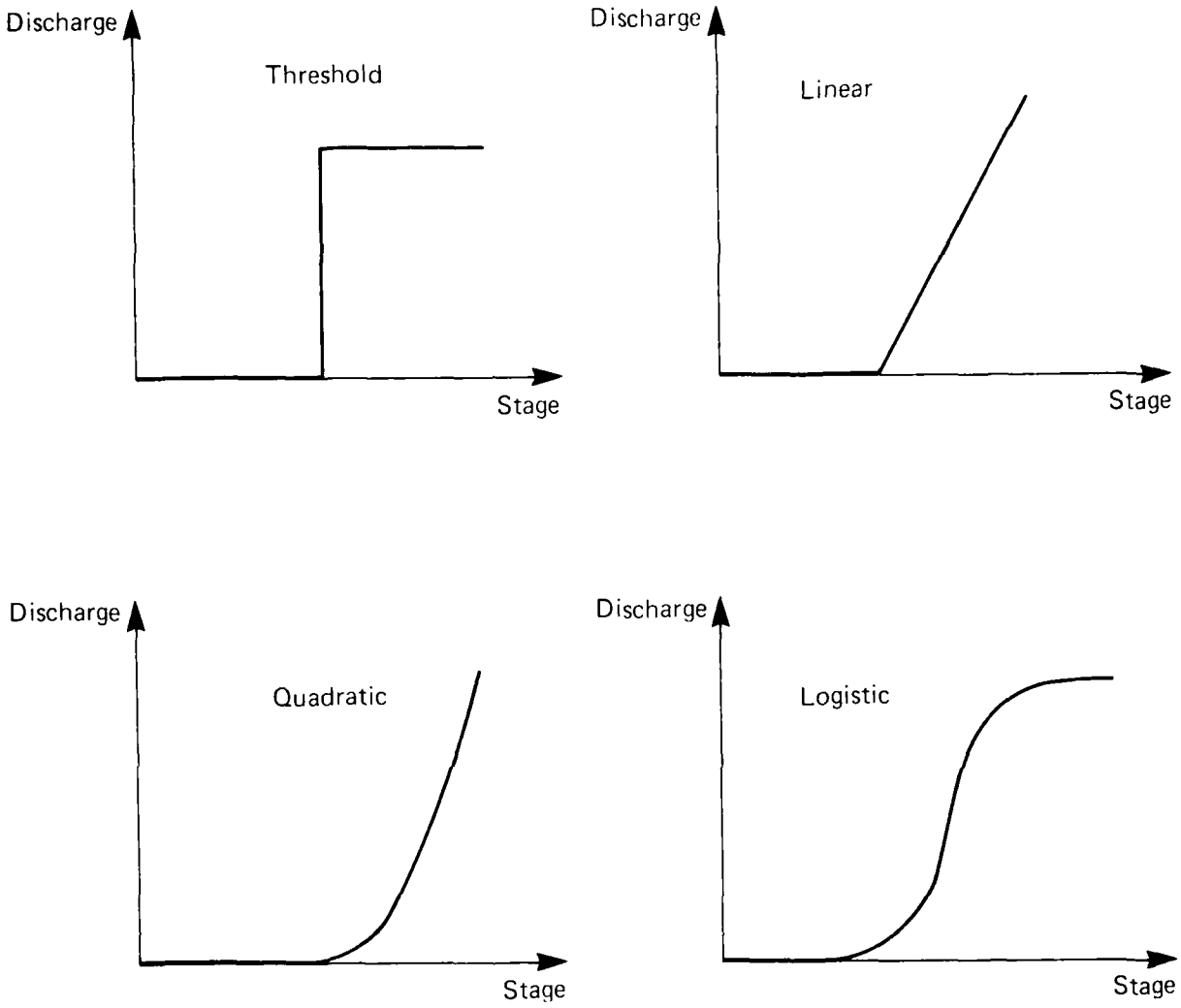


Figure 3-3

Some Simple Reservoir Operating Rules

area extending from the Mississippi River to the upland bluff line (recall Figure 2-6). As mentioned earlier, the upper portion of this aquifer is composed of an overburden characterized by a high clay content. The thickness and hydraulic conductivity of this overburden determine the degree of interaction between surface and subsurface flow. Depending on one's interpretation of existing data, it is possible to identify two distinct conceptual models of the regional flow system -- a layered confined aquifer model and a vertically homogeneous unconfined aquifer model. These models are briefly described in the following paragraphs.

Alternative Models of the Alluvial Aquifer

The layered confined model of the alluvial aquifer assumes that the hydraulic head in the aquifer is greater than the elevation of the upper boundary, implying the existence of pressurized conditions. In this case, the amount of water stored in the aquifer changes relatively little when the hydraulic head varies. Such a model would be an appropriate description of conditions in the alluvial aquifer if the clay overburden were sufficiently thick and impermeable to greatly restrict the vertical movement of ground water. The upper clay layer appears to be between 10 and 20 feet thick at the borehole locations sampled by the U.S. Army Corps of Engineers (1980). Depth-to-water measurements taken by the USGS in wells screened below the clay layer are generally less than this (United States Geological Survey, 1986), suggesting that confined conditions do prevail in at least some parts of the region. It should be noted, however, that ground water mounds observed after periods of high precipitation suggest that the clay layer is sufficiently leaky to allow some vertical flow from the surface.

If the aquifer is only moderately leaky it still may behave much like a idealized confined aquifer. In this case, aquifer and surface water head profiles will look like those shown in Figure 3-4. The diagram assumes, for purposes of illustration, that the river stage is high and that antecedent precipitation is significant. One of the most important features of the confined model is the relative independence of surface and subsurface heads observed over most of the region pictured in the cross-section. This is a natural consequence of the confining layer, which tends to isolate the ground water system from the surface.

It should be noted that the river appears to extend below the regional confining layer in its center, where the bottom elevation is about 230 feet MSL. The flow net analysis conducted later in this section suggests, however, that the aquifer heads must be lower than river heads during flood periods. This implies that the river and aquifer are hydrologically decoupled, although not necessarily completely independent. The decoupling effect may be the result of river bottom clay deposits, which can restrict seepage and create a head gradient between the river and the aquifer.

The difference between surface and subsurface heads acts as a driving force for vertical flow through the confining layer. This flow moves

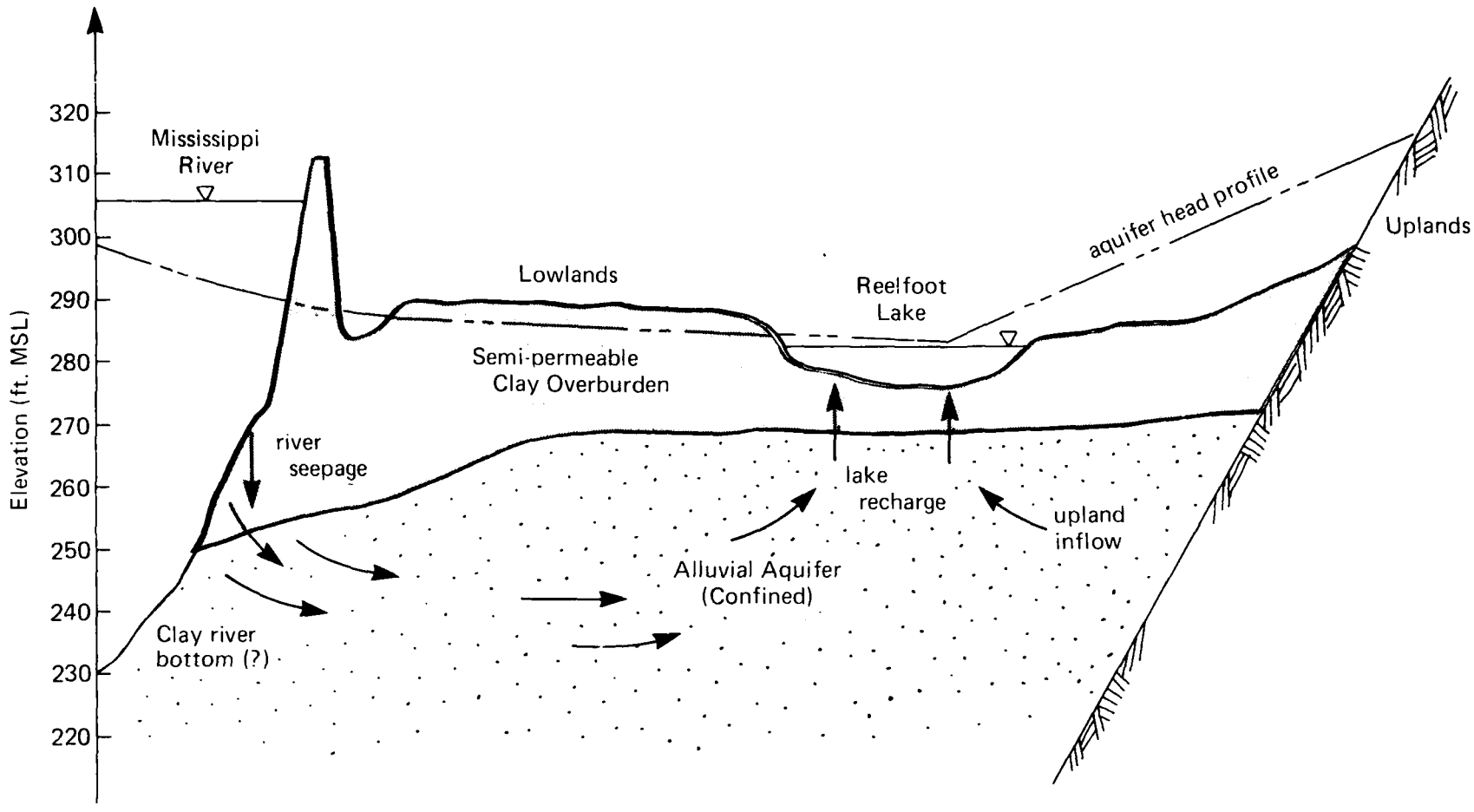


Figure 3-4 Confined Aquifer Model of the Reelfoot Region

downward (infiltrates) when the surface head is higher than the subsurface head and upward (exfiltrates) when the surface head is lower than the subsurface head. The confined model suggests that ground water heads on the landward side of the Mississippi River levee are large enough during high river stages to generate significant exfiltration (or seepage) from the aquifer into local surface waters. This phenomena is discussed in detail in levee design documents such as U.S. Army Corps of Engineers (1978; 1980) and illustrated in Figure 3-4.

It should be noted that the confined model shown in Figure 3-4 assumes that some ground water can move vertically, either upward or downward, through the overburden beneath Reelfoot Lake. The rate of water movement is probably not uniform, but varies with the thickness and composition of the overburden. Upwelling of fresh ground water could account for aerial observations of clear patches amidst the generally turbid waters of the lake.

The vertically homogeneous unconfined model of the alluvial aquifer assumes that the upper boundary of the aquifer is a free surface with approximately hydrostatic conditions applying below. In this case, the amount of water stored in the aquifer can change significantly when the hydraulic head varies. Such a model would be an appropriate description of conditions in the alluvial aquifer if the clay overburden were too conductive to act as a confining layer. The implications of this viewpoint are illustrated in Figure 3-5, which again shows a regional cross-section with aquifer and surface water head lines superimposed.

Figure 3-5 demonstrates, in contrast to Figure 3-4, how unconfined conditions tend to tie the subsurface head profile to surface water elevations. This is particularly evident at the river, where the aquifer head merges with the river stage. The unconfined model implies that flows between the aquifer and the river or lake are horizontal rather than vertical and that groundwater gradients are large near the river and uplands boundaries. Robbins (1985) adopts the unconfined aquifer assumption in his two-dimensional computer model of the alluvial aquifer. Subsurface heads in this model are tied to surface water elevations at the river, at Reelfoot Lake, and along major streams. Flow along the eastern upland boundary is set equal to a seasonally varying value estimated from well observations taken on the east side of the lake. Robbins (1985) indicates that water levels predicted by his model are generally within a few feet of observed values for the periods August-September and November-December, 1984.

