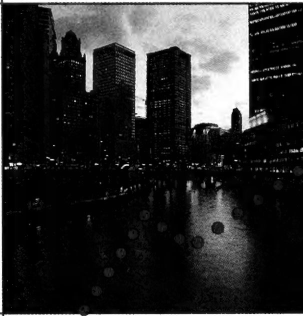
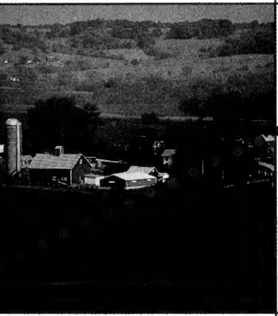
The Changing Illinois Environment: Critical Trends





Technical Report of the Critical Trends Assessment Project
Volume 2: Water Resources

Illinois Department of
Energy and Natural Resources

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Volume 2: Water Resources

Illinois Department of Energy and Natural Resources
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June 1994

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Volume 1: Air Resources

Volume 2: Water Resources

Volume 3: Ecological Resources

Volume 4: Earth Resources

Volume 5: Waste Generation and Management

Volume 6: Sources of Environmental Stress

Volume 7: Bibliography

Volume 2
Water Resources

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ABOUT THE CRITICAL TRENDS ASSESSMENT PROJECT

The Critical Trends Assessment Project (CTAP) is an on-going process established to describe changes in ecological conditions in Illinois. The initial two-year effort involved staff of the Illinois Department of Energy and Natural Resources (ENR), including the Office of Research and Planning, the Geological, Natural History and Water surveys and the Hazardous Waste Research and Information Center. They worked with the assistance of the Illinois Environmental Protection Agency and the Illinois departments of Agriculture, Conservation, Mines and Minerals, Nuclear Safety, Public Health, and Transportation (Division of Water Resources), among other agencies.

CTAP investigators adopted a "source-receptor" model as the basis for analysis. Sources were defined as human activities that affect environmental and ecological conditions and were split into categories as follows: manufacturing, transportation, urban dynamics, resource extraction, electricity generation and transmission, and waste systems. Receptors included forests, agro-ecosystems, streams and rivers, lakes, prairies and savannas, wetlands, and human populations.

The results are contained in a seven-volume technical report, *The Changing Illinois Environment: Critical Trends*, consisting of *Volume 1: Air Resources*, *Volume 2: Water Resources*, *Volume 3: Ecological Resources*, *Volume 4: Earth Resources*, *Volume 5: Waste Generation and Management*, *Volume 6: Sources of Environmental Stress*, and *Volume 7: Bibliography*. Volumes 1-6 are synopsized in a summary report.

The next step in the CTAP process is to develop, test, and implement tools to systematically monitor changes in ecological and environmental conditions in Illinois. Given real-world constraints on budgets and human resources, this has to be done in a practical and cost-effective way, using new technologies for monitoring, data collection and assessments.

As part of this effort, CTAP participants have begun to use advanced geographic information systems (GIS) and satellite imagery to map changes in Illinois' ecosystems and to develop ecological indicators (similar in concept to economic indicators) that can be evaluated for their use in long-term monitoring. The intent is to recruit, train, and organize networks of people — high school science classes, citizen volunteer groups — to supplement scientific data collection to help gauge trends in ecological conditions.

Many of the databases developed during the project are available to the public as either spreadsheet files or ARC-INFO files. Individuals who wish to obtain additional information or participate in CTAP programs may call 217/785-0138, TDD customers may call 217/785-0211, or persons may write:

Critical Trends Assessment Project
Office of Research and Planning
Illinois Department of Energy and Natural Resources
325 West Adams Street, Room 300
Springfield, IL 62704-1892

Copies of the summary report and volumes 1-7 of the technical report are available from the ENR Clearinghouse at 1/800/252-8955. TDD customers call 1/800/526-0844, the Illinois Relay Center. CTAP information and forum discussions can also be accessed electronically at 1/800/528-5486.

FOREWORD

"If we could first know where we are
and whither we are tending,
we could better judge what we do
and how to do it..."
Abraham Lincoln

Imagine that we knew nothing about the size, direction, and composition of our economy. We would each know a little, i.e., what was happening to us directly, but none of us would know much about the broader trends in the economy — the level or rate of housing starts, interest rates, retail sales, trade deficits, or unemployment rates. We might react to things that happened to us directly, or react to events that we had heard about — events that may or may not have actually occurred.

Fortunately, the information base on economic trends is extensive, is updated regularly, and is easily accessible. Designed to describe the condition of the economy and how it is changing, the information base provides the foundation for both economic policy and personal finance decisions. Typical economic decisions are all framed by empirical knowledge about what is happening in the general economy. Without it, we would have no rational way of timing these decisions and no way of judging whether they were correct relative to trends in the general economy.

Unfortunately, this is not the case with regard to changes in environmental conditions. Environmental data has generally been collected for regulatory and management purposes, using information systems designed to answer very site-, pollutant-, or species-specific questions. This effort has been essential in achieving the many pollution control successes of the last generation. However, it does not provide a systematic, empirical database similar to the economic database which describes trends in the general environment and provides a foundation for both environmental policy and, perhaps more importantly, personal decisions. The Critical Trends Assessment Project (CTAP) is designed to begin developing such a database.

As a first step, CTAP investigators inventoried existing data to determine what is known and not known about historical ecological conditions and to identify meaningful trends. Three general conclusions can be drawn from CTAP's initial investigations:

Conclusion No. 1: The emission and discharge of regulated pollutants over the past 20 years has declined, in some cases dramatically. Among the findings:

- Between 1973 and 1989, air emissions of particulate matter from manufacturing have dropped 87%, those of sulfur oxides 67%, nitrogen oxides 69%, hydrocarbons 45%, and carbon monoxide 59%.
- Emissions from cars and light trucks of both carbon monoxide and volatile organic compounds were down 47% in 1991 from 1973 levels.
- Lead concentrations were down substantially in all areas of the state over the 1978-1990 period, reflecting the phase-out of leaded gasoline.
- From 1987 to 1992, major municipal sewage treatment facilities showed reductions in loading of biological/carbonaceous oxygen demand, ammonia, total suspended solids and chlorine residuals that ranged from 25 to 72%.
- Emissions into streams of chromium, copper, cyanide, and phenols from major non-municipal manufacturing and utility facilities (most of them industrial) also showed declines over the years 1987-1992 ranging from 37% to 53%.

Conclusion No. 2: Existing data suggest that the condition of natural ecosystems in Illinois is rapidly declining as a result of fragmentation and continual stress. Among the findings:

- Forest fragmentation has reduced the ability of Illinois forests to maintain biological integrity. In one Illinois forest, neotropical migrant birds that once accounted for more than 75% of breeding birds now make up less than half those numbers.

- In the past century, one in seven native fish species in Lake Michigan was either extirpated or suffered severe population crashes and exotics have assumed the roles of major predators and major forage species.

- Four of five of the state's prairie remnants are smaller than ten acres and one in three is smaller than one acre — too small to function as self-sustaining ecosystems.

- Long-term records of mussel populations for four rivers in east central Illinois reveal large reductions in numbers of all species over the last 40 years, apparently as suitable habitat was lost to siltation and other changes.

- Exotic species invasions of Illinois forests are increasing in severity and scope.

Conclusion No. 3: Data designed to monitor compliance with environmental regulations or the status of individual species are not sufficient to assess ecosystem health statewide. Among the findings:

- Researchers must describe the spatial contours of air pollutant concentrations statewide using a limited number of sampling sites concentrated in Chicago and the East St. Louis metro area.

- Much more research is needed on the ecology of large rivers, in particular the effects of human manipulation.

- The length of Illinois' longest stream gaging records is generally not sufficient to identify fluctuations that recur less frequently than every few decades.

- The Sediment Benchmark Network was set up in 1981 with some 120 instream sediment data stations; by 1990 the network had shrunk to 40 stations, the majority of which have data for only one to three years.

CTAP is designed to begin to help address the complex problems Illinois faces in making environmental policy on a sound ecosystem basis. The next edition of the Critical Trends Assessment Project, two years hence, should have more answers about trends in Illinois' environmental and ecological conditions to help determine an effective and economical environmental policy for Illinois.

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WATER RESOURCES: VOLUME SUMMARY

SUMMARY AND SIGNIFICANT RESULTS

The Critical Trends Assessment Project (CTAP) Water Resources volume examines environmental issues related to hydrologic processes in Illinois. It concentrates on those issues deemed of major concern in regard to surface and ground-water resources. Each chapter of this report describes historic information and possible trends over time, allowing a critical review of the state of the particular resource. This review, a combination of many sources of information, can aid in our understanding and potential management of these resources. The ongoing compilation and collection of these data are essential to this understanding and must be recognized as a valuable resource to the people of Illinois and one which merits continuing support. The following sections summarize the eight major issues addressed in the report.

Chemical Surface Water Quality

Ambient water quality data collection began in the early 1970s, and there are continuous data since that time for a number of locations in Illinois. Data on water quality parameters for Illinois streams and lakes were analyzed to determine water quality trends for 15 chemical constituents. These data are available on STORET, a database maintained by the Illinois Environmental Protection Agency (IEPA).

Water quality trends indicate a general improvement in Illinois streams and rivers. In particular, there is a decreasing trend in the concentrations in streams of metals (arsenic, cadmium, chromium, lead, and mercury). Decreasing trends in cadmium, lead, and mercury were especially strong. Significant decreasing trends were also identified in chlorides and chemical oxygen demand (COD). Increases in dissolved oxygen—a favorable trend—were observed, but not at a statistically significant level. However, two constituents experienced significant increasing levels, causing a degrading impact: phosphorous and nitrate/nitrite nitrogen ($NO_2 + NO_3$). The likely source of these constituents is nonpoint pollution from agricultural areas. All the other parameters that were examined (phenolics, fecal coliform, pH, total dissolved solids, and ammonia nitrogen) show little or no trend.

The temporal trends described above were observed throughout most of the major watersheds in the state. However, selected quality parameters in a few watersheds displayed trends that were contrary to the statewide norm. The DesPlaines, Kankakee, and Illinois River basins show increasing concentrations of cadmium, chromium, and chloride, respectively. The Ohio River basin shows a decreasing concentration in nitrates.

No trends were observed for any of the water quality parameters examined for lakes in Illinois. The analysis was encumbered by limited data with many missing values for some parameters.

Ground-Water Quality

Long-term temporal trends in ground-water quality over selected areas of Illinois were examined using data from private and municipal wells. The concentrations of six chemical constituents were examined: hardness, iron, sulfate, chloride, nitrate, and total dissolved solids. The analysis indicates that on a county-wide scale, ground water has not been degraded with respect to the six chemicals examined. Data limitations precluded study of trace-level contaminants, but it is imperative that such an assessment be undertaken in the future.

Much of the contamination of Illinois ground water is generally localized. It is clear that the quality of some ground water, particularly in the metropolitan Chicago area, has been degraded by anthropogenic activity, resulting in increased chloride and total dissolved solids. This contamination can render a private or municipal ground-water supply unusable. Once contaminated, ground water is very difficult and expensive to clean, and the process may take many years to complete. Preventing ground-water contamination is thus in the best interests of the people of Illinois.

Since the mid- to late 1980s, national concern has focused on ground-water contamination and its potential impacts for those individuals who rely on ground water for their drinking water. This concern has led to the initiation of several laws and agency policy shifts to help ward off this imposing threat or to help create a monetary base for research and remediation of existing contamination. Illinois is one of only a handful of states that has adopted legislation in an attempt to respond to this concern. In 1987, P.A. 85-0863 was introduced as a comprehensive, prevention-based policy focusing on beneficial uses of ground water and preventing degradation. This act, known as the Illinois Groundwater Protection Act (IGPA), relies upon a state and local partnership and, although directed toward protection of ground water as a natural and public resource, it specifically targets drinking water wells in Illinois.

The IEPA's synoptic analysis of public water supply wells indicates that the quality of the state's ground water is generally good. The analysis of the information used for this report tends to support this view. The IEPA and the Illinois State Water Survey (ISWS) also agree that chemical levels are limiting use of the resource in some areas in Illinois. The IEPA reported that 4.6 percent of the tested public water wells had detectable levels of organic chemical contamination.

Erosion and Sedimentation

The estimated annual gross soil erosion from croplands in Illinois is 158 million tons, or nearly 90 percent of the total gross erosion for the state (180 million tons). It is estimated that 2 to 9 inches of Illinois topsoil has eroded since its initial cultivation by early settlers. The most severe erosion has occurred in southern Illinois, a hilly and highly erosive area that was settled and farmed earlier than the rest of the state. Erosion has also been significant in the western Illinois, where 6 to 7 inches of topsoil has eroded. Central and northeastern Illinois have fared better with 2 to 4 inches of erosion.

Three agencies, the ISWS, the U.S. Geological Survey (USGS), and the IEPA, have collected instream sediment data over the last 20 years. Analysis of the measured sediment concentrations for selected streams in northern, central, and southern Illinois shows that since 1980, sediment concentrations have been decreasing in the Rock River in northern Illinois, have been essentially constant in the Sangamon River in central Illinois, have been decreasing slightly in the Kaskaskia River in south-central Illinois, and have been increasing slightly in the Cache River in southern Illinois. The spatial distribution of instream sediment shows that the highest amounts of sediment are from regions along the Illinois River and in west-central Illinois, along with some areas in southern Illinois. The northeastern and central sections of the state show the least instream sediment.

The major impact of soil erosion is the eventual accumulation of the eroded soils in lakes and reservoirs. The gradual loss of capacity in water supply lakes due to sedimentation has been a serious problem and has been investigated intensively for a long time. More recently, greater concern has focused on the impact of sedimentation on environmental quality and on the impact of continuing sedimentation on the Illinois River valley.

The Illinois River drains nearly half of the state and many major streams drain into it. The main sources of sediment to the Illinois River valley are watershed erosion, stream bank erosion, and bluff erosion. The sediment yield calculations show that, on the average, 13.8 million tons of sediment are delivered to the Illinois River annually. The average annual outflow of sediment from the Illinois River at Valley City is 5.6 million tons. Thus, on the average, 8.2 million tons of sediment are delivered from tributary streams and deposited in the Illinois River valley. The temporal trend analysis indicates that sediment concentration and load have been decreasing in the Illinois River at Valley City since 1980. But the primary cause, at least for the sediment load, is the decrease in average streamflow over the same period.

Major areas impacted by sediment deposition in the Illinois River valley are backwater lakes. Sediment rate calculations show that the backwater lakes had lost from 20 to 100 percent of their capacities by the year 1990. The average capacity loss is 72 percent. The conditions in Peoria Lake over the years have clearly illustrated the impact of sedimentation in the Illinois River valley. As of 1985, Peoria Lake had lost 68 percent of its 1903 capacity due to sedimentation. The average depth of the lake had been reduced from 8 feet to 2.6 feet.

Most of the chemicals found in lake sediments are transported from source areas and upland watersheds, which include urban and agricultural areas, through stream networks. Profiles of lead and zinc concentrations in lake sediments from Lake Peoria indicate that the highest concentration of lead was in the late 1960s, while that for zinc was highest in the early 1950s. The concentrations of the two heavy metals in the sediment have been decreasing since the peak periods of deposition in the lake. The top sediment layer shows much lower concentrations of lead and zinc than the lower layers, which reflect earlier periods. Similar patterns are also observed for many other chemicals in Illinois River sediments.

Ground-Water Mining

Ground water is a finite resource that is not uniformly distributed throughout the state. In some areas of Illinois, demand for this resource has caused it to become well developed. Demand can exceed supply, especially in urbanized areas of Illinois, and potential problems can arise from competition for the resource. The major concern is that annual use, in the long term, should not exceed the *average annual recharge* available to a specific aquifer system. When annual use does exceed average annual recharge over a prolonged period, ground-water mining occurs.

In Illinois the most significant problem, in terms of ground-water mining, occurs in the Chicago region. This problem started during the 1950s when demand exceeded what the natural systems could effectively recharge. Ground-water levels in one of the major aquifer systems of this region have declined by almost 1,000 feet since pumping began. The economic result has been increased pumping costs due to increased lift requirements. The mining of the natural system also puts it at risk of compaction, which could permanently damage the aquifer. A lawsuit brought by Wisconsin ultimately required the state of Illinois to decrease its pumpage from the major aquifer supplying the Chicago region.

Steps are being taken to relieve the stress on the aquifer system. The substitution of Lake Michigan water for ground water is having positive impacts, but this strategy will only buy a few years. It is projected that by the year 2005, ground-water mining of the principal aquifer supplying the Chicago region will resume.

No other area in Illinois has had a more historically adverse impact on ground-water levels than has the Chicago region. There are other areas where heavy ground-water use has affected the ground-water flow system. These include two industrial centers, Peoria and the American Bottoms region near East St. Louis, and one agricultural area in eastern Kankakee and northern Iroquois Counties. None of these areas has a ground-water mining problem similar to the Chicago situation. But ground-water mining has the potential to be a critical concern in each of these areas.

Drought Impacts on Water Resources

Droughts occur in Illinois on average once every eight to ten years. The identification of these droughts generally requires some socioeconomic impact resulting from a lack of water. The most widely recognized impacts of water shortages are those associated with public water supply and agriculture, but aquatic habitat, river navigation, and recreation can also suffer due to water shortages. This chapter concentrates on drought impacts from the perspective of streamflow, ground water, and public water supply. From this perspective, the most severe droughts occurred in 1930-1931, 1952-1955, and 1962-1964. The recent minor droughts were those of 1976-1977, 1980-1981, and 1988-1989. Though the most severe droughts have not occurred in the last 30 years, there is no evidence that their frequency of occurrence has been altered.

The impacts of each of these droughts on public water supplies have always brought about a renewed awareness of inadequacies in the existing water supply systems. Thus, the greatest amount of activity to upgrade water supply systems occurs following droughts. Many systems throughout the state are much better equipped to handle shortages associated with drought conditions than in the past. Yet it is estimated that, of the surface water systems susceptible to drought impacts, almost 40 percent could be severely impacted during a 50-year drought. While this is an improvement over the percentage of systems that had shortages during the severe historical droughts, it is not a particularly significant improvement. Most ground-water systems are buffered from the impacts by drought and few of these would be impacted by the same type of drought.

Reducing water use during drought is one way to reduce the impact of shortages on water supply systems. During the 1988-1989 drought, more than 20 percent of the public water supply systems imposed or requested water conservation measures. Lawn watering was the most often restricted water use, followed by car washing and domestic water use. Water conservation practices were reportedly successful for 40 percent of the public water supplies that used them. But despite the water conservation measures, most systems indicate a large increase in total water use during drought conditions, particularly during the early stages before the drought is actually recognized. Understanding the conditions that lead to drought may allow us to develop better strategies to help eliminate or reduce its impact. Yet at this point it is apparent the occurrences of droughts still catch us off-guard, and that mitigative measures are not begun until the drought impacts become obvious.

Water Supply and Use

Water use in the state has increased a modest 27 percent since 1965. Most of that increase is in power generation. Water use for public water supplies has risen only about 7 percent during that time, less than the concurrent percentage increase in population. The number of public ground-water supply facilities within Illinois has also risen significantly, yet the total amount supplied by ground water remains near 25 percent.

A dependable, adequate source of water is essential to sustain the existing and potential population demands and industrial uses in Illinois. Modifications and practical management of the use of both surface and ground water have helped make this vital resource reliable in Illinois. As individual facilities experience increases in water use, innovative alternative approaches to developing adequate water supplies must arise. In particular, this is likely to involve conjunctive use of surface and ground waters. Major metropolitan centers such as the Chicago area, Peoria, Decatur, and Bloomington-Normal have already developed both surface and ground water to meet their needs for development and to sustain growth. The construction of impounding reservoirs has become and will remain economically and environmentally expensive, making it a less common approach.

Proper management of water resources is also necessary to ensure a reliable, high-quality supply for the population. Water conservation practices will become increasingly important to reduce total demand and avoid exceeding available supplies. Both our ground-water resources and surface reservoir storage must be preserved to maintain reliable sources for future generations.

Streamflow Conditions, Flooding, and Low Flows

Most streams throughout Illinois have experienced an increase in flow conditions during the last 25 years, in particular for normal flows and low flows. These increases are particularly significant throughout much of the northern third of Illinois. The greatest cause for these increases appears to be climate variability; much of this area has experienced precipitation increases > 10 percent. For many streams low flows are also highly impacted by increases in the amount of waste water returned to streams.

Trend analysis indicates that much of the northeastern quarter of Illinois and a part of northwestern Illinois have experienced increased average flow and low flows. This widespread trend in streamflow is attributed to changes in climate, particularly in total precipitation. Streams in central Illinois have also seen above average flows in the last 25 years, but not to a scale such that they produce a significant trend. Examination of average flow conditions to determine cyclical or gradual trends indicates that the increased flows have occurred over the last 25 years and that their departures from the long-term normal flows appear to be related to concurrent increases in the average precipitation. For most locations, high flows and flooding have not been noticeably affected by climate variability. One region where an increase in high flows is identified is the Kankakee River basin.

Urbanization is the one land use change where an impact on streamflow conditions is easily detected. Many smaller urban streams in northeastern Illinois have considerable increases in flood volumes and peak flows, regardless of whether stormwater detention facilities are present. Increases in low flows are common, but not universal among urban streams. Many streams show sizable increases in low flows as the result of wastewater effluents.

The existence of reservoirs normally creates a large change in the amount of streamflow downstream. Although high flows and flooding are reduced in reservoirs that are designed for flood control, they may not be greatly impacted by other reservoirs. The impact on low flows is most greatly affected by the reservoir operation and use of its outlet facilities. Most large reservoirs provide for a minimum release of water, which often increases the amount of downstream flow compared to natural drought conditions. Reservoirs that do not provide minimum releases and use their storage primarily for water supply are most apt to cause a decrease in flow downstream. But most of these reservoirs occur on small watersheds that ordinarily have no flow during dry conditions.

Low flows in Illinois streams are most greatly impacted by return flows of wastewater coming from municipalities and industry. For many large streams in the state the amount of return flows can often comprise over 30 percent of the total flow in the stream during low flow. Several small streams in northeastern Illinois virtually lack low flows because wastewater returns comprise over 90 percent of the flow during dry conditions.

Instream Flow Uses, Needs, and Protection

A fundamental issue in all future water management programs and decisions is the protection of instream flow uses. Instream flows are valuable in maintaining: 1) aquatic habitat during low-flow or critical periods, 2) water-based recreation and associated streamwater quality and quantity, 3) a stream's assimilative capacity to receive effluents from wastewater plants, 4) stream integrity in terms of biodiversity and strength of biotic communities, and 5) sufficient water quantity for downstream municipal and industrial water supplies during emergency and severe drought conditions.

The protection of instream flows has been under serious consideration by the state natural resource agencies for the last two decades. The absence of suitable aquatic habitat assessment models (in terms of hydraulic and habitat simulations) and the lack of financial support for an integrated statewide study of desirable protected flow levels have seriously hindered instream flow regulation and the development of an associated infrastructure. The adoption of a protected flow standard involves consideration of conflicting goals and needs. Both tangible and intangible benefits are associated with a protected flow level, and these benefits vary with the level of protection. There is also an associated cost for adopting and maintaining a protected flow level in a stream. A cost-benefit approach will provide a framework for analyzing the economics of objectively selecting and adopting a particular protected flow level to meet various needs

Low-flow releases from reservoirs may have to be mandated to protect downstream interests. Preference or suitability curves for Illinois fish species and their life stages need to be developed or improved with respect to flow parameters and channel substrates. Field studies for streams in various physiographic areas are also necessary to determine various parameters that affect habitat evaluations.

BACKGROUND

Robert A. Sinclair and Kenneth J. Hlinka
Illinois State Water Survey

HISTORY

Environmental issues related to water in the state of Illinois have been discussed and written about for more than a century. Erosion, sedimentation, water use, flood control, water quality, and water pollution have been major concerns for decades. Many state and federal agencies involved in resource planning have worked jointly on various planning commissions, task forces, and committees and have prepared numerous reports describing threats to the quality of the environment, the health and well-being of the people of the state, and the adequacy of the water supply. *Water For Illinois - A Plan For Action* (Office of the Governor, 1967) is a good example.

As discussed in the *Report of the Illinois State Fish Commissioner* (1899), one of the most frequent complaints reaching the commission was water pollution due to the waste from gas factories, paper mills, etc., entering several points along the Fox, Des Plaines, and Illinois Rivers. The destruction of fish due to these discharges was great. The Illinois State Board of Health's *Report of the Sanitary Investigations of the Illinois River and Its Tributaries* (1901) stated that "due to the sewage of Chicago being dumped into a stretch of the Chicago River from its mouth to a point past Bridgeport, the river was a seething, festering mass of decomposing sewage from house and factory, giving up great quantities of noisome gases; the surface of the river in many places having the appearance of a boiling caldron. Below Peoria, the river banks were strewn with dead fish due to the washings of the cattle barns at Peoria."

The effect of point and nonpoint pollution on surface and ground-water quality has been a continuing problem for decades (Illinois State Water Plan Task Force, 1984). The Illinois Environmental Protection Agency reported that since 1979, several Illinois rivers and streams have shown improving trends in general water quality, including the Illinois and Mississippi Rivers, and the Rock River (IEPA, 1990). The major causes of continuing water quality problems are siltation, nutrients, habitat/flow alteration, organic enrichments/dissolved oxygen, ammonia, metals, and suspended solids. Streamflow conditions and the amount of withdrawals from the state's streams are of major concern because of the impact on water quality, transportation, and availability for downstream users (State Water Plan Task Force, 1992b).

Ground-water monitoring and assessment information to date indicate that statewide ground-water quality is generally good. However, many activities, past and present, contribute to ground-water contamination in Illinois (IEPA, 1992). Major sources of identified contamination include leaking underground gasoline storage tanks, large quantities of above-ground petroleum storage, agricultural chemical operations, salt piles, landfills, and treatment storage/disposal units. New approaches to defining and solving the point and nonpoint pollution problems of the state are an ongoing process (State Water Plan Task Force, 1992a).

Sediment in Illinois streams is recognized as the number-one pollution problem in the surface waters of the state (Bhowmik, 1986). Erosion and sedimentation impact many agencies and businesses in addition to being very destructive to the land, lakes, and waterways of the state (ISWS, 1952). Sediment is very costly to remove from drainageways and lakes (Fitzpatrick et al., 1987). Many reaches of Illinois' commercially navigable rivers require dredging on a continuing basis so that barge traffic can be kept moving and profitable (IDOT, 1988). More than 1,700 drainage districts in the state require periodic maintenance to remove silt at a cost of millions of dollars.

The Illinois State Water Plan Task Force (1984) also listed erosion and sediment control at the top of the list of critical issues. Many biologists believe that sediment is the most destructive factor in the aquatic component of the ecosystem. Sediment transport and deposition have a major impact on the aquatic habitat of lakes and streams. Public drinking water utilities spend large sums of money on water treatment to reduce turbidity and sedimention levels. Sedimentation also causes large annual losses of reservoir capacity in more than 100 Illinois instream or side-channel impoundments.

Water use, water conservation, and droughts (ISWS, 1952; Office of the Governor, 1967; Illinois State Water Plan Task Force, 1984) have been a major concern in portions of the state since the droughts of the 1930s. Although ground water is a major resource in northern Illinois, excessive drawdown of the ground-water level has occurred in portions of northeastern Illinois since the 1920s (Office of the Governor, 1967).

Because the interior southern half of the state of Illinois has very limited ground-water resources, major public surface water districts have been established in the areas of Kinkaid Reeds Creek, Carbondale, Kaskaskia, and Rend Lake. More than 90 public water supply lakes in Illinois serve major communities such as Springfield, Decatur, Danville, Taylorville, Bloomington, and Carbondale. The cost of potable water varies widely over the state due to the cost of availability, treatment, and distribution.

As the state population grew and people began to live and work in the lowlands, flooding and flood control became important issues. Losses due to flooding run into millions of dollars each year. Reports documenting the numerous floods during the period 1904 through the early 1940s (Alvord and Burdick, 1919; Mulvihill and Cornish, 1929; Illinois Department of Public Works and Buildings, 1946) along with the State Water Plans of 1967 and 1984 (Office of the Governor, 1967; Illinois State Water Plan Task Force, 1984) point to the fact that flooding and flood control continue to be critical issues. A number of more urbanized areas of the state have established stormwater management districts for improving flood control and reducing losses due to flooding.

Since the mid- to late 1980s, there has been growing national concern over ground-water contamination and its potential impacts on those individuals who rely on this resource for their drinking water. This concern has led to the initiation of several laws and agency policy shifts to help ward off this imposing threat or to help create a monetary base for research and remediation of existing contamination. Illinois is one of only a handful of states that has adopted legislation in an attempt to respond to this concern. In 1987, the Illinois Groundwater Protection Act (P.A. 85-0863) was passed as a comprehensive, prevention-based approach focused upon beneficial uses of ground water and preventing degradation. This act relies on state and local partnership and, although directed toward protection of ground water as a natural and public resource, it specifically targets drinking water wells in Illinois. This and many other legislative initiatives have set the tone for environmental protection throughout the entire nation. It has become apparent that the concern for our natural resources is a high priority, and the detailed analysis of degenerative trends of these resources may open the opportunity to develop management practices to help secure a safe and protected environment.

AVAILABILITY OF WATER RESOURCES IN ILLINOIS

Illinois has an abundant supply of surface water within its borders. Unfortunately, these waters are unevenly distributed throughout the state. In a sense, Illinois is almost an island with fresh water surrounding its interior. Its western border consists of the Mississippi River, the southern and southeastern borders are defined by the Ohio and Wabash Rivers, respectively, and Lake Michigan borders it to the northeast. These are not the only sources of fresh surface water to Illinois. Its interior is crossed with large supplies of available water from major rivers such as the Illinois, the Rock, the Kankakee, and the Kaskaskia, as well as numerous other smaller rivers and streams.

Illinois also has abundant buried ground-water reserves. Major aquifer units supply millions of gallons per day for public and industrial use in Illinois. These aquifers are also unevenly distributed throughout Illinois. However, in most cases, where one resource is unavailable, the other or a combination of the two will be available for the required need. The distribution of these resources is detailed in figures 1 and 2. This chapter describes the environmental issues and concerns associated with these resources in Illinois.

This report examines environmental issues related to hydrologic processes in Illinois. It concentrates on those issues deemed of major concern in regard to surface and ground-water resources. Each chapter of the report describes historic information and possible trends over time, allowing a critical review of the state of the particular resource. This review is a combination of many sources of information and can aid in our understanding and potential management of these resources. The ongoing compilation and collection of these data are essential to this understanding and must be recognized as a valuable resource to the people of Illinois that merits continuing support.