It is likely that reality lies somewhere between the extremes implied by the two conceptual models postulated here. Available evidence suggests that interaction between the surface and subsurface systems varies throughout the region, sometimes reflecting confined conditions and sometimes reflecting unconfined conditions. The most accurate conceptual model of the Reelfoot flow system would be a fully three-dimensional description which accounts explicitly for spatial variability. Unfortunately, we do not currently have

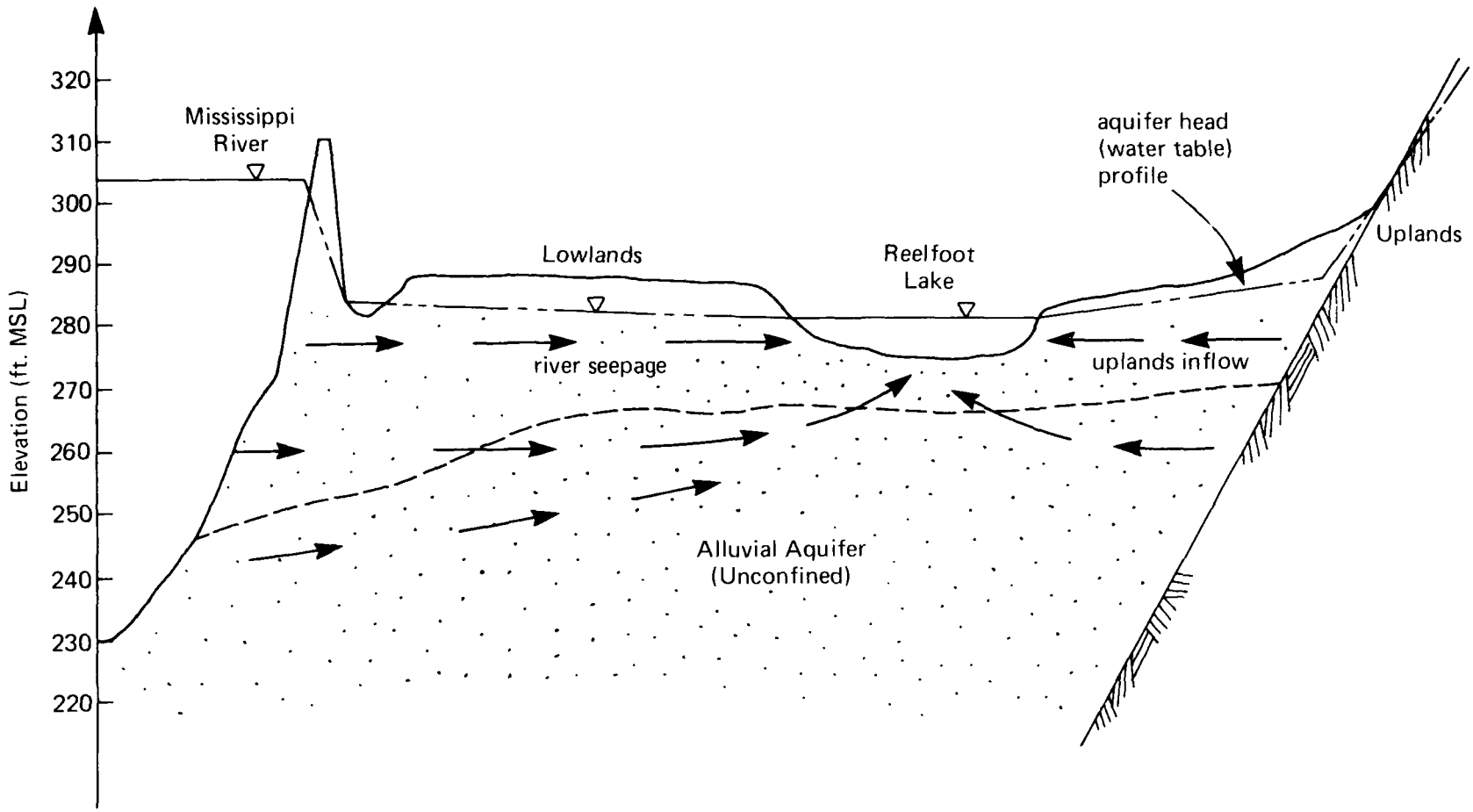


Figure 3-5 Unconfined Aquifer Model of the Reelfoot Region

enough data to develop such a description. Management studies undertaken in the near future will probably have to rely on relatively simple two-dimensional models similar to those described above.

The primary sources of information on surface-subsurface interactions in the Reelfoot region are the geological observations described in Strausberg and Schreuers (1958) and U.S. Army Corps of Engineers (1980) and the ground water level measurements collected by the United States Geological Survey (1986) during 1984-1986. Although it is far from definitive, this information can help us decide which of the two simplified models is closest to reality. A preliminary analysis is presented in the following two subsections.

Geohydrologic Data

As mentioned in Chapter 2, the geological maps presented in U.S. Army Corps of Engineers (1980) indicate that the clay overburden is essentially continuous over the region between the river and the upland boundary. This is not suprising, given the common alluvial origins of the clay deposits laid down in the historic floodplain. The overburden is sufficiently impermable in the vicinity of the Mississippi River levee to require the use of relief wells to moderate subsurface pressure fluctuations near concrete culverts and channels (U.S. Army Corps of Engineers, 1974). There is good reason to believe that the hydraulic properties observed near the levee apply throughout much of the inland region as well. Although geological evidence supports the confined aquifer hypothesis, it is too limited to be conclusive. It is useful to supplement geological observations with a hydrologic analysis based on the USGS water level data set.

The USGS water level data suggest that subsurface flow patterns in the alluvial aquifer depend primarily on the elevation of the Mississippi River and on antecedent precipitation. We can examine these effects in some detail if we identify four quasi-steady-state scenarios which correspond to the following conditions: 1) high river-high rainfall, 2) high river-low rainfall, 3) low river-high rainfall, and 4) low river-low rainfall. Detailed definitions of these scenarios are provided in Table 3-2. The second column of this table identifies USGS well observation dates which meet the requirements of each scenario definition. The final column indicates the months when each of the scenarios is most likely to occur. These selections are based on river stage duration data reported by the U.S. Army Corps of Engineers (1974) and on the monthly average hydrologic data plotted in Figure 2-3.

Table 3-3 lists available well water level measurements and representative river and lake elevations for each of the four scenario dates. The wells are grouped by their general location (more exact locations are indicated in Figure 2-7). Although drilling logs giving information on screen depths and installation procedures for these wells are not available, we assume here that the recorded water levels measure

TABLE 3-2

HYDROLOGIC SCENARIO DEFINITIONS FOR
THE REELFOOT LAKE REGION

Scenario	Date	River condition	Rainfall condition	Most likely months
1	9 Jan, 1985	high	high	March - May
2	12 Dec, 1985	high	low	Dec. - Feb
3	24 Oct, 1984	low	high	Oct. - Feb.
4	20 Sept, 1985	low	low	June - Oct.

TABLE 3-3

SELECTED SURFACE AND SUBSURFACE WATER LEVEL MEASUREMENTS
FOR THE REELFOOT LAKE REGION
(all elevations in feet MSL)

Location	Scenario 1 9 Jan, 1985	2 12 Dec, 1985	3 24 Oct, 1984	4 20 Sep, 1985
Surface water gages				
River @ HW173	292	296	268	267
River @ Tiptonville	279	282	254	253
Reelfoot Lake	283	282	283	281
Wells				
Eastern boundary				
8	---	280	281	279
10	289	287	288	285
11	317	313	308	309
12	305	300	300	300
15	306	296	295	295
17	283	282	281	280
River boundary				
19	288	284	283	281
34	289	284	284	284
36	286	283	281	280
39	291	290	280	280
41	296	298	<280	<280
42	288	286	285	282
43	283	283	278	<278
Interior lowlands				
18	285	280	---	281
21	284	283	283	282
22	283	282	283	282
23	286	284	284	284
24	282	282	282	282
25	281	280	280	280
32	282	281	280	280
35	287	284	284	284
38	286	284	284	280

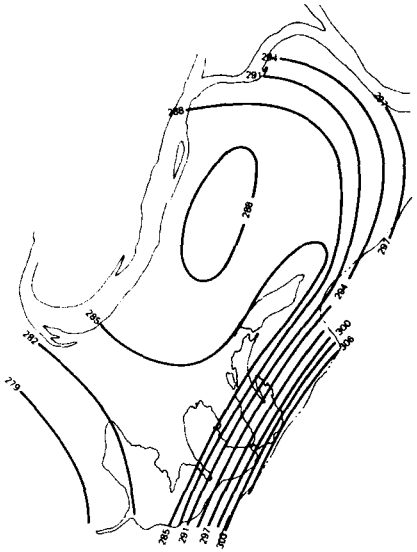
vertically averaged aquifer heads.

The data presented in Table 3-3 suggest that ground water heads in the Reelfoot region fluctuate very little over time except at a few scattered wells. Wells RF19, 34, 36, and 39 through 43 seem to be affected by the river while wells RF18, 19, 34, and 36 seem to be affected by antecedent precipitation infiltrating into the aquifer. There does not appear to be any consistent pattern in the temporal fluctuations noted in the remaining wells, including those on the eastern side of the lake. The unusually high water levels measured in wells RF11, 12 and 15 are probably related to their location near the upland boundary. There is a good chance that these wells are influenced by upland ground water formations which are not part of the alluvial aquifer, although there is no way to know without inspecting well logs.

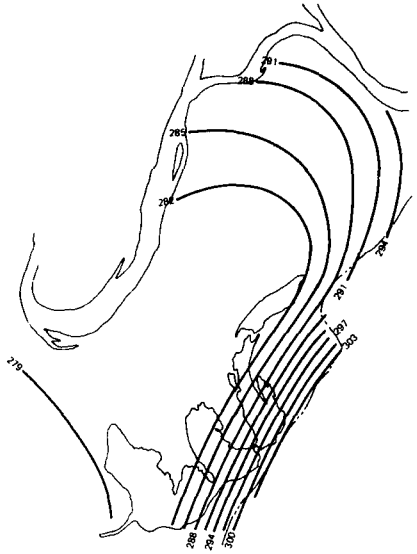
Figure 3-6 shows the vertically averaged head maps obtained for each of the four scenarios if measurements from wells RF11, 12, and 15 are averaged to give a more uniform estimate of near-upland aquifer heads and confined conditions are assumed (i.e. measurements are contoured independently of the river and lake stages). The plotted area more or less coincides with the portion of the alluvial aquifer extending from the southern end of Reelfoot Lake north to the Mississippi River. The eastern boundary is the upland bluff line which runs from Samburg, TN to Hickman KY. The maps in Figure 3-6 are consistent with a confined aquifer model of the region since they do not explicitly account for the influence of boundary conditions imposed at the river and lake. The effects of these surface waters may, however, be reflected in the head contours obtained from well observations located further inland.

It should be noted that the relatively limited spatial coverage of available well observations leaves much room for interpretation in the contouring process, particularly in the areas between widely spaced wells. In some cases, we have identified major hydrologic features, such as ground water mounds or depressions, from only one or two well observations. Moreover, head differences between nearby wells located in the middle of the lowland flood plain (e.g. wells 22 and 23 or wells 19 and 36) can be as large as head differences between more widely spaced wells in the same region. The contour maps presented here and in other reports using the same basic data set (e.g. Robbins, 1985) really only give a rough indication of regional flow patterns. This should be recognized when subsurface flow estimates derived from such maps (either with or without the aid of a computerized simulation model).

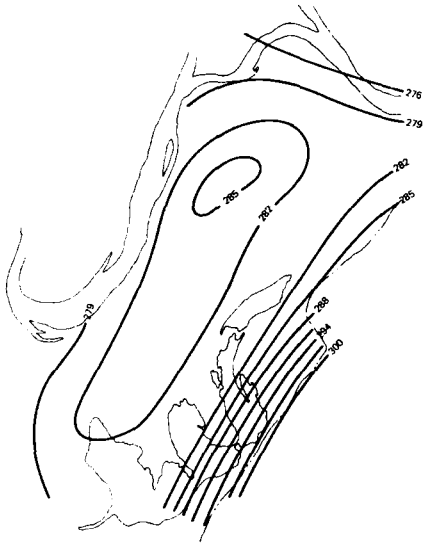
Despite the obvious limitations of the available database, the head contour maps enable us to draw some general conclusions about subsurface flow patterns and surface-subsurface interactions in the Reelfoot region. Such maps can be interpreted in much the same way as common topographic maps -- water flows down-gradient from regions of high head to regions of low head. The broad arrows superimposed on the maps of Figure 3-6 indicate the



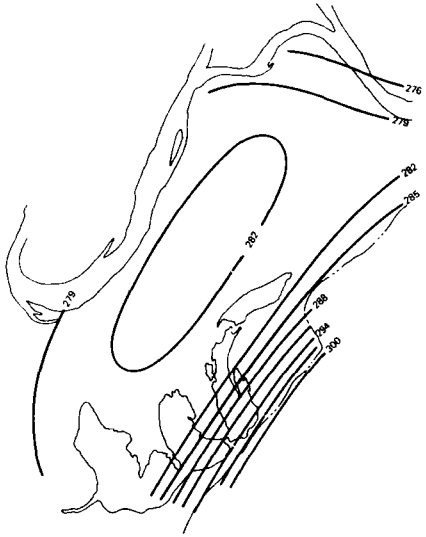
a. Scenario 1 - high river, high rainfall



b. Scenario 2 - high river, low rainfall



c. Scenario 3 - low river, high rainfall



d. Scenario 4 - low river, low rainfall

Figure 3-6 Head Contour Maps for the Four Hydrologic Scenarios

average flow direction at various points in the region. The head gradients are relatively mild over much of the region, the major exceptions being along the uplands boundary to the east of the lake and in the northern lowland region near the Mississippi River (note that the contour line intervals vary). The steeper gradients observed in these areas suggest larger horizontal subsurface fluxes. A convenient graphical technique called flow net analysis can be used to investigate this phenomenon in more detail. A flow net analysis of the Reelfoot ground water data is outlined in the following paragraphs.

Flow Net Analysis

Flow net analysis is a widely used hydrologic technique which provides a convenient way to identify flow paths and estimate fluxes. The basic concepts are described in texts such as Freeze and Cherry (1979) and applications are found throughout the ground water literature. A flow net is a two-dimensional diagram constructed by plotting a set of streamlines on a head contour map. Such diagrams may be plotted in either the horizontal or vertical plane, depending on the application. Figure 3-7 shows a horizontal plane flow net constructed from the Scenario 4 head map of Figure 3-6d. The streamlines are indicated with solid lines and the head (or equipotential) lines are indicated with dashed lines. This flow net is consistent with a confined aquifer model of the region since it does not explicitly account for the influence of boundary conditions imposed at the river and lake. The effects of these surface waters may, however, be reflected in the head contours obtained from well observations located further inland.