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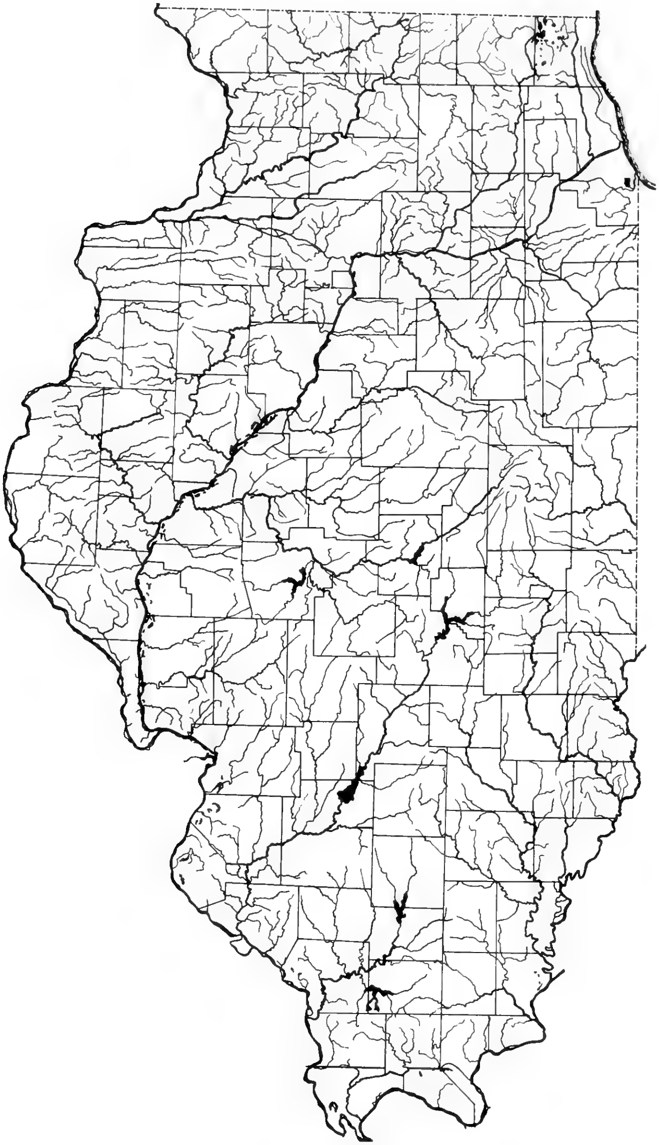

Figure 1. Surface water resources of Illinois

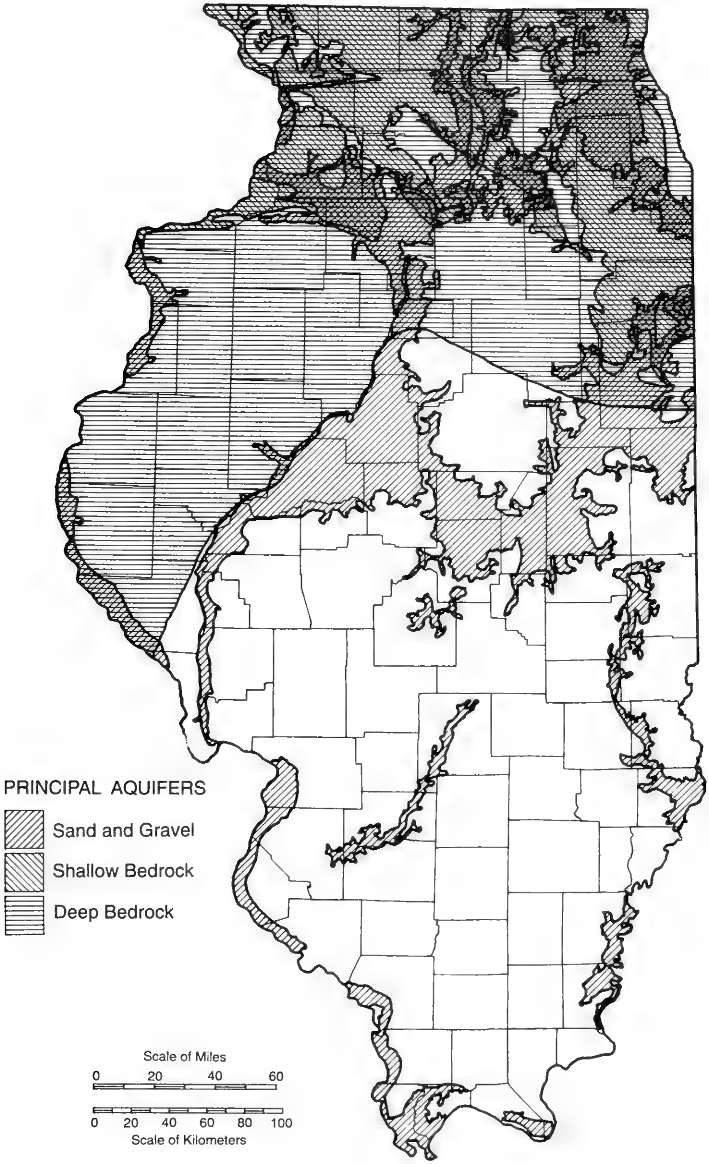

Figure 2. Principal aquifers in Illinois

CHEMICAL SURFACE WATER QUALITY: AMBIENT WATER QUALITY TRENDS IN STREAMS AND LAKES

Ganapathi S. Ramamurthy
Illinois State Water Survey

INTRODUCTION

During the last decade increased awareness and concern for the environment have changed human lifestyles and contributed to changes in industrial and commercial activities. Governments at the local, state, and federal levels are interested in assessing the impact of environmental policies that address the problem of externality and target entities that pollute. Water quality data collection began in the early 1970s, and a number of locations in Illinois now have long-term data. Consequently, it is now possible to evaluate trends in water quality and determine whether increased environmental awareness in conjunction with public policy for pollution abatement has contributed to a general improvement in water quality. This chapter describes a method for identifying trends in parameters that are generally used in water quality studies. The data sources and limitations are described briefly. Finally, the results of the analysis of water quality data are illustrated, followed by suggestions for future research.

DATA SOURCES AND LIMITATIONS

Data on water quality parameters for streams and lakes in Illinois are available in STORET, a database maintained by the Illinois Environmental Protection Agency (IEPA). To analyze and determine water quality trends in Illinois streams and rivers, data collected at water quality stations in the Ambient Water Quality Monitoring Network (AWQMN) were used (21ILAMB in STORET). The database contains observations for the period 1971 to 1991 at 204 stations in 15 different river basins in Illinois (figure 1). Not all parameters are recorded at all stations in the network. For example, phosphorus concentrations are measured at all 204 stations, while arsenic concentrations are available at only 67 stations in the AWQMN.

Water quality data are also measured at Illinois lakes. To determine water quality trends in Illinois lakes, data collected at 650 lake water quality stations in the AWQMN were used in this study (21LLAKE in STORET) and their locations are shown in figure 2. The locations of the major Illinois drainage basins included in the IEPA database are shown in figure 3.

Water quality measurement procedures for parameters such as metals indicate whether the metal was detected and whether the reading was below a certain threshold value. This threshold value varies for different parameters. With lead, for example, the measurements indicate if the concentration was <5 parts per billion (ppb), or <50 ppb, or >50 ppb. There is no acceptable procedure to convert such measurements to unique concentration values. Where exact concentrations are not available, the observations are first grouped by categories such as low, medium, and high, based on the frequency distribution of the observations and water quality standards established by the IEPA for that parameter. The percentage of observations that fall in each group is then computed for each parameter for each year. For example, for arsenic for 1985, 25 percent of the observations lie in the first group (0-1 ppb), and the remaining 75 percent lie in the second group (>1 ppb). Data for the other four metals—cadmium, chromium, lead, and mercury—and for chloride and phenolics were grouped into three categories. The percentage values in each category and the time were used instead of actual concentration values to determine temporal trends.

When exact concentration values are available, the data groupings are not needed. The mean values of all the observations in a particular year for each parameter are averaged—first for the entire state and then for each basin. The average concentration for each parameter is used to determine temporal trends.

METHODOLOGY

Detection of temporal trends in water quality consists of the following five steps. Some assumptions needed for this test are explained later.

1. State the null hypothesis for the test. For this analysis, the null hypothesis is that the water quality concentration data have no temporal trend.
2. Calculate an appropriate test statistic to evaluate the time-series data.
3. Interpret the test statistic by comparing it with its known probability distribution.

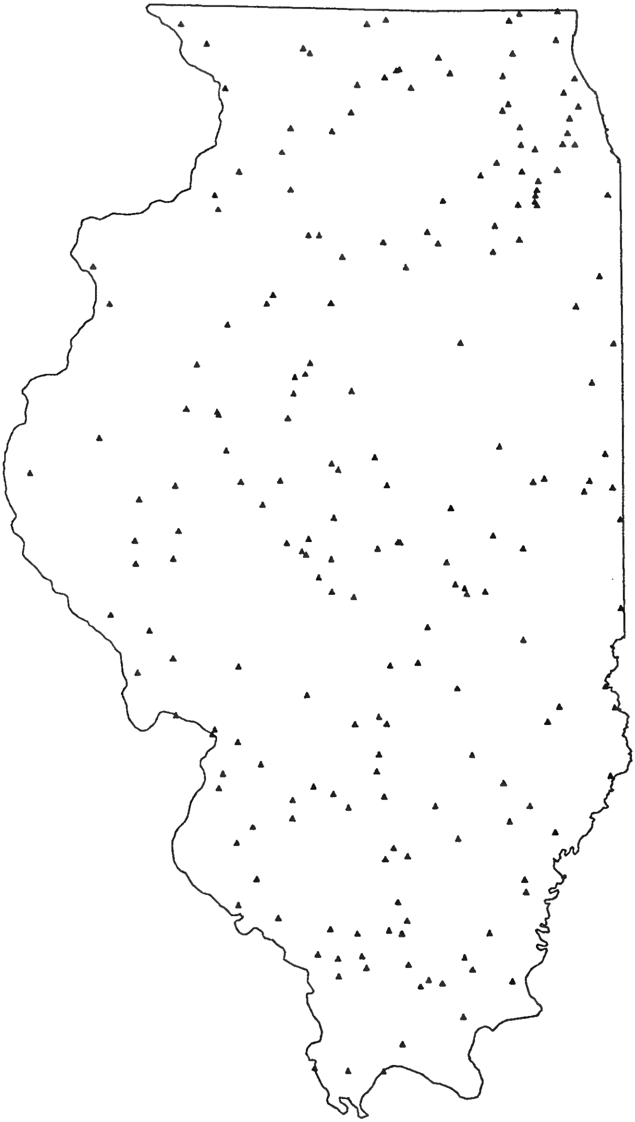

Figure 1. Streamwater quality stations in the Illinois Ambient Water Quality Monitoring Network

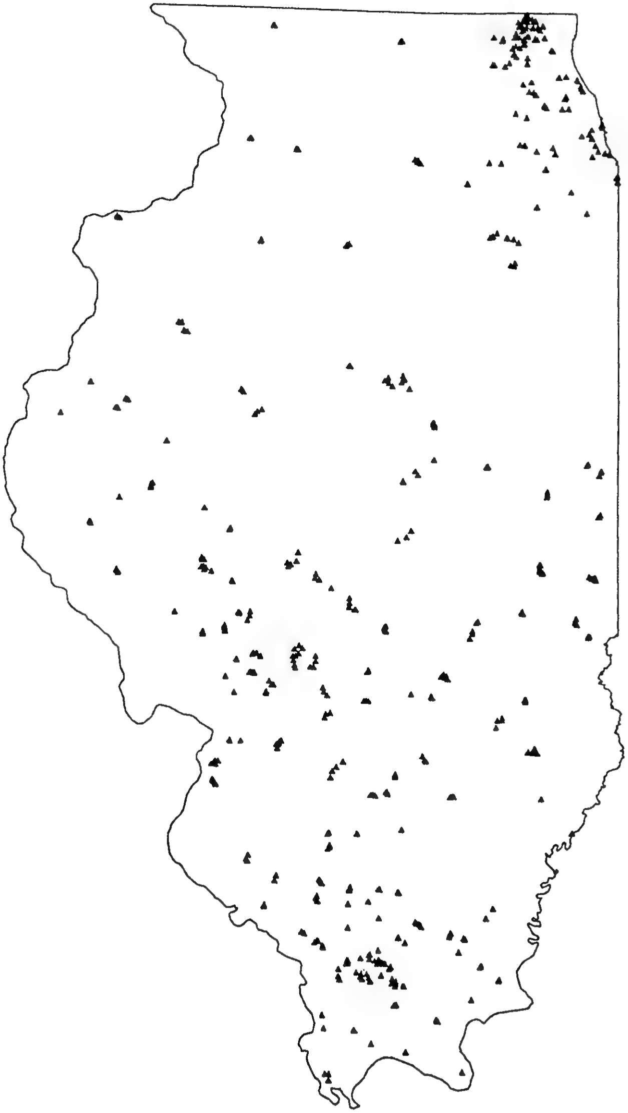

Figure 2. Lake water quality stations in the Illinois Ambient Water Quality Monitoring Network

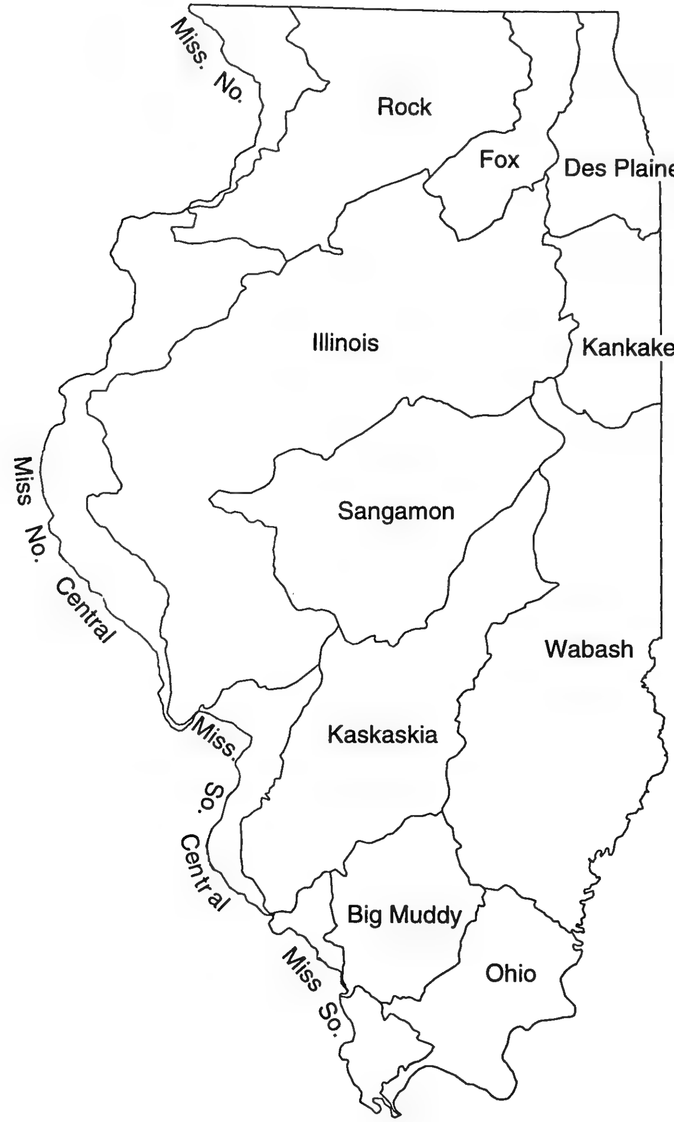

Figure 3. Major drainage basins in Illinois

4. If the test statistic falls within preselected values, then accept the null hypothesis.
5. If the test statistic does not fall within preselected values, then reject the null hypothesis. In this case we can conclude that the time-series data exhibit a statistically significant trend.

The limits are calculated for a preselected level of probability, denoted by α. Usually a value of $\alpha = 0.1$ is selected. This corresponds to a confidence level of 10 percent, which is not a very high level of significance. An α value of 0.01, or a confidence level of 1 percent, however, indicates a very high level of significance. To detect trends at various levels of significance, three different values were selected for α, 0.1, 0.05, and 0.01, which correspond to confidence levels of 10, 5, and 1 percent statistical significance, respectively. The significance level is not very meaningful, however, when there are an inadequate number of observations. In this study, the significance level is not reported in cases with less than eight years of data.

One common test for trend is based on ordinary least-squares regression of the water quality variable as a function of time. The assumptions necessary to statistically determine the presence of trends begin with a dependent variable that is normally, independently, and identically distributed. Water quality data series frequently violate these assumptions, however, making the statistical test invalid.

Distribution-free tests that use the relative rankings of the data series rather than their magnitude do not require that the data conform to certain probability distributions. The distribution-free test employed in this study is the Kendall tau (Kendall, 1970). This procedure does not require the data series to be normally distributed, only that it is independently and identically distributed. The Kendall test does not provide a measure of the magnitude of the trend, but only indicates whether or not a trend is present. This procedure has been used in many studies of water quality data. Some recent examples include a study of trends for total phosphorus (Smith et al., 1982) and the determination of surface water quality trends in Virginia (Zipper et al., 1992).

Kendall's Tau-b Association Measure

Kendall's tau-b is a nonparametric measure of association between two continuous variables. This rank measure uses the rank or order of the observations, rather than the actual value of the variables. It is based on concordance and discordance; that is, the degree to which values of two variables respectively vary together for pairs of observations. It has a range of -1 to 1.

To calculate the Kendall correlation, the observations are first ranked in terms of values of the first variable, and then in terms of values of the second variable. The number of interchanges that occur in the position of the first variable is noted and used to compute the Kendall tau-b. A correction is made for pairs that are tied.

Data Groups and Average Concentrations

Water quality measurement procedures for parameters such as metals only indicate whether the metal was detected and whether it was below a certain threshold value. This threshold value varies for different parameters. For example, in the case of lead, the measurements indicate if concentrations were <5 ppb, or <50 ppb, or >50 ppb. The concentrations of arsenic, cadmium, chromium, lead, and mercury were all very low, and some values were reported as less than the detection limit. Other values reported as greater than the detection limit were still less than the limit of quantitation (Keith et al., 1983). Where exact concentrations were not available, the observations in such cases were first grouped in low, medium, and high categories, based on the frequency distribution of the observations and water quality standards established by the IEPA for that parameter. The percentage of observations that fall in each group is then computed for each parameter for each year. Kendall correlations were calculated between the percentage values in each category and the time needed to identify any significant change over time in the percentage of observations in that category.

When exact concentration values are available these data groupings are not needed. The mean values of all the observations in a particular year for each parameter are averaged for the entire state and for each basin. Then Kendall correlation tests are performed for each parameter between the "year" and the "average concentration." This procedure was used to determine time trends for all parameters for the entire state of Illinois as well as for each basin.

ANALYSIS OF STREAMWATER QUALITY IN ILLINOIS

The water quality time-series data underwent the Kendall analysis on an IBM 6000 RISC workstation using the Statistical Analysis System (SAS©). A summary of the streamwater quality data used for the trend analysis is shown in table 1. The results of the Kendall correlation analyses of selected water quality parameters for streams averaged over the entire state of Illinois are given in table 2.

In general for all the metals, a decreasing trend was found in the levels of concentration. For chromium, however, the tau-b values were positive for the lower group and negative for the higher group, showing some movement in the observations from the higher group to the lower group. Although the highest groups for cadmium, lead, and mercury showed a significant negative trend, the rest of the correlation values were low and insignificant.

The tau-b value of -0.63 or the >10 group for cadmium means that 60 percent of the pairs of observations were concordant. This indicates a moderate declining trend in cadmium concentrations over time. This association was also highly significant, and the probability of its being a null relationship was less than 1 percent.

Only the lowest value group in chloride exhibited a significant negative trend. The results show average and highly significant trends for chemical oxygen demand (COD) at 0.50 and for phosphorus at 0.46. COD concentration levels decreased over time, while phosphorus displayed a positive trend. There is also some evidence of an increasing trend, albeit small, for dissolved oxygen (DO).

The data for nitrate nitrogen (NO_2+NO_3) show a highly significant positive trend, indicating increasing levels of concentration over time. There was no evidence of any temporal trends for total dissolved solids (TDS). Significant positive trends for nitrate nitrogen were detected in the Rock, Kaskaskia, and Illinois River basins, with the correlations varying in magnitude from 0.4 to 0.5. In contrast, the Ohio River basin displayed a significant negative trend of -0.41 for this parameter, indicating that concentrations had decreased over time.

No significant temporal trends could be detected for water quality parameters classified as pesticides. The number of nonzero average values for all the years for all parameters in this category, for the state or for any basin, ranged between 2 and 5. Annual water quality concentrations for selected parameters in streams are plotted as a function of time in figures 4-7.

Table 1. Illinois Streamwater Quality Data Summary

Parameter	*Units*	*Number of stations*		*Total years of record*	*Total number of observations*
		Minimum	*Maximum*		
Arsenic	µg/L	1	98	19	5427
Cadmium	µg/L	1	203	22	23277
Chromium	µg/L	1	204	20	23458
Lead	µg/L	1	204	19	24789
Mercury	µg/L	1	176	22	18592
Chloride	µg/L	1	171	31	16005
Phenolics	µg/L	1	79	17	4275
Chemical oxygen demand (COD)	mg/L	3	125	17	16562
Fecal coliform	#/100 ml	1	125	23	13687
Nitrogen ammonia	mg/L	1	125	19	16818
DO	mg/L	1	123	21	9494
pH	SU	2	125	23	17051
Phosphorus	mg/L	1	125	22	12444
Nitrate nitrogen (NO_2+NO_3)	mg/L	1	204	19	26928
Total dissolved solids (TDS)	mg/L	2	11	15	922

Note:
µg/L = micrograms per liter or parts per billion (ppb)
mg/L = milligrams per liter or parts per million (ppm)
#/100 ml = number per 100 milliliters
SU = standard units

Table 2. Streamwater Quality Trends for Selected Parameters in Illinois

Parameter	*Group*	*K.C.*	*Average*	*S.D.*	*Minimum*	*Maximum*
Arsenic	0.1	0.046	0.95	0.23	0	1
	>1	-0.146	3.10	2.54	2	50
Cadmium	0-3	0.193	2.40	1.18	0	3
	3-10	-0.216	5.3	1.48	4	10
	>10	-0.633***	78.84	132	11	884
Chromium	0-5	-0.176	4.06	1.95	0	5
	5-50	-0.124	11.47	7.16	6	50
	>50	-0.121	150	137	51	1100
Lead	0-5	0.098	2.52	2.50	0	5
	5-50	-0.193	45.40	12.41	6	50
	>50	-0.338*	131	197	51	5000
Mercury	0-0.05	0.209	0.03	0.02	0	0.05
	0.05-0.5	-0.253	0.12	0.08	0.06	0.50
	>0.5	-0.516**	1.47	2.11	0.60	12.90
Choride	0-250	-0.604***	54.58	48.03	0	250
	250-500	0.133	330	64.93	251	500
	>500	0.011	765	393	505	2680
Phenolics	0-10	0.103	4.53	1.69	0	10
	10-20	-0.061	15.08	2.90	11	20
	>20	-0.018	85.70	177	22	950
COD		-0.500***	25.21	25.64	0	700
Fecal coliform		0.178	3969	130962	0	1.5×10^7
DO		0.286*	9.17	3.00	0	26.70
pH		-0.052	7.65	0.51	4.10	12.0
Phosphorus		0.463***	0.42	0.76	0	30
TDS		0.0	412	332	0	1930
Ammonia nitrogen	-0.041	0.43	1.40	0	34	
Nitrate nitrogen (NO_2+NO_3)		0.590***	3.70	3.73	0	88

Notes:

*, **, and *** denotes significance at the 10, 5, and 1 percent probability level, respectively.

S.D. = Standard deviation; K.C. = Kendall correlation

See table 1 for units for each parameter.

ANALYSIS OF STREAMWATER QUALITY BY RIVER BASINS

The results of the Kendall correlation analyses for selected streamwater quality parameters for 14 basins in Illinois are given in tabular form in Ramamurthy (1993) and are summarized below.

- Big Muddy basin: A positive trend for the low group (0.36) and a negative trend for the middle group (-0.60) for chromium implies that concentration levels are declining over time. The mean COD concentration has also decreased during this period.
- Des Plaines River basin: Significant trends were observed for the low and middle groups of chromium: a negative trend (-0.68) for the low group and a positive trend for the middle group (0.58). This means that chromium levels have increased in this basin over time, in contrast to the Big Muddy basin. The high group of cadmium shows a strong negative trend (-0.87). A strong negative trend (-0.79) was also observed for ammonia nitrogen.
- Fox River basin: Chromium concentrations are increasing over time, similar to the trend in the Des Plaines basin. A weak negative trend was found for ammonia nitrogen in this basin.
- Kankakee River basin: Chromium levels showed a strong increase from the low group to the middle group.
- Kaskaskia River basin: Some evidence indicates a moderate positive trend for phosphorus concentrations and a strong negative trend for COD. These trends are similar to the average trends observed for the state. The middle group for chromium exhibits a moderate negative trend (-0.42).
- Mississippi River, north basin: No significant trends were observed for any of the parameters analyzed.
- Mississippi River, central basin: No significant trends were observed for any of the parameters analyzed.

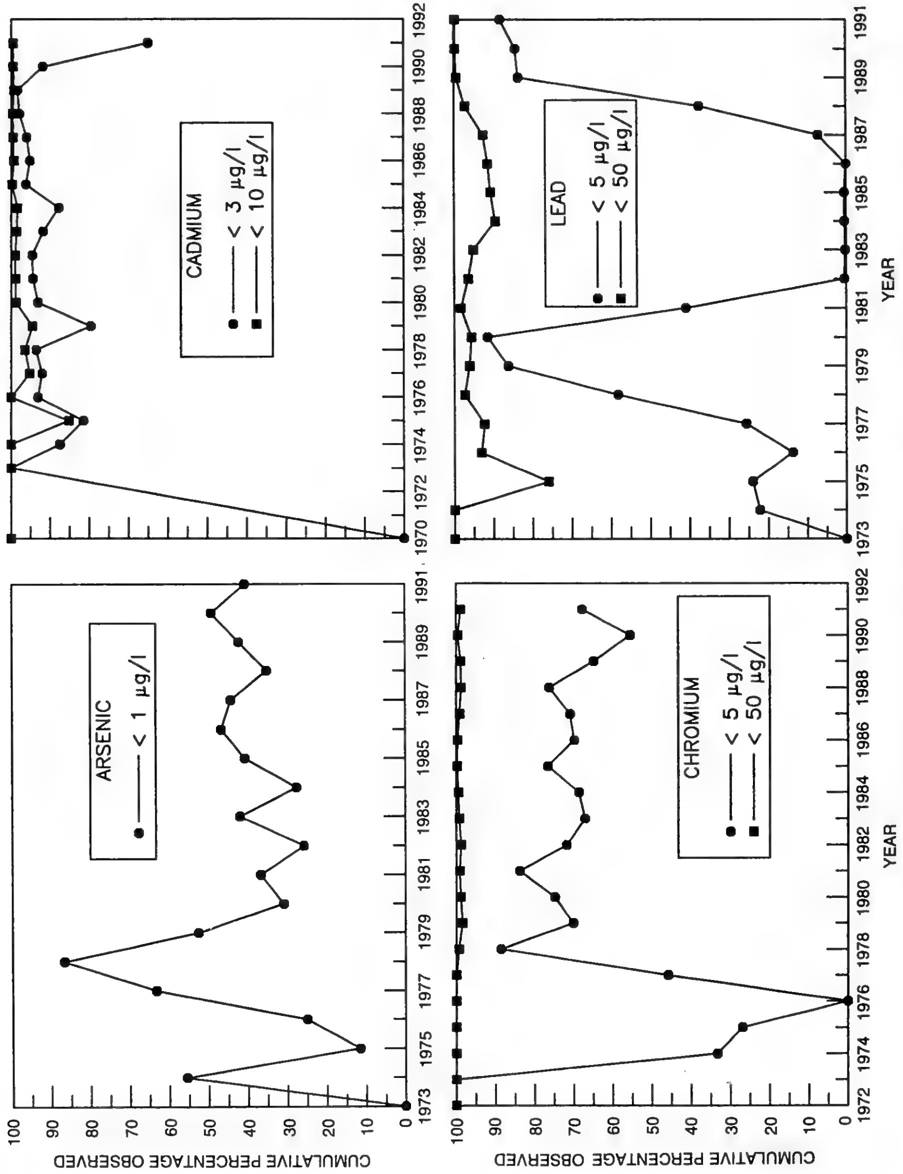

Figure 4. Annual statewide average streamwater concentration levels for arsenic, cadmium, chromium, and lead

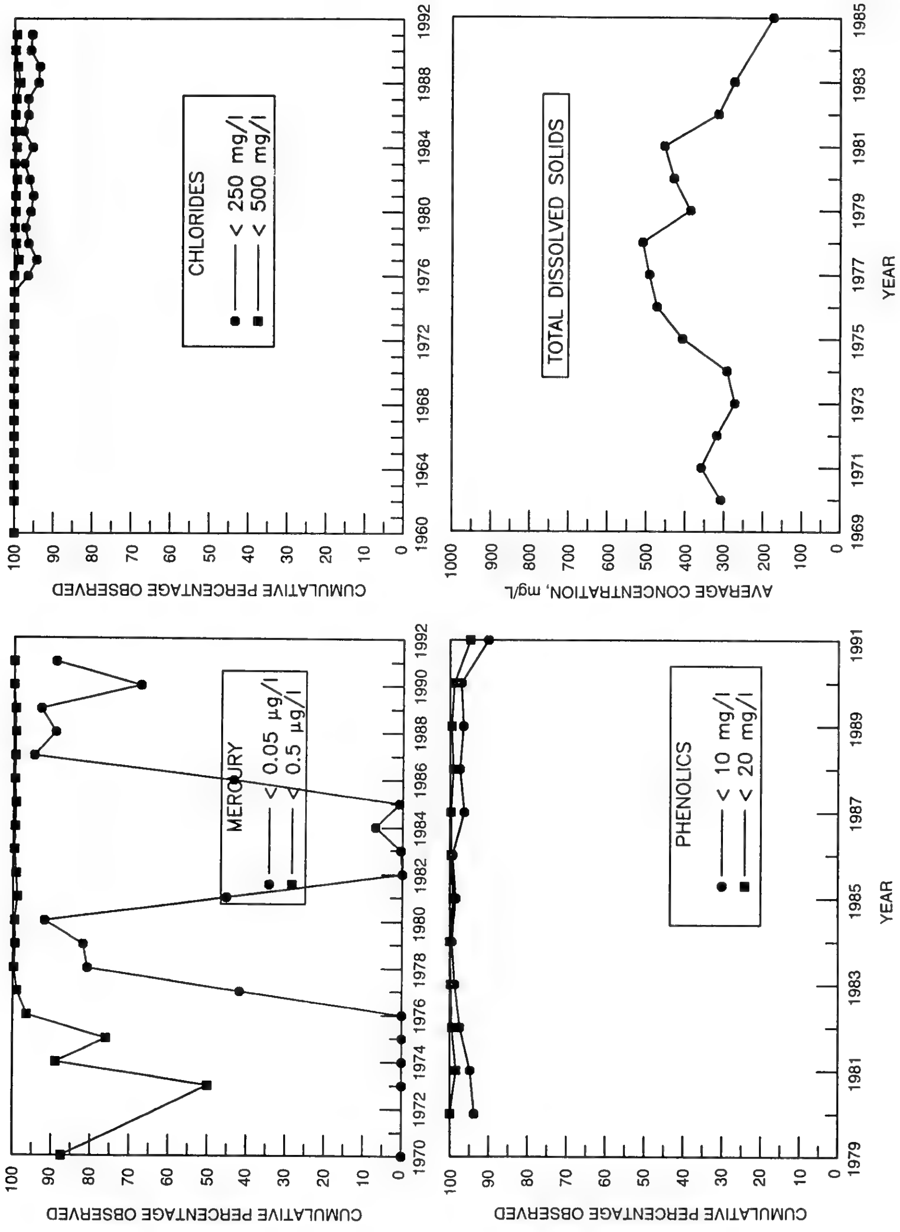

Figure 5. Annual statewide average streamwater concentration levels for mercury, chloride, phenolics, and total dissolved solids

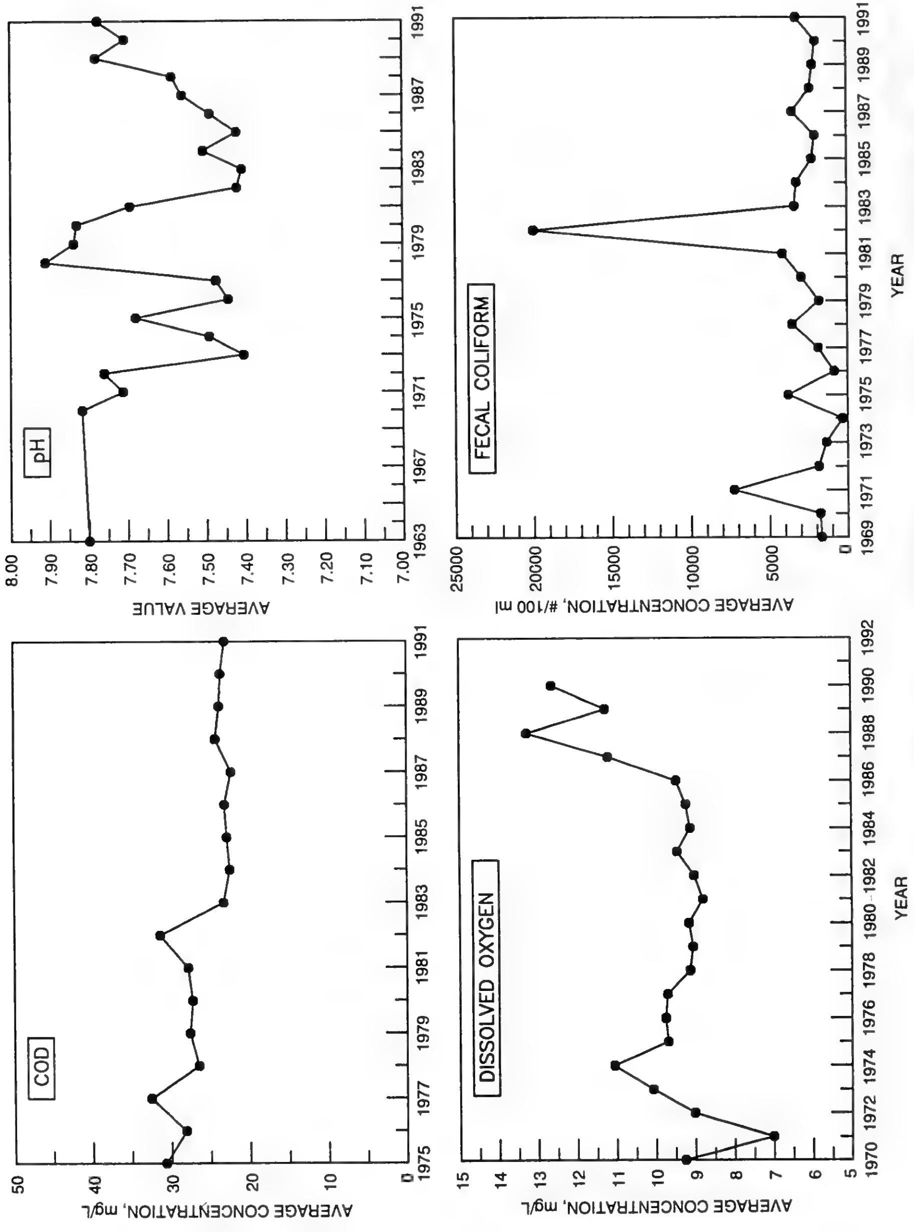

Figure 6. Annual statewide average streamwater concentration levels for chemical oxygen demand, pH, dissolved oxygen, and fecal coliform

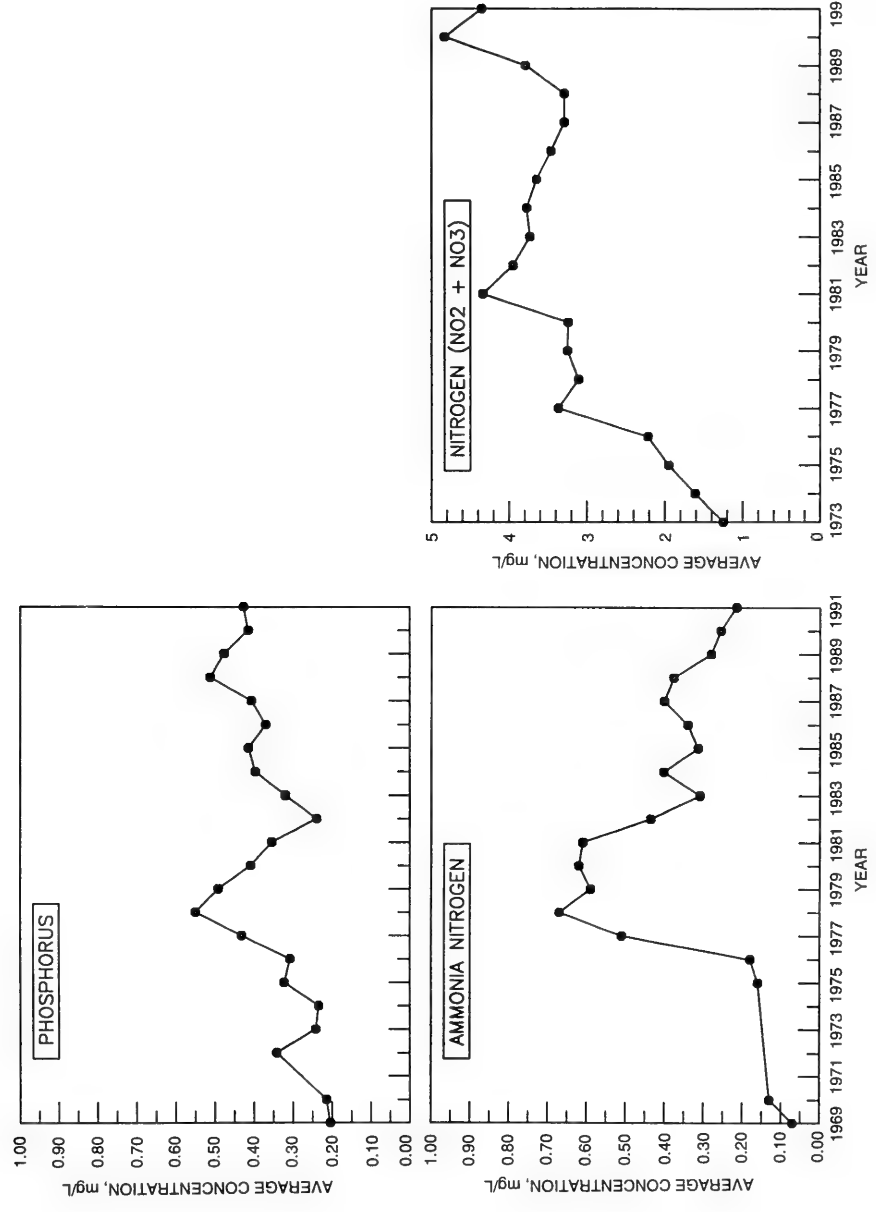

Figure 7. Annual statewide average streamwater concentration levels for phosphorus, ammonia nitrogen, and nitrate nitrogen

- Mississippi River, north-central basin: No significant trends were observed for any of the parameters analyzed.
- Mississippi River, south basin: With a negative correlation (-0.54), the high group of lead displayed a declining trend over time. A moderate decrease (-0.46) was found in the percent of observations for chromium in the 5-50 ppb level.
- Mississippi River, south-central basin: No significant trends were observed for any of the parameters analyzed.
- Ohio River basin: Several trends were noticeable in the Ohio River basin. The proportion of observations in the low category for arsenic has been increasing, with a corresponding decrease in the high category. This implies that arsenic levels are decreasing. Cadmium concentration levels were also decreasing, with a moderate negative trend (0.50) in the high group. The low and high groups of lead showed an increasing trend, while the middle group showed a decreasing trend. This implies that in recent years, lead levels have been either in the 0-5 ppb range or in the >50 ppb range, which may be due to changes in the procedure for measuring lead concentrations.
- Rock River basin: No significant trends were observed for any of the parameters analyzed.
- Wabash River basin: Both the low and high groups for chloride showed negative trends at different levels of significance. Phosphorus concentration levels exhibited a moderate increasing trend (0.50).
- Illinois River basin: A negative trend was observed for COD. A negative trend for the low group and a moderate positive trend in the middle group indicate that chloride concentration levels have been increasing over time.

Since a trend was observed for nitrate nitrogen in a number of basins, the average concentrations of this parameter for four years, 1975, 1980, 1985, and 1990, are shown in figures 8 and 9. These figures provide some insight into the spatial variation in nitrate nitrogen concentrations for the four time periods.

ANALYSIS OF LAKE WATER QUALITY IN ILLINOIS

A summary of the lake water quality data used for the trend analysis is shown in table 3. The results of the Kendall correlation analyses of selected water quality parameters for lakes averaged over the entire state of Illinois are given in table 4.

No trends were observed for any of the parameters analyzed for lakes in Illinois. Data on DO, phenolics, chlordane, dieldrin, and DDT were very sparse, with many missing values, and thus could not be analyzed. Data values for pesticides such as chlordane, dieldrin, and DDT were ≤0.01 micrograms per liter (µg/L) for the few observations that were available. Annual water quality concentration levels for selected parameters in lakes are plotted as a function of time in figures 10-12.

ANALYSIS OF LAKE WATER QUALITY BY RIVER BASINS

The results of the Kendall correlation analyses for selected lake water quality parameters for 13 Illinois basins are given in tabular form in Ramamurthy (1993) and are summarized below.

For most of the basins, no significant trends were observed for any of the parameters analyzed. A moderate decreasing trend (-0.47) was observed for phosphorus in the Fox River basin. In the Kaskaskia River basin, a highly significant positive trend (0.50) was observed for nitrate nitrogen, which suggests that concentration levels are increasing over time. A highly significant positive trend (0.50) was found for ammonia nitrogen in the Mississippi River, north-central basin. A moderately significant positive trend (0.49) was observed for nitrate nitrogen in the Rock River basin. Similar trends for both ammonia nitrogen and nitrate nitrogen were also seen in the Wabash River basin.

SUMMARY AND CONCLUSIONS

Significant negative (or decreasing) concentration trends were observed for cadmium, mercury, chloride, and COD. Phosphorus and nitrate nitrogen concentrations exhibited equally significant positive (or increasing) trends. No significant trends were observed for arsenic, chromium, phenolics, fecal coliform, DO, pH, and TDS.

Significant temporal trends were observed in the Ohio, Des Plaines, Kaskaskia, Wabash, Illinois, Big Muddy, Mississippi south, Fox, and Kankakee River basins. The Des Plaines River basin, in contrast to the statewide trend, showed increasing cadmium concentration levels over time. An increasing trend in chromium

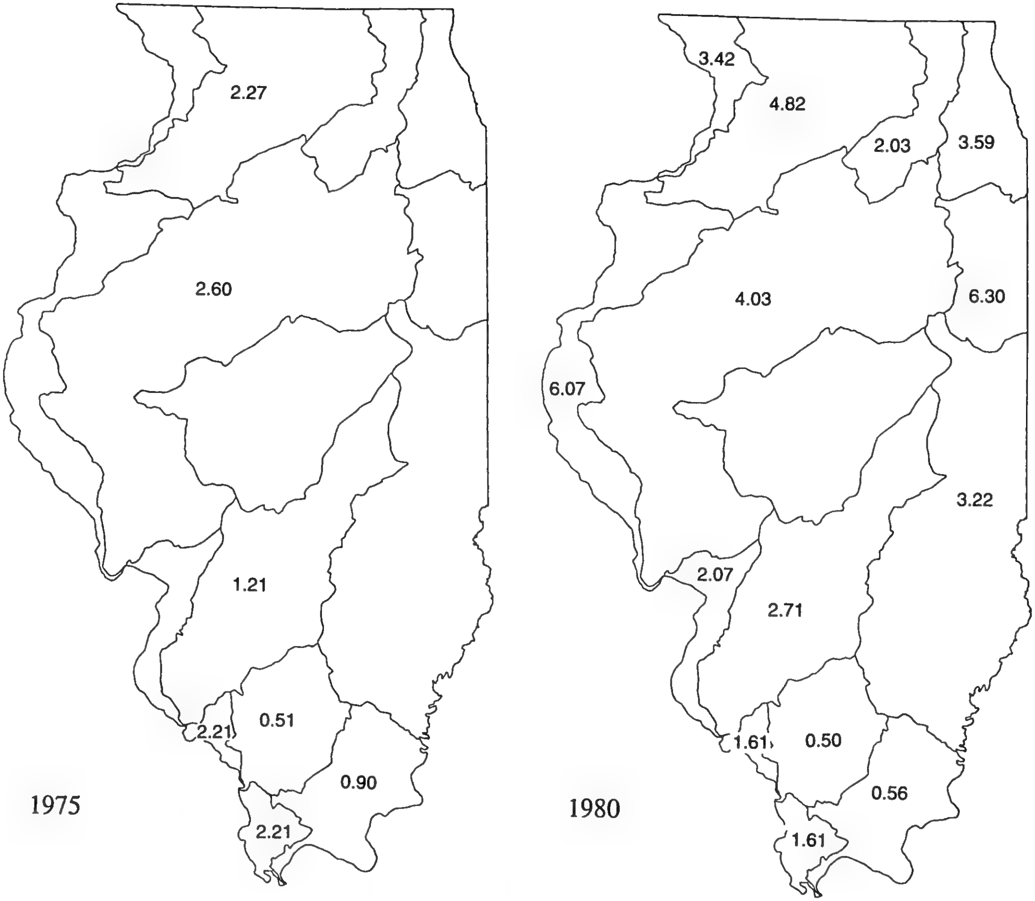

Figure 8. Nitrate nitrogen concentration levels in major river basins in Illinois, 1975 and 1980

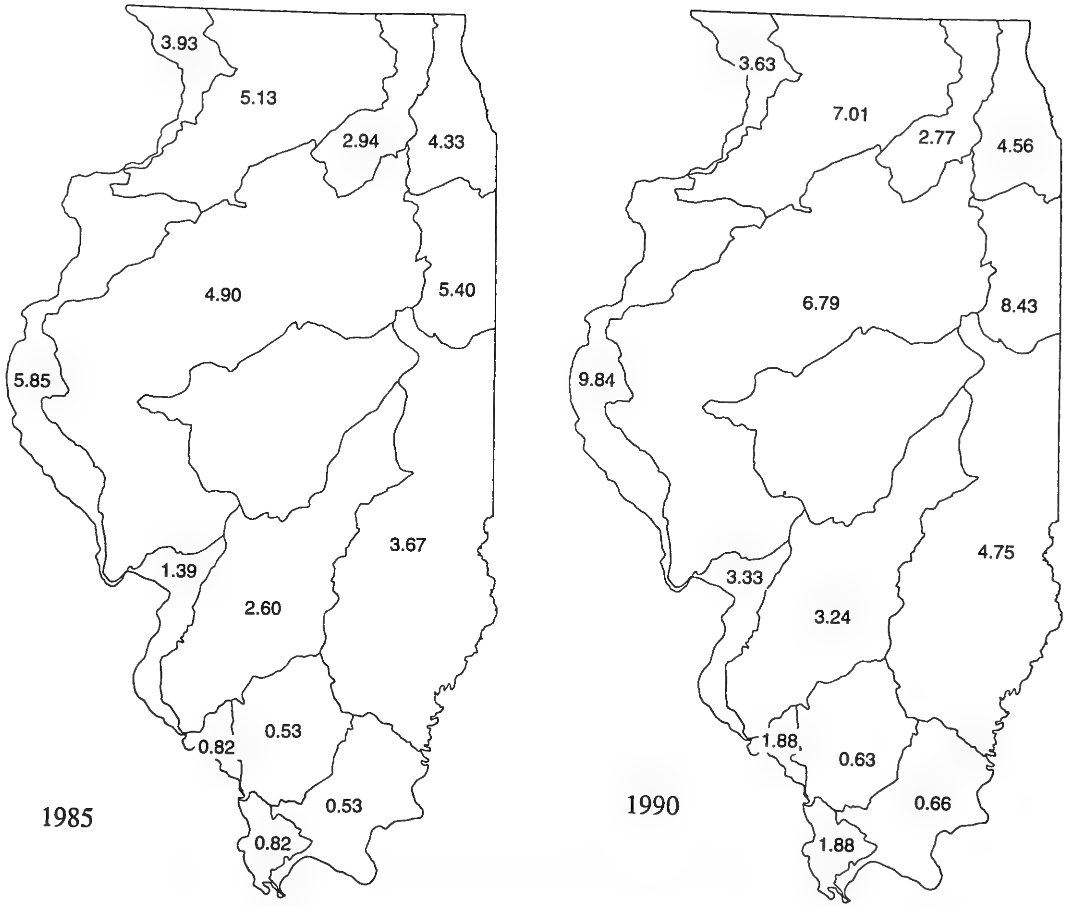

Figure 9. Nitrate nitrogen concentration levels in major river basins in Illinois, 1985 and 1990

Table 3. Illinois Lake Water Quality Data Summary

Parameter	Units	*Number of stations* Minimum	Maximum	Total years of record	Total number of observations
Arsenic	µg/L	4	218	13	1083
Cadmium	µg/L	3	218	13	1333
Chromium	µg/L	3	218	13	1329
Lead	µg/L	3	218	13	1334
Chloride	mg/L	3	218	9	1441
Chemical oxygen demand (COD)	mg/L	54	211	13	6976
Fecal coliform	#/100 ml	1	218	5	1431
Nitrogen ammonia	mg/L	54	304	15	9067
pH	SU	54	283	15	8994
Phosphorus	mg/L	54	303	15	9051
Nitrate nitrogen (NO_2+NO_3)	mg/l	54	304	15	8847

Notes:
µg/L = micrograms per liter or parts per billion (ppb)
mg/L = milligrams per liter or parts per million (ppm)
#/100 ml = number per 100 milliliters
SU = standard units

Table 4. Illinois Lake Water Quality Trends for Selected Parameters

Parameter	*Group*	*K.C.*	*Average*	*S.D.*	*Minimum*	*Maximum*
Arsenic	0-1		0.92	0.27	0	1
	>1	0.359	4.93	5.33	2	62
Cadmium	0-3	0	2.47	0.50	2	3
	3-10	0	5.03	0.45	4	10
	>10		24		24	24
Chromium	0-5	-0.028	4.91	0.32	1	5
	5-50	0.521	10.12	4.20	6	46
	>50		80		80	80
Lead	0-5		0.10		0.10	0.10
	5-50	0	41.06	16.66	10	50
	>50		108	48.39	76	300
Chloride		0.278	19.43	220	1	460
COD		0.030	25.17	17.60	1	350
Fecal coliform		0.236	2018	27767	0	900000
pH		0.047	7.88	0.72	2	10.30
Phosphorus		0.029	0.17	0.40	0	14
Ammonia nitrogen	0.105	0.270	0.76	0	18	
Nitrate nitrogen (NO_2+NO_3)		0.277	1.06	2.58	0	39

Notes:
S.D. = Standard deviation; K.C. = Kendall correlation
See table 1 for units.

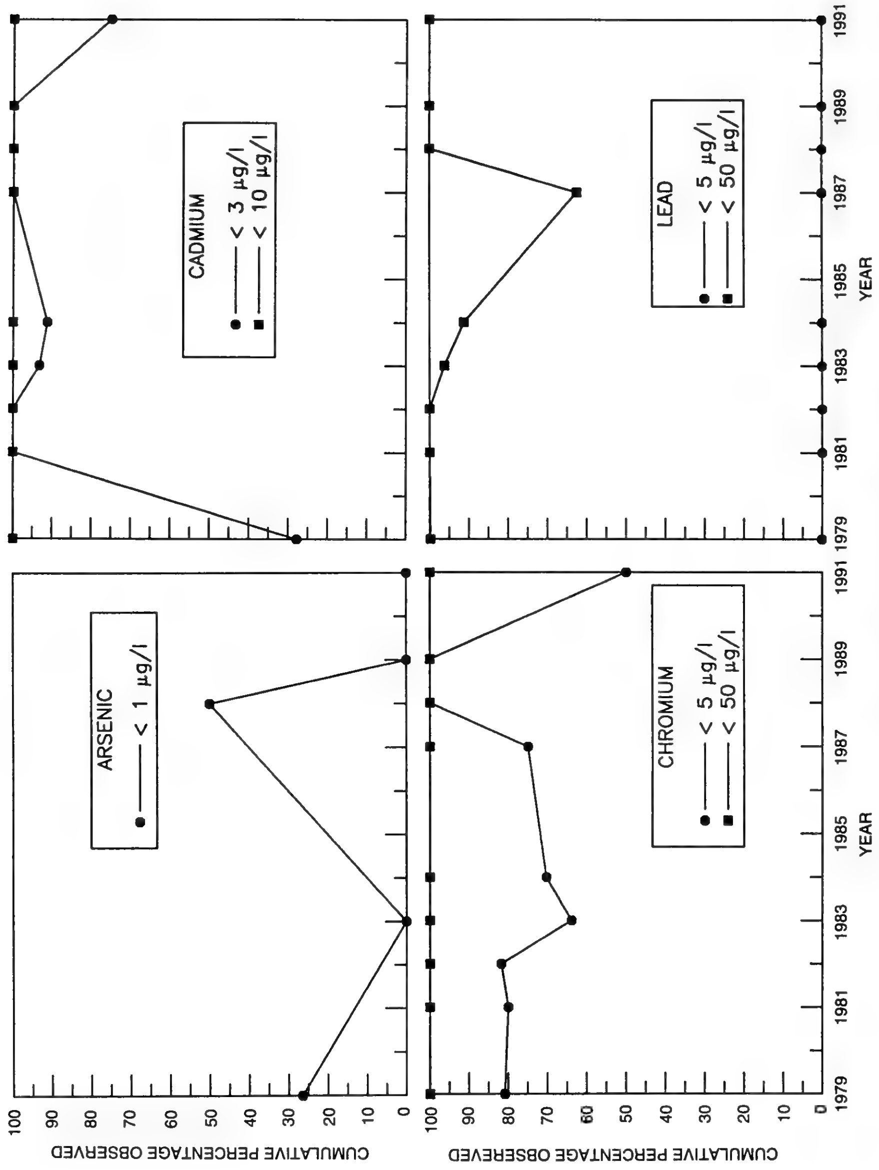

Figure 10. Annual statewide average lake water concentration levels for arsenic, cadmium, chromium, and lead

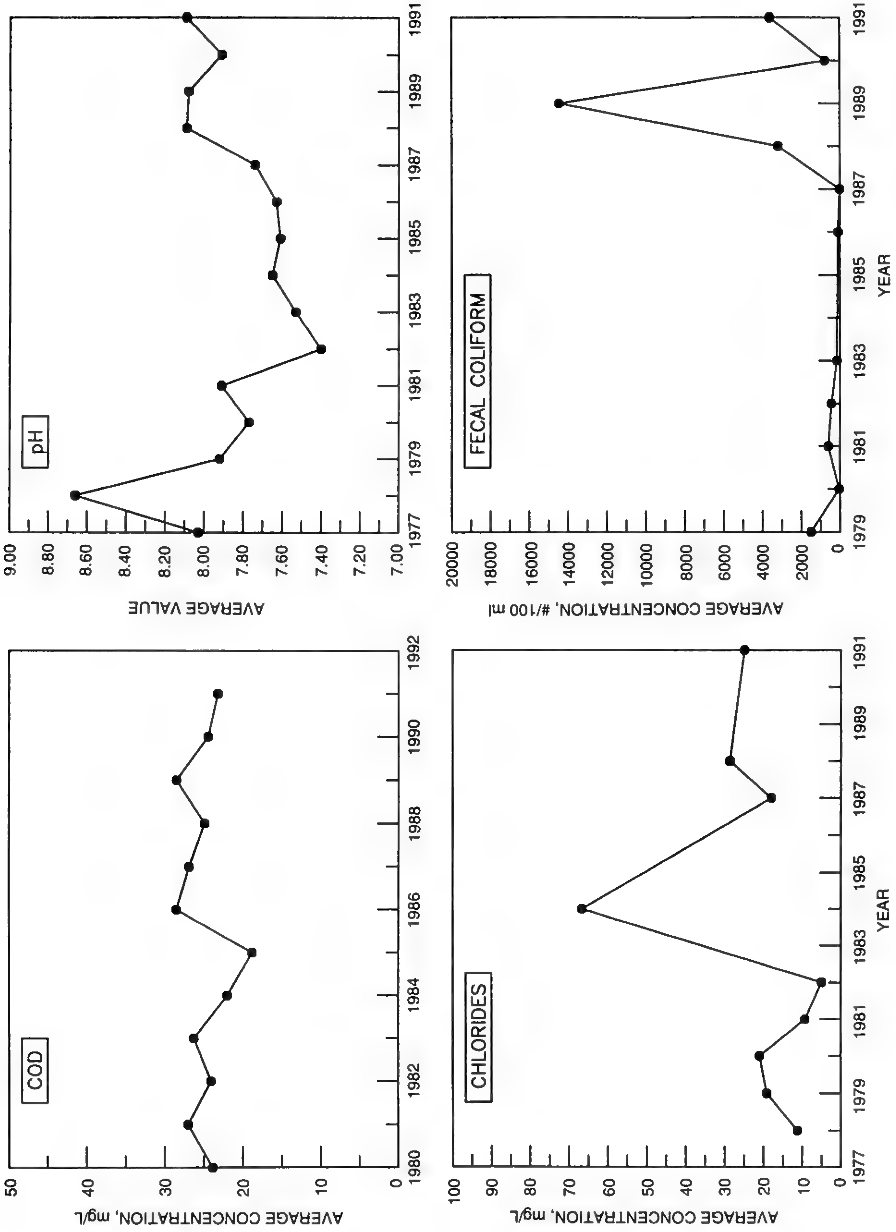

Figure 11. Annual statewide average lake water concentration levels for chemical oxygen demand (COD), pH, chloride, and fecal coliform

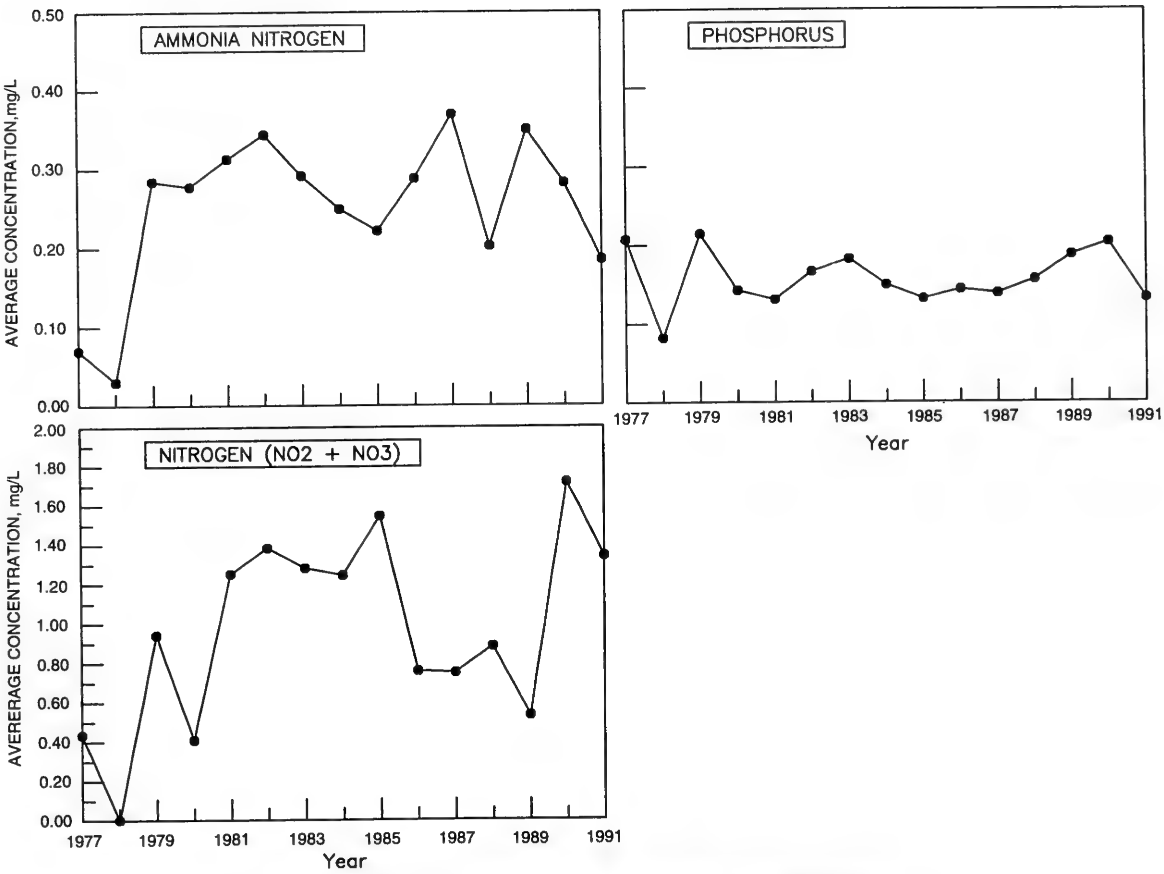

Figure 12. Annual statewide average lake water concentration levels for ammonia nitrogen, phosphorus, and nitrate nitrogen

concentrations was observed for the Kankakee River basin. A moderate increase in chloride concentrations was found in the Illinois River basin. Lead concentrations in the Ohio River basin increased for part of the observation period, but decreased in others. The Ohio River basin also revealed decreasing concentrations of nitrate nitrogen, which is contrary to the overall trend observed for the state.

No trends were observed for any of the water quality parameters analyzed for lakes in Illinois. Since data on some parameters were very limited with many missing values, they could not be analyzed.

LIMITATIONS OF THIS STUDY

Water quality variables are generally known to exhibit seasonal trends. Therefore, water quality data series should be tested for inherent seasonal effects. If, for example, a periodicity of one year exists in water quality data, one should compare only observations within a particular month for each year. The Kendall tau test should be designed to reflect this seasonality (Smith et al., 1982). The correlation test used here has not been adjusted to allow for seasonality in water quality data.

Temporal trends have been analyzed with water quality concentration levels. Pollutant loadings that are influenced by both concentration and flow levels have not been analyzed. For parameters such as COD, phosphorus, and DO, concentration levels can be strongly influenced by flow levels. The concentration values should be adjusted for flow variations. Such a procedure requires several iterations to estimate the adjustment equations, and it has not been performed in this analysis.

As mentioned earlier, data recorded for some water quality variables are not precise. Consequently, the observations for such variables had to be grouped. The Kendall statistics therefore indicate movement in concentration levels from one group to another, rather than the decrease/increase that can occur within a group. Because percentage values are used in such cases, the data for each year are assumed to come from identical distributions, irrespective of the sample size for the year.

SUGGESTIONS FOR FUTURE RESEARCH

As outlined above, new and improved methodologies need to be introduced to extend the analysis of water quality undertaken in this study. Future work on this topic should comprise the following specific tasks:

1. Develop a seasonal Kendall estimator to test for seasonality in water quality data and estimate seasonal temporal trends. The number of seasons in each year and the duration of each season are empirical issues and should be determined using appropriate analytical procedures.

2. Develop pollutant loadings for different parameters using data on concentration levels and average streamflow values. The concentration values of certain parameters such as COD, phosphorus, and DO are strongly influenced by flow conditions. These concentration values should be adjusted for flow variations using iterative procedures suggested in the literature. The development of pollutant loadings and the use of flow-adjusted concentration values provide a more realistic measure of ambient water quality conditions.

3. There is no acceptable procedure to convert water quality measurement values for parameters such as metals to unique concentration values. Consequently, the observations for such parameters had to be grouped. Appropriate statistical procedures should be used to determine the expected concentration values by assuming an underlying distribution for such measurements. This procedure will yield a consistent set of concentration values that can be used to determine temporal and spatial trends.

4. Develop appropriate statistical methods to test and estimate the impact of surface water quality trends on selected water quality concentration levels and pollutant loads.

5. Integrate the results of water quality and water quantity trend analyses to identify environmental indicators based on chemical surface water quality. These can be combined with information developed on biological trends to identify biochemical environmental indicators.

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STATEWIDE GROUND-WATER QUALITY

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INTRODUCTION

The purpose of this report is to begin to examine the records of ground-water quality for temporal trends in selected portions of Illinois. Increasingly, ground-water contamination is discussed in the news media, and it may seem that the entire ground-water resource has been impacted. However, these contamination events are often localized and may not represent widespread degradation of the ground-water resource. By examining the temporal trends in ground-water quality of county-sized regions, it may be possible to determine if large-scale degradation of the ground-water resource has occurred.