Each streamline included in a flow net is drawn so that, at any given time and location, it's tangent vector points in the direction of groundwater flow. If the aquifer's soil properties are isotropic (i.e. do not depend on direction), the velocity vectors point down-gradient and the streamlines are perpendicular to the head contours. If, in addition, the ground water system is in steady-state each streamline coincides with the path taken by a hypothetical parcel of water moving down-gradient from its source to its ultimate destination. The small nearly rectangular regions formed by the intersections of head contours and streamlines are the individual <u>elements</u> of the flow net.

Flow nets may be used to estimate the quantity of water moving through a vertically homogeneous steady-state ground water system. This is accomplished by applying the principle of mass conservation to a control volume which spans adjacent elements of the flow net. Figure 3-8 illustrates the procedure with a small section of the Reelfoot aquifer flow net. Since the element sides are drawn along flow lines, water can enter or leave the elements only across the upstream and downstream head contours or across the top and bottom of the control volume. Also, the change of storage within the control volume must be zero in the steady-state. The element mass balance equation for this volume is therefore:

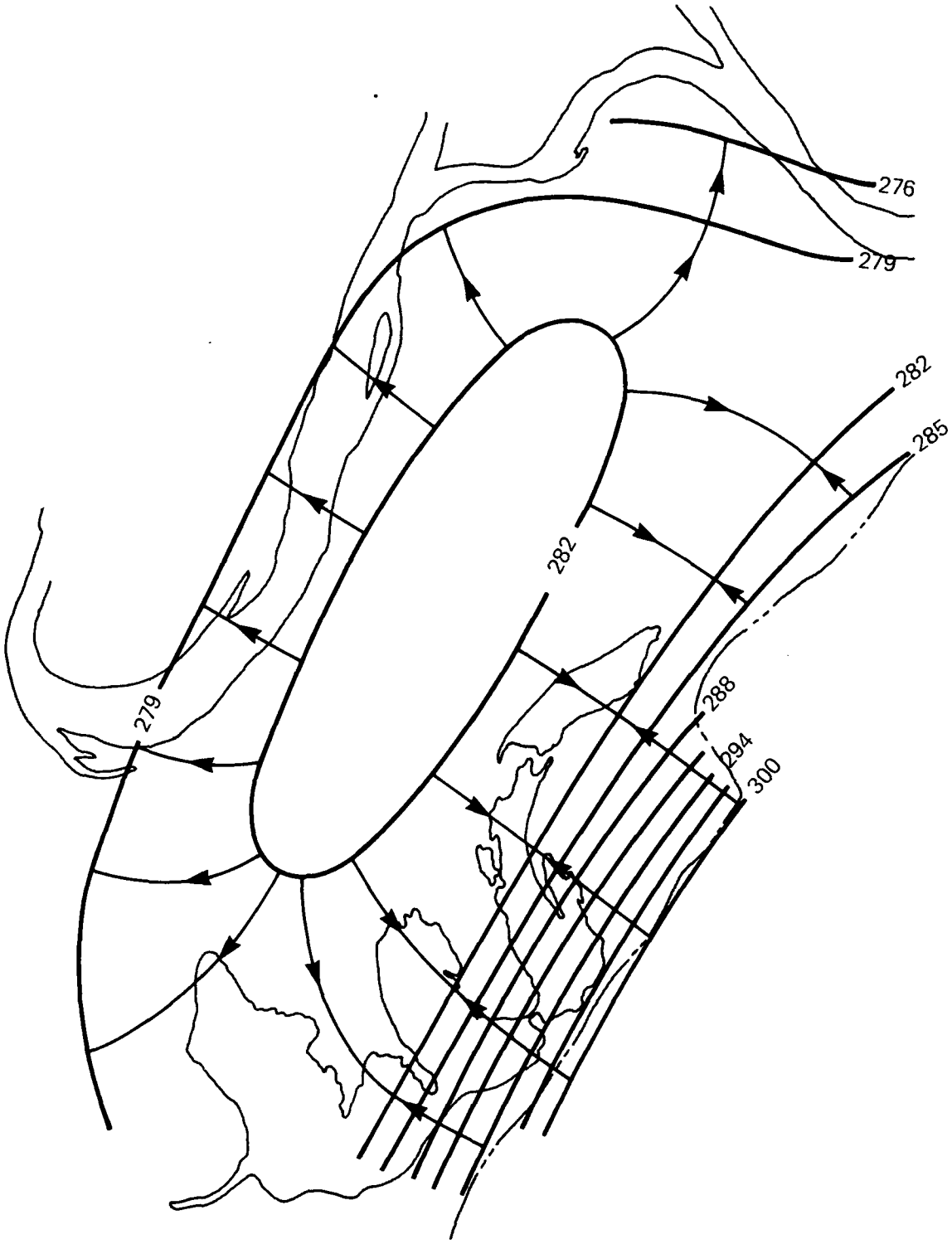


Figure 3-7

Flow Net for Scenario 4 (Confined Conditions)

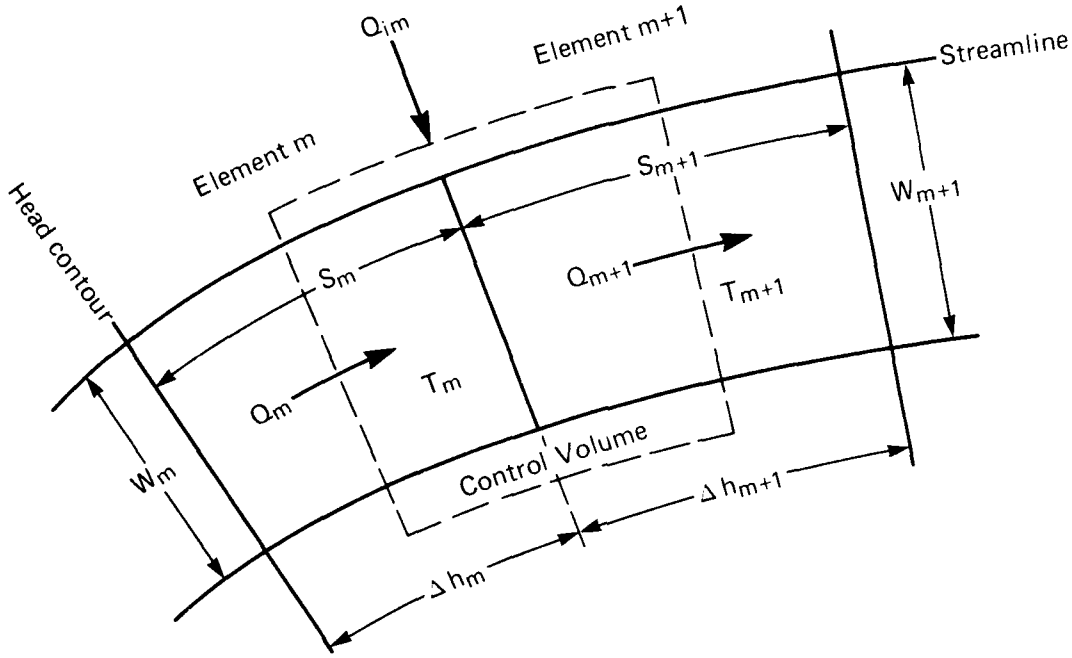


Figure 3-8

Illustration of Flow Net Computations

$$Q_m - Q_{m+1} + Q_{im} = 0 \qquad (3\text{-}5)$$

where:

Q_m = horizontal (vertically averaged) flow through element m, with element numbers understood to increase in the downstream direction (L^3T^{-1})

Q_{im} = net infiltration across the top of control volume m (L^3T^{-1})

Note that the above expression assumes that there is no flow across the bottom of the control volume. This reflects our interest in the alluvial aquifer, which lies above relatively impermeable tertiary layer below the deposits. Infiltration across the bottom boundary could be easily included, if appropriate.

The horizontal element flows appearing in Equation (3-3) may be estimated by applying the following two-dimensional version of Darcy's law (Freeze and Cherry, 1979):

$$Q_m = T_m w_m \Delta h_m / \Delta s_m \qquad (3\text{-}6)$$

where:

T_m = transmissivity in element m (L^2/T)

w_m = average width of element m (L)

Δh_m = difference between the head contour values at the upstream and downstream boundaries of element m (L/L)

Δs_m = average length of element m (L)

In this case we assume, for simplicity, that the flow net elements are approximately rectangular so that the element length and width are nearly constant.

Darcy's law is one of the most fundamental relationships used in ground water hydrology. In the form given in Equation (3-6) it states that the flow per unit width through a uniform porous medium is proportional to the head gradient. The proportionality constant is a soil property called the transmissivity. Transmissivity values tend to be higher where the aquifer

is deep or where it is composed of conductive (e.g. sandy) material. Conversely they tend to be lower where the aquifer is shallow or where it is composed of unconductive (e.g. clay) material. Robbins (1985) reports that pump tests in Mississippi River alluvium similar to that found in the lowlands of the Reelfoot region typically give transmissivities of about 45,500 ft^2/day while the U.S. Army Corps of Engineers (1980) reports that grain size computations from borehole samples near the Mississippi River levee give transmissivities which vary from 12,500 to 47,800 ft^2/day.

When Equations (3-5) and (3-6) are combined, the following expression results:

$$[Tw\Delta h/\Delta s]_m - [Tw\Delta h/\Delta s]_{m+1} + Q_{im} = 0 \qquad (3\text{-}7)$$

where it is understood that subscripts apply to all the variables enclosed in bracketed terms. Equation (3-7) may be simplified if the contour interval is the same for each of the two elements. In this case, the result is:

$$T_m a_m - T_{m+1} a_{m+1} + Q_{im} = 0 \qquad (3\text{-}8)$$

where:

$a_m = w_m/s_m$ = aspect ratio of element m (L/L)

This expression can be used to develop some rules for interpreting flow net diagrams:

1. If infiltration is negligible ($Q_{im} = 0$) and transmissivity is uniform ($T_m = T_{m+1}$), the element aspect ratio should remain constant ($a_m = a_{m+1}$).

2. If infiltration is negligible but the aspect ratio changes ($a_m \neq a_{m+1}$), the element transmissivity changes in accordance with the ratio $T_{m+1}/T_m = a_m/a_{m+1}$.

3. If the transmissivity is uniform but the aspect ratio changes ($a_m \neq a_{m+1}$), the net infiltration is given by $Q_{im} = T_m(a_{m+1} - a_m)$.

Note that Rules 2 and 3 can both explain a change in aspect ratio. Additional information must be supplied before we can determine whether such a change is due to transmissivity variations (Rule 2), infiltration (Rule 3), or both.

The concepts summarized above provide a convenient way to investigate the relative merits of the confined and unconfined aquifer models. The Scenario 4 flow net plotted in Figure 3-7 is consistent with a confined aquifer hypothesis since the river and lake heads are not imposed as boundary conditions. If an unconfined aquifer hypothesis is adopted, the river and lake can be expected to control aquifer heads near the flow net boundaries. These boundary effects can be included if contours of constant river elevation and constant lake level are added to the net. The contours may be estimated from water surface measurements taken at Hickman, KY and HW173 (for the river) and at Tiptonville, TN (for the lake). The Scenario 4 gage readings give an average river slope of 0.5 feet/mile and a lake elevation of 281 feet MSL. Figure 3-9 shows the revised Scenario 4 flow net obtained when the river and lake boundary conditions are imposed. It is apparent that the river boundary, in particular, has a dramatic effect.

The dramatic change in head gradient observed near the river boundary of the unconfined flow net produces a large contrast in the element aspect ratio along a line moving inland from the river. From the rules given above we know that this implies a change in transmissivity, infiltration from the surface, or some combination of both. If infiltration is assumed to be zero and the transmissivity is assumed to have the 45,500 ft^2/day value reported by Robbins (1985), Equation (3-8) implies that the transmissivity further inland is at least ten times larger. Such a large transmissivity contrast is unlikely given available geological information, particularly since it would have to extend along the entire river boundary. If, on the other hand, the transmissivity is assumed to have a uniform value of 45,500 ft^2/day, Equation (3-8) implies that the infiltration rate near the river is approximately 0.8 in/day. This is unrealistically large for Scenario 4 conditions when rainfall is small and the ephemeral streams in the area are typically dry.

Although the aspect ratio contrast obtained with an unconfined flow net could be explained by the combined effect of a smaller transmissivity contrast and a smaller infiltration rate, it seems unlikely that such a combination would be much more plausible than either of the two extreme cases considered above. In reality, the river boundary condition creates an artificially large subsurface flow which cannot be explained. There is simply no source for all the water which would have to enter the river if this boundary condition were correct. The only surface water in the region during the dry conditions of Scenario 4 is Reelfoot Lake. But the head gradients between the lake and the river are very mild, suggesting that subsurface flows in this area are small.