The general term "ground-water quality" refers to the chemical composition of ground water. Ground water originates as precipitation that filters into the ground. As the water infiltrates, it begins to change chemically due to reactions with air in the soil and with the earth materials through which it flows. In addition, human-induced chemical changes can also occur. Contamination of ground water generally refers to human-induced chemical changes and not naturally occurring processes.

As a general rule, local ground-water quality tends to remain nearly constant under natural conditions because of long ground-water travel times. Therefore, significant changes in ground-water quality can often indicate degradation of the ground-water resource.

DATA SOURCES

Two distinct types of information, water quality and aquifer delineation, have been used in the preparation of this report. The water quality data come from two sources: private wells and municipal wells. The private well water quality data are compiled by the Chemistry Division of the Illinois State Water Survey (ISWS) as part of their water testing program and are maintained by the Office of Ground-Water Information in a water quality database. The municipal well data come from Water Survey analyses and from the Illinois Environmental Protection Agency (IEPA) Laboratories. The combined database now contains about 50,000 records of chemical analyses from samples analyzed at the Water Survey laboratories and the IEPA laboratories. Some of these analyses date to the early part of the century, but most are from 1970 to the present. Before 1987, most analyses addressed inorganic compounds and physical parameters. Since then, many organic analyses have been added to the database from the IEPA Safe Drinking Water Act compliance monitoring program.

The geologic information, including approximate depth, thickness, and boundaries of various aquifer units, was obtained from the Illinois State Geological Survey.

Data Limitations

Several limitations to the data must be understood before any meaningful interpretation can begin:

1. Representativeness of the sample
2. Location information
3. Charge balance check of the laboratory analysis
4. Extrapolation to larger areas

The private well samples are likely not completely representative of regional ground-water quality. In most cases, private well owners submit samples for analysis only when they believe there may be a problem such as high iron or an odd odor or taste. This suggests that perhaps one or more constituents may not be representative, but in general, the remainder of the chemical information will be accurate and useful. As a result, the composite data may be skewed toward analyses with higher than normal concentrations.

On the other hand, the private well information probably provides a better picture of the spatial distribution of chemical ground-water quality than municipal well information because of the larger number of samples spread over a large area. The recent IEPA data from municipal wells will not be skewed because each well is sampled and analyzed on a regular basis. While this produces a much more representative sample overall, samples are generally limited to specific areas where municipalities are located. Therefore, these data may not be good indicators of regional ground-water quality.

Much of the location information for the private wells is based solely on the location provided by the driller at the time the well was constructed. Generally, the locations are given to the nearest 10- acre plot of land. For our purposes here, that degree of resolution is adequate. However, it is not uncommon for the given location to be in error by up to as much as 6 miles. To circumvent the possible location errors, this report presents results on a county basis.

The validity of water quality data was checked by calculating a charge balance for each analysis. Charge balance is a simple measure of the quality of a water quality analysis. It measures the deviation from the constraint of electrical neutrality of the water by comparing total cations (positively charged ions) with total anions (negatively charged ions). Because many of the early analyses were performed for specific chemical constituents, a complete chemical analysis is not always available from which to calculate a charge balance. Based on a search of the water quality database for analyses with sufficient chemical constituents to perform an ion balance, it was found that more than 98 percent of the analyses produced an acceptable mass balance. This gives us confidence that the chemical analyses are accurate.

The question of extrapolation of a point value (a well water sample) to a regional description of ground-water quality is difficult and theoretically beyond the scope of this report. However, several general points can be raised. First, none of the data provide a uniform spatial coverage. Therefore, it seemed best to summarize the data on a county basis to ensure that an adequate number of values would be available. The private well analyses are more numerous and will likely provide better spatial coverage than the municipal well data, which are concentrated in isolated locations.

Chemical Components Selected for Trend Analysis

In many cases, ground-water contamination refers to the introduction into ground water of industrial or agricultural chemicals such as organic solvents, heavy metals, fertilizers, or pesticides. However, recent evidence suggests that many of these contamination occurrences are localized and form finite plumes that extend downgradient from the source. Much of this information is relatively recent, dating back a few decades, but long-term records at any one site are rare. As mentioned earlier, changes in the concentrations of naturally occurring chemical elements such as chloride, sulfate, or nitrate also can be indicative of contamination. Increasing chloride concentrations may indicate contamination from road salt or oil field brine. Increasing sulfate concentrations may be from acid wastes, for example metal pickling. Increasing nitrate concentrations may result from fertilizer application, feed-lot runoff, or leaking septic tanks. These naturally occurring substances are the major components of mineral quality in ground water and are routinely included in ground-water quality analyses. Fortunately, the Illinois State Water Survey has maintained records of routine water quality analyses of private and commercial wells that extend as far back as the 1890s. After examination of these records, six chemical constituents (table 1) were chosen for trend analyses based on the large number of available analyses and because they may be indicators of human-induced degradation of ground-water quality.

Aquifer Unit Delineation

Ground water occurs in many types of geological materials and at various depths below the land surface. This variability results in significant differences of natural ground-water quality from one part of Illinois to another and from one aquifer to the next even at the same location. For the purposes of trend analyses, six aquifer designations were delineated: alluvial valley aquifers, bedrock valley aquifers, shallow drift aquifers, deep drift aquifers, shallow bedrock aquifers, and deep bedrock aquifers. Each of these aquifer designations represents a unique set of conditions that are of interest for assessing overall trends in ground-water quality.

Alluvial Valley Aquifers. These aquifers underlie many of the major rivers and streams in Illinois, such as the Illinois River, the Wabash River, and the Mississippi River. The aquifers tend to be near the land surface and of limited lateral extent. These aquifers are made up of a variety of materials in grain sizes ranging from sand and gravel to clay. Some of these aquifers tend to be vulnerable to contamination because they are near the land surface and often in proximity to intense industrial activity located along the rivers.

Bedrock Valley Aquifers. Bedrock valley aquifers occur along former river channels. The major bedrock valley aquifers are largely sand and gravel and can be several hundred feet thick. Some of these aquifers are exposed at the land surface, such as in Mason County, while others, such as the Mahomet Valley aquifer, are buried beneath more than 200 feet of fine-grained material that provides protection in some areas. The shallow bedrock valley aquifers are just as vulnerable to contamination as the alluvial valley aquifers, but the more deeply buried aquifers tend to be less vulnerable.

Shallow Drift Aquifers. These aquifers were formed by glacial meltwater and tend to be more laterally

Table 1. Dissolved chemical components of ground water chosen for trend analyses

Component	*Abbreviation*
iron	Fe
total dissolved solids	TDS
sulfate	SO_4
nitrate	NO_3
chloride	Cl
hardness	as $CaCO_3$

extensive than the valley aquifers. They are composed of unconsolidated sand and gravel and are typically very permeable. In general, the shallow drift less than 100 feet deep is potentially more vulnerable from a contamination perspective.

Deep Drift Aquifers. Although of similar geologic origin as the shallow drift aquifers, the greater depth of the deep drift aquifers provides more protection from human-induced contamination.

Shallow Bedrock Aquifers. Bedrock aquifers are lithified materials such as limestone, dolomite, or sandstone. "Shallow" in this context generally refers to the uppermost bedrock unit, even though it may be buried by several hundred feet of glacial material. These aquifers, where covered by fine-grained material, are generally less vulnerable to contamination. However, in regions where the bedrock is at or near the land surface, the potential for contamination is much greater.

Deep Bedrock Aquifers. Deep bedrock aquifers are typically more than 500 feet below land surface. As a general rule, the water in the deep aquifers tends to be more highly mineralized than some of the shallow aquifers, but it varies from location to location. The potential for contamination by vertical migration of chemicals from the land surface is low. Other contamination pathways, such as abandoned wells, are probably a much greater threat to the ground-water quality in deep bedrock aquifers.

Counties Selected for Analysis

Two counties were selected for trend analysis of shallow drift aquifers. Three counties were selected for trend analysis of the other aquifer categories. The counties associated with each aquifer designation are given in table 2, along with the associated well depths from which samples were taken. The locations are also shown in figure 1.

Table 2. County and aquifer designations for trend analysis

Aquifer designation	*County*	*Depth (feet)*
Alluvial valley	Winnebago	< 150
	Madison/St. Clair	< 150
	Gallatin	< 165
Bedrock valley	Bureau	< 400
	Mason	< 230
	Champaign	< 440
Shallow drift	DuPage	< 100
	Effingham	< 100
Deep drift	DuPage	101 - 130
	McLean	87 - 380
	Macon	102 - 293
Shallow bedrock	DuPage	131 - 350
	Whiteside	200 - 400
	Kankakee	150 - 400
Deep bedrock	Winnebago	> 500
	Cook	> 500
	Knox	> 500

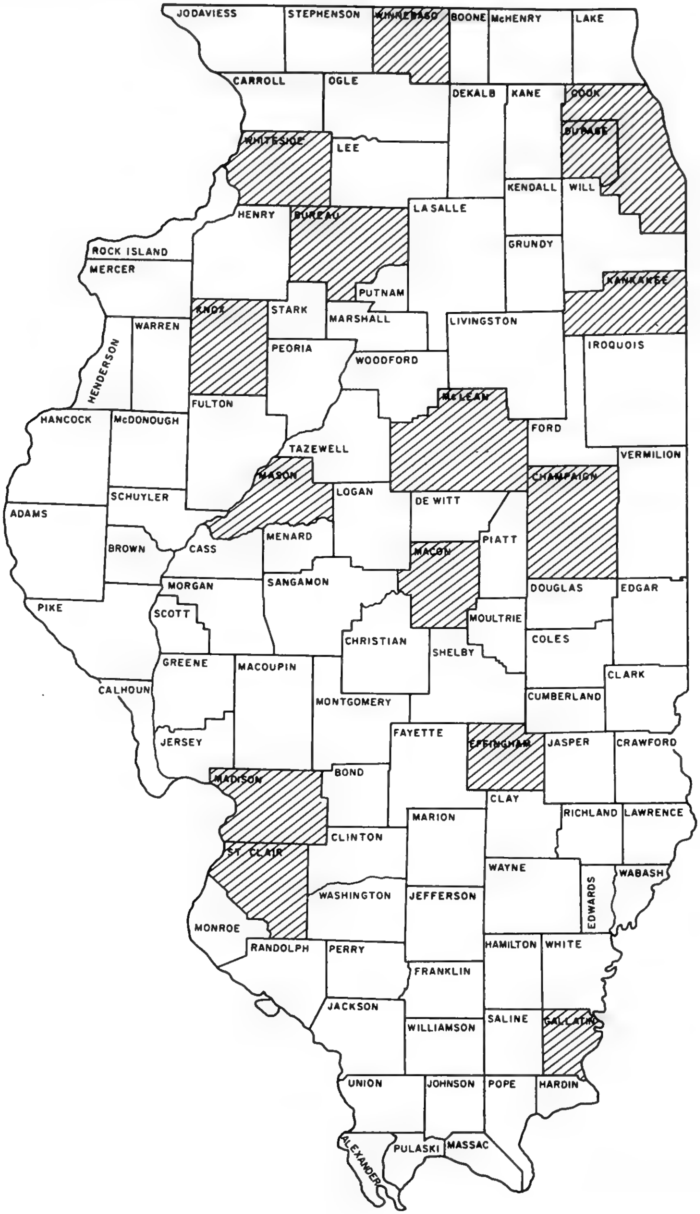


Figure 1. Counties containing aquifers included in the assessment of ground-water quality trends

Alluvial Valley Aquifers

Winnebago County. The alluvial aquifer associated with the Rock River runs north and south through the county. Much of the aquifer system underlies the Rockford metropolitan area, creating a high potential for ground-water contamination. In fact, one portion of the aquifer was recently designated as the "Southeast Rockford Superfund Site" because of a large plume of volatile organic contaminants.

Madison/St. Clair Counties. The alluvial aquifer located in the region known as the American Bottoms along the Mississippi River near St. Louis has been intensely developed for many years. Many industries concentrated near the river contribute contaminants to the aquifer. Further east, the area is largely agricultural. This region is similar to Winnebago County because of the high potential for ground-water contamination.

Gallatin County. The aquifer along the Wabash River differs from the other two because this is a largely rural county, and industrialization is not expected to be a significant source of contamination.

Bedrock Valley Aquifers

Bureau County. Located in the ancestral valley of the Mississippi River, this aquifer is increasingly being used for irrigation. This additional usage is currently within the safe yield of the aquifer. Leaching of agrichemicals, particularly nitrate, is of some concern in this area.

Mason County. Also located along the ancestral Mississippi River, now the Illinois River, this aquifer is essentially exposed at the land surface. It is an area of significant irrigation and may represent an analog to future conditions in Bureau County.

Champaign County. The Mahomet Bedrock Valley aquifer extends from the Illinois/Indiana border to the Illinois River. Near Champaign, the aquifer is buried beneath some fine-grained glacial material that provides protection. The aquifer in Champaign County is less vulnerable to contamination than in the other two counties.

Shallow Drift Aquifers

DuPage County. Several aquifers are present in DuPage County, and the three uppermost ones will be examined. This will be particularly interesting because DuPage County has undergone a tremendous amount of urbanization over the past 100 years. As a result, the impact of human activity on the quality of the ground water may be documented. It is anticipated that the shallowest aquifer will show the greatest impact, while the deepest aquifers may not. The shallow drift aquifer is used primarily by private, low-capacity wells, whereas the deeper aquifers are the major source of water to many of the municipalities.

Effingham County. Agricultural activities and shallow, domestic large-diameter wells dominate the picture in Effingham County because of the paucity of good sand-and-gravel deposits. Recent ISWS research suggests that shallow large-diameter wells are particularly susceptible to contamination.

Deep Drift Aquifers

DuPage County. This is probably a continuation of the overlying shallow drift aquifer, but being somewhat deeper, less human-induced chemical changes should be evidenced in the ground water.

McLean County. The largely agricultural activity in this county provides a nice contrast to the urbanized land use of DuPage County.

Macon County. The county is a mixture of rural and urban land uses. The aquifer is composed of sand-and-gravel deposits at depths of 100 to 300 feet.

Shallow Bedrock Aquifers

DuPage County. The shallow dolomitic limestone of Silurian age has been heavily used throughout this county for domestic, municipal, and industrial purposes. It underlies the sand-and-gravel deposits of the deep drift aquifer, and the ground-water qualities of these two systems should provide a good contrast.

Kankakee County. The shallow Silurian dolomite has become a major aquifer system for irrigation needs in this area. The area is mainly used for specialty crop production and is similar to the other counties in this category in regard to the depth and thickness of the aquifer system.

Whiteside County. The deeper water-bearing bedrock formations in this county consist of the Silurian dolomite and the Galesville sandstone. This county differs from the others of this group in that it is predominantly agricultural.

Deep Bedrock Aquifers

Winnebago County. The unconsolidated material of this county overlies more than 2,000 feet of Cambrian sandstones and less than 600 feet of Ordovician dolomite providing ground water for multiple needs. These aquifer systems have been used throughout the history of this area, and water quality is generally dependent on the types of geologic material within which the water is stored.

Cook County. This county is similar to Winnebago County in that its industrial activity is centered over the deep Cambrian-Ordovician aquifer system. The depths of these deeper systems should prove to better protect them from contamination by surface activities.

Knox County. In contrast to Winnebago and Cook Counties, this county has mostly agricultural activities. The deep Glenwood-St. Peter and Ironton-Galesville sandstones are ground-water sources for municipal wells and are the most dependable aquifers for high-capacity wells in the county.

LITERATURE REVIEW

Although many reports on the ground-water resources of Illinois summarize the chemical quality of the water, relatively few look at temporal trends in ground-water quality. One of the earliest studies to examine temporal trends in Illinois ground-water quality was presented by Gibb and O'Hearn (1980). They lumped data for the period 1940 to 1979 into five aquifer categories: 1) drift wells < 50 feet deep, 2) drift wells > 50 feet deep, 3) Pennsylvanian aquifers, 4) shallow limestone and dolomite aquifers, and 5) deep sandstone aquifers. They calculated median chemical concentrations per township for six parameters: 1) total dissolved solids (TDS), 2) hardness as $CaCO_3$, 3) sulfate, 4) nitrate, 5) chloride, and 6) iron. Their results suggest that, as expected, natural variability characterizes the spatial distribution of ground-water quality.

In addition to looking at the spatial distribution of water quality, Gibb and O'Hearn also examined the temporal trends in ground-water quality for 21 well fields around the state. At five locations (Champaign-Urbana, Clinton, Edwardsville, Fairbury, and Farmer City) no long-term trends in chloride, hardness, sulfate, nitrate, or TDS were observed. Two municipalities for which trends in ground-water quality were observed, Bethalto in Madison County and Gibson City in Ford County, have well fields in sand-and-gravel aquifers. Increases in chloride and TDS were noted at Bethalto. Gibb and O'Hearn suggest that the increases near Bethalto are caused by a leaky surface water runoff retention pond near the well field. At Gibson City, only nitrate was not observed to increase. Again, Gibb and O'Hearn suggest a local source for the contamination, possibly a leaking storm sewer line. The observed increases in the concentrations of chemical constituents in the well water at Gibson City and Bethalto appear to be due to a local, human-induced source, rather than widespread degradation of the ground-water resource.

Gibb and O'Hearn found no trends in the Enfield well field, which taps Pennsylvanian-age rocks in White County. Of the four well fields tapping shallow dolomite or limestone aquifers that Gibb and O'Hearn examined, only Millstadt in St. Clair County did not show a trend of deteriorating ground-water quality. The other three cities (LaGrange, Libertyville, and Naperville) showed increases in concentrations in two or more of the five constituents examined. It is important to recognize that each of these communities is part of the rapidly urbanizing Chicago metropolitan area in northeastern Illinois. Gibb and O'Hearn hypothesized that the expanded use of road salt beginning in about 1960 in the Chicago metropolitan area led to a regional degradation of ground-water quality in the shallow Silurian dolomite aquifer.

Of the nine municipalities with deep sandstone well fields that Gibb and O'Hearn examined, seven had no long-term trends in ground-water quality (Dixon, Elgin, Geneva, Monmouth, Ottawa, Peru, and Rockford). A trend of increasing chloride in one of the wells at Bensenville in DuPage County is likely due to nearby improperly abandoned wells that are allowing poorer quality ground water from the overlying carbonate aquifers to migrate downward to the deep sandstone aquifer. A similar degradation of water quality in the well field at Freeport, Stephenson County, is also likely related to leakage in the wells, which is allowing poorer quality water from overlying units to migrate downward.

Several preliminary conclusions can be drawn from the work of Gibb and O'Hearn (1980). First, degradation of ground-water quality is more of a problem for shallow aquifers and less of a problem for deeper aquifers. Second, many cases of ground-water quality degradation can be traced to local problems, such as improperly constructed or abandoned wells or some nearby source such as an infiltration pond or leaking sewer line. The rapid urbanization of large portions of northeastern Illinois appears to have caused a more widespread degradation in ground-water quality, particularly in regard to chloride from road salt.

DISCUSSION AND RESULTS

The temporal trends of the six chemical constituents in the six types of aquifers are summarized in this section. Box plot representations are used because they summarize both the average behavior and the variability in the data. Figure 2 explains the box plot representation of the data. The center line of each box is the median concentration for the samples in that category. For example, the median hardness concentration for the decade of 1940-1949 from alluvial valley aquifers is about 500 milligrams per liter (mg/L) as $CaCO_3$ (figure 3). This means that one-half of the samples have hardness greater than 500 mg/L, and one-half have hardness less than 500 mg/L. The top and bottom of each box represent the 75 percent and 25 percent values, respectively. The 75 percent value, about 750 mg/L as $CaCO_3$ in the example above, implies that three-quarters of the analyses had hardness less than 750 mg/L. Beyond the box are a whisker and a dot at each end. The upper and lower whiskers represent the 90 percent and 10 percent levels, respectively. The circles are the 95 percent and 5 percent levels. The whiskers and circles provide valuable information about variability within the data and can be useful in identifying outliers in the data. Outliers are loosely defined as data values that are so much larger or smaller than the majority of the data that they should be viewed with caution. Outliers may indicate an erroneous data point, but they may also represent an anomalous local condition.

Outliers were not plotted in figures 3-8. The data are plotted in figures 3-8 by decade, beginning with 1900-1909 (decade 1), 1910-1919 (decade 2), etc., through the 1990s. Therefore, the decade of the 1990s is plotted as decade 10. Each decade covers the corresponding ten-year period, except for the partial decade of the 1990s. The data from the three counties in each aquifer classification were combined to yield a composite view of the ground-water quality.

An added feature of the box plot is an indication of the number of data points used to create the respective box. As noted in figure 2, a single horizontal line signifies that less than four data points were available. If only the box is present, four to ten data points were found. Adding the whiskers indicates 11 to 20 values. If more than 20 data points are present, then the full box plot and the circles are used. This representation of the number of data points is helpful for assessing the results. If only a few data points are known for a three-county area over an entire decade, little confidence can be given to those results.

Hardness

Hardness, given as mg/L of $CaCO_3$, is presented in figure 3. Typically, the water in the shallower aquifers tends to be slightly harder than in the deeper aquifers. Median concentrations fluctuate from decade to decade for each aquifer classification. Some trends are observable, such as the apparent increase in hardness over time in the shallow bedrock aquifers and a corresponding decrease in the shallow drift and deep bedrock. Given the limitations of the data however, it is very difficult to know if these trends are significant.

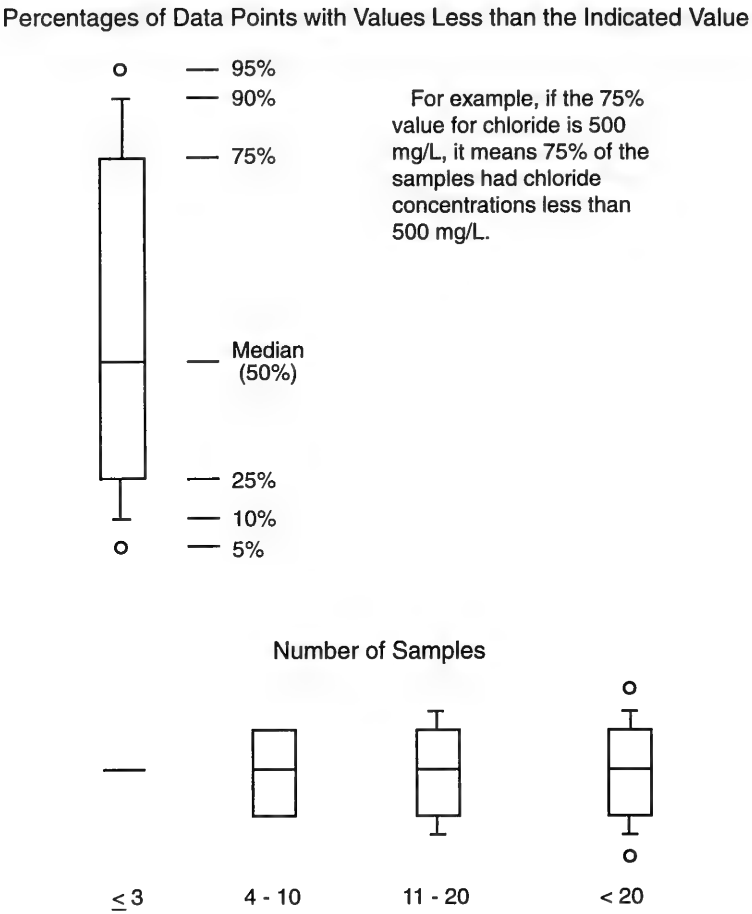
Iron

Iron concentrations for each of the aquifer classifications are given in figure 4. With the exception of the deep bedrock aquifers, the median iron concentrations are often well above the class I potable ground water standard of 0.5 mg/L. Iron tends to be quite variable, with a few values in the range of 50 to 60 mg/L. This clearly indicates a great deal of spatial variability in the iron concentrations of ground water.

By ignoring boxes with fewer than 20 data points, it is clear that there are no significant temporal trends in the iron concentrations in ground water over the past century. The reader should recall that each box represents the data from three counties over a ten-year period. The lack of temporal trends indicates that when viewed in large scale, ground water quality with respect to iron has remained stable. However, it must be recognized that on a local scale (on the order of several acres), significant degradation of ground-water quality may have occurred.

Sulfate

Median sulfate concentrations (figure 5) do not appear to be changing with time, except for concentrations in the deep bedrock aquifers. A trend of decreasing sulfate is evident, from near 400 mg/L at the beginning of the century to 100 mg/L by the 1980s. This trend, however, may be an artifact because the last two decades have less that 20 data points each, which may not be an adequate number of samples. The significant fluctuations in the median concentrations from decade to decade, especially for the deep drift and bedrock valley aquifers, are symptoms of the data limitations.



For example, if the 75% value for chloride is 500 mg/L, it means 75% of the samples had chloride concentrations less than 500 mg/L.

Figure 2. Explanation of the box and whisker plot

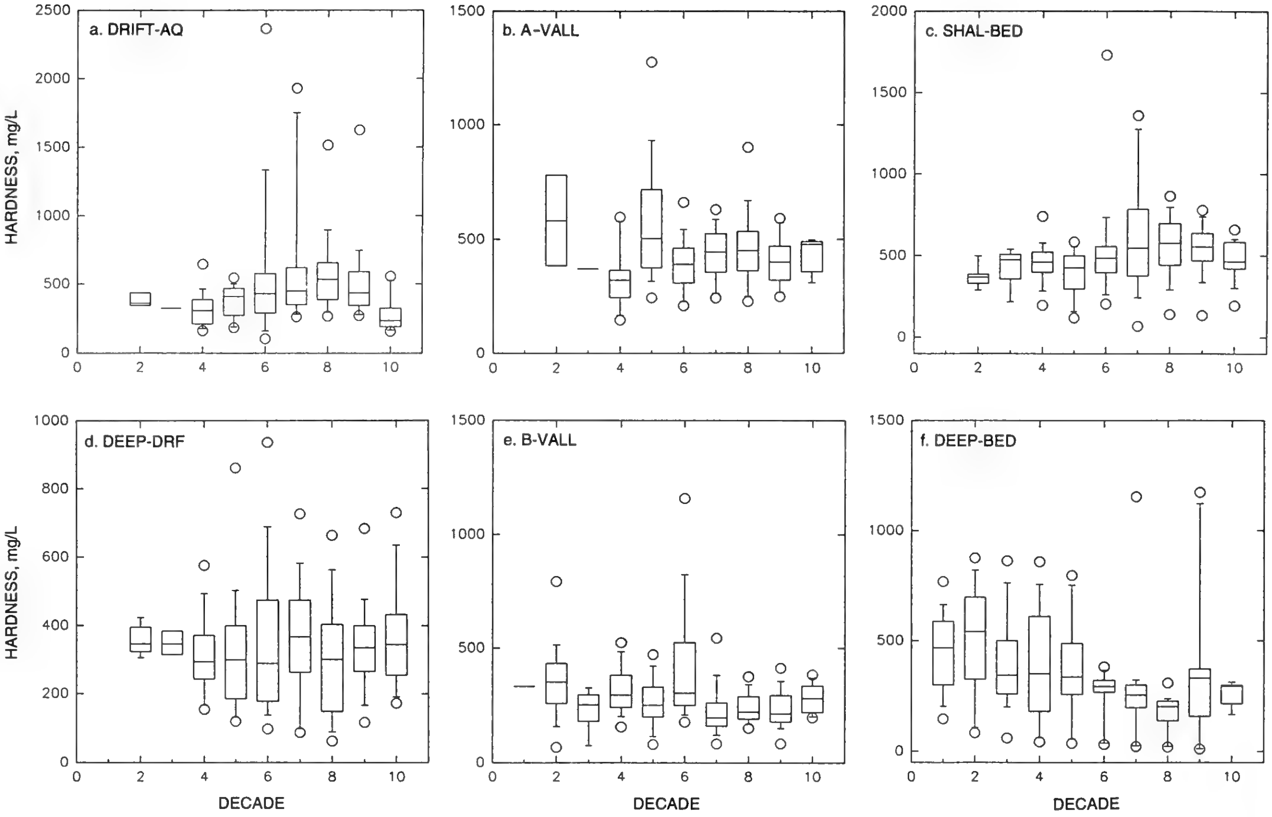


Figure 3. Hardness trends in Illinois ground water as shown in six representative types of aquifers

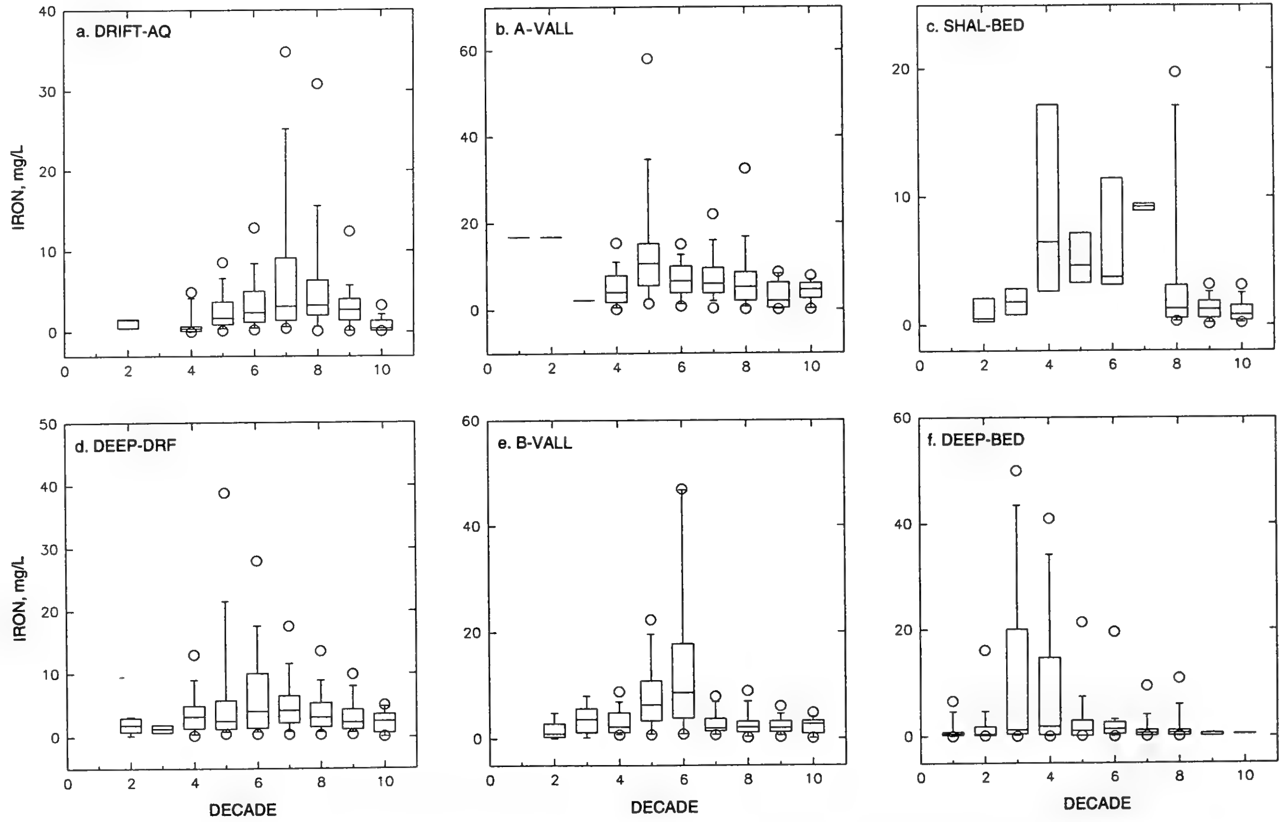


Figure 4. Iron concentration trends in Illinois ground water as shown in six representative types of aquifers

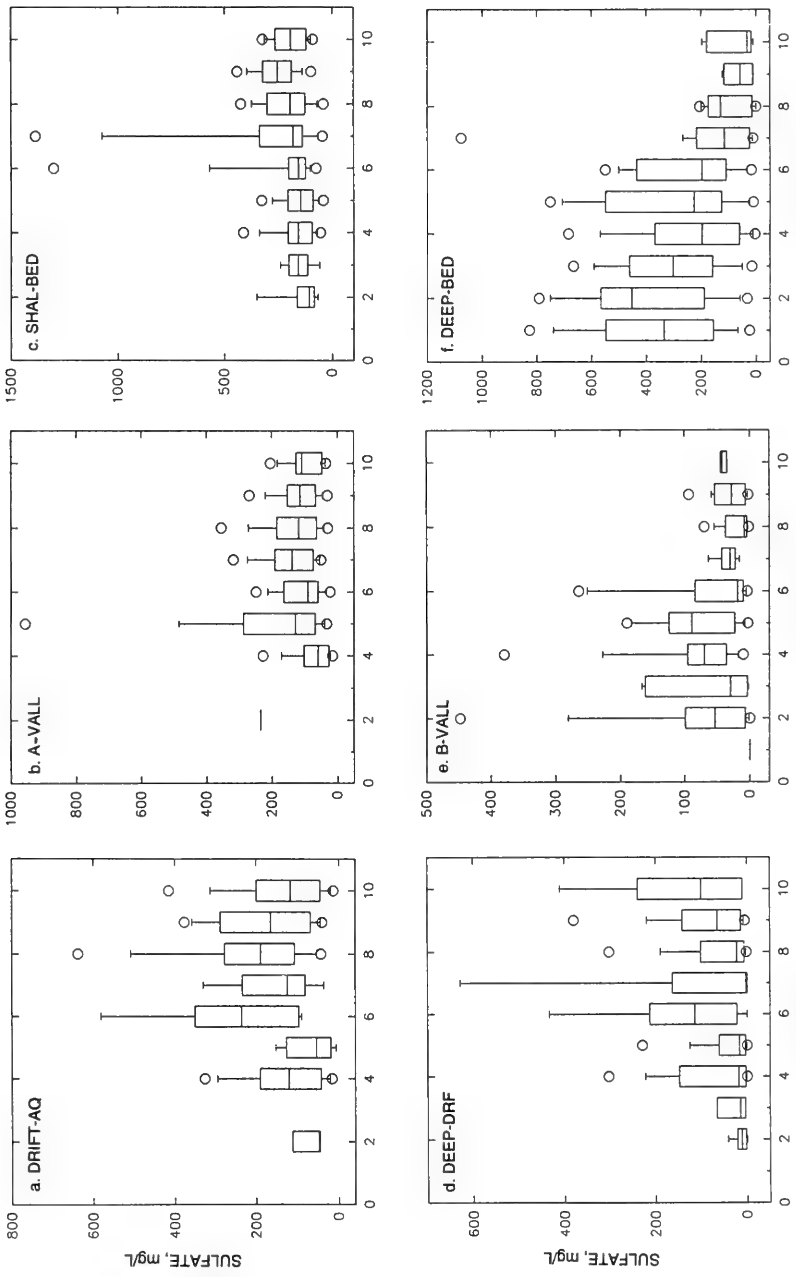


Figure 5. Sulfate concentration trends in Illinois ground water as shown in six representative types of aquifers

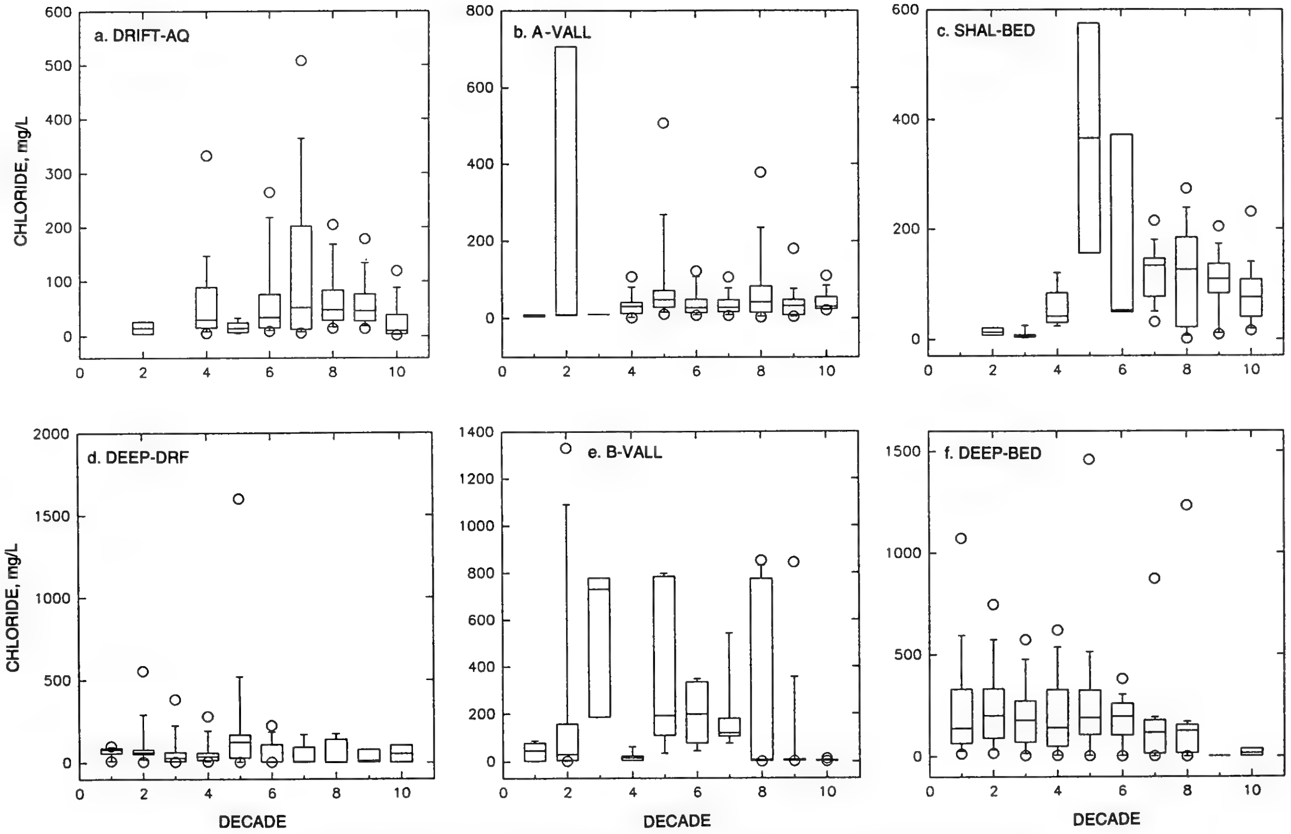


Figure 6. Chloride concentration trends in Illinois ground water as shown in six representative types of aquifers

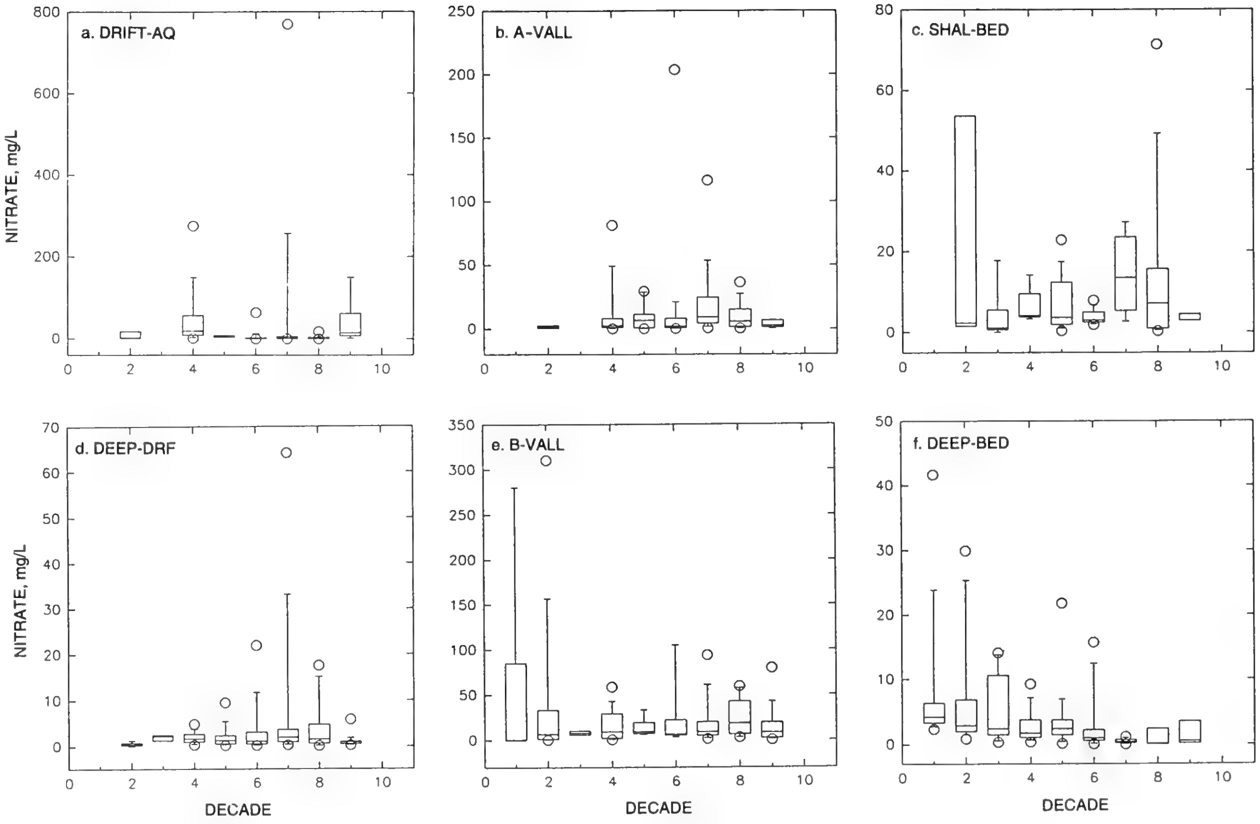


Figure 7. Nitrate concentration trends in Illinois ground water as shown in six representative types of aquifers

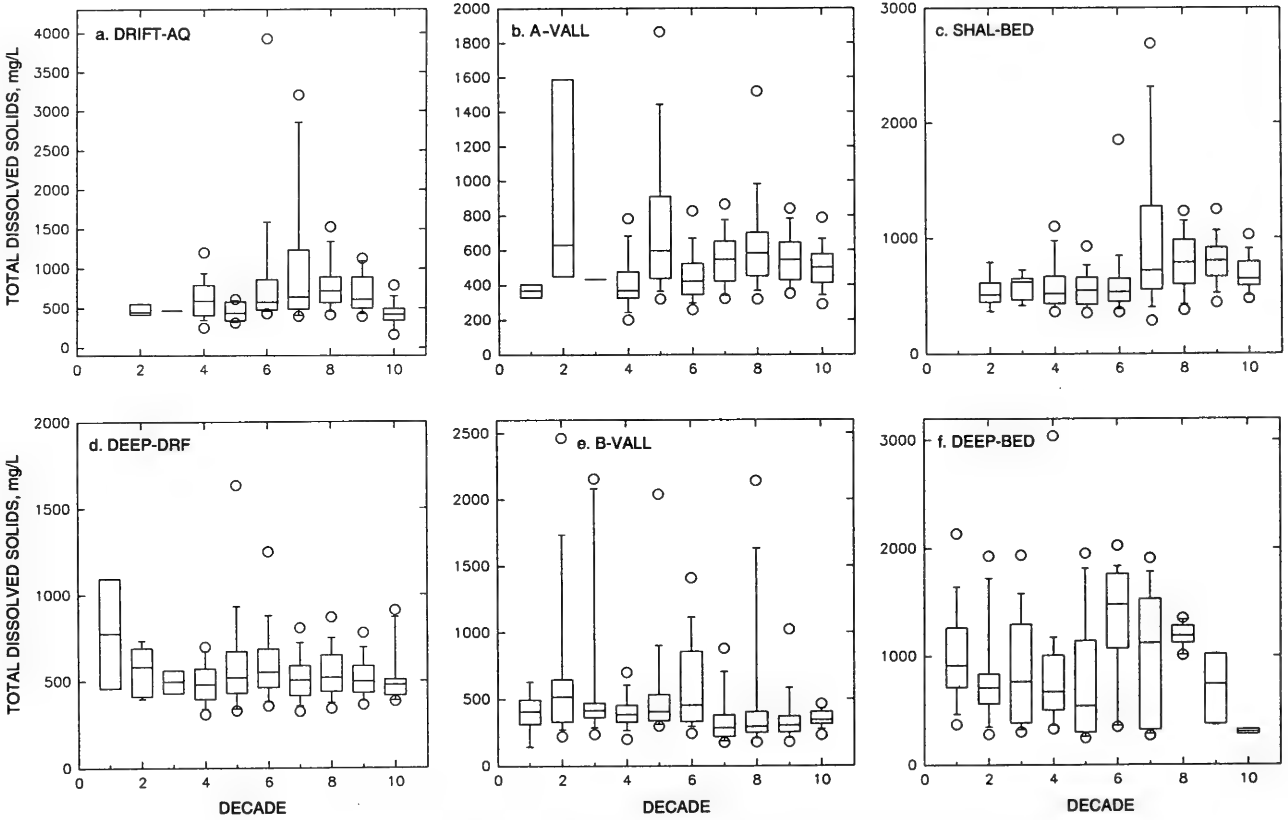


Figure 8. Total dissolved solids trends in Illinois ground water as shown in six representative types of aquifers

These fluctuations typify the difficulties of working with data that do not come from a specially designed monitoring program.

Chloride

Of the constituents examined in this report, chloride is one of the most likely to indicate the impacts of anthropogenic activity on ground water. Yet, if one examines figure 6 and discounts the boxes with fewer than 20 data points, there are no noticeable trends in chloride concentrations. Despite documented cases of road salt contamination of ground water, no large-scale degradation due to chloride is apparent.

Nitrate

One might expect nitrate to show significant trends over the past 50 years because of increased fertilizer application. Nonetheless, no significant trends in nitrate concentrations (figure 7) suggest long-term, widespread degradation of ground-water quality. On the other hand, the ISWS has documented numerous cases of elevated nitrate levels associated with rural private wells (Wilson et al., 1992). The evidence may suggest that rural well contamination is associated more with farmstead contamination of the local ground water or well rather than regional contamination of major portions of an aquifer from the land application of fertilizers. However, this is an active research topic, and it requires a great deal of additional study before definitive conclusions can be drawn.

Total Dissolved Solids

The total dissolved solids concentration (figure 8) is a lumped measure of the total amount of dissolved chemical constituents in ground water. As such, it will not be a sensitive indicator of trace level contamination, but is a good indicator of major inputs of ions or cations to ground water. As with the other constituents, significant variability exists in the mean concentration, but no clear trend is apparent. As noted above, the fluctuations from one decade to the next are more likely related to the data limitations and not to any inherent changes in ground-water quality.

SUMMARY

This work was undertaken to examine long-term temporal trends in ground-water quality over selected areas of Illinois. The data from private and municipal wells were the primary source of information used to construct figures that showed the trends in six chemical constituents in ground water from six aquifer classifications. These figures demonstrate that on a county-wide scale, ground water has not been degraded with respect to the six chemicals examined. Because of data limitations, trace-level contaminants were not studied, but it is imperative that such an assessment be undertaken in the future. It is clear from the earlier work of Gibb and O'Hearn (1980) that the quality of some ground water, particularly in the metropolitan Chicago area, has been degraded by anthropogenic activity, resulting in increases of chloride and total dissolved solids.

Much of the contamination of Illinois ground water is generally localized. Nonetheless, this contamination can render a private or municipal ground-water supply unusable. Once contaminated, ground water is very difficult and expensive to clean and may take many years to complete. Clearly, it is in the best interests of the people of Illinois to protect their ground-water resource through prevention of contamination.

During the 1970s, national environmental concern focused on those resources that were impacted by contaminants that could be seen or smelled. Surface and air contamination was the primary concern, whereas ground water was not considered to be at risk because it was hidden from view. Historically, protection of water supplies was centered on keeping those contaminants that carried disease out of the drinking supply. Some inorganic chemicals and a few common industrial chemicals also made the protection list.

However, a major shift in definition of the term "unsafe drinking water" began to emerge in the early 1980s. The need to protect the population from the potential threat of very small doses of chemicals was and currently is the primary driving force for ground-water protection in the nation. Today, ground-water contamination by a variety of commonly used toxic chemicals, such as volatile organic compounds, is considered a major environmental issue at both the national and state levels.

Since the mid- to late 1980s, national concern has focused on ground-water contamination and its potential impacts to those individuals who rely on it for their drinking water. This concern has led to the initiation of several laws and agency policy shifts to help ward off this imposing threat or to help create a monetary base for research and remediation of existing contamination. Illinois is one of only a handful of states that has adopted legislation in an attempt to respond to this concern. In 1987, P.A. 85-0863 was introduced as a comprehensive, prevention-based policy focused on beneficial uses of ground water and preventing degradation. This act, known as the Illinois Groundwater Protection Act (IGPA), relies upon a state and local partnership and, although directed toward protection of ground water as a natural and public resource, it specifically targets drinking water wells in Illinois.

The act details the process in which the environmental agencies in the state shall initiate and develop educational, investigation, and management techniques to protect Illinois' ground water. The monitoring of this process was organized with the establishment of the Interagency Coordinating Committee on Groundwater. This committee is responsible for reporting the progress of the agencies cooperating in the IGPA initiatives to the Governor on a regular basis and for publishing this progress in a biennial report.

The Illinois State Water Survey is one of several agencies involved in the research and educational aspects of this act. The agencies involved include:

- Illinois Environmental Protection Agency (Chair)
- Illinois Department of Energy and Natural Resources
- Illinois Department of Mines and Minerals
- Office of the State Fire Marshal
- Illinois Department of Transportation - Water Resources Division
- Illinois Department of Agriculture
- Illinois Emergency Services and Disaster Agency
- Illinois Department of Nuclear Safety
- Illinois Department of Commerce and Community Affairs

The act details several preventative initiatives to be handled by various environmental agencies and calls for several activities related to education, management, and research of ground water in Illinois. It sets the policy framework for the management of the resource and responds to the need to protect ground-water quality under a unified ground-water protection program. In short, the act:

- Sets a ground-water protection policy
- Enhances cooperation
- Establishes water well protection zones
- Provides for surveys, mapping, and assessments
- Establishes recharge area protection
- Requires new ground-water quality standards

Currently, two short-term projects mandated by the IGPA have been completed: the recharge area delineation and prioritization, and an initial report on the impacts of pesticides on ground water. The site surveys of each public water supply are near completion. These surveys detail the well location and the land surface activities around it.

The Illinois Environmental Protection Agency has conducted a synoptic analysis of the public water supply wells, which indicated that the quality of the state's ground water is generally good. The analysis of the information used for this paper also tends to support this view. The IEPA and the ISWS also agree that in some areas in Illinois chemical levels are limiting use of the resource. The IEPA reported that 4.6 percent of the tested public water wells had detectable levels of organic chemical contamination (Interagency Coordinating Committee on Groundwater, 1990).

The IGPA was established to ultimately protect Illinois' ground-water resources. The work currently being completed will help guide this protection. However, the fiscal resources needed for statewide assessment and management of this nature are not now available. Ultimately, the concept of protection versus cleanup is sound. The cost of cleanup of ground water is far greater than that of protection. This act is one step toward the protection of these vital resources.

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EROSION AND SEDIMENTATION

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INTRODUCTION

Erosion and sedimentation have been important issues in Illinois for a very long time. In the early stages, the concern was primarily with the loss of soil productivity for agricultural crops, with less emphasis on off-site environmental impacts. In southern Illinois, where most of the state's population lived at the turn of the century, topsoil from the unglaciated Shawnee Hills areas was severely eroded by the early 1900s. Some areas were "... abandoned because so much of the surface soil had been washed away, and there were so many gullies that further cultivation was unprofitable." (Walker, 1984). Much of the present-day Shawnee Forest consists of severely eroded areas that were purchased by the federal government and planted with trees.

In recent years most of the concern around erosion and sedimentation has focused on its impact on environmental quality. The Illinois Water Quality Management Plan, developed after extensive research and public review, stated that "The most severe agricultural-related water quality problem is soil erosion and sedimentation" (IEPA, 1982). Similarly, the Illinois State Water Plan, developed in 1984 after three years of public review and discussion of all water resources issues in the state, identified erosion and sediment control as the number-one water resources issue. The plan stated that "Excessive soil erosion on 9.6 million acres of Illinois farmland is threatening their productive capacity, degrading water quality, accelerating eutrophication of reservoirs, silting streams, and degrading fish and wildlife habitat" (Illinois State Water Plan Task Force, 1984).

More recently, the discussion of the erosion and sedimentation issue has focused on the impact of continuing sedimentation on the Illinois River valley. Several conferences have been organized in recent years to discuss the issue. After the first Illinois River Conference in 1987, the Governor requested the State Water Plan Task Force to review the conference proceedings, *Management of the Illinois River System: The 1990s and Beyond* (WRC, 1989), and make recommendations for actions that could be implemented. As a result, the State Water Plan Task Force prepared the *Illinois River Action Plan* (1987). The report ranked "soil erosion and siltation" as the top-priority problem for the Illinois River and stated that "sedimentation, today's major pollutant of our nation's agricultural waterways, is the primary obstacle in preserving some semblance of the historic Illinois River for future generations."

After the first Governor's Conference on the Management of the Illinois River System in 1987, Bill Mathis and Glenn Stout summarized the discussions: "Most of the problems uppermost on the minds of the participants included significant problems with soil erosion and siltation. All groups recognized that soil erosion and siltation from land-use practices threatened the Illinois River, its backwater lakes, and associated biota" (Mathis and Stout, 1987).

At the 1991 Governor's Conference on the Management of the Illinois River System, Colonel James Craig, Commander of the St. Louis District of the U.S. Army Corps of Engineers, stated that "The greatest challenge facing us on this portion of the Illinois River is sedimentation. Sedimentation clogs the navigation channel, and increases turbidity of the river. In the last 35 years, we have had to dredge over 14 million cubic yards of sediment from the river" (Craig, 1991). Several other public officials and scientists have expressed similar messages over the years.

Based on the review of the concerns and assessment of natural resources and environmental agencies in the state, soil erosion and sedimentation are unquestionably important natural resources and environmental issues in Illinois. It is generally agreed that the erosion rate is above the tolerable limit and that the off-site impacts of the eroded soil must be addressed by the agricultural and environmental communities of the state. A major contribution of the Critical Trends Analysis project (CTAP) will be to stress the importance of the issue, point out what has been done to control the problem, indicate any measurable changes over time, identify where the problem is most serious, and identify the problem areas that must be addressed in the future.

As a product of CTAP, two reports on soil erosion and sedimentation have been prepared. The first (Akanbi and Demissie, 1993) is a technical report that contains available data on the subject from the Illinois State Water Survey (ISWS), the U.S. Geological Survey (USGS), and the Illinois Environmental Protection Agency (IEPA). The data were compiled and analyzed, including regional sediment yields and temporal sediment concentration trends.

This report, the second on erosion and sedimentation, discusses the issue in a broader perspective and presents results from previous studies conducted at the ISWS: *Erosion and Sedimentation in the Illinois River Basin* (Demissie et al., 1992); *Peoria Lake Sediment Investigation* (Demissie and Bhowmik, 1986); *Conceptual Models of Erosion and Sedimentation in Illinois* (Bhowmik et al., 1984); *Sediment Loads of Illinois Streams and Rivers* (Bhowmik et al., 1986); *Sedimentation and Hydrologic Processes in Lake Decatur and Its Watershed* (Fitzpatrick et al., 1987); and *Sedimentation Investigation of Lake Springfield, Springfield, Illinois* (Fitzpatrick et al., 1985). Information from these reports and the Akanbi and Demissie report (1993) has been used extensively for this report.

BACKGROUND

Erosion and sedimentation are critical environmental and economic issues that have been discussed extensively in the literature for generations. Civilizations and productive environments have collapsed because of the mismanagement of land, and excessive erosion has rendered vast areas useless for sustainable agriculture. Excessive sedimentation has also obliterated highly productive and important natural aquatic environments. What must be realized, however, is that soil erosion and the resulting deposition of eroded soil in aquatic environments (sedimentation) are natural processes. They have been taking place since the creation of the earth and are responsible for gradually reshaping the surface of the earth over geologic times.

Erosion and sedimentation are inseparable. Wherever there is erosion there will be sedimentation, and wherever there is sedimentation there must have been erosion somewhere else. When erosion and sedimentation rates are within tolerable limits, changes are gradual and not noticeable. However, when human activities such as agriculture, construction, mining, timber harvesting, and water course management drastically accelerate the erosion and sedimentation processes, then economic and environmental impacts are significant and long lasting. In the 1984 *State of the World* report, Brown estimated that 4 billion tons of soil are washed into the oceans annually worldwide (Brown, 1984). Some regions are impacted more seriously than others.

In the United States, the issue of soil erosion and its impact on agricultural productivity and the environment have been discussed and studied widely. Despite significant time and resources spent to control soil erosion and reduce its impacts in the United States, the problem persists and might even be getting worse in some areas. William K. Reilly, former president of the Conservation Foundation and former head of the U.S. Environmental Protection Agency (USEPA) summarized the issue of soil erosion in the United States succinctly and eloquently in Sandras Batie's book, *Soil Erosion: Crisis in America's Croplands?* (1984):

> Soil erosion is not yet a crisis in this country. The products of American farms still feed a good part of the world, and will continue to do so for some time. But despite 50 years of federal efforts and billions of dollars expended to conserve productive soils, erosion persists as one of this country's major conservation problems. Erosion not only robs farmland of its fertility, it also seriously pollutes the nation's waterways. It may even have accelerated as farmers responded during the past decade to economic opportunities and pressures by planting more cropland, including marginally productive lands and lands prone to erosion, and abandoning conservation measures. Ironically, most Americans believe our soil erosion problem was resolved during the 1930s when severe droughts and dust storms swept across the prairies, and midwestern soil accumulated on windowsills of the Capitol in Washington, DC.
>
> For this generation, with its new farm technology and its dim recollection of the social and economic catastrophe to which soil erosion contributed in the 1930s, we need to put this issue on the nation's agenda. This book is part of the effort to do that. If Americans do not take seriously the accumulating evidence about the extent and consequences of erosion, the country's agricultural future may be undermined, perhaps not this decade or next, but sometime early in the twenty-first century. If this happens, then I believe decision makers of today would have violated a trust they hold for future generations of Americans.

Even though soil erosion has not reached a crisis level, it is recognized as a major environmental, resource, and economic problem. Many federal and state programs have attempted to manage it, but the problem persists. More efforts will be launched to control soil erosion, but their success will depend on the proper understanding of the problem and implementation of programs that work. The main contributions of the scientific community in such an effort are to evaluate past practices, to identify the key problem areas, and to recommend solutions that work. Significant resources have been spent on soil erosion control programs in the past, but the results are not encouraging. Soil erosion is still a major problem, and the resulting sedimentation is significantly impacting aquatic environments and water resource facilities.

The negative impacts of erosion and sedimentation are generally grouped into on-site and off-site impacts (Clark et al., 1985). The on-site impacts, those that occur at the erosion site, generally involve the loss of fertile topsoil on the farm, in excess of the tolerable limit that will not reduce the productivity of the land. There is total unanimity on the concept of controlling soil erosion on the farm to retain the fertile soil and maintain its productivity. The controversy is generally on how to do it and who should pay for it.

The other major on-site impact relates to streambank erosion. General agreement holds that excessive streambank erosion, whether in rural or urban areas, is not good for the property owners and should be controlled. Even though certain land-use practices and hydrologic and hydraulic modifications could be directly linked to the erosion problem, mitigating the problem has not been easy. Federal and state agencies have spent billions of dollars on streambank erosion projects without solving the problem. Again the controversy is how to manage it and who should pay for it. In most cases, little attention goes to preventing the problem in the first place, even though this might be the least expensive and most enduring solution.

Off-site impacts of erosion and sedimentation have moved into the forefront in the last two decades. These impacts are caused by the transport and deposition of eroded soil to places other than the erosion sites. These environments are generally associated either with moving or standing water. Most streams, rivers, lakes, reservoirs, and wetlands are impacted by the transport or deposition of excessive sediment. The annual off-site damage caused by sediment in the United States is estimated to exceed $6 billion, of which more than one-third is attributed to erosion from cropland (Clark et al., 1985).

Excessive sediment movement and deposition can cause rivers, reservoirs, lakes, wetlands, navigation channels, drainage ditches, and canals to silt up and lose their capacity to carry and store water. Correcting these problems is generally very expensive. It costs millions of dollars to dredge even small stretches of navigation channels and water supply reservoirs.

Other off-site impacts of erosion and sedimentation are related to water quality and aquatic habitats. Sediment is generally included in what is referred to as "nonpoint source" or "diffuse" pollution. In evaluating the quality of the nation's waters, the USEPA concluded that "...the two leading pollutants affecting the nation's rivers and streams are predominantly of diffuse origin. These two pollutants are siltation—the smothering of streambeds by sediments, usually from soil erosion—and nutrients" (USEPA, 1990). The nationwide USEPA survey is summarized in figures 1 and 2, which rank the top ten causes and sources of pollution for rivers, streams, lakes, and reservoirs. Siltation (sedimentation) is identified as the number-one pollutant for rivers and streams and the number-two pollutant for lakes and reservoirs. Illinois reported that 94 percent of its impaired rivers and streams and 100 percent of its impaired lakes and reservoirs are affected by siltation (USEPA, 1990).

Even though other land-use practices contribute significantly, especially in localized situations, agriculture is believed to be the main source of the erosion and sedimentation problem. In Illinois, with more than 65 percent of the land used for crop production, agriculture was identified by the IEPA as the source of pollution for 99 percent of the impaired rivers, streams, and lakes.

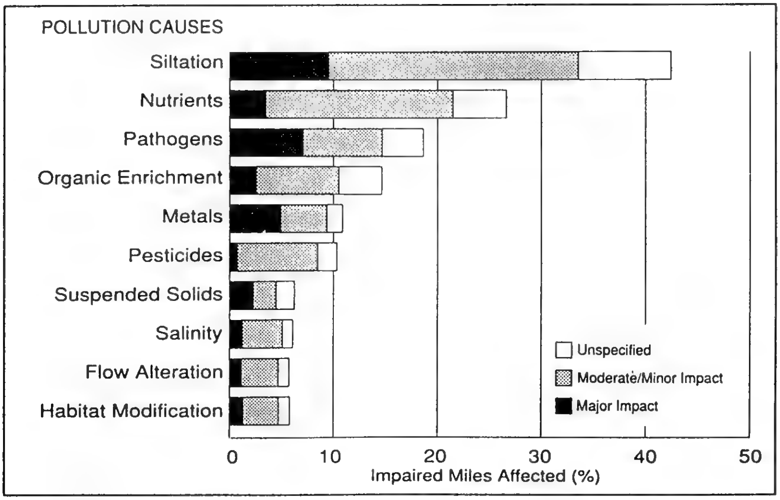
Therefore, in general it can be concluded that erosion and sedimentation are global problems, despite significant attempts to control erosion and reduce its impact on the productivity of agricultural lands and on the environment. Even with all the efforts and enormous resources spent to control it, a more scientific basis for erosion control and mitigation of its impacts remains to be developed. The monitoring, analysis, and evaluation of soil erosion rates, sediment transport, and sedimentation rates must be the basis for scientific programs and policies that can eventually control the problem.