In light of these results and the geological evidence cited earlier, we feel that the unconfined aquifer hypothesis does not apply near the river. In particular, the river elevation should not be used as a boundary condition, either in a flow net analysis or in a more elaborate computer simulation of ground water flow. This is in direct contrast to the approach taken in the modeling study described by Robbins (1985). We believe that

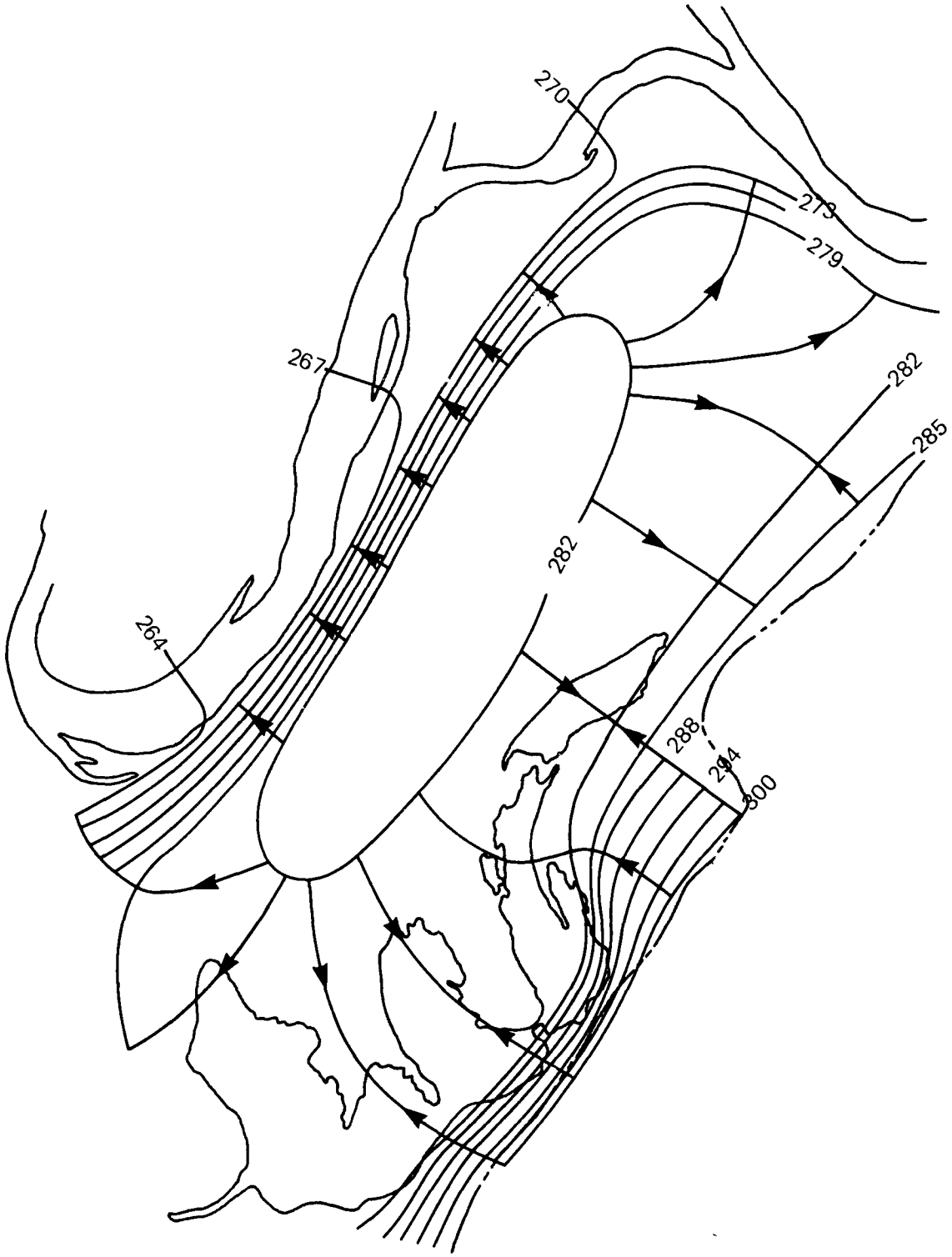


Figure 3-9

Flow Net for Scenario 4 (Unconfined Conditions)

available evidence indicates that flow between the river and the aquifer moves vertically rather than horizontally, in response to differences between the aquifer and river heads. The mechanism for this vertical interaction is illustrated in the vertical plane flow net drawn in Figure 3-10. The same basic process probably applies to vertical interactions between the aquifer and Reelfoot Lake and between the aquifer and Running Slough.

If we now adopt the confined aquifer hypothesis we can use flow nets based on Figure 3-6 to examine surface-subsurface interactions in various sections of the Reelfoot region. In particular, we can estimate the aquifer-lake ($\epsilon_{\ell n}$) and aquifer-stream (ϵ_{sn}) exfiltration rates which appear in Equations (3-3) and (3-4). It is apparent from the maps of Figure 3-6 that there is a significant change in head gradient (and, therefore, in element aspect ratio) on the east side of the lake and a somewhat smaller change in the vicinity of Running Slough. Both of these appear to be the result of exfiltration (negative infiltration) from the aquifer to the surface. Table 3-4 summarizes the flow net computations used to obtain estimates for the Running Slough and Reelfoot Lake exfiltration rates. These are based on Equation (3-8). The Running Slough exfiltration rates show more variation than the lake exfiltration rates and are, as might be expected, considerably smaller. These scenario-oriented flux estimates are used in the seasonal water balance computations described in Section 3.3.

Summary

The flow net analysis presented above provides a physically reasonable, though somewhat speculative, picture of subsurface water movement in the Reelfoot Lake region. The alluvial ground water system appears to act as a leaky confined aquifer, as illustrated in Figure 3-4. Water enters this aquifer primarily as subsurface inflow from the eastern uplands and leaves primarily as subsurface outflow across the region's southern boundary. There is also some ground water inflow from river seepage during periods when the river stage is high. Relatively small amounts of ground water appear to flow into the surface water system, primarily into Running Slough and Reelfoot Lake. Infiltration from the surface to the alluvial aquifer occurs primarily in the western lowland region during wet periods. Regional subsurface fluxes and head gradients are relatively small except along the eastern shore of Reelfoot Lake. There is little seasonal variability in subsurface flow except in the areas influenced by river seepage.

3.3 FLOW ESTIMATION

The conceptual models and hydrologic analyses presented in Section 3.2 indicate how the fluxes appearing in the Reelfoot Lake water budget equations (Equations (3-3) and (3-4)) can be estimated from available data sources. In this section we develop specific quantitative flux estimates which can be used in quarterly and annual long-term average water budgets.

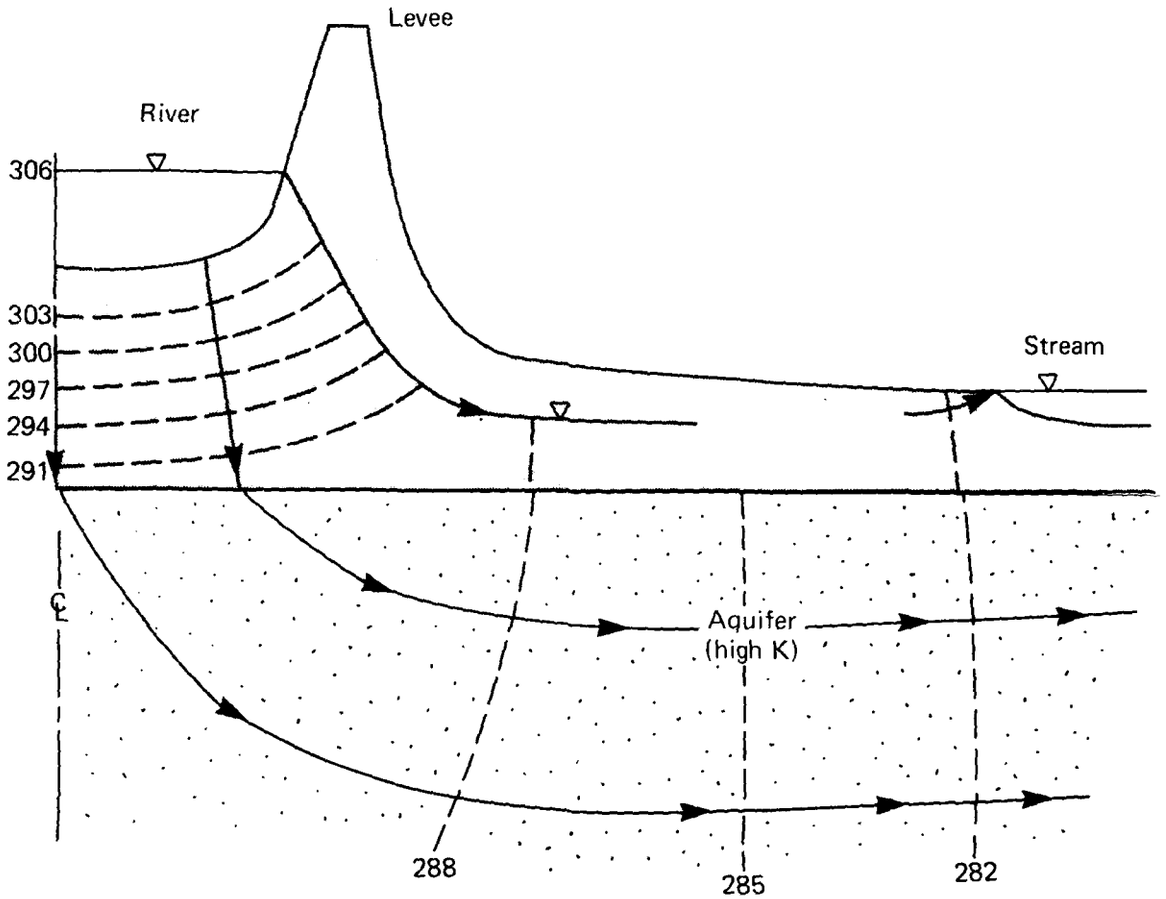


Figure 3-10

Stream-aquifer Interactions

TABLE 3-4

GROUND WATER FLOW NET COMPUTATIONS
FOR THE REELFOOT LAKE REGION (BY SCENARIO)
(TAF = thousands of acre-feet)

Variable	Scenario 1	2	3	4
Net exfiltration from aquifer into Running Slough				
Upstream head gradient (feet/mi)	2.5	2.5	0.8	0.8
Upstream transmissivity (ft^2/day)	26,000	26,000	26,000	26,000
Upstream flow width (mi)	5	5	5	5
Upstream flow (AF/day)	7.5	7.5	2.4	2.4
Downstream head gradient (feet/mi)	0.0	1.1	1.3	1.3
Downstream transmissivity (ft^2/day)	26,000	26,000	26,000	26,000
Downstream flow width (mi)	5	5	5	5
Downstream flow (AF/day)	0.0	3.3	3.9	3.9
Net exfiltration (AF/day)	7.5	4.2	-1.5	-1.5

TABLE 3-4
(continued)

Variable	Scenario 1	2	3	4
Net exfiltration from aquifer into Reelfoot Lake				
Upstream head gradient (feet/mi)	24.0	18.0	16.0	16.0
Upstream transmissivity (ft^2/day)	26,000	26,000	26,000	26,000
Upstream flow width (mi)	12	12	12	12
Upstream flow (AF/day)	171.9	128.9	114.6	114.6
Downstream head gradient (feet/mi)	2.0	2.0	2.0	0.0
Downstream transmissivity (ft^2/day)	26,000	26,000	26,000	26,000
Downstream flow width (mi)	12	12	12	12
Downstream flow (AF/day)	14.3	14.3	14.3	0.0
Net exfiltration (AF/day)	157.6	114.6	100.3	114.6

We also discuss connections between the average conditions considered in the long-term water budgets and the more extreme conditions considered in the four hydrologic scenarios introduced in Section 3.2.

The fluxes and storage terms which form the basis for our water budget analysis can be conveniently categorized as follows (see Equations (3-3) and (3-4)):

Inflows:

1. Precipitation ($P_{\ell n}$)

2. Stream inflow (I_{sn})

3. Net exfiltration from the aquifer to the lake ($\epsilon_{\ell n}$)

Outflows

4. Evaporation ($E_{\ell n}$)

5. Stream outflow (Q_{sn})

Storage change

6. Change in lake volume ($S_{n+1} - S_n$)

Estimates of quarterly and annual long-term historical average values for each of these fluxes are developed in the following subsections.

Inflows

1. Precipitation

The total precipitation crossing the surface of Reelfoot Lake over any given time period depends both on the lake surface area and on the areally averaged rainfall intensity. The applicable equation for a quarterly analysis is:

$$P_{\ell n} = A_{\ell}(y_n)p_n \quad ; \quad n = 1,4 \qquad (3\text{-}9)$$

where:

y_n = average lake stage over quarter n (L)

$A_\ell(y_n)$ = lake surface area evaluated at stage y_n (L^2)

p_n = average rainfall intensity over quarter n (LT^{-1})

The area-stage curves shown in Figure 2-8 may be used to derive the required surface area values from the measured lake stages plotted in Figure 2-3. Since the lake stage is nearly always between 282 and 283 feet, the likely range of surface areas is between 12000 and 18400 acre-feet. Table 3-5 gives the quarterly and annual precipitation fluxes obtained when these area figures are combined with the rainfall intensity data plotted in Figure 2-3.