EROSION AND SEDIMENTATION ISSUES IN ILLINOIS

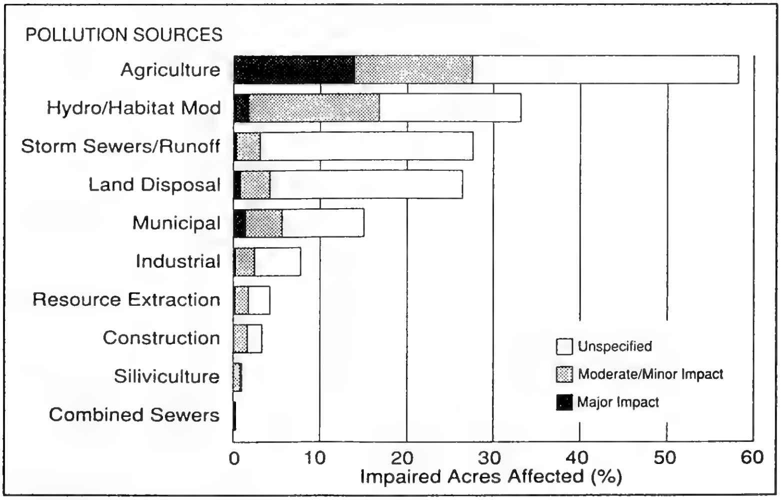
The following sections will present brief discussions of the major erosion and sediment issues as they apply to Illinois.

Watershed Erosion

Watershed erosion refers primarily to sheet, rill, and gully erosion from agricultural and nonagricultural areas. It does not include streambank erosion and erosion from construction sites and mining operations. Since more than 65 percent of the Illinois land surface

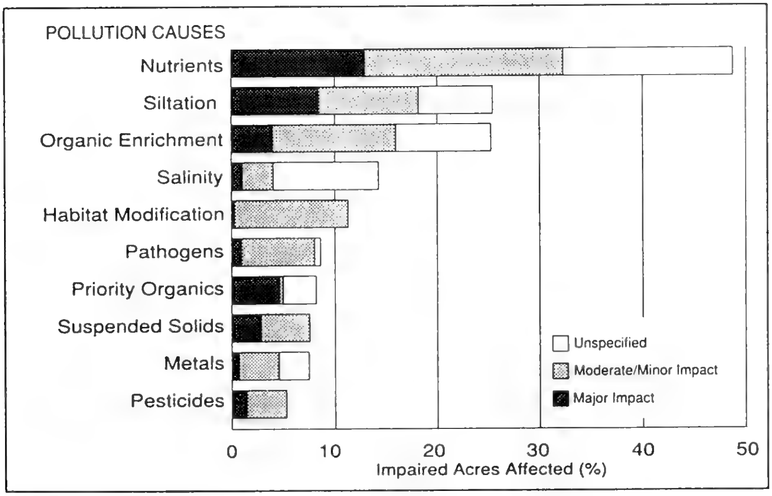


Source: 1988 State Section 305(b) Reports.



Source: 1988 State Section 305(b) Reports.

Figure 1. Causes and sources of pollution for U.S. streams and rivers (USEPA, 1990)



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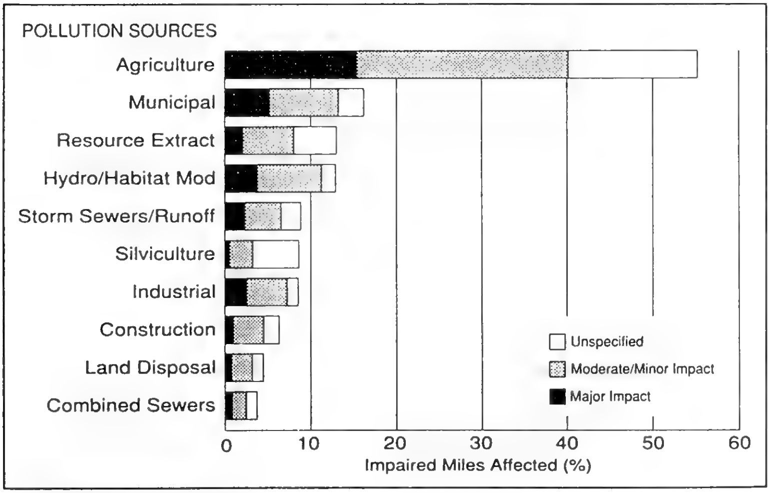


Source: 1988 State Section 305(b) Reports.

Figure 2. Causes and sources of pollution for U.S. lakes (USEPA, 1990)

is used for agriculture, watershed erosion is significantly influenced by cultural practices. The annual gross soil erosion from croplands is estimated to be 158 million tons, nearly 90 percent of the total gross soil erosion of 180 million tons for the state (IEPA, 1982). Erosion from nonagricultural lands therefore accounts for about 10 percent of the total erosion in the state. In relation to overall watershed erosion from croplands, most of erosion occurs within a small portion of the watershed. These "critical erosion areas" generate disproportionate amounts of sediment.

The results of centuries of erosion on Illinois topsoil are summarized in figure 3, where its present-day thickness is compared to what is estimated to have been its original thickness. With the exception of the Illinois, Mississippi, and Ohio River valleys, which have extensive sediment buildup, the whole state has lost 2 to 9 inches. The most severe erosion occurred in southern Illinois, where the hilly and highly erosive area was settled and farmed earlier than the rest of the state. Erosion has also been significant in the western part of the state, where 6 to 7 inches of topsoil has been lost. The central and northeastern parts of the state have fared better with 2 to 4 inches of erosion.

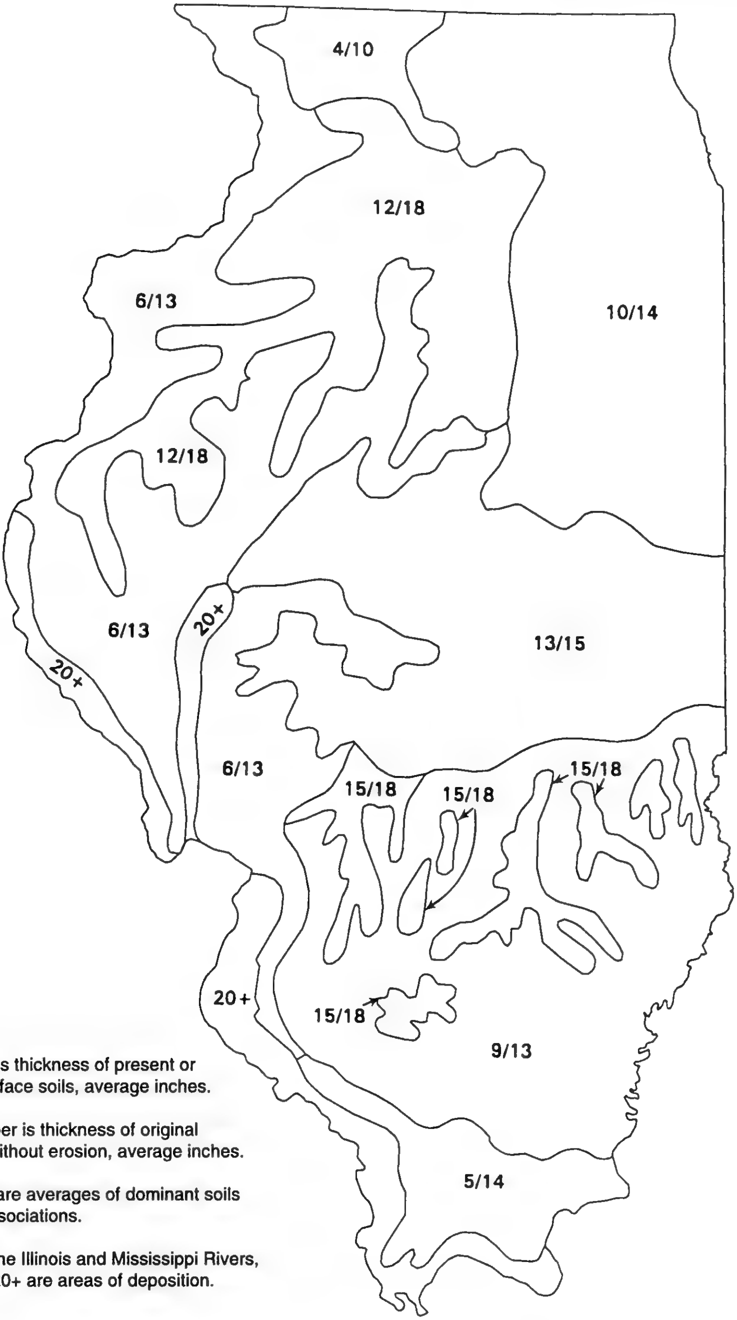
In Illinois most watershed erosion control activities for agricultural lands are carried out by the Illinois Department of Agriculture through the Soil and Water Conservation Districts (SWCD). "T by 2000" is a major Illinois initiative to reduce erosion from agricultural lands to tolerable soil loss limits ("T") by the year 2000. "T" is defined as the maximum average annual soil loss in tons per acre per year that can be tolerated by the soil and still sustain production into the future (Illinois Department of Agriculture, 1991). Nichols (1989) summarized the soil erosion control programs of the Illinois Department of Agriculture in the Illinois River basin.

The department allocates cost-share monies for erosion control projects through two programs: the Conservation Practice Program (CPP) and the Watershed Land Treatment Program (WLTP). The CPP encourages soil conservation practices by providing cost-share money for projects such as terracing, grassed waterways, grading, and sediment detention structures. The WLTP deals primarily with agricultural areas identified as critically eroding. Nichols identified 3.8 million acres of agricultural land in 36 SWCDs, primarily within the Illinois River basin, that are eroding at rates greater than the "T" values. He estimated that remediation will require the implementation of conservation practices for 4.5 million acres of agricultural lands at a cost of $327 million. The department spent nearly $6 million from 1986 to 1989 from the "Build Illinois" fund for erosion control in the region. In 1990, $0.8 million from the General Revenue Fund was allocated for erosion control within the same area. Thus, some progress is being made to control erosion from agricultural lands, but much more needs to be done. Of the total estimated cost of $327 million to control agricultural erosion within the watershed, roughly $7 million was expended in five years. Full realization of the "T by 2000" program through state and federal funding will go a long way toward controlling erosion and sedimentation problems in Illinois.

Streambank Erosion

Illinois has an estimated 13,200 miles of streams. Most streams experience some form of bank erosion. In cases where vegetation has been removed from streambanks, bank erosion is excessive. Many channelization projects and river crossing structures such as bridges tend to increase the streambank erosion potential. In attempts to quantify the percent of a stream's sediment load that originates from bank erosion, different investigators have reported 20 to 80 percent. The actual value will depend on the local conditions for a particular stream. In any case, streambank erosion is believed to be a major contributor of sediment to streams in the Illinois River basin.

Many streambank stabilization projects have been initiated in the Illinois River basin, primarily by local governments. The Illinois Department of Conservation promotes several demonstration projects using vegetation as the stabilizing agent although no statewide or basinwide control programs exist in Illinois. Realizing the significance of the problem and the fact that sedimentation problems will not be solved unless excessive streambank erosion is controlled in the basin, a comprehensive streambank erosion control program is needed. The program should identify major streambank erosion areas throughout the watershed and quantify how many stream miles are eroding at a significant rate. The types of streambank failures and the suspected causes also should be documented. This is important because all streambank erosion is not of the same type or initiated by the same cause. Once the locations, types, and causes of streambank erosion in the basin have been identified, appropriate streambank stabilization techniques can be recommended. Most of the streambank stabilization techniques were outlined in a report to Congress by the U.S. Army Corps of Engineers in 1981 (USACOE, 1981).



1) First number is thickness of present or remaining surface soils, average inches.
2) Second number is thickness of original surface soil without erosion, average inches.
3) Thicknesses are averages of dominant soils within Soil Associations.
4) Areas along the Illinois and Mississippi Rivers, indicated by 20+ are areas of deposition.

Figure 3. Average thickness of Illinois topsoils (after IEPA, 1979)

Instream Sediment Transport

Only a percentage of the soil particles eroded from a watershed reach the stream system and are transported downstream from the erosion site. The ratio of the soil reaching the stream network to the total erosion in the watershed is defined as the delivery ratio. The delivery ratio depends on many physical and geomorphic factors, although the drainage area is one of the most important. It can vary from as low as 3 percent for large watersheds to over 95 percent for small watersheds. To understand the off-site environmental and ecological impacts of soil erosion and sedimentation, it is essential to determine how much of the eroded soil reaches the waterways.

Since the methods and techniques used to quantify erosion and delivery ratios are generally empirical and highly unreliable, it is important to measure the actual sediment being transported by streams. Monitoring of the instream sediment load over a long period of time is the most reliable method of quantifying the amount of soil that moves from one place to another. Monitoring can detect changes in erosion rates, transport capabilities, impacts of hydrologic changes in the watershed, and effectiveness of land management practices. However, because of the expense of collections, instream sediment load data are not widely available. When they are available, they are of short duration.

Three Illinois agencies, the ISWS, the USGS, and the IEPA, have been collecting instream sediment data over the last 20 years. The distribution, the number of stations where data have been collected in Illinois, and the length of record at the stations are shown in figure 4. Data collection peaked in 1981 when the Water Survey initiated the Sediment Benchmark Network. However, the number of stations has declined since then, with 40 stations in operation in 1990. The major weakness in the database is the length of record at each station. The majority of the stations have data only for one to three years. The nature of the data has also changed over time. Other than the four USGS stations, sediment data are collected only weekly by the ISWS and the IEPA. This makes sediment load and budget calculations very difficult and unreliable.

However, even sediment concentration values alone provide valuable information on general trends in streams and rivers, such as those shown for selected streams in northern, central, and southern Illinois in figure 5. As shown in the figure, sediment concentrations in the Rock River in northern Illinois have been decreasing since 1980. They have been essentially constant in the Sangamon River in central Illinois, slightly decreasing in the Kaskaskia River in south-central Illinois, and slightly increasing in the Cache River in southern Illinois. As the length of these data increase, significant changes in sediment concentrations in streams can be detected more precisely. These changes in sediment concentrations can then be correlated to changes in land-use practice, climate change, or other natural or man-made modifications in the watersheds.

The other more significant use of instream sediment data is in calculating sediment yields from different watersheds. This information is not only important in detecting trends and evaluating the impacts of projects and land-use changes, it is essential in designing reservoirs and predicting sedimentation rates in streams, lakes, reservoirs, and wetlands. The rate of sedimentation is directly proportional to the amount of sediment in the flow. Comparison of regional sediment yields would identify the spatial pattern of sediment yield in the state.

All available sediment load data from 35 sediment monitoring stations were used to compute the spatial distribution and the annual sediment yields in Illinois. When the annual sediment yields were plotted against the annual water discharge, all the data fell into four groups (figure 6), implying that four equations could be used to calculate sediment yield from Illinois watersheds. The spatial distribution of sediment yield is shown in figure 7. The regions along the Illinois River and in west-central Illinois were found to be the highest sediment-producing areas, along with some in southern Illinois. Northeastern and central Illinois show the least sediment yield.

Lake and Reservoir Sedimentation

One of the major off-site impacts of erosion is the eventual accumulation of the eroded soil in lakes and reservoirs, which become natural traps for sediment transported by streams and rivers. Because of the significant reductions in flow velocity, most of the sediment transported by streams and rivers settles out in lakes and impoundments. This continuous sediment accumulation gradually reduces the impoundments' depth and consequently their capacity to store water. For water supply lakes, the gradual loss of storage capacity is a major concern. In many cases, sediment has to be dredged at great expense. In some cases, significant effort is expended to reduce erosion rates in the watershed and subsequent sediment inflow to lakes. In very few cases, attempts are made to route the

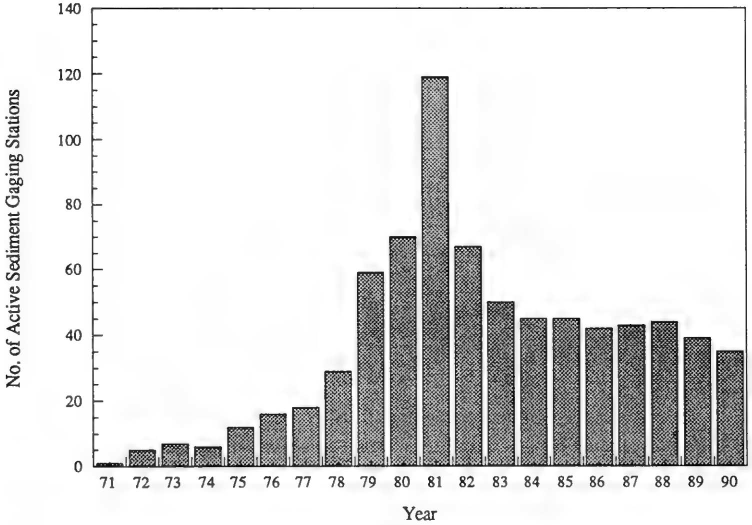


Figure 4a. Distribution of combined number of active sediment gaging stations by record lengths, 1971-1990

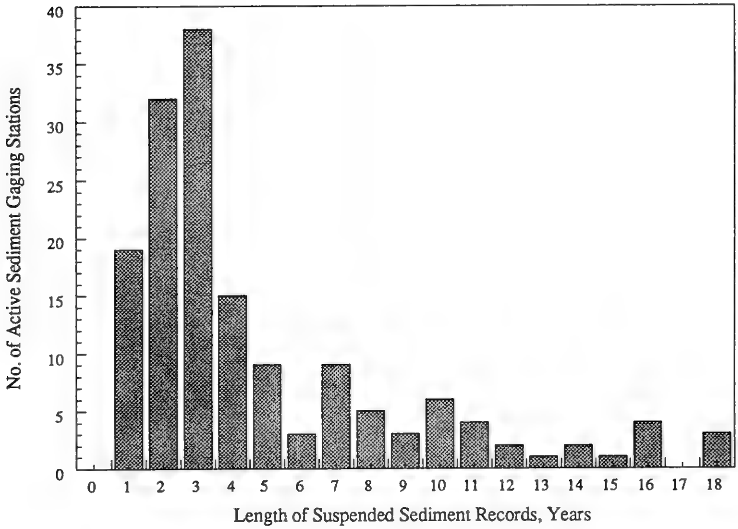


Figure 4b. Distribution of combined suspended sediment gaging stations by record lengths, 1971-1990

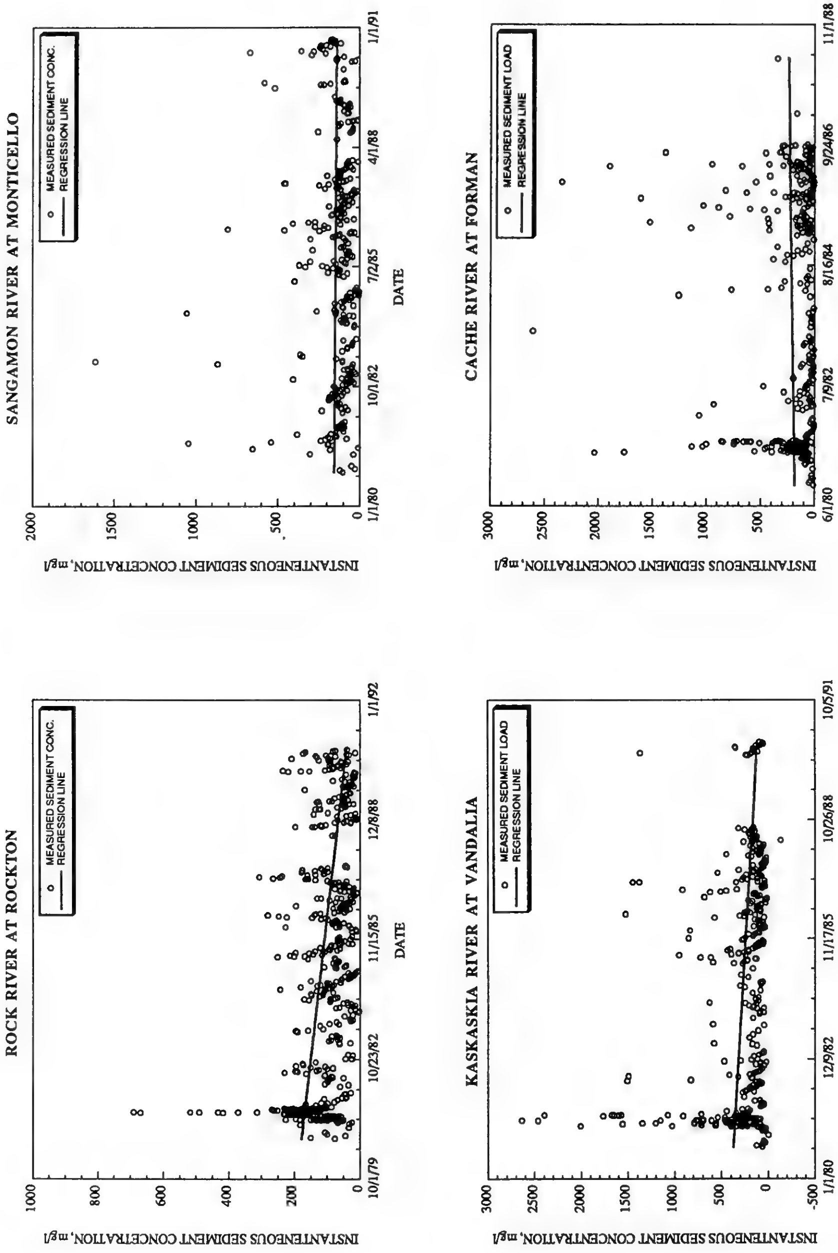


Figure 5. Variation of sediment concentration for selected streamflow stations in Illinois

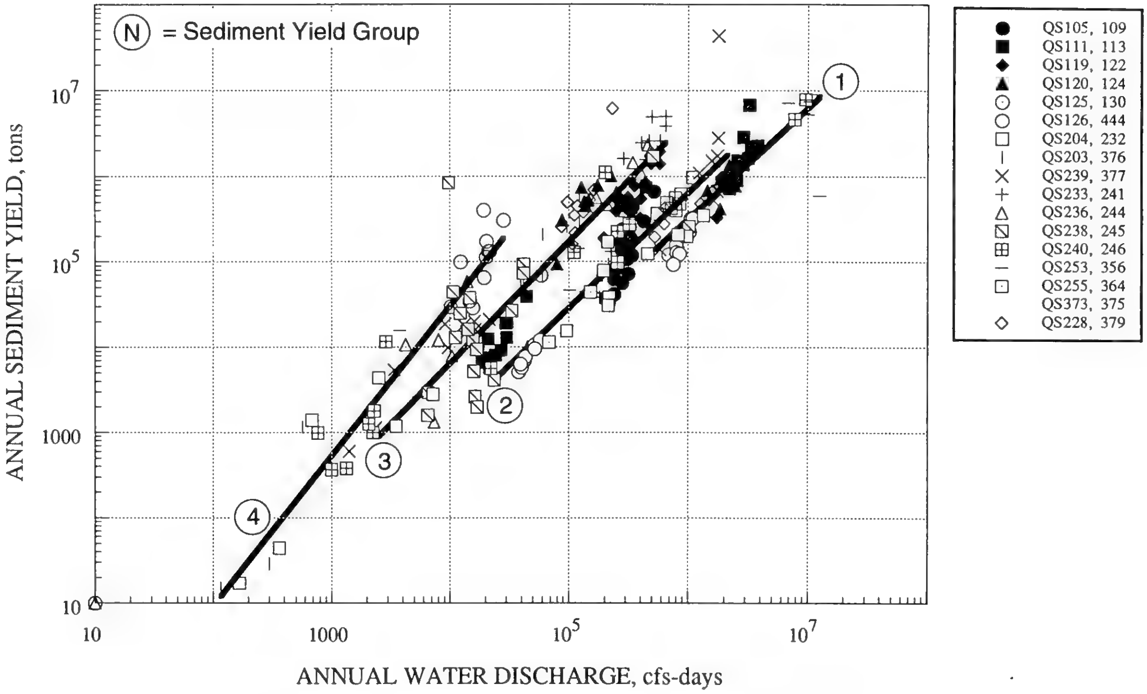


Figure 6. Sediment yield-water discharge rating relation for Illinois streams

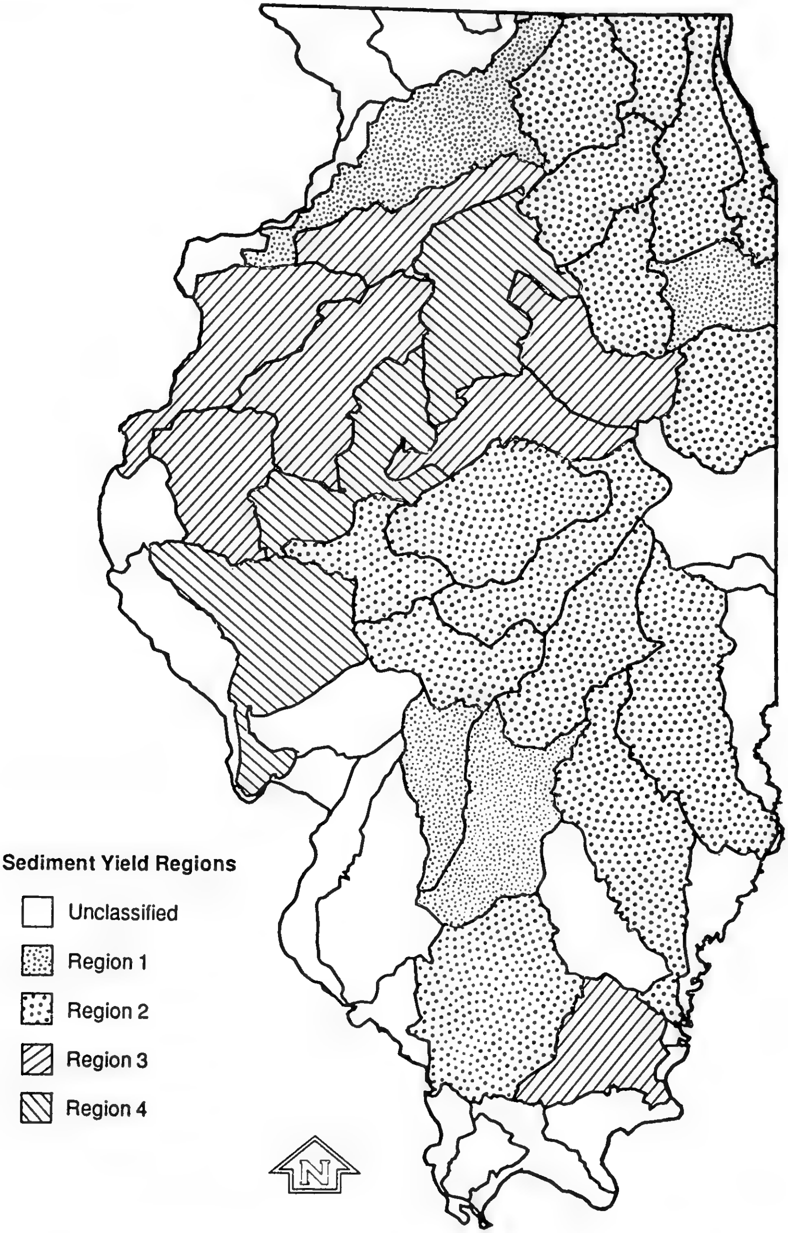


Figure 7. Regional distribution of sediment yield rates in tributary drainage basins in Illinois

sediment past or around lakes. In all cases, the problem of sedimentation in lakes and reservoirs is expensive.

In Illinois, lake sedimentation has been a serious problem and has been investigated intensively. Sedimentation surveys are among the basic tools used to quantify sedimentation rates in order to project future water storage needs or shortages. They provide information on original and current lake capacity, sedimentation rates for different periods, sedimentation patterns, changes in depth of water, and sources of sediment. Information generated through sedimentation surveys is used in future water supply planning in areas such as projecting available storage capacities, lake dredging projects to increase storage capacities, and spillway and dam modifications when possible.

The Illinois State Water Survey has taken the issue of lake sedimentation as one of its primary missions since the early 1930s and has conducted more than 180 sedimentation surveys of more than 130 lakes in Illinois, compiling comprehensive lake sedimentation survey data. The Water Survey's data have been used by engineers, researchers, and planners throughout the world. The distribution of the surveys over time is shown in figure 8. Most were conducted in the 1950s, a time of acute concern for water supply storage during drought, although lake sedimentation surveys have been conducted fairly regularly since the 1940s, with more than ten surveys per decade.

Two good examples of water supply lakes with sedimentation problem are Lakes Decatur and Springfield in central Illinois. Both lakes are located in the Sangamon River basin, and serve as the sole source of drinking water for the cities of Decatur and Springfield, respectively. Lake Decatur was built in 1922, while Lake Springfield was built in 1934. The reduction of storage capacity over time for both lakes is shown in figure 9. Even though their capacity loss rates are in the range 0.3 to 0.5 percent per year, both lakes had to implement programs to restore storage capacities and reduce sedimentation rates. In 1956, the city of Decatur had to install gates on the spillway to increase the storage capacity of the lake. Springfield spent more than $10 million to dredge a small portion of the lake in 1988, and the city of Decatur is planning a major dredging operation in the near future. Both cities have been attempting to reduce the rate of erosion in the watershed and the delivery of sediment into the lakes.

The problems these two cities face in maintaining the water storage capacities of their lakes symbolize the problem of sedimentation as it relates to water supply needs. Some smaller cities have more serious problems with sedimentation and have had to rely on state and federal assistance to restore their lakes. As most lakes in Illinois age, the problem is expected to be more serious. The need for additional water storage capacities will require either more dredging or raising of spillway elevations. Under strict environmental regulations, these options are neither cheap nor feasible.

Sedimentation in the Illinois River Valley

As mentioned in the introduction, the Illinois River has become the focus of the erosion and sedimentation issue in Illinois in recent years. Because of its importance, the Illinois River represents the environmental status of Illinois streams, rivers, and lakes. Because of its central location and natural geomorphology, the river has been significantly impacted by erosion and sedimentation. Therefore, understanding the impacts of erosion and sedimentation on the Illinois River provides a very good indication of the problem in the state.

The following discussion is based on the results of a recent study on erosion and sedimentation in the Illinois River basin (Demissie et al., 1992). The Illinois River drains nearly half of the state. Many of the major streams in Illinois drain into it. In addition to its drainage, transportation, and commercial value, the Illinois River is an important ecological resource. With its numerous backwater lakes, wetlands, and floodplain forests, the Illinois River valley provides significant habitat for fish, waterfowl, birds, and other animals.

The Illinois River's environment has been subjected to many of the impacts associated with developments in the watershed, including waste discharges from urban areas, water-level control for navigation, and sediment and chemical inflow from agricultural lands. The water quality of the river was severely degraded for several decades prior to the 1970s when environmental regulations were enacted to control pollutant discharges. Since then the quality of the river water has been gradually improving.

However, problems associated with erosion and sedimentation have not been improving and are recognized as the number-one environmental problem in the Illinois River valley. The main sources of sediment to the Illinois River valley are watershed erosion, streambank erosion, and bluff erosion. The contribution of watershed erosion to the sedimentation problem in the Illinois River valley can be quantified by analyzing the sediment yields of tributary streams that drain into the valley. The contribution of bank erosion in the Illinois

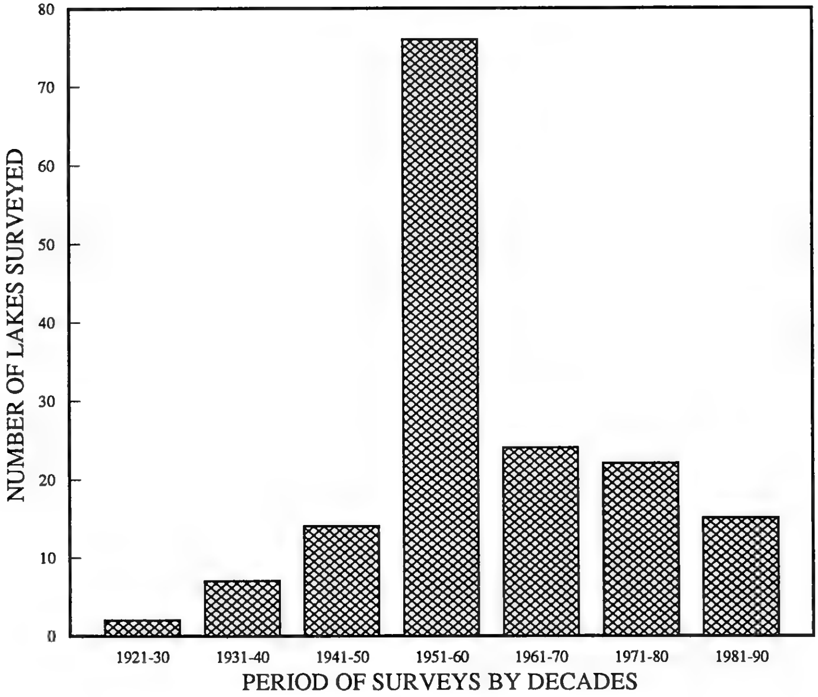


Figure 8. History of lake sedimentation surveys in Illinois

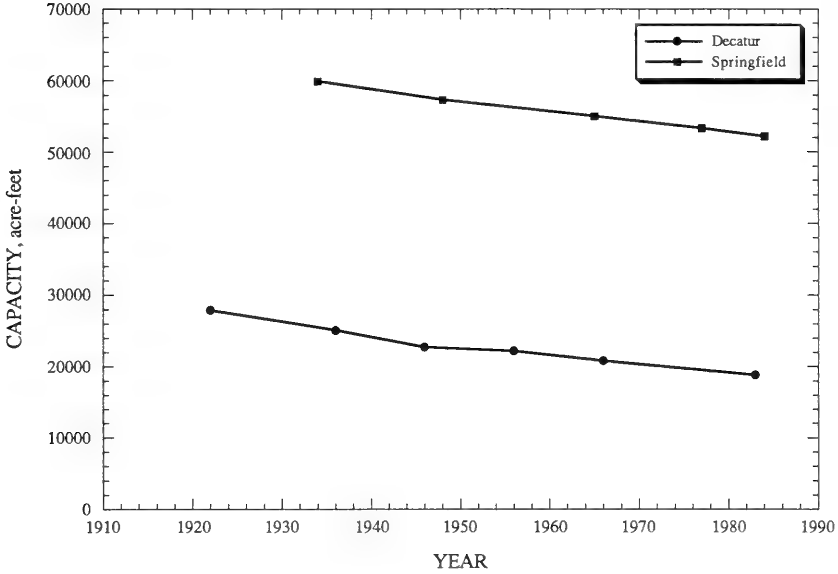


Figure 9. Storage capacity losses at Lakes Decatur and Springfield

River valley and bluff erosion along the Illinois River are much more difficult to quantify at present because of the lack of data.

In an attempt to quantify the problem, sediment yields were calculated from tributary streams of the Illinois River based on suspended sediment load data collected by the USGS (Demissie et al., 1992). The sediment yield calculations were then used to construct an approximate sediment budget for the Illinois River valley. The calculations show that on the average, 13.8 million tons of sediment are delivered to the Illinois River valley annually. The average annual outflow of sediment from the Illinois River at Valley City is 5.6 million tons. This means that an average of 8.2 million tons of sediment are delivered from tributary streams and deposited in the Illinois River valley each year. The actual figure is expected to be higher than 8.2 million tons because of the contributions of bank and bluff erosion, which are not included in these calculations.

The temporal trends in sediment concentration and load in the Illinois River at Valley City (figure 10) have been decreasing since 1980. But the primary cause, at least for the sediment load, is the decreasing trend in streamflow over the same period.

Major areas impacted by sediment deposition in the Illinois River valley are backwater lakes, which had lost 20 to 100 percent of their capacities by the year 1990. The average capacity loss is 72 percent. Therefore most of the lakes, which are remnants of a much larger glacial river system that once occupied the Illinois River valley, have lost a large part of their capacities, and some of them have already filled completely with sediment.

The impact of sedimentation in the Illinois River valley has been clearly illustrated by the conditions in Peoria Lake over the years (Demissie and Bhowmik, 1986). Peoria Lake is the largest and deepest bottomland lake in the Illinois River valley. But a combination of accelerated erosion and hydraulic regulations has resulted in severe sedimentation rates in the bottomland lakes in recent decades. As of 1985, Peoria Lake had lost 68 percent of its 1903 capacity due to sedimentation. The average depth of the lake had been reduced from 8 to 2.6 feet. The reduction of lake capacity and depth over time is shown in figure 11.

The severity of the sedimentation in Peoria Lake is illustrated by figure 12, in which the 1903 and 1985 lake bed profiles are compared at four locations along the lake. As shown, much of the lake has filled with sediment. The sedimentation rate is higher in the upper lake than in the lower lake. Moreover, the lake is shallower in the upstream direction, so much of its upper end has filled entirely with sediment. The deeper channel through the lake is maintained for navigation.

The net result of sedimentation in Peoria Lake is the loss of the deeper parts of the lake. In figure 13, the portions of the lake deeper than 5 feet are compared for 1903 and 1985. In 1903 much of the lake would have been deeper than 5 feet under present-day normal pool conditions, while in 1985 much of the lake was shallower than 5 feet, with only a narrow navigation channel through the middle. As sedimentation continues and the shallow flat areas start supporting vegetation, much of the lake will be transformed into a wetland that will be flooded regularly. The transformation of Peoria Lake into a narrow navigation channel with bordering wetlands and mudflats will not only reduce aesthetics but will also have negative impacts on recreation, real estate values, and tourism.

Soil erosion and sediment yield are related to land-use practices in the watershed. In the Illinois River basin, 80 percent of the watershed is used for agriculture. Thus, an investigation of the land-use practices, especially those of agriculture, should explain the high erosion and sedimentation rates in the Illinois River basin.

Agricultural acreage in the state and in the Illinois River watershed both increased slightly from 1925 to 1981 and then started to decline. The total acreage in Illinois varied from a low of 17.8 million acres in 1934 to a high of 23.9 million acres in 1980. For the Illinois River basin, the total acreage varied from a low of 11.7 million acres in 1934 to a high of 15.9 million acres in 1977. The Illinois River basin contains more than 60 percent of the agricultural acreage in the state. The percentage of agricultural lands in the basin as compared to the state's total has declined slightly since the 1930s.

The major crops harvested in the basin are corn, soybeans, wheat, oats, and hay. The changes in acreage for the leading Illinois crops are shown in figure 14. Corn acreage has been almost steady for the last 62 years (1925-1987), with more than 6 million acres harvested. On the other hand, soybean acreage has dramatically increased since the 1920s, from virtually no acreage in 1925 to nearly 6 million acres in 1987. At the same time, the acreage in grassy crops (wheat, oats, and hay) has declined in proportion to the increase in soybean acreage. Thus acreage of row crops (corn and soybeans) has significantly increased, while acreage for grassy crops has steadily decreased. This changing

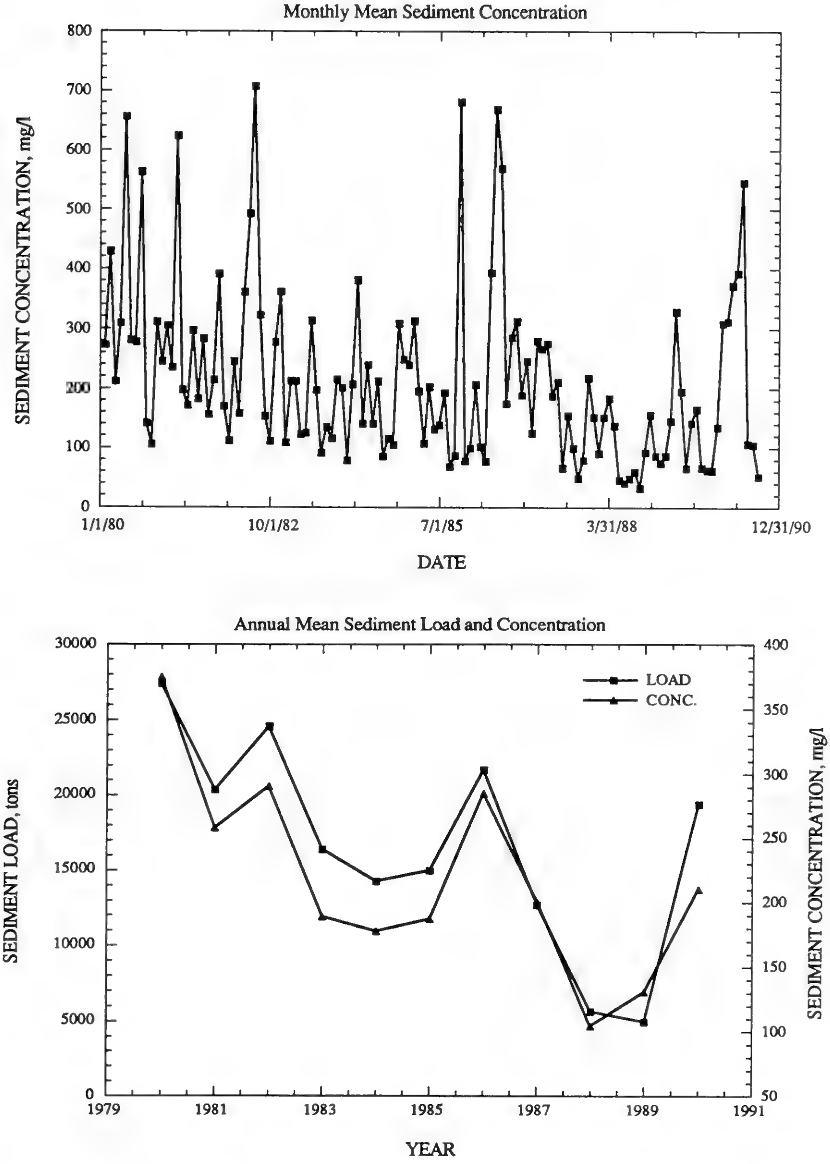


Figure 10. Variation in sediment concentration and load for the Illinois River at Valley City

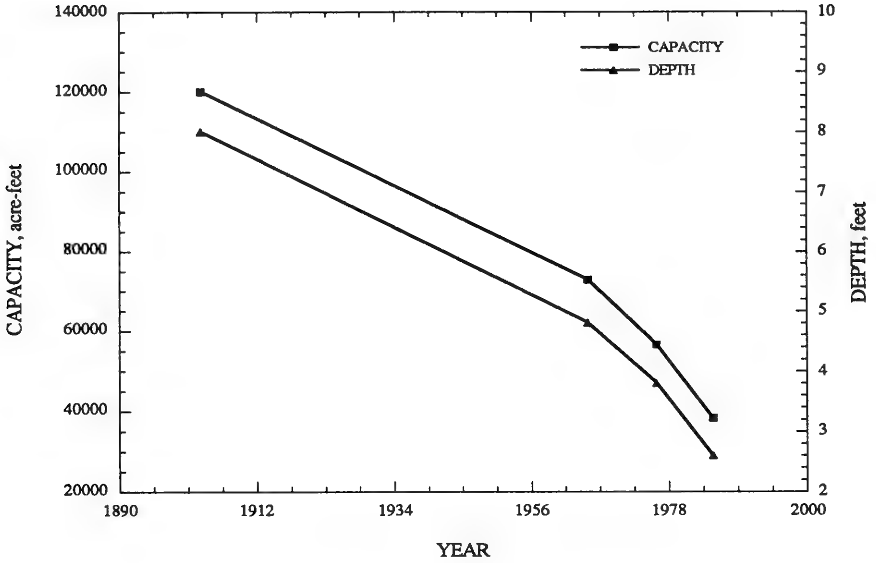


Figure 11. Variation of capacity and depth for Peoria Lake

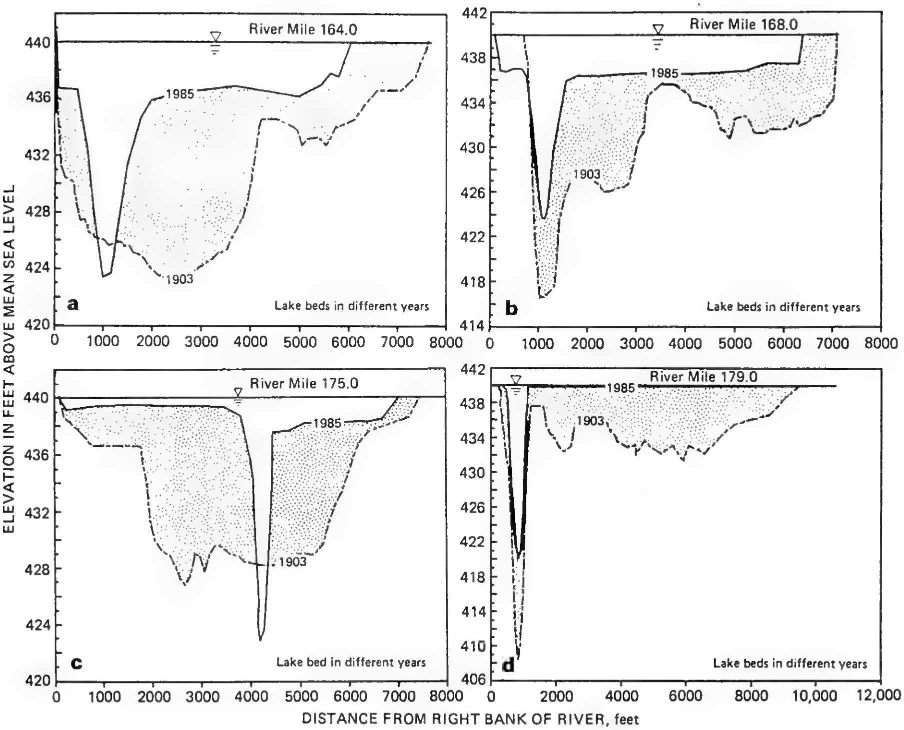


Figure 12. Comparison of 1903 and 1985 lake bed profiles for Peoria Lake

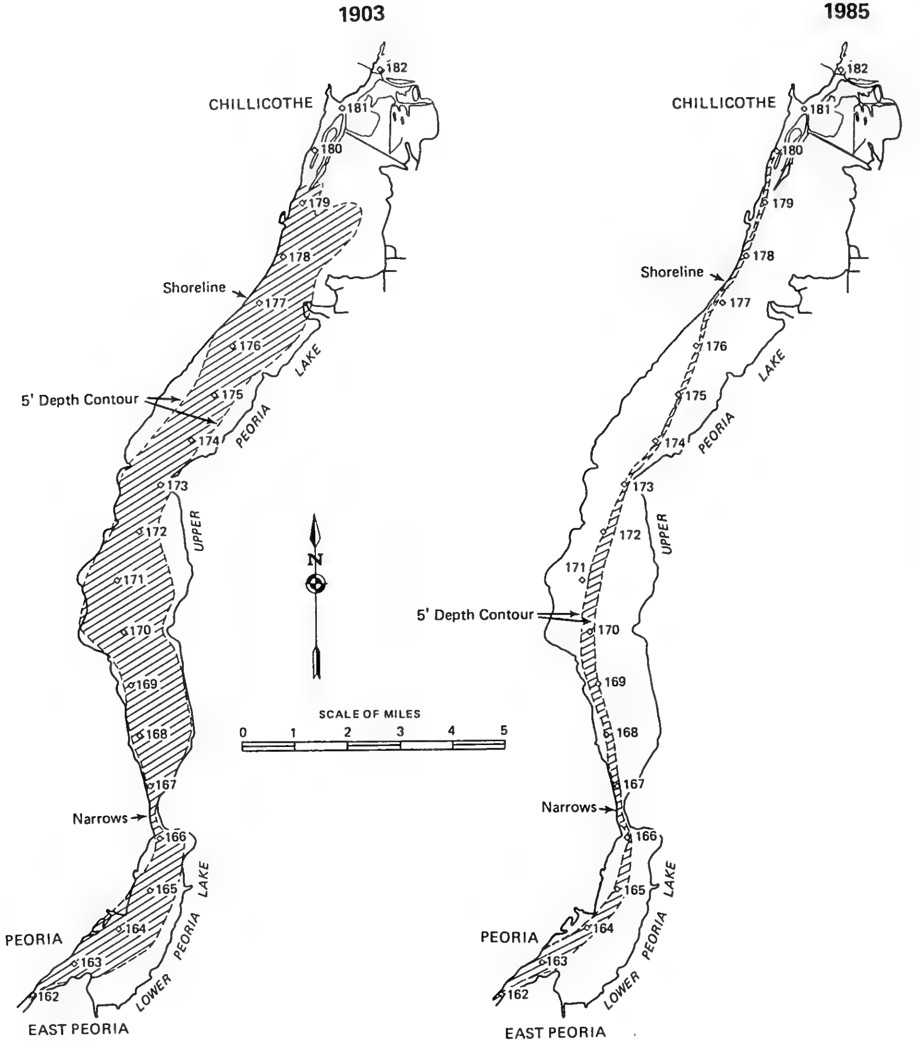


Figure 13. Lake area deeper than 5 feet in 1903 and 1985

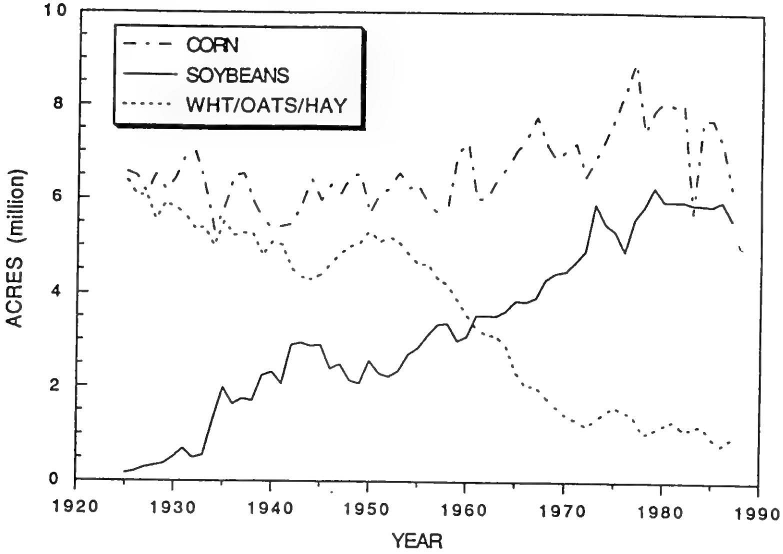


Figure 14. Acreage of various crops in the Illinois River watershed

land-use pattern and improvements in farm technology are generally assumed to be the major causes for the increased erosion and sedimentation in the Illinois River valley.

Sediment Quality

Releases of chemicals to the atmosphere, land surfaces, and surface and ground water occur continuously in both urban and agricultural surroundings. Once chemicals are released to the environment, they are inevitably transported and deposited at other locations by either air or water. Those transported through the atmosphere eventually end up in water bodies, while the final sink for these chemicals is either surface water impoundments or ground water. While ground-water contamination is limited to chemicals in the dissolved state, surface water contamination includes both dissolved and particulate chemicals. Most of the chemicals in surface waters have a strong affinity for finer sediment particles. Some of the chemicals are adsorbed (i.e., attached) onto the sediment particles, while others exist in particulate form mixed with the sediments.

The chemical characteristics of the different layers of lake sediments are very good indicators of the history of the environmental quality of their surroundings. For example, lake sediments clearly show the periods of atmospheric testing of nuclear weapons and periods of serious pollution by different chemicals.

Examples of chemical profiles in lake bed sediments from Peoria Lake are shown in figure 15, where the concentration of zinc and lead in the sediment are plotted against the depth of the sediment and the age of the sediment layers. The highest concentration of lead was in the late 1960s, while that for zinc was in the early 1950s. The concentrations of the two heavy metals in the sediment have been decreasing since the peak periods of deposition in the lake. The top and most recent sediment layer shows much lower concentrations of lead and zinc than the lower earlier layers. Similar patterns can also be observed for other chemicals in Illinois River sediments, and analysis of sediment core samples at other locations can provide the history of pollution in the region.

Most of the chemicals found in lake sediments are transported from source areas and upland watersheds, including urban and agricultural areas, through stream networks. Some chemicals are deposited directly into lakes from dry and wet atmospheric depositions and direct waste discharges. The transport and fate of chemicals that enter the stream network, lakes, and reservoirs are poorly understood and not very well documented in Illinois. There is, however, general consensus that the accumulation of chemicals in stream and lake sediments is a serious environmental problem, since it has a detrimental effect on water quality and aquatic biota.

SUMMARY AND CONCLUSIONS

Erosion and sedimentation have been important issues in Illinois for a very long time. In the early stages, the concern was primarily with the loss of soil productivity for agricultural crops, with less emphasis on off-site environmental impacts. In recent years most of the concern has focused on impacts on environmental quality and on continuing sedimentation on the Illinois River valley. The annual gross soil erosion from croplands has been estimated at 158 million tons, which is nearly 90 percent of the total annual gross soil erosion of 180 million tons for the state. Erosion from nonagricultural lands therefore accounts for about 10 percent of the total erosion in Illinois.

With the exception of the Illinois, Mississippi, and Ohio River valleys, which have extensive sediment buildup, 2 to 9 inches of Illinois topsoil has eroded. The most severe erosion took place in southern Illinois, where the hilly and highly erosive area was settled and farmed earlier than the rest of the state. Erosion has also been significant in the western part of the state, where 6 to 7 inches of topsoil has eroded. The central and northeastern parts of the state have fared better, with 2 to 4 inches of erosion.

The major impact of soil erosion is the eventual accumulation of the eroded soils in lakes and reservoirs. In Illinois, lake sedimentation has been a serious problem and has been investigated intensively. The Illinois State Water Survey has conducted more than 180 sedimentation surveys of more than 130 lakes in Illinois and has compiled comprehensive lake sedimentation survey data. Most of the lake surveys were conducted in the 1950s, a time of acute concern for water supply storage during the drought period. The gradual loss of water storage capacity in water supply lakes is a major concern. This has been illustrated by examining two water supply lakes with sedimentation problems in central Illinois: Lakes Decatur and Springfield. The storage capacity reductions over time for both lakes are in the range 0.3 to 0.5 percent per year. Nevertheless, both cities had to implement programs to restore storage capacities by reducing erosion rates in the watershed and the delivery of sediment into the lakes.

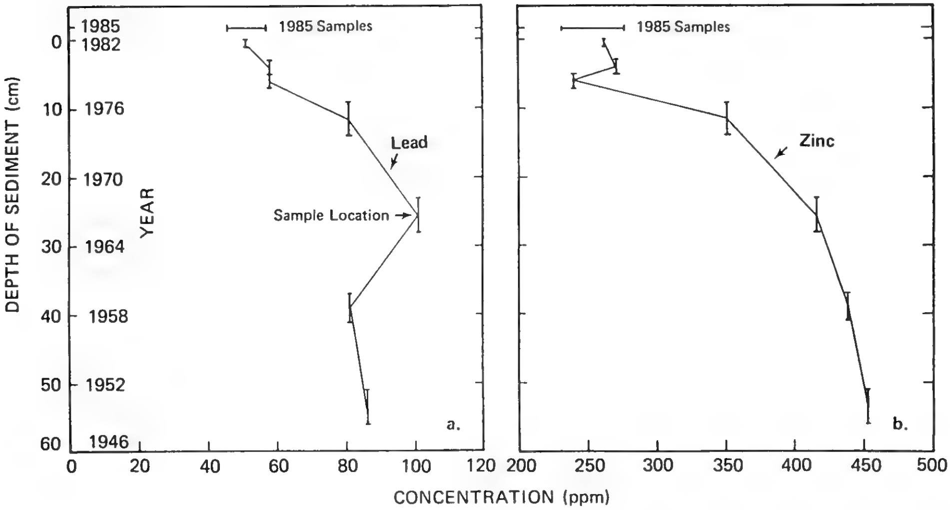


Figure 15. Change in the concentrations of lead and zinc with depth in Peoria Lake sediment

Three Illinois agencies, the ISWS, the USGS, and the IEPA, have been collecting instream sediment data over the last 20 years. Data collection peaked in 1981 when the Water Survey initiated the Sediment Benchmark Network. However, the number of stations has been declining since then, with a combined total of 40 stations operating in 1990. Analysis of the distribution of measured sediment concentrations for selected streams in northern, central, and southern Illinois shows that since 1980, sediment concentrations have been decreasing in the Rock River in northern Illinois, essentially constant in the Sangamon River in central Illinois, slightly decreasing in the Kaskaskia River in south-central Illinois, and slightly increasing in the Cache River in southern Illinois.

Analysis of data from 35 sediment monitoring stations for the annual sediment yields shows that four equations could be used to calculate sediment yield from Illinois watersheds. The spatial distribution of sediment yield shows that the regions along the Illinois River and in west-central Illinois are the highest sediment-producing areas, along with some areas in southern Illinois. The northeastern and central sections of the state show the least sediment yield.

Because of its central location and natural geomorphology, the Illinois River has been significantly impacted by erosion and sedimentation. The Illinois River drains nearly half of the state, and many of the major streams in Illinois drain into it. The main sources of sediment to the Illinois River valley are watershed erosion, streambank erosion, and bluff erosion. The sediment yield calculations show that on the average, 13.8 million tons of sediment are delivered to the Illinois River valley annually. But the average annual outflow of sediment from the Illinois River at Valley City is 5.6 million tons. Thus on the average, 8.2 million tons of sediment are delivered annually from tributary streams and deposited in the Illinois River valley.

The temporal trend analysis of sediment concentrations and load in the Illinois River at Valley City over the last ten years shows that they have been decreasing since 1980. But the primary cause, at least for the sediment load, is the decreasing trend in streamflow over the same period.

Major areas impacted by sediment deposition in the Illinois River valley are the backwater lakes. Sediment rate calculations show that the backwater lakes had lost 20 to 100 percent of their capacities by the year 1990, with an average capacity loss of 72 percent. The impact of sedimentation in the Illinois River valley has been clearly illustrated by the conditions in Peoria Lake over the years. As of 1985, Peoria Lake had lost 68 percent of its 1903 capacity due to sedimentation, and the average depth of the lake had been reduced from 8 to 2.6 feet.

Releases of chemicals to the atmosphere, land surfaces, and surface and ground waters occur continuously in both urban and agricultural surroundings. Most of the chemicals found in lake sediments are transported from source areas and upland watersheds, which include urban and agricultural areas, through stream networks. Chemical profiles for zinc and lead in lake sediments from Peoria Lake indicate that the highest concentration of lead was in the late 1960s, while that for zinc was in the early 1950s. The concentrations of the two heavy metals in the sediment have been decreasing since those peak periods of deposition. The top sediment layer shows much lower concentrations of lead and zinc than the lower layers, reflecting earlier periods. Similar patterns have also been observed for other chemicals in Illinois River sediments.

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GROUND-WATER MINING—WHEN DISCHARGE EXCEEDS RECHARGE

Stephen L. Burch and Kenneth J. Hlinka
Illinois State Water Survey

INTRODUCTION

Ground water is an economically important, renewable resource. Each day Illinois uses large quantities of ground water to meet its supply needs for drinking water, industry, and power generation. Over one billion gallons of ground water are displaced and/or consumed daily for these uses (IWIP, 1991). Major metropolitan areas require vast amounts of water to sustain the needs of the people and businesses within their boundaries. No matter the size of these supplies, however, they are not infinite in their ability to meet demand. When the limits of renewability are exceeded, ground-water mining occurs. While some "overdrafts" in the hydrologic budget can be tolerated and might even be desirable, long-term mining of ground water should be avoided.

Understanding the availability of ground water in Illinois also requires understanding the concept of ground water and the processes associated with its availability. In general terms, ground water is any precipitation on the land surface that percolates down through the soil and reaches the water table or the zone of total saturation near the land surface. This zone is open to atmospheric pressures and responds quickly to fluctuations in precipitation. It also acts as a reservoir that slowly recharges the water-bearing geologic materials beneath it. Some strata buried below the land surface store water in sufficient quantities to make it economically possible to withdraw this water. These formations are called aquifers. An aquifer is best defined as a saturated, permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients (Freeze and Cherry, 1979). The distribution of the materials that constitute aquifers is highly variable throughout Illinois, as are the amounts of ground water available within them.

Ground-water availability is highly dependent upon the geologic material within which it is stored. For example, sand-and-gravel formations found in the unconsolidated materials above bedrock store and release ground water with relative ease. Yield is determined by the interconnection of pore spaces between the sand-and-gravel particles and the amounts of clay and/or other claylike geologic materials blended within them. These clay or claylike materials will retard an aquifer's ability to release water when pumped. Limestone-type aquifers, on the other hand, can release large quantities of water, depending upon the degree and interconnection of the cracks and crevices found within the limestone. Sandstone aquifers are limited, inversely, in their ability to transmit ground water by the amount of cementation of the sand grains that make up the rock.

Ground-water scientists describe an aquifer's ability to transmit water in terms of transmissivity. Values can range from perhaps 300,000 down to 10,000 gallons per day per square foot (gpd/ft^2). Usually the unconsolidated deposits of sand and gravel in Illinois have the highest transmissivity values. By contrast, the values for bedrock aquifers composed of sandstone or limestone usually are only a few thousand gpd/ft^2.

Aquifers have existed for thousands and even millions of years. In fact, long before humans began using ground water, flowpaths were established within these aquifer systems. A kind of equilibrium or steady-state condition existed between recharge and discharge, even though the aquifers were completely full. Typically these two actions balance in an annual cycle. Thus, if more water flowed out of the system, then more ground water could be added during the next recharge part of the cycle, so that the overall amount of storage remained the same.

Recharge normally occurs throughout the entire state of Illinois on an annual cycle. During a drought, which may last several years, there may be little recharge to an aquifer, while demand for ground water is typically the greatest. During wet times, there may be so much water available for recharge, that it exceeds the infiltration rates and bypasses the ground-water system. The two key points to remember are that recharge is seasonal and that it varies in amount from year to year. Hydrologists can estimate an *average annual recharge* for an aquifer, and if pumpage data are available, they can predict with some certainty where problems may arise. This average would likely be based on 20 or perhaps even 30 years.

In several areas in Illinois, trends in ground-water use have prompted investigations of an aquifer's ability to supply a sustained yield of ground water for the required need. Bowman (1991) identified areas in Illinois where the ground-water use is approximately equal to or has exceeded the available yield of the aquifer system. Of the areas that were identified, only the Chicago region has experienced ground-water mining due to both the intense demand and the relatively low transmissivity of the major aquifer supplying the region.

This chapter examines ground-water use in the Chicago region and contrasts it with three other areas in the state (Peoria region, eastern Kankakee and Northern Iroquois Counties, and the American Bottoms region) where major changes in ground-water use have occurred. It examines the hydrogeologic factors associated with these areas, the potential yield of each aquifer system, and the impacts caused by demand for the ground-water resource. These four high-use areas were chosen because data are available and because ground water meets the demand of a significant segment of their population, important industries, or irrigation needs. Ground-water mining has the potential to be of critical concern to each of these areas.

THE CHICAGO REGION

Problem Statement

The Chicago region has been a focus of ground-water research for decades. In one of the best overall assessments of the region, Suter et al. (1959) noted that some of the bedrock aquifers that underlie the area had been used for nearly 100 years. That early report, known as *Cooperative Report No. 1,* between the Illinois State Water and Geological Surveys, correctly recognized that the diversity of underground water sources (aquifers) had helped promote the industrial expansion of the area. It also recognized that withdrawals from the key aquifer, the Ironton-Galesville Sandstone, were outstripping the sustained yield of the aquifer. That is, ground-water mining had begun.

The inevitable consequence of ground-water mining is that critical water levels will be reached and well yields will decline significantly. This situation was recognized in the early 1960s in the Chicago region and resulted in a lawsuit being brought by the state of Wisconsin against the state of Illinois. Consequently, in 1966 the U.S. Supreme Court issued a decree concerning ground-water withdrawals in the Chicago region. As a result of an amendment to that decree, planners for Illinois had to formally recognize the need to reduce pumpage from the Cambrian-Ordovician aquifer system in northeastern Illinois (Fetter, 1981). Accordingly, the 81st General Assembly directed the Illinois Department of Transportation/Division of Water Resources (IDOT/DWR) to implement a long-term program for allocating Lake Michigan water. The program regulates the use of Lake Michigan water by Illinois and has funded impact studies of pumpage from the deep sandstone aquifer underlying northeastern Illinois.