2. *Stream inflow*

The discussion of surface water movement provided in Section 3.2 suggests that surface water inflows to Reelfoot Lake can be estimated by adding exfiltration rates obtained from a ground water flow net analysis to direct runoff rates obtained from seasonally varying runoff coefficients. The applicable equations for each region and quarter are:

$$I_{sn} = C_n A_w p_n + \epsilon_{sn} \quad ; \quad n = 1,4 \tag{3-10}$$

$$C_n = (I_{gn} - \epsilon_{gn})/A_g p_n \tag{3-11}$$

where:

C_n = derived runoff coefficient for quarter n

A_w = total watershed area (L^2)

ϵ_{sn} = net exfiltration from the aquifer into local streams over quarter n (L^3T^{-1})

I_{gn} = total stream discharge over quarter n, as measured at a specified gage (L^3T^{-1})

ϵ_{gn} = net exfiltration from the aquifer into the gaged portion of local streams over quarter n (L^3T^{-1})

A_g = area of the gaged portion of the watershed (L^2)

TABLE 3-5

LONG-TERM AVERAGE PRECIPITATION AND EVAPORATION FLUX COMPUTATIONS FOR REELFOOT LAKE
(TAF = thousands of acre-feet)

Variable	Quarterly values				Annual
	Dec-Feb	Mar-May	June-Aug	Sept-Nov	average
Lake stage (feet MSL)	282.3	282.6	282.2	281.8	282.2
Surface area (acres)	15,547	17,080	15,380	14,183	15,547
Precipitation (in/quarter)	12.06	15.27	11.20	10.80	12.33
Evaporation (in/quarter)	2.04	10.60	16.40	8.80	9.46
Precipitation (TAF/quarter)	15.6	21.7	14.4	12.8	16.13
Evaporation (TAF/quarter)	2.6	15.2	21.1	10.4	12.33

Recall that the stream exfiltration terms are required only in the Running Slough watershed, where the effects of river seepage may be significant.

The Running Slough exfiltration estimates presented in Table 3-4 are expressed in terms of the four hydrologic scenarios used to characterize river stage and precipitation conditions in the Reelfoot region. We need to convert these scenario-based estimates into seasonal (quarterly) values which can be used in our historical water budget analysis. The best way to do this is to determine the fraction of time that each scenario applies during each season. Each quarterly exfiltration estimate may then be expressed as a weighted sum of the four scenario values. The applicable equation is:

$$\epsilon_{sn} = f_{1n}\epsilon'_{s1} + f_{2n}\epsilon'_{s2} + f_{3n}\epsilon'_{s3} + f_{4n}\epsilon'_{s4} \quad ; \quad n = 1,4 \qquad (3\text{-}12)$$

where:

ϵ'_{sm} = stream exfiltration for scenario m (L^3T^{-1})

f_{mn} = fraction of Scenario m allocated to quarter n

Table 3-6 gives approximate allocation fractions derived from a few years of daily river stage measurements collected at HW gage 173 and daily precipitation measurements collected at the Samburg TN rain gage. These fractions are generally consistent with the scenario definitions introduced in Table 3-2, indicating that high river, high rainfall conditions are most common in the winter and spring while low river, low rainfall conditions are most common in the summer and fall.

Table 3-7 gives the seasonal Running Slough exfiltration rates obtained from Equation (3-12). It is apparent that the allocated exfiltration rates are significant only in the winter and spring. The fall rate is very slightly negative, indicating that a small amount of surface water may infiltrate from the stream into the aquifer during this period.

Table 3-8 summarizes the computations used to derive the upland and lowland runoff coefficients used in our water budget analysis (Equation (3-11)). The Reelfoot Creek discharge depths and Samburg TN precipitation rates used to estimate the upland runoff coefficients both span a period of about 22 years. The Running Slough discharge depths and corresponding Samburg TN precipitation rates used to estimate the lowland runoff coefficients cover a much shorter period (about 21 months). Also, the Reelfoot Creek gage measures flow from about 85 percent of the upland drainage area while the Running Slough gage measures flow from only about 15 percent of the lowland drainage area. These observations suggest that the lowland runoff coefficients are probably less representative of long-term average conditions than their upland counterparts. Nevertheless, the

TABLE 3-6

SCENARIO ALLOCATIONS FOR THE REELFOOT LAKE REGION

Scenario	Quarterly fraction				Annual
	Dec-Feb	Mar-May	June-Aug	Sept-Nov	fraction
1	0.40	0.70	0.20	0.10	0.35
2	0.40	0.10	0.20	0.10	0.20
3	0.10	0.10	0.30	0.20	0.175
4	0.10	0.10	0.30	0.60	0.275

TABLE 3-7

LONG-TERM AVERAGE EXFILTRATION COMPUTATIONS
FOR THE REELFOOT LAKE REGION
(TAF = thousands of acre-feet)

Scenario	Quarter				Annual
	Dec-Feb	Mar-May	June-Aug	Sept-Nov	average
Net exfiltration from aquifer into Running Slough (TAF/quarter)					
1	0.27	0.47	0.14	0.07	0.24
2	0.15	0.04	0.08	0.04	0.08
3	-0.01	-0.01	-0.04	-0.04	-0.03
4	-0.01	-0.01	-0.04	-0.08	-0.04
Total	0.40	0.49	0.14	-0.01	0.25
Net exfiltration from aquifer into Reelfoot Lake (TAF/quarter)					
1	5.67	9.93	2.84	1.42	4.97
2	4.13	1.03	2.06	1.03	2.06
3	0.90	0.90	2.71	1.81	1.58
4	1.03	1.03	3.09	6.19	2.84
Total	11.73	12.89	10.70	10.44	11.45

TABLE 3-8

SURFACE WATER RUNOFF COEFFICIENT COMPUTATIONS
FOR THE REELFOOT LAKE REGION
(TAF = thousands of acre-feet)

Variable	Quarterly values Dec-Feb	Mar-May	June-Aug	Sept-Nov	Annual average
Upland Runoff Coefficient					
Reelfoot Creek discharge (TAF/quarter)	32.1	33.9	10.7	8.5	21.3
Reelfoot Creek gaged area (mi^2)	110	110	110	110	110
Reelfoot Creek runoff (in/quarter)	5.46	5.79	1.83	1.47	3.64
Precipitation (in/quarter)	12.06	15.27	11.20	10.80	12.33
Upland runoff coef. (unitless)	0.45	0.38	0.16	0.14	0.30

TABLE 3-8
(continued)

Variable	Quarterly values Dec-Feb	Mar-May	June-Aug	Sept-Nov	Annual average
Lowland Runoff Coefficient					
Running Slough discharge (TAF/quarter)	3.3	4.7	0.4	0.3	2.2
Running Slough exfiltration (TAF/quarter)	0.4	0.5	0.1	- 0.0	0.3
Running Slough runoff (TAF/quarter)	2.9	4.2	0.3	0.3	1.9
Running Slough gaged area (mi^2)	11	11	11	11	11
Running Slough runoff (in/quarter)	4.9	7.2	0.5	0.5	3.3
Precipitation (in/quarter)	11.1	14.4	16.2	13.5	13.8
Lowland runoff coef. (unitless)	0.44	0.50	0.03	0.04	0.25

general pattern of seasonal variation exhibited by the upland and lowland runoff coefficients is similar and the magnitudes are reasonably close, especially during the wetter winter-spring period. Although the runoff coefficients are only rough approximations, they probably give a reasonable qualitative indication of the relative importance of surface inflows to Reelfoot Lake.

The complete set of stream inflow computations for the upland and lowland regions is summarized in Table 3-9. These computations reveal that seepage-induced exfiltration in the lowland region is minor compared to direct runoff. In terms of more familiar units, exfiltration provides a baseflow of between 0.0 and 2.8 ft^3/sec, depending on season, as compared to runoff-related discharge of between 7.0 and 120.0 ft^3/sec. The upland and lowland contributions to total stream inflow are in rough proportion to their respective drainage areas, as might be expected given the similarity of the derived runoff coefficients for the two regions.

3. *Exfiltration from the aquifer to the lake*

The flow net analysis described in Section 3.2 provides estimates of the amount of ground water flowing from the alluvial aquifer into Reelfoot Lake for each of the four hydrologic scenarios. These exfiltration estimates, which are summarized in Table 3-4, need to be converted into seasonal (quarterly) values which can be used in our historical water budget analysis. The required seasonal estimates can be obtained by applying the weighting approach described earlier. The applicable equation is:

$$\epsilon_{\ell n} = f_{1n}\epsilon'_{\ell 1} + f_{2n}\epsilon'_{\ell 2} + f_{3n}\epsilon'_{\ell 3} + f_{4n}\epsilon'_{\ell 4} \quad ; \quad n = 1,4 \qquad (3\text{-}13)$$

where:

$\epsilon'_{\ell m}$ = lake exfiltration for scenario m (L^3T^{-1})

f_{mn} = fraction of Scenario m allocated to quarter n

The allocation fractions appearing in this expression are defined in Table 3-6. Table 3-7 gives the resulting Reelfoot Lake exfiltration rates for each quarter. Note that the seasonal fluctuations in these rates are relatively small. This is reasonable considering that exfiltration into the lake is controlled by the difference between the lake stage and the head in the underlying aquifer. Both of these quantities vary relatively little over the year.

It is instructive to evaluate the vertical hydraulic conductivity needed to achieve the average lake exfiltration rate given in Table 3-7. This can be inferred from the following form of Darcy's law:

TABLE 3-9

LONG-TERM AVERAGE STREAM INFLOW COMPUTATIONS FOR REELFOOT LAKE
(TAF = thousands of acre-feet)

Variable	Quarterly values Dec-Feb	Mar-May	June-Aug	Sept-Nov	Annual average
Upland Stream Inflows					
Precipitation (in/quarter)	12.06	15.27	11.20	10.80	12.33
Runoff coef. (unitless)	0.45	0.38	0.16	0.14	0.30
Runoff (in/quarter)	5.46	5.79	1.83	1.47	3.64
Drainage area (mi^2)	130	130	130	130	130
Total discharge (TAF/quarter))	37.9	40.0	12.6	10.1	25.2

TABLE 3-9
(continued)

Lowland Stream Inflows					
Precipitation (in/quarter)	12.06	15.27	11.20	10.80	12.33
Runoff coef. (unitless)	0.44	0.50	0.03	0.04	0.25
Runoff (in/quarter)	5.30	7.64	0.34	0.43	3.43
Drainage area (mi^2)	74	74	74	74	74
Total runoff (TAF/quarter)	20.9	30.2	1.3	1.7	13.5
Exfiltration (TAF/quarter)	0.4	0.5	0.1	-0.0	0.3
Total discharge (TAF/quarter)	21.3	30.7	1.4	1.7	13.8

$$K_v = \frac{D\epsilon_\ell}{A_\ell(h_a - h_\ell)} \tag{3-14}$$

where:

K_v = vertical hydraulic conductivity of "confining" layer (LT^{-1})

D = thickness of confining layer (L)

ϵ_ℓ = vertical ground water flow (L^3T^{-1})

A_ℓ = effective flow area (L^2)

h_a = hydraulic head in aquifer (L)

h_ℓ = water surface elevation in lake (L)

Although most of the variables appearing in this equation are highly uncertain, it is possible to obtain a rough estimate of K_v by assuming the following "typical" values:

ϵ_ℓ = 12.0 TAF/quarter

A_ℓ = 7500 acres (approximate area of the eastern half of the lake)

D = 25 feet

h_ℓ = 282 feet MSL

h_a = 285 feet MSL

In this case, K_v is about 0.15 ft/day or 5.0×10^{-5} cm/sec. This value is similar to those given by the U.S. Army Corps of Engineers (1980) for vertical hydraulic conductivities in the vicinity of the Mississippi River levee. Although these calculations are highly speculative and uncertain, they do lend some credibility to the exfiltration estimates obtained from the flow net analysis.

Outflows

4. *Evaporation*

An analysis similar to the rainfall flux computation outlined above may be used to estimate the total flux of water leaving the surface of Reelfoot Lake via evaporation. The applicable equation is:

$$E_{\ell n} = A_{\ell}(y_n)e_n \quad ; \quad n = 1,4 \qquad (3\text{-}15)$$

where:

e_n = average pan evaporation rate over quarter n (LT^{-1})

Table 3-5 gives the quarterly and annual evaporation fluxes obtained when the lake surface area values discussed earlier are combined with the pan evaporation data plotted in Figure 2-3.

5. *Stream outflow*

Here we briefly consider how the operating rule approach described in Section 3.2 can be used to evaluate historical long-term average outflows from the Reelfoot Lake spillway. An approximate historical operating rule may be derived from daily discharge measurements collected at stream gage 07027010, which is located on Running Reelfoot Bayou less than one mile downstream of the spillway. The record at this gage covers about thirty months during the period 1982 through 1985. Figure 3-11 is a plot of the apparent daily spillway discharge versus the daily lake stage at a depth gage located a few hundred yards upgradient from the spillway (Reelfoot Lake gage 07027000). Although there is much scatter in this plot, it does suggest that spillway outflows during the 1982-1985 period tended to increase when the lake stage was high. The outflow data appear to divide into two distinct sets which reflect, respectively, gradual and abrupt changes in spillway discharges. This division may be due to a change in operating practices during the period of record or it may reflect the effects of increasing leakage.

It is possible to fit the historical daily stage-discharge record with a smooth function and then derive long-term average discharge records from long-term average lake stages. Although there are many ways to do this, the approach outlined in the following paragraphs is sufficiently general to illustrate the basic concept. We begin by assuming a daily operating rule which has the following quadratic form:

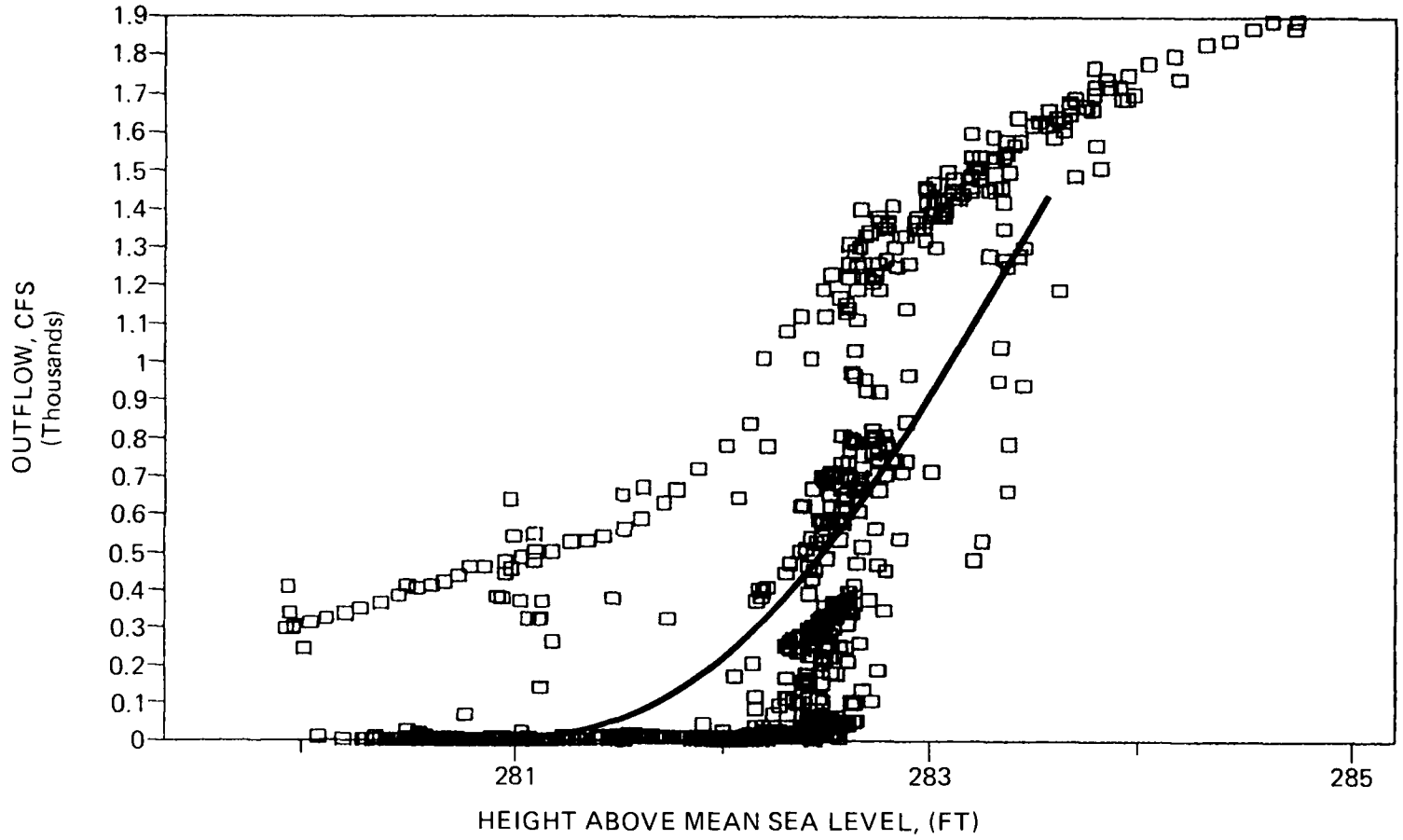


Figure 3-11 Historical Daily Discharge and Stage Val es for the Reelfoot Lake Spillway

$$q_s(y) = \alpha(y - y_o)^2 \quad ; \quad y \geq y_o \tag{3-16}$$

$$q_s(y) = 0 \quad ; \quad y < y_o$$

where:

q_s = daily spillway discharge (L^3T^{-1})

y = measured daily average lake stage at gage 07027000 (L)

y_o = stage at which release goes to zero (L)

α = specified coefficient (LT^{-1})

The coefficients y_o and α may be adjusted to obtain the desired discharge response. For present purposes we adopt the rule curve illustrated with a solid line in Figure 3-11. This curve increases spillway outflows gradually, starting from a threshold of 281.22 feet MSL. The resulting operating rule coefficients are:

$$\alpha = 222 \text{ feet/sec}$$

$$y_o = 281.22 \text{ feet MSL}$$

It is important to note that we do not claim that this quadratic rule curve was actually used to determine spillway outflows over the 1982-1985 period. In reality, lake outflows over the last several years do not appear to be the result of any consistent operating policy. These outflows are most likely due to the combined effects of unintentional leakage and haphazard adjustments to the aging spillway structure. Our curve is intended only to provide a convenient description of available observations. If future discharges are regulated more consistently, rule curve computations can be expected to provide more accurate estimates of lake outflow.

The total spillway discharge over a period extending between times t_1 and t_2 may be derived by integrating the rule curve equation:

$$Q_{sn} = \int_{t_n}^{t_{n+1}} q_s[y(t)]\, dt = \int_{t_n}^{t_{n+1}} \alpha(y - y_o)^2\, dt \tag{3-17}$$

In order to integrate this equation we need to know how the daily lake stage varies over time. Long-term records indicate that the average daily stage

can be approximated reasonably well by a sinusoidal function with a period of one year (see Figure 2-3):

$$y(t) = 282.22 + 0.5\mathrm{Sin}(0.0172t) \tag{3-18}$$

Here the time t is the number of days elapsed since February 1. When Equation (3-18) is substituted into Equation (3-17) and the integration is performed the result is:

$$Q_{sn} = \alpha \left\{ 1.125(t_{n+1} - t_n) + 58.14[\mathrm{Cos}(0.0172t_n) - \mathrm{Cos}(0.0172t_{n+1})] + 3.63[\mathrm{Sin}(0.0344t_n) - \mathrm{Sin}(0.0344t_{n+1})] \right\} \tag{3-19}$$

This expression gives the average lake outflow which would have been obtained over the period between t_n and t_{n+1} if the operating rule of Equation (3-16) had been used to determine the spillway release. The quarterly stream outflow estimates given in Table 3-10 were obtained by substituting the indicated values of t_n and t_{n+1} into Equation (3-19). Of course, these estimates are based on simplified approximations to actual historical conditions and should be viewed with some scepticism. Nevertheless, the operating rule approach appears to provide a useful way to estimate spillway outflows, particularly when discharge data are highly variable and only cover a relatively brief period.

Storage Change

6. *Change in lake volume*

The final element of the long-term average water budget for Reelfoot Lake is the change-in-storage term which appears on the left-hand side of Equation (3-3). This term may be evaluated by combining the lake stage values plotted in Figure 2-3 with the lake area-stage curves plotted in Figure 2-8. The applicable equation is:

$$S_{n+1} - S_n = A_\ell(y_n)(y_{n+1} - y_n) \quad ; \quad n = 1,4 \tag{3-20}$$

The resulting storage change computations are summarized in Table 3-11. Note that the annual storage change is zero since the long-term average lake stage is periodic (i.e. the lake level at the end of the year returns to its initial value). Also, the summer decline in storage is as large as the total storage increase observed over the other three seasons. This is a direct consequence of the nonlinear shape of the area-stage curve.

TABLE 3-10

LONG-TERM AVERAGE STREAM OUTFLOW COMPUTATIONS
FOR REELFOOT LAKE
(TAF = thousands of acre-feet)

Variable	Quarterly values				Annual
	Dec-Feb	Mar-May	June-Aug	Sept-Nov	average
t_n	-30	61	153	245	
t_{n+1}	60	152	244	335	
Total discharge (TAF/quarter)	51.0	82.0	33.0	12.0	44.5

TABLE 3-11

LONG-TERM AVERAGE STORAGE CHANGE COMPUTATIONS FOR REELFOOT LAKE
(TAF = thousands of acre-feet)

Variable	Quarterly values			
	Dec-Feb	Mar-May	June-Aug	Sept-Nov
Lake stage (ft. MSL) (final)	282.38	282.54	281.82	282.08
Lake stage (ft. MSL) (initial)	282.08	282.38	282.54	281.82
Increase in lake stage (ft.)	0.30	0.16	-0.72	0.26
Average lake surface area (acres)	18,400	18,400	17,200	14,800
Increase in lake storage (TAF/quarter)	5.5	3.0	-12.4	3.9

3.4 WATER BUDGETS

The computations summarized in the tables of the preceding section provide all the information needed to construct historical quarterly and annual water budgets for Reelfoot Lake. Many of the fluxes presented in these tables can also be used to construct future water budgets which examine the consequences of alternative management strategies. Some typical examples are discussed in the following paragraphs. It should be noted at the outset that the water budgets presented here depend on limited data which are often ambiguous and difficult to interpret. Although the general picture of lake hydrology revealed by these budgets is plausible, some of the component flux estimates may differ significantly from reality. The discussion of data collection issues provided in Chapter 4 attempts to identify the areas where our assumptions are most uncertain and to suggest where additional data are most needed.

Historical Water Budgets

Table 3-12 presents the historic water budgets obtained from the flux and storage change estimates developed in Section 3.3. These budgets reflect long-term average quarterly or annual hydrologic conditions rather than the conditions observed in any particular year. The mass balance error statistics listed at the bottom of the table provide a rough indication of the accuracy of each of the five water budgets. These errors vary considerably from season to season, from a low of 5 percent to a high of 32 percent. The annual error is just under 15 percent, a result which is reasonably good considering the limited amount of data available for some of the component fluxes. Of course, a good mass balance error only indicates that the water budget conserves mass, not that it is correct. It is quite possible that errors in different water budget fluxes cancel, giving a deceptively good mass balance error. This is particularly likely if the hydrologist constructing the budget is able to adjust unknown coefficients (e.g. runoff coefficients or outflow curve slopes) to achieve an artificial balance. Such adjustments should be used with discretion since they are easily abused.

Keeping the uncertainties of the water budget analysis in mind, it is useful to briefly summarize some of the more important conclusions revealed by Table 3-12:

1. Surface water outflows are generally the most important single component of the lake water budget. The primary exception occurs during the fall period when many of the fluxes have similar magnitudes. This is the season when surface water inflows and outflows are at their annual lows.

TABLE 3-12

LONG-TERM AVERAGE REELFOOT LAKE WATER BUDGETS
(All values given in thousands of acre-feet)

Variable	Quarter				Annual total
	Dec-Feb	Mar-May	June-Aug	Sept-Nov	
Inflows					
Precipitation (1)	15.6	21.7	14.4	12.8	64.5
Stream inflow (2)					
upland	37.9	40.0	12.6	10.1	100.6
lowland	21.3	30.7	1.4	1.7	55.1
Net ground water inflow (3)	11.7	12.9	10.7	10.4	45.7
Total inflow	86.5	105.3	39.1	35.0	265.9
Outflows and Storage Change					
Evaporation (4)	2.6	15.2	21.1	10.4	49.3
Stream outflow (5)	51.0	82.0	33.0	12.0	178.0
Increase in lake volume (6)	5.5	3.0	-12.4	3.9	0.0
Total outflow and storage change	59.1	100.2	41.7	26.3	227.3
Mass Balance Error					
Mass balance error	27.4	5.1	-2.6	8.7	38.6
(% of total inflow)	31.7	4.8	-6.7	24.9	14.5

2. Total surface water inflows are much larger than ground water inflows in the winter, spring, and annual water budgets. The groundwater contribution is most significant during the relatively dry summer and fall periods.

3. Lowland stream inflows are insignificant during the drier summer and fall periods when low lake levels are of most concern. They account for about 20 percent of total inflow on an annual basis.

4. Seasonal changes in lake volume are small compared to most other components of the water budget.

These observations and the flow net results discussed in Section 3.2 together suggest that Reelfoot Lake, despite its historic connection with the Mississippi River, is sustained and controlled primarily by surface waters flowing out of its tributary watershed. Surface waters in the lowland region are effectively isolated from the river by the levee system and ground water inflow comes almost entirely from uplands areas which are not connected to the river. These are important conclusions which have both management and research implications.

The historical water budgets provide a good starting point for a number of other related analyses of historical conditions in the lake. For example, a useful measure of the lake's assimilative capacity is provided by the residence time, which may be defined as follows:

$$\tau = V_\ell / Q_s \qquad (3\text{-}21)$$

where:

V_ℓ = Total volume of the lake (L^3)

Q_s = Steady-state flow rate through the lake (L^3T^{-1})

If we assume that Q_s is equal to the annual average surface outflow to Running Reelfoot Bayou and adopt an average lake level of 282.22 ft. MSL, the total storage is about 80,400 acre feet and the residence time is about 0.45 years (5.4 months). This relatively short residence time, which is typical of such shallow water bodies, implies that the waters of the lake are replenished, on the average, nearly twice a year. The residence time is often used in water quality calculations, including formulas which attempt to relate a lake's eutrophic state to nutrient inflows. Such calculations may help shed some light on the factors responsible for the serious eutrophication problems which plague Reelfoot.

Techniques similar to those used to construct the historic water budgets may also be used to develop historic nutrient and sediment budgets. These budgets are based on mass balance equations which resemble Equation (3-3). A sediment mass balance equation for Reelfoot Lake may, for example, be written as follows:

$$C_{n+1}S_{n+1} - C_nS_n = C_{sn}I_{sn} - C_nQ_{sn} - \rho C_nS_n \qquad (3\text{-}22)$$

where:

C_n = sediment concentration in the lake at time t_n (ML^{-3})

C_{sn} = sediment concentration in tributary streams at time t_n (ML^{-3})

ρ = net deposition rate of lake sediment (T^{-1})

Note that precipitation, evaporation, and ground water exfiltration are not included since nearly all sediment enters and leaves through surface waters. However, a reaction term is included to account for removal of mass from the waters of the lake (in this case, as a result of deposition on the bottom). Nutrient and sediment mass balance equations often include such reaction terms. A complete historical sediment budget requires estimates of tributary and lake sediment concentrations and lake sediment deposition rates as well as the water budget fluxes which appear in Equation (3-22). If all of these are available, the budget may be constructed and a sediment mass balance error computed. A set of quarterly and annual long-term average sediment budgets could provide valuable information about the importance of different sediment sources affecting Reelfoot Lake. Similar comments apply to nutrients such as nitrogen and phosphorous. Future studies of the lake should give high priority to the development of a consistent set of sediment and nutrient budgets.

Future Water Budgets

The flux estimates derived in Section 3.2 and 3.3 can be used to construct future water budgets which attempt to predict how Reelfoot Lake will respond to specified hydrologic conditions or management actions. Here we consider a few typical examples which address some of the management issues discussed in Section 2.2. These examples are intended primarily to illustrate the general concepts involved in constructing hypothetical water budgets. They should be viewed as preliminary analyses which identify some interesting topics for further study.

The approach adopted in most predictive water budgets is the one outlined in Section 3.1. Values are postulated for all but one of the water budget fluxes and the remaining flux is adjusted to achieve a mass balance. In the examples presented here most of the inflows and outflows are assigned

historical quarterly values derived either from the scenario analyses of Section 3.2 or from the long-term average analyses of Section 3.3. The free variable used to achieve a mass balance is the spillway outflow, which is the most easily controlled component of the lake water budget.

If the spillway outflow is governed by an operating rule, it is possible to incorporate this rule directly into the discretized mass balance expression given in Equation (3-3). When, for example, the operating rule gives the spillway outflow over some period as a function of the lake stage at the beginning of the period, the resulting modified mass balance equation may be written as:

$$S_{n+1} - S_n = P_{\ell n} + I_{sn} + \epsilon_{\ell n} - E_{\ell n} - Q_{sn}[Y_n(S_n)] \qquad (3\text{-}23)$$

where:

$Q_{sn}(Y_n)$ = total spillway discharge over the period between t_n and t_{n+1}, expressed as a function of lake stage at time t_n (the spillway operating rule)

$Y_n(S_n)$ = lake stage expressed as a function of lake storage volume (stage - volume curve), both evaluated at time t_n.

This equation, which is written here with storage as the dependent variable, may be used to simulate the lake's response to a number of different operating strategies. If the time period $t_{n+1} - t_n$ is taken to be one day, the function $Q_{sn}(Y_{sn})$ will be a daily operating rule. If it is one month, this function will be a monthly operating rule, etc. Depending on the application, it may be convenient to develop a computerized simulation model based on Equation (3-23). Such a model could simulate the long-term response of the lake to varying hydrologic inputs. When more inflow data become available, this may prove to be a useful way to investigate the future of Reelfoot Lake.

For present purposes, we are interested in the special case obtained when the spillway outflow is adjusted to keep the lake level constant. Then the right-hand-side term $S_{n+1} - S_n$ is zero and the spillway outflow is given by:

$$Q_{sn} = P_{\ell n} + I_{sn} + \epsilon_{\ell n} - E_{\ell n} \qquad (3\text{-}24)$$

Note that Equation (3-24) does not include an explicit operating rule since the outflow does not depend on a single readily measured variable (such as lake stage). Although it does not specify how an operator would actually determine the spillway release on a day-to-day basis, this simplified mass

balance expression probably provides a reasonable picture of long-term average lake response when the outflow is adjusted to maintain lake levels close to a specified target.

If we assume that Equation (3-24) is used to determine spillway outflows and we obtain the fluxes on the left-hand side from Sections 3.2 and 3.3, we can readily construct some informative hypothetical water budgets. Four particular cases are presented in Table 3-13. These may be briefly summarized as follows:

1. Wet Period -- This water budget describes the lake's response during an unusually wet three month period. Precipitation and runoff rates are increased to levels which are 50 percent above the long-term average values observed in the spring (March-May) quarter. Evaporation rates are assigned long-term average spring quarter values and ground water inflows are assigned quarterly values based on Scenario 1 conditions.

2. Dry Period -- This water budget describes the lake's response during an unusually dry three month period. Precipitation and runoff levels are decreased to levels which are 50 percent below the long-term average values observed in the fall (Sept-Nov) quarter. Evaporation rates are assigned long-term average fall quarter values and ground water inflows are assigned quarterly values based on Scenario 3 conditions.

3. Wet Period + Lake No. 9 -- This water budget describes the lake's response during the period considered in Case 1 above, but with the additional assumption that the complete Lake No. 9 project diverts all water within its 21 mi^2 drainage area from Reelfoot Lake to the Mississippi River.

4. Dry Period + Lake No. 9 -- This water budget describes the lake's response during the period considered in Case 2. above, but with the additional assumption that the complete Lake No. 9 project diverts all water within its 21 mi^2 drainage area from Reelfoot Lake to the Mississippi River.

The wet and dry period definitions introduced here provide a way to examine the sensitivity of the water budget to variable hydrologic inputs. This could be extended to provide a detailed analysis of the distribution of lake outflows or storage levels, given a specified or computed distribution of precipitation and evaporation inputs.

The water budgets presented in Table 3-13 illustrate how much the water balance for a particular (unusual) quarter can be expected to deviate from the long-term average conditions described in Table 3-12. Stream outflows for the wet and dry periods vary from over 150,000 acre feet/quarter to essentially zero. This range appears to be consistent with available

TABLE 3-13

PREDICTED REELFOOT LAKE WATER BUDGETS
FOR SELECTED HYPOTHETICAL CONDITIONS
(All values given in thousands of acre-feet)

Variable	Wet Period	Dry Period	Wet Period + Lake No. 9	Dry Period + Lake No. 9
Inflows				
Precipitation (1)	32.6	6.4	32.6	6.4
Stream inflow (2)				
upland	60.0	5.1	60.0	5.1
lowland	47.4	0.7	33.3	0.5
Net ground water inflow (3)	14.2	9.0	14.2	9.0
Total inflow	154.2	21.2	140.1	21.1
Outflows and Storage Change				
Evaporation (4)	2.6	21.1	2.6	21.1
Stream outflow (5)	151.6	0.1	137.5	0.0
Increase in lake volume (6)	0.0	0.0	0.0	0.0
Total outflow and storage change	154.2	21.2	140.1	21.1

discharge records from Running Reelfoot Bayou, although the record length is too short to provide a reliable quantitative confirmation.

The two water budgets which include the effects of diversions from the Lake No. 9 drainage project are of particular interest since this project is the subject of considerable controversy (see Section 2.2). The impact of the project can be roughly estimated by assuming that all runoff generated in the watershed tributary to the drainage channel is diverted from Reelfoot Lake through the levee discharge structure to the Mississippi River. Since the area drained by the complete (as originally authorized) project is 21 mi^2 and the entire lowland drainage is 74 mi^2, the runoff contribution to lowland inflow would be reduced by about 28 percent (given the uniform runoff coefficient assumptions introduced in Section 3.3) if the entire project were operational. The impact of the project on the ground water system is difficult to estimate, but a conservative approach is to assume that the project eliminates all exfiltration from the aquifer into Running Slough. The water level maps and flow net analyses of Section 3.2 suggest that direct subsurface inflows into the lake will be unaffected by the Lake No. 9 project since they come from the upland region to the east. Well observations confirm that upland ground water levels are essentially unrelated to subsurface conditions in the lowland region drained by the Lake No. 9 project.

The net outcome of these various assumptions is that the complete Lake No. 9 project would reduce inflows into the lake by about 100 acre feet/quarter during unusually dry periods and by about 14,100 acre feet/quarter during unusually wet periods. The larger of these two values is only 9 percent of the total wet period inflow to the lake and is of the order of the mass balance error obtained in the long-term average water budgets presented earlier. These results confirm that the drainage project will have the greatest effect during wet periods when inflows to the lake are much larger than is required to maintain a constant lake elevation.

It is worth noting that the largest annual discharge from the existing Lake No. 9 project was about 6600 acre feet, released during the 1984 water year (Mike Gatewood, Memphis District, U.S. Army Corps of Engineers, personal communication). Since the existing project drains about 12 mi^2, this is equivalent to a rate of about 4200 acre feet/quarter for the entire 21 mi^2 authorized project area. This suggests that the 14,100 acre feet/quarter figure cited above is, indeed, a conservative upper bound which is considerably larger than the discharge rates which have occurred to date.

Analyses similar to those outlined here could also be used to investigate the effects of management strategies designed to control excessive sediment and nutrient inputs to the lake. In this case, the input concentrations appearing in the appropriate mass balance expression (for example, Equation (3-22)) would be modified to account for some action such as the construction of sediment detention facilities and the mass balance

equation would be solved for the resulting lake sediment concentration. Although it may be desirable to perform the required calculations on a computer, rough estimates of the impacts of the management strategy could be developed with a simple quarterly or annual analysis similar in concept to the one used to obtain Table 3-13. This general approach may be viewed as a screening procedure which can provide guidance for subsequent studies and, hopefully, can set the stage for informed discussions of alternatives.

4. MANAGEMENT IMPLICATIONS

As mentioned earlier, the desktop analysis of Chapter 3 is intended primarily to illustrate how general hydrologic concepts can be used to investigate real world case studies. But it is evident that this analysis also has implications for the management of Reelfoot Lake. It seems worthwhile to briefly consider some of these, particularly in light of the controversy which currently surrounds the discussion of alternative management strategies. Our discussion of management implications focuses on several topics. The first, and perhaps the most important, deals with data collection. The data collection discussion is followed by a brief review of several of the management issues originally identified in Section 2.2. Our comments on these issues are intended to stimulate discussion and to highlight some of the more interesting results of the flow net and water budget analyses. They are, of course, limited by the many assumptions and simplifications adopted in our investigation.

Data Collection

The detailed discussions of hydrologic pathways and flux estimates presented in Chapter 3 clearly indicate the need for more data in several critical areas. The primary sources of uncertainty in our historical and future water budgets may be somewhat subjectively ranked, in order of decreasing uncertainty, as follows:

1. Stream outflows -- These fluxes are based on a hypothetical operating rule curve which provides only a rough approximation to the limited historical outflow records currently available.

2. Net ground water inflows -- These fluxes are based on a small number of somewhat inconsistent well observations taken at the edge of the alluvial aquifer system.

3. Lowland stream inflows -- These fluxes are estimated from a limited streamflow record which reflect conditions in only a small fraction of the lowland drainage area.

4. Aquifer description -- The simplified confined aquifer model adopted in our analysis relies on a small amount of somewhat circumstantial geohydrologic data. This model has a significant influence on assumptions made about surface-subsurface interactions in the Reelfoot region

Clearly, additional data collection efforts are needed to clarify the role of all of these fluxes. This implies continuous monitoring of existing stream gages on Running Reelfoot Bayou and Running Slough, possible expansion of the lowland stream monitoring program to include smaller

tributaries, and much more extensive monitoring of ground water levels around the lake, particularly on the east side.

An expanded ground water monitoring program should be designed to help resolve the question of confined vs. unconfined flow and, in particular, should clarify the role of the river and lake boundaries. Subsurface flow must move vertically, at least locally, in order for these surface waters to interact with the underlying aquifer. Since this implies that ground water heads must vary with depth, the monitoring program should include a few clusters of wells screened at different depths, particularly near areas where ground water recharge or discharge appear to be taking place. Water level observations at these well clusters will provide a better picture of the vertical fluxes which control surface-subsurface interactions in the Reelfoot region.

The actual flux of ground water flowing through a given region of the alluvial aquifer is linearly proportional to the effective hydraulic conductivity of that region. This important hydrologic parameter cannot be measured directly but must, instead, be inferred from pump tests or other indirect measurement techniques. The effective hydraulic conductivity probably varies significantly over the alluvial aquifer, reflecting variations in the conditions responsible for the deposition of the alluvial material. It is likely that the effective conductivity is greater in the horizontal plane than in the vertical direction. Directional differences may also occur within the horizontal plane, particularly in areas where deposition processes had a clear directional component (for example, in buried stream channels). Such directional (anisotropic) behavior can have an important effect on groundwater movement and on the validity of simplified two-dimensional aquifer models such as those described in Section 3.2. An expanded ground water monitoring program should include a number of carefully planned large-scale pump tests which can provide estimates of effective hydraulic conductivities, including vertical and possibly horizontal anisotropy ratios. Such tests could help make future analyses of the regional ground water system more accurate and reliable.

Although the major focus of our analysis has been hydrologic, it is apparent that a carefully planned water quality and sediment sampling program should be included in any expanded data collection effort. This sampling program should be designed to provide the inputs needed for long-term sediment and nutrient mass budgets and should, therefore, include plans for periodic sampling on all major tributaries over an extended period of time. The sampling frequency will inevitably depend on the resources made available but it should be frequent enough to detect important seasonal variations and to provide information on the correlation between streamflow, sediment load, and nutrient concentration.

A comprehensive hydrologic and water quality study of Reelfoot Lake and its watershed will require a significant investment of money and manpower which will need to be continued over many years. Data collection efforts

should be carefully planned, with close coordination between the various agencies which have become involved with lake management, so that available financial resources can be efficiently allocated. Otherwise, it will be difficult to develop the database needed to formulate successful solutions to the lake's problems.

Management of the Reelfoot Lake Spillway

The spillway which discharges into Running Reelfoot Bayou at the southern end of Reelfoot Lake is an aging structure which is plagued by leaks and maintenance problems. Although the recent fifty-year management plan developed by TWRA (Tennessee Wildlife Resources Agency, 1986) does not address the question of spillway repair, it seems obvious that major renovations will be required before the lake level can be properly controlled. This seems an appropriate occasion to reevaluate the operation of this spillway. It would be relatively easy to evaluate proposed operating policies with a lake simulation model based on Equation (3-3). This model should be run for a long enough period to check on operating rule performance under a variety of conditions, including prolonged wet or dry periods. When the alternatives have been evaluated, the best one should be adopted and put into a form which is easily implemented in practice.

One of the more controversial proposals for lake level control is the mid-summer drawdown plan briefly described in Section 2.2 (Tennessee Wildlife Resources Agency, 1986). Although our desktop hydrologic analysis does not provide much information about the potential impacts of this plan, it indicates that there is sufficient water to refill the lake during a normal year if the lake elevation is lowered to the proposed level of 276.4 feet MSL. If this were the elevation at the end of August, approximately 80,000 acre-feet would have to be added to bring the elevation up to the proposed winter level of 283.3 feet MSL (see Figure 2-8). Our long-term water budget analysis indicates that this would take until early February during an average fall-winter season if no water is released from the spillway. This is consistent with the estimate provided in Tennessee Wildlife Resources Agency (1986). If, however, the fall and winter quarters are unusually dry, it could take longer, perhaps until late spring, to refill the lake. Since the inflow figures used to obtain these results are uncertain, we believe that a more extensive hydrologic analysis should be undertaken before the drawdown plan is approved. Given our earlier comments, this implies that at least a few more years of data should be included in the lowland exfiltration and runoff coefficient computations outlined in Section 3.3.

Lake No. 9 Drainage Project

In recent years, concern with the degrading quality and reduced accessibility of Reelfoot Lake has focused increased attention on the management of the surrounding watershed and, in particular, on drainage, channel improvement, and sediment control projects which can be expected to

affect the lake. The Lake No. 9 project briefly discussed in Sections 2.2 and 3.4 is an example. In its present partially completed form this project reduces flood damage in the northern portion of the lowland region, especially during unusually wet years. The project may also reduce inflows to Reelfoot Lake since its objective is to remove water from the lake's drainage basin. The USGS is currently studying this issue, with particular emphasis on subsurface connections between Reelfoot Lake and its watershed (United States Geological Survey, 1986a).

The flow net and water budget analysis presented in Chapter 4 indicates that the potential impacts of the Lake No 9 project on Reelfoot Lake are minor. This analysis rests on the following observations and assumptions:

1. The lowland drainage area affected by the Lake No. 9 project (either in its present or its completed authorized form) contributes only a small fraction of the total surface water inflow to Reelfoot Lake. Even if the lowland surface water contribution were totally eliminated, the lake could be maintained at current levels.

2. Ground water inflow to Reelfoot Lake from the portion of the alluvial aquifer lying beneath the Lake No. 9 project area is negligible. This is a direct consequence of the very low head gradients observed in the regions along the northern and eastern boundaries of the lake. Most ground water entering the aquifer in the lowland region flows past the lake to the south or, during low river periods, toward the Mississippi.

3. The ground water contribution to streamflow (exfiltration) in the lowland region is only a few percent of the total lowland inflow. This seepage flow, which occurs primarily in Running Slough, has virtually no impact on the lake water budget.

4. The time when the Lake No. 9 project removes the most water, i.e. during flood periods, is a time when lake inflows are much greater than required to maintain stable lake levels. Spillway outflows during such periods greatly exceed the amount of inflow lost by diverting lowland inflows.

The greatest area of uncertainty in our analysis of the Lake No. 9 project is the role of subsurface inflow from the lowland region to the lake. It is clear that surface water diversions from lowland tributaries cannot have a significant impact on the lake as a whole. This naturally focuses attention on the ground water component of the lake water budget. Although more ground water data would undoubtedly help clarify a number of unresolved issues about subsurface flow in the region, we believe that the existing database supports the analysis given here.

Sedimentation

The issue of sediment inflow to the lake from the surrounding watershed, particularly from upland agricultural areas, has received considerable attention over the years (Soil Conservation Service, 1956; McIntrye and McHenry, 1984; Tennessee Wildlife Resources Agency, 1985). The USGS has estimated, on the basis of stream samples taken during the period May 1984 through May 1985, that the annual suspended sediment influx to Reelfoot Lake is about 300,000 tons (Robbins et al., 1985). If we assume a bulk density of 1.2 g/ml (McIntrye and McHenry, 1984), this gives a volumetric inflow of about 200 acre-feet/year, a value relatively close to the estimate of 160 acre-feet/year reported by the Soil Conservation Service (1956). The normal pool volume is, by comparison, 80,300 acre-feet (Robbins, 1985). The USGS sediment inflow estimate implies, therefore, that the lake's lifetime will be over 400 years, even if we make the very conservative assumption that all sediment entering the lake is deposited on the bottom. This 400 year expected lifetime is consistent with the observation noted in Chapter 2 that the lake's volume-storage characteristics have not changed significantly since the 1930's (see Figure 2-8).

It is instructive to compare the sediment inflow analysis outlined above with the sediment deposition analysis described by McIntrye and McHenry (1985). Their deposition estimates, which are based on Cesium-137 measurements taken in Buck Basin (see Figure 2-2), average about 1 cm/yr. If this rate is applied throughout the lake, the resulting net sediment estimate is about 430 acre-feet/year, a value that is the same order of magnitude as the 200 acre-feet/year value cited above.

As more suspended sediment data become available, it should be possible to use the water budgets of Chapter 3 to construct reasonably accurate estimates of seasonal sediment fluxes into and out of Reelfoot Lake. These estimates will have to be reconciled with the deposition measurements mentioned above before a credible sediment budget can be constructed. Once this is done, it should be possible to evaluate the benefits of upstream sediment control in an objective way so that a cost-effective sediment management plan can be developed.

5. SUMMARY AND CONCLUSIONS

This report has attempted to demonstrate, by example, that desktop analysis provides a convenient and informative way to study complex hydrologic problems. This does not imply that simple analytical techniques should be relied on exclusively or that they will always prove to be as useful as in the Reelfoot Lake case study. Nevertheless, we believe that thoughtful desktop analysis can often supply as much insight as much more expensive computerized techniques. This is true partly because real-world environmental studies are almost always based on a limited quantity of uncertain data collected by different investigators over a extended period of time. In such cases, many of the inputs required by elaborate computer simulations must be developed judgementally, making the models ultimately just as subjective as desktop techniques which appear to rely on shaky assumptions and simplifications. In practice, data availability, not analytical sophistication, is the factor which usually has the greatest impact on the quality of environmental predictions.

It is useful at this point in our discussion to briefly review the desktop techniques used in the Reelfoot Lake case study and to consider how these techniques might be improved or extended when more data become available. The major techniques introduced in Chapter 4 can be classified as follows:

1. Mass Balance Analysis -- This category covers a number of different techniques ranging from qualitative investigations of hydrologic pathways to quantitative water budget calculations. The common objectives of these techniques are to identify the sources and pathways of water moving through the region and to quantify relevant flux rates and storage changes. The specific computations required depend on the time and space scales selected -- the mass balance analysis carried out in the case study is concerned primarily with the seasonal (quarterly) behavior of Reelfoot Lake as a whole. More detailed studies could consider the daily or weekly response of particular sections of the lake or its watershed.

2. Flow Net Analysis -- Flow net techniques are used to identify subsurface flow paths and to derive regional subsurface fluxes. The diagrams which form the basis for flow net analysis are constructed from water level observations taken at wells scattered throughout the region of interest. Flow nets can identify the locations of recharge and discharge areas and can help clarify the role of interactions between the surface and subsurface flow systems.

3. Runoff Coefficients -- Seasonally varying runoff coefficients relate observed stream discharge to precipitation without explicitly distinguishing the relative contributions of surface runoff and

subsurface exfiltration. The runoff coefficient approach requires reasonably extensive records of historical precipitation and discharge and can be used to predict only the portion of stream flow which is directly related to precipitation. It is particularly useful in regions where stream gage records must be extrapolated to ungaged areas.

4. Spillway Operating Rule Computations -- Spillway operating rules provide a way to relate long-term average discharges to the daily values of readily observable variables such as lake stage. Averages derived from these rules can be used in water budgets when historical discharge records are limited. Operating rule analyses also provide a rigorous basis for predicting a lake's long-term response to fluctuating (wet-dry) hydrologic conditions.

There are many more desktop techniques that could be applied in a more extensive study of Reelfoot Lake. These include graphical analysis of pump test results (to provide improved estimates of aquifer properties), Thiessen polygon analysis of spatially variable rainfall measurements (to provide improved estimates of precipitation and stream discharge), sediment and nutrient mass balance analysis (to provide a better understanding of water quality problems), and anisotropic extensions of flow net analysis (to provide a better description of vertical flow in the alluvial aquifer system). This is an area where imagination and a willingness to experiment can yield significant rewards.

Although desktop techniques can be powerful and very cost-effective, they clearly have their limits. As pointed out in Chapter 1, the boundary between desktop and computerized approaches is beginning to blur as inexpensive, easy to use computers become readily available. A single average annual water budget can be constructed easily by hand or with a spreadsheet program. If, however, this analysis is to be repeated many times for different input conditions (as in a multi-year simulation), the speadsheet approach is obviously preferable. Similarly, a single highly aggregated flow net analysis can probably be performed more quickly by hand than with a computerized ground water simulation model. But if more detail is desired or a sensitivity analysis is needed, the simulation approach becomes much more attractive.

It seems obvious that engineers and planners will continue to shift towards increased use of packaged software as data management programs and simulation models become cheaper and easier to use. For the most part, this is a desirable trend, since computerization should provide more time for reflection and critical analysis of results. If, however, computerized analysis is used as a substitute for careful thought, the overall impact of increased automation may be negative. As mentioned above, data limitations usually constitute the greatest obstacle in our understanding of practical environmental problems. Data interpretation is often difficult and highly subjective, even when field measurements are abundant. Although ambiguities

and apparent inconsistencies in field data are perplexing and inconvenient, they should be confronted directly since they may actually help to reveal conceptual errors. This aspect of environmental analysis may be obscured by too much reliance on automation. It is wise for the investigator to retain a certain amount of scepticism and periodically check computer output with some quick back-of-the-envelope calculations.

Looking back on the Reelfoot Lake case study, it is somewhat suprising that there have been so few systematic efforts to carefully describe and quantify the hydrologic processes which affect the lake. A notable exception is the USGS study by Robbins (1985) which will, hopefully, be the first in a series of attempts to organize and interpret available data on local hydrology. Today there are still a number of unresolved issues which need to be carefully examined before large amounts of money and manpower are committed to new construction or to controversial management strategies. These include the influence of the Mississippi River on subsurface flow in the Reelfoot region, the nature of interactions between the lake and the underlying alluvial aquifer, and the importance of the sedimentation problem. Although this report has offered some opinions on these and other issues, our conclusions are clearly speculative and uncertain. It seems obvious that the agencies responsible for studying and managing the lake will need to coordinate their efforts more closely if existing controversies are to be adequately resolved. A concerted effort to collect data and develop a consistent description of regional hydrology and water quality will ultimately be more useful than hastily prepared management plans that stand little chance of being adopted.

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Research Document No. 28	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION The Hydrologic Engineering Ctr. — 6b. OFFICE SYMBOL (If applicable) CEWRSC-HEC	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Corps of Engineers 609 Second Street Davis, CA 95616	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Water Resources Support Center — 8b. OFFICE SYMBOL (If applicable) CEWRSC	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Casey Building Fort Belvoir, VA 22060	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Desktop Techniques For Analyzing Surface-Ground Water Interactions
The Reelfoot Lake Case Study

12. PERSONAL AUTHOR(S)
None

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Research	FROM _____ TO _____	May, 1988	89

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Groundwater Hydrology; Surface Water Hydrology; Conjunctive Use

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report illustrates how simple "desktop" analyses can be used to investigate complex hydrologic systems. The techniques are applied to a case study of Reelfoot Lake, Tennessee, a shallow eutrophic lake which is plagued by a number of water quality problems. The report focuses on the way desktop methods help reveal data gaps and uncertainties which tend to be obscured in more elaborate computer modeling studies and upon the qualitative conceptual issues which must be addressed.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☑ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION
22a. NAME OF RESPONSIBLE INDIVIDUAL Darryl W. Davis	22b. TELEPHONE (Include Area Code) (916) 551-1748 — 22c. OFFICE SYMBOL CEWRSC-HEC

DD Form 1473, JUN 86 — Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
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GPO 585-063/89629

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