The allocation program initiated two hydrogeologic modeling studies (Prickett and Lonnquist, 1971; Burch, 1991) in an attempt to characterize water-level trends, pumpage, and recharge rates of this system. These computer models were (and currently are) used as tools in the management of the ground-water resource. The first model, developed by Prickett and Lonnquist, was a predictive or deterministic one. Like all models, it solves equations numerically and is useful in describing certain cause-and-effect relationships. Because it uses simplifying assumptions about ground-water flow equations, aquifer boundaries, and initial starting conditions, the model can be used to predict water levels. Conclusions about ground-water drawdowns or recoveries can then be made by comparing the results of different simulations.

Burch (1991) redeveloped the original Chicago model partly because computer hardware has moved beyond the mainframes and punch cards that Prickett and Lonnquist used. Burch sought to use the model in a microcomputer/personal computer (PC) environment, which allows low-cost preprocessing of input data and postprocessing of model calculations. With this new version of the Chicago model, Burch was able to determine the impact of substituting Lake Michigan water for ground water in the Chicago region. His investigation made use of the detailed pumpage and hydrogeologic data available by merging classical methods with new mapping techniques.

Water Use in the Chicago Region

Since 1980, the Water Survey has maintained computer records of ground-water pumpage. Prior to that, however, only penciled notations on paper forms were kept for most communities, industries, and golf courses in northeastern Illinois. The Water Survey periodically published summaries of these notes, which generally represented annual compilations for each usage type by county. These early records, which were diligently maintained between 1964 and 1980, were combined with computer data to form the best available record of ground-water pumpage in northeastern Illinois.

Figure 1 illustrates the modern history of ground-water pumpage from public and industrial wells in the

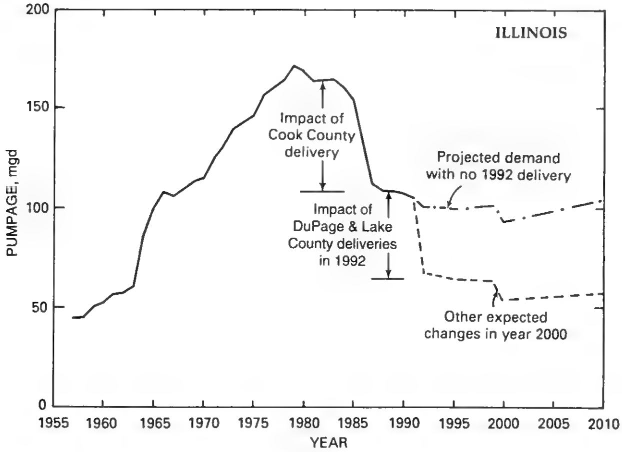

Figure 1. Northeastern Illinois pumpage and impact of Lake Michigan water deliveries (actual and forecast)

Chicago region. It clearly indicates that major pumpage from this area increased for several decades until the 1980s and 1990s.

Water-Level Trends: Lesson in Responsiveness to Lake Michigan Substitutions

Each year since 1959, the heavy demand on the most significant aquifer in northeastern Illinois has exceeded the resource's ability to recharge. Consequently, pumpage has had an ever-increasing effect on ground-water levels. By 1960, the drawdowns at the pumping centers associated with each community had overlapped enough to produce a regional cone of depression. Ground-water levels declined by more than 1,000 feet at some locations. In many parts of the Chicago region, the ground-water level had fallen to elevations below sea level.

With the deliveries of Lake Michigan water to communities in Cook County in the 1980s, however, the trend began to reverse. Sasman et al. (1986) reported that water levels were rising in some areas that previously had relied on the deep Cambrian-Ordovician aquifer system. Figure 1 shows the impact of this trend on pumpage. More conversions to Lake Michigan water in the late 1980s at Des Plaines, Arlington Heights, and Mt. Prospect resulted in even more areas of rising water levels according to Visocky's 1991 observations (Visocky, 1993). This trend is expected to continue as more Lake Michigan water is delivered to DuPage County and parts of Lake County. The computer simulation by Burch (1991) predicts that this trend may result in a 650-foot rise centered on the community of Elmhurst by the year 2010.

Other changes in Illinois pumpage patterns are likely to occur during the model simulation period (1986-2010). The most notable change will occur when the Joliet and Wilmington public water supply systems shift their pumpage from ground water to the Kankakee River. Other decreases in pumpage from the Cambrian-Ordovician aquifer are also anticipated at Aurora, Batavia, Geneva, Montgomery, North Aurora, and Crystal Lake as these communities diversify their sources of water. A few communities (Sugar Grove, Cary, and Rockdale) are expected to hold their Cambrian-Ordovician pumpage steady at present levels and meet future growth from shallower aquifers.

The key observation to be made, however, is that if pumpage is decreased to a level equal to the average annual recharge, then ground-water mining will cease. As a result of aggressive resource evaluation and management, Illinois has an opportunity to match Cambrian-Ordovician pumpage in the Chicago region with the practical sustained yield of the aquifer. If this occurs, it will mark the first time since the late 1950s that the system has been in balance.

THE PEORIA REGION

Ground-water mining is not currently a problem in the Peoria region. Although it too has a long history of industrial development and heavy demand for ground-water supplies, the area has not experienced the water resource problems described for the Chicago region. Although the aquifer properties and reasons for problems in the two areas differ, the regions share a responsiveness to water-level declines.

The Peoria region is located in north-central Illinois and includes parts of Peoria, Tazewell, and Woodford Counties. It covers about 600 square miles and is approximately 30 miles long and 20 miles wide. The region has had a great history of industrial growth, mainly in the manufacture of heavy earth-moving equipment and in the distillation of alcoholic beverages, which requires large amounts of water. Fortunately, this area lies over the very prolific Sankoty aquifer. This deposit of unconsolidated sand averages 100 feet in thickness and is an order of magnitude more transmissive than the major aquifer supplying the Chicago region.

Even with this great resource, heavy pumpage lowered water levels in certain well fields and prompted concern for resource management as early as the 1940s. Many of the industrial facilities located in the Peoria region required low-temperature water. Ground water became the favored resource of the area because of its availability and temperature. The Illinois River was only used on a limited basis, due to its traditional pollution problems (prior to environmental regulations of the 1970s) and its high summer temperatures. As a consequence of the ever-increasing demand for ground water, water levels in the well fields declined steadily, partly because pumpage exceeded replenishment by natural recharge *and* partly because the wells were too closely spaced. By 1940 local concern had reached such an alarming level that the Illinois State Water Survey was asked to study the situation (Horberg et al., 1950; Suter and Harmeson, 1960).

The Water Survey subsequently determined that the overpumpage of ground water was between 8 and 10 million gallons per day (mgd) and demonstrated the need to adopt conservation measures and some method of artificial recharge. Several methods were investigated, including induced infiltration (using natural water bodies to increase flow), landflooding (inundating a tract of land with water), channel construction (modification of a stream channel), recharge wells (induced flow directly into the aquifer), and recharge pits (gravity flow from excavated pits into the aquifer).

Preliminary tests in August and September 1941 (Suter and Harmeson, 1960) on an abandoned gravel pit indicated that these pits, if refilled by river water, would increase ground-water levels with an acceptable increase in ground-water temperature. Water levels within Water Survey monitoring wells reacted almost immediately to this recharge method. This became the method of choice primarily because other methods were more expensive, the required mechanisms for them were unavailable, or the increase in ground-water temperature associated with them was unacceptable.

Consequently, in 1949 funds were appropriated for the Water Survey to construct and operate a research pit with a capacity of 0.3 mgd. Pit 1 was built on the property of the Water Survey Laboratory, and began operation on October 4, 1951. This pit was operated for seven more seasons through 1959. Pit 2 (2.0 mgd capacity) was built in 1956 on leased land adjoining Water Survey property, and artificial recharge within the pit was initiated in October 1957. Both pits yielded recharge rates higher than expected.

The successful operation of the first Water Survey recharge pits led to the construction of two other similar installations. The Bemis Bros. Bag Company and the Peoria Water Works Company both built artificial recharge pits to re-establish ground-water levels for their pumping needs during the 1950s. Construction and operation of the Water Survey pits and privately owned pits was deemed very successful in relieving the stress, at least for a few years, caused by heavy ground-water pumpage in a small area of Peoria.

Water-Level Trends: The Lesson of Artificial Recharge

Today, our water-use data reveal that industrial pumpage has declined, while public water supply use has remained relatively steady since 1968 (in the Peoria region). Ground-water mining is not a problem here. In fact, water levels in this region are higher today than they were 50 years ago. The experience at Peoria is relevant, however, because it shows how overpumpage and poor spacing of high-capacity wells can lead to problems. It also reveals that, like the experience in Chicago, the resource can recover when pumpage stops.

Today the privately owned utility supplying water to Peoria and many of its industries is concerned about future growth. Estimates through the year 2005 indicate that the current Illinois-American Water Company facilities may be inadequate to handle the estimated peak demand for the year 2005 from their central well field. As a result, they funded a Water Survey hydrologic investigation of this well field (Schicht, 1992). That study found that the required need could be met, with little or no impact to the current well field, by developing a new well field to the north of the existing field. The study considered inputs to the hydrologic system (by observing scientific aquifer tests) and balanced them against estimated withdrawals. It also concluded that induced recharge from the Illinois River would play an important role in balancing supply and demand.

Fortunately, the Water Survey has a long history of monitoring and study at Peoria. Thus it can more confidently calculate the long-term yield of the Sankoty aquifer in that area. But the Water Survey does not always have necessary background information when asked pointed questions about ground-water mining in other areas. The following section differs from the first two because it describes a situation in which little was known until a problem arose.

EASTERN KANKAKEE AND NORTHERN IROQUOIS COUNTIES

In the late 1980s, the Kankakee/Iroquois County area was rife with highly charged emotions regarding ground-water use. The concerns arose in response to increased irrigation during a period of low rainfall. Water supply interruptions in area domestic wells were perceived by some to mean that too much water being removed from the ground. A competition for ground water among uninformed users began in an area served by multiple aquifers.

The area, located south of the Chicago region and along the eastern border of Illinois, has two distinct aquifers (Cravens et al., 1990). A reasonably productive bedrock aquifer consisting of Silurian- and Devonian-age dolomite is frequently used by irrigators. This aquifer is overlain by a surficial sand-and-gravel aquifer system that sometimes is used to provide ground water for domestic use and livestock watering. At the time of the study, no high-capacity irrigation wells were using the surficial deposits for their supply, although the sand has the potential in some areas to serve as a viable source of irrigation water.

The issue of ground-water mining came about because water supply interruptions in domestic supply wells began to be reported in the early 1980s. These interruptions were temporary (lasting from hours to months), which made it necessary for some well owners to replace or deepen their wells, lower their pump intakes, or change the type of pump being used. Soon the linkage to irrigation pumpage was made, and the inevitable "finger-pointing" began. The conflict grew to such an extent that the area was specifically identified by an amendment to the Water Use Act of 1983 (P.A. 85-1330). Not only were the ground-water interruptions observed and emergency restrictions contemplated in Illinois, but also in two adjacent counties in Indiana. Basch and Funkhouser (1985) reported that an intensive irrigation project in the dolomite aquifer in these two Indiana counties affected nearly 130 domestic wells. These problems resulted in litigation and legislation protecting small well owners in Indiana.

The experience in eastern Kankakee and northern Iroquois counties illustrates that the issue of ground-water mining can have interstate ramifications. This was also the case in the Chicago region when Wisconsin sued Illinois in the U.S. Supreme Court and won.

Seasonal Impacts of Intensive Water Use

In 1987, a near-normal year for precipitation, public water supply pumpage (typically for communities) amounted to approximately 16 percent of the total ground-water use, or 493.77 million gallons for the area. Rural-domestic use accounted for about another 17 percent (586 million gallons) of the annual pumpage. Industrial facilities accounted for only 1.6 percent of the total use (54.86 million gallons). Irrigation, however, accounted for more than 63 percent of the total ground-water use, or approximately 2,122 million gallons. Unlike other water uses, irrigation water demands are entirely seasonal. Most irrigation water withdrawals occur during the summer months, June-August. This intense short-term usage places enormous stress on the aquifer system, which in turn creates the potential for supply interruption of domestic wells finished in the upper part of the bedrock aquifer.

But in 1988, ground-water pumpage rose dramatically for most users in Illinois in response to the drought conditions. By July 7 that year, total ground-water withdrawals for irrigation in this area amounted to 2,227 million gallons; by midsummer withdrawals for this area had already exceeded the irrigation pumpage for the previous year by 105 million gallons. By the end of 1988, total ground-water use for irrigation was estimated to be 5,658 million gallons. During this time, approximately 120 complaints of well-supply interruptions were filed in the study area. Detailed investigation of 71 of these complaints revealed that 25 pertained to Silurian-age dolomite wells (the bedrock aquifer), 37 pertained to shallow sand-and-gravel wells (the surficial aquifer), and 9 were fictitious. Remedial actions to re-establish water supplies were undertaken by the owners of four dolomite wells and four sand-and-gravel wells.

Water Level Trends: Lesson of Timing, Area, and the Potential for Conflicts

The "use-to-yield" concept is a somewhat crude strategy that Illinois, and more specifically the Water Survey (Bowman and Collins, 1987), developed for locating areas of the state where ground-water conflicts might arise. It involves examining the actual use in the township and contrasting it with the township's potential aquifer yield. This use-to-yield percentage, expressed as "use/yield" represents a qualitative assessment of the percentage of the total resource being used. Although not meant to be used as the basis for site-specific technical analysis, this use/yield comparison has the potential to help identify those regions where an aquifer may be overdeveloped.

Water Survey investigators (Cravens et al., 1990) considered three different scenarios in evaluating the long-term viability of the dolomite aquifer of eastern Kankakee and northern Iroquois Counties. Each scenario involved the "use/yield" concept, and in each case, difficulties were encountered in applying this statewide tool to a specific area. The first scenario considered the effects of precipitation on the previously predicted use/yield ratio. It found that in a near-normal precipitation year, the use/yield ratio was determined to be 0.12 over the 414-square-mile (sq mi) study area, and in 1988 this value increased to 0.25.

But when the Cravens team looked more closely at the area from which water was being diverted (the second scenario) and contrasted it with the total pumpage during the 90-day irrigation season, they calculated a different use/yield ratio. They determined the ratio to be 0.32 and 0.77 in 1987 and 1988, respectively. Clearly, seasonal impacts can modify the ratio, especially when considering only the area (271 sq mi) from which ground water was being diverted to the irrigated area.

In the third scenario for the dolomite aquifer, the Cravens study examined the use/yield ratio when only the irrigated lands in the study site were considered. They found that the ratio increased dramatically when viewed with such a narrow focus. A ratio of 2.00 was determined for 1987, while a ratio of 4.54 was found for the entire year of 1988. That is, when narrowly viewed, use of ground water on irrigated lands exceeded the aquifer's ability to keep up with demand. But in the real world, not all lands overlying an aquifer are irrigated, so this scenario is unrealistic.

Bowman (1991) had assumed that a use/yield ratio of 1.0 or more indicated a potential problem area and that a ratio of 0.5 to 0.999 indicated the possibility (not the probability) of overdevelopment. She determined that a ratio of less than 0.5 indicated an area where over-pumpage probably does not occur. It is clear that her larger view of demand, which was tied to 30-year averages for precipitation, found fewer conflict areas.

Cravens et al. (1990) found that the volumes of recharge and discharge can vary widely at different locations within the eastern Kankakee and northern Iroquois County study area. Recharge to the dolomite aquifer is much greater in areas where the surficial sand directly overlies the bedrock than where clay or till separates the bedrock from the surficial system. They also determined that the presence of major river systems and their effect on the ground-water recharge regime are not taken into account. These systems increase water levels and recovery rates both during and after the irrigation season.

Ground-water mining is not a problem in eastern Kankakee and northern Iroquois Counties. The resources are adequate to provide ground water to present users without causing long-term depletion of the resource. Although record declines in the potentiometric surface (the surface to which water rises in a well under normal conditions) occurred during the drought of 1988, long-term depletion of the resource will only occur if irrigation continues to be developed without regulation and if precipitation continues at below-normal levels (Cravens et al., 1990). We should recognize that short-term extremes in demand, which could exceed one year, do not constitute mining of the ground-water resource. Ground-water managers must keep in mind the long view and base any decisions on average annual figures of supply and demand.

AMERICAN BOTTOMS REGION

The American Bottoms area in southwestern Illinois is one of the most heavily populated, industrialized areas in the state. It encompasses the communities of Alton, Wood River, Granite City, Collinsville, East St. Louis, and Cahokia. The ground-water resource of the sand-and-gravel aquifer underlying the area once was developed extensively. These deposits range in depth from several feet near the bluff edge and the Chain of Rocks reach of the Mississippi River to more than 170 feet, with an average depth of 120 feet across the entire area.

The experience in the American Bottoms area, as it is known on topographic maps, is presented here because it is the exact opposite of ground-water mining. The difficulties that water managers face, though, are similar to those described in the three preceding regions. The problem is that ground-water levels are rising, in fact, so much so that they are causing flooded basements and highway underpasses. The Illinois Department of Transportation even has a network of dewatering wells to keep roadways in some areas from being inundated by ground water. Some 10 million gallons are pumped to waste each day!

This is an uncommon situation because ground water is typically an economic asset to a region, not a liability. Although the problem in the American Bottoms is not mining, the problem of rising ground-water levels is due largely to the intense development of a resource without an understanding of equilibrium conditions; that is, predevelopment water levels, ground-water flow patterns, future total pumpage, and estimates of average annual recharge.

The first significant withdrawal of ground water in the American Bottoms started in the late 1890s. Prior to 1900, ground water was primarily used for domestic and farm supplies. Since then ground-water withdrawals have been mostly for industrial and municipal use. Increasing pumpage in the area continually lowered water levels throughout the entire region until the 1960s. During this time, infrastructure maintenance and construction designs allowed for only the current water-level safety margins. When the demand for ground water declined in the late 1960s, however, ground-water levels rose and kept rising. The rising ground-water levels are believed to have resulted in costly destruction of household basements and sewer and gas lines, as well as foundation problems. The situation has become so dire that the U.S. Army Corps of Engineers initiated a feasibility study (USACOE, 1987) and an environmental impact statement concerning the design of a proposed ground-water withdrawal plan to reduce the damages caused by ground-water flooding.

This region has been of major interest to the Water Survey for many years. As a result, a network was created of 19 observation wells, five of which are monitored continuously by water-level recorders. The Water Survey has also established a practice of measuring more than 200 wells throughout this area about every five years. The most recent, widespread measurement was conducted in 1990. The results of the previous measurements are summarized periodically in Water Survey publications.

Figure 2 illustrates the historical trend of ground-water pumpage in the American Bottoms area. It shows that the estimated pumpage from wells increased from 2.1 mgd in 1900 to 111.0 mgd in 1956. Pumpage then declined sharply to 92.0 mgd in 1958, and by 1964 it had again increased to 110.0 mgd. After 1966, pumpage steadily declined to 54.4 mgd in 1981, before slowly increasing to 60.1 mgd in 1985. Recent pumpage increases appear to be associated with the IDOT dewatering well networks along roadways in the area. This dewatering effort prevents water levels from rising above the road surfaces. These continuing efforts have created a cone of depression in the ground-water level's surface centered on the metropolitan East St. Louis (Metro East) area.

Water-Level Trends: Reverse Lesson of Ground-Water Mining

Ground-water levels in the American Bottoms have been measured periodically for more than 45 years by the Water Survey and other concerned public and private parties. As mentioned above, the Water Survey still maintains a network of monitoring wells in this area. Some of these wells were established when pumping was at its peak in the region. The hydrograph of one such well (Water Survey well No. 01081, Marathon Oil observation well) is detailed in figure 3, which clearly indicates the rising trend of ground-water levels since 1965 due to the overall decrease in ground-water use.

Recharge in this area is from precipitation, induced infiltration from the Mississippi River and lesser water bodies in the area, and subsurface flow from the bluffs bordering the surface materials and into the sand-and-gravel deposits (Kohlhase, 1987). Recharge by induced infiltration occurs where pumpage from wells has lowered the level of the ground water below the elevation of the surface water body. All the available information indicates that lack of recharge of the sand-and-gravel deposits is not a concern. The construction of major underground infrastructures during the high-use era has set the stage for destruction by rebounding ground-water levels.

The U.S. Army Corps of Engineers has been charged with initiating some type of plan to help minimize the destruction of property from rising water levels. To this end, they have detailed a major plan (USACOE, 1987) that will withdraw 41.25 mgd from wells in 57 locations. The initial cost is estimated at almost $8 million with a yearly maintenance cost of more than $1 million. Obviously, the cost of rising water levels can have economic consequences.

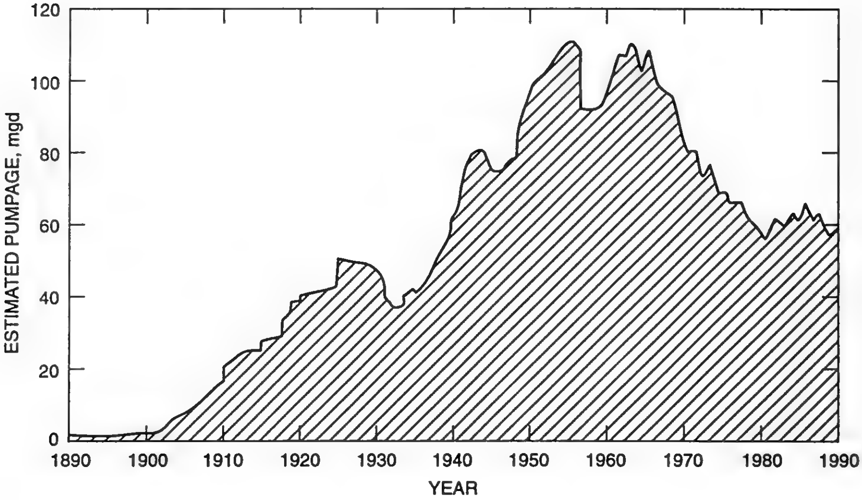

Figure 2. Estimted pumpage in the American Bottoms area, 1890-1990

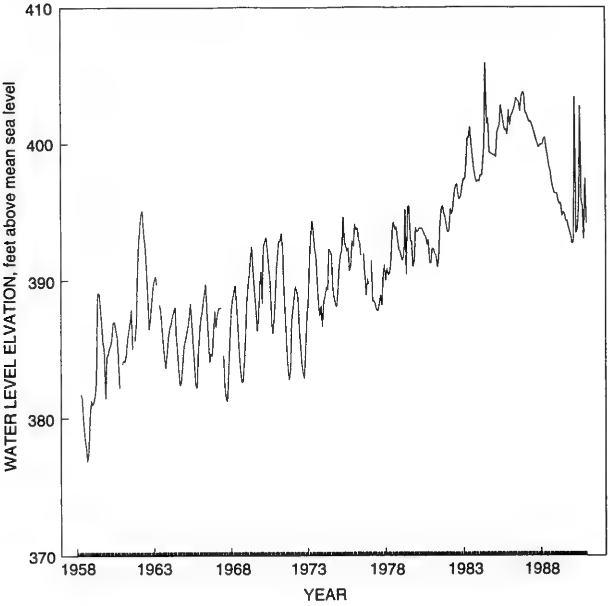

Figure 3. Hydrograph of Water Survey observation well #01081, 1958-1991

SUMMARY AND CONCLUSIONS

Ground water is a finite resource that is not uniformly distributed throughout the state. In some areas of Illinois, demand for this resource has caused it to become well developed. Demand can exceed supply, especially in urbanized areas of Illinois, and potential problems can arise from competition for the resource. The major concern is that annual use, in the long term, should not exceed the *average annual recharge* available to a specific aquifer system. When annual use does exceed average annual recharge over a prolonged period, ground-water mining occurs.

This chapter summarizes the hydrologic situations in four industrial centers of Illinois: Chicago, Peoria, eastern Kankakee and northern Iroquois Counties, and the American Bottoms. The use of ground water in each region is summarized, along with a discussion of any problems associated with this use.

In Illinois the most significant problem, in terms of ground-water "mining," occurs in the Chicago region. This problem started during the 1950s when demand exceeded what the natural systems could effectively recharge. Ground-water levels in one of the major aquifer systems of this region have declined by almost 1,000 feet since pumping began. The economic result has been increased pumping costs due to increased lift requirements. (A lawsuit brought by Wisconsin ultimately required the state of Illinois to decrease its pumpage from the major aquifer supplying the Chicago region.) The mining of the natural system also puts it at risk of compaction, which could permanently damage the aquifer.

No other area in Illinois has had a more historically adverse impact on ground-water levels than has the Chicago region. While heavy ground-water use has affected the ground-water flow system in the other areas discussed, none appear to equal the Chicago situation. Steps are being taken to relieve the stress on the aquifer system. The substitution of Lake Michigan water for ground water is having positive impacts, but this strategy will only buy a few years. Burch (1991) projected that by the year 2005, ground-water mining of the principal aquifer supplying the Chicago region will resume.

The issue of ground-water mining involves lengthy study and continuous, long-term monitoring of pumpage and ground-water levels. From the four case studies presented in this chapter, it is possible to make some suggestions about how to avoid ground-water mining:

- Determine average annual recharge for each aquifer.
- Maintain adequate spacing between high-capacity wells.
- Establish a long-term program for measuring ground-water levels.
- Maintain records of well locations and how much they pump.
- Recognize that seasonal extremes may cause interruptions to inadequately constructed wells, but this problem is not indicative of mining.
- Recognize that ground-water level declines can have interstate consequences.

By following these guidelines, resource managers can avoid long-term ground-water mining so that Illinois can make the best use of its vast ground-water resources.

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DROUGHT IMPACTS ON WATER RESOURCES

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INTRODUCTION

Illinois is considered a water-rich state. In one sense the state is surrounded by fresh water—major river systems border its west, south, and east boundaries; and Lake Michigan borders the northeast. The interior is crossed by several large tributaries of these major border rivers. These rivers and Lake Michigan are the major surface water resources of the state. In addition, the state has abundant ground-water resources; however, the distribution of these is not uniform throughout the state, making their availability variable. Many climatological and socioeconomic factors influence the quantities and qualities of the water resources in Illinois. This section details the impacts on Illinois water resources by one relatively infrequent but consequential condition: drought.

Studying drought conditions heightens our awareness of the impacts of drought and serves as a basis for planning for future drought conditions. It is essential that drought conditions be investigated because droughts are defined by a mixture of a) their physical dimensions (such as percent of normal rainfall or streamflow), and b) their socioeconomic impacts (Changnon, 1980). A drought cannot be truly defined until some form of human endeavor or the environment begins to experience stress from a water deficiency. Ever-changing land uses and water management facilities, such as new water supply lakes, stream channelization, and new ways of planting crops, collectively affect water quantity and quality. These in turn are affected differently by deficiencies of moisture, thus making historical analysis of drought conditions necessary (Changnon et al., 1982).

There is no one definition of a drought. A summer dry period lasting several weeks may constitute an "agricultural drought," but hardly qualifies as a drought with respect to its impacts on streamflow, reservoirs, or ground water. One or more years of deficient precipitation may be needed before certain water demand areas are affected and thus denote a drought (Changnon, 1980). Regardless, the identification of a drought generally requires some socioeconomic impact resulting from a lack of water. Changnon et al. (1982) identify five categories of possible drought impacts:

- Public water supplies
- Agriculture and rural dwellers
- Transportation
- Recreation and the environment
- Social behavior and health

The following discussion of drought impacts focuses primarily on the first of the five impacts, i.e., public water supplies, and the physical characteristics (streamflow and ground-water levels) that directly impact water supplies. Drought impacts on barge transportation are also briefly covered. Other impacts are not addressed largely because of available time, and in some cases little available data. The interested reader can obtain details of individual droughts from several past Water Survey reports, which are summarized below.

LITERATURE REVIEW

The Illinois State Water Survey (ISWS) is mandated to collect and disseminate water resource information in Illinois. As part of this mandate, several documents have been published detailing various aspects of droughts. Reports such as ISWS Bulletin 50, *Drought Climatology of Illinois* (Huff and Changnon, 1963) and *Droughts in Illinois: Their Physical and Social Dimensions* (Changnon et al., 1987), provide general descriptions of drought-related phenomena in Illinois. Additional studies by Gerber (1932), Hudson and Roberts (1955), Changnon et al. (1982), Lamb et al. (1992), and Riebsame et al. (1991) focus on the characteristics and impacts of specific drought periods.

Changnon et al. (1982) summarized the drought period of 1980-1981, detailing the climatological, meteorological, streamflow, and ground-water conditions and impacts during this time. Four major recommendations were presented to allow for better planning for future drought conditions:

1. Develop more informed and organized local and state programs for addressing droughts in Illinois. Education in water conservation and management would allow a more informed, less frantic response to drought conditions.
2. Renovate older water supply systems. These are the systems that tend to come under stress very easily and quickly in times of drought.

3. Employ water conservation, water reuse, and higher water prices based on true value and limits of this resource.
4. Develop and use new and emerging technologies to assist in increasing water supplies and to apply these technologies concurrently with improved water management practices.

With the development of stricter Illinois Environmental Protection Agency regulations in regard to public water supply systems, the development and strengthening of large professional organizations (such as the American Water Works Association) in Illinois, and better resource tracking programs by state environmental agencies, steps have been taken toward implementing many of these recommendations.

Lamb et al. (1992) described the meteorological causes and climatological characteristics of the drought of 1988-1989, and assessed the diverse impacts of the drought on soil moisture, plant water use, surface heat exchanges, streamflows and lake levels, ground-water conditions, and agricultural production. This report also includes a description of the administrative framework used by the state of Illinois to address drought-induced water problems. This infrastructure had largely evolved and was partially shaped by the recommendations of the 1982 report. Drought management strategies recommended in the 1982 report were also used on a real-time basis during the 1988-1989 drought to monitor and respond to the drought-related problems that emerged.

IMPACTS ON SURFACE WATER RESOURCES

Physiographic and Geographic Influences in Surface Water Droughts

Streamflow during a drought period originates almost entirely from subsurface storage that seeps into the streambed. From a simplistic concept, this baseflow can be viewed as originating from two sources: 1) the soil and subsoil, and 2) shallow ground water. The soil/subsoil contribution is greatly impacted by periods of extreme below-normal rainfall during summer and fall (typically lasting four to six months) when soil moisture supplies are already depleted by high evapotranspiration rates. Shallow ground water is depleted over a longer period of time, and typically is at its lowest only when there is below-normal rainfall (and hence low ground-water recharge) during the previous spring. A combination of these two factors, i.e., a dry spring followed by an extremely hot and dry summer, will produce the most severe low flows. The extent to which a particular stream is impacted depends partly on physiographic differences across the state.

Southern Illinois. In most southern Illinois watersheds, relatively small amounts of shallow ground water are contributed to streams. For this reason, streams will experience low flows following any hot, dry summer. The flow may be especially low if preceded by a dry spring.

Central Illinois. The shallow ground-water contribution to streamflow in central and western Illinois is considerably greater than in the south, yet less than the northern portion of the state. For significant drought flow conditions to occur, it is generally necessary to have both a dry spring and a hot, dry summer.

Northern Illinois. Baseflow in northwestern Illinois streams occurs at high rates, and the predominant portion of this baseflow originates from both shallow ground water and from bedrock aquifers that are intersected by the stream. In many cases, low streamflows are relatively independent of summer conditions and occur only when preceded by one or two years of low recharge. Baseflow in northeastern Illinois streams is closer in character to that of central Illinois streams.

Sandy Regions. A relatively small portion of Illinois has sandy soils. The most notable are the Kankakee-Iroquois River basins and the Havana Lowlands in Mason County. Low streamflows in these areas are most greatly impacted by periods of both precipitation deficit and high evapotranspiration rates. The lowest streamflows therefore primarily occur at the end of hot, dry summers. Once cooler temperatures arrive in the fall, streamflow levels in these areas have a chance to rebound.

Data Sources - Measures of Drought Severity and Impacts

Three types of data are available to analyze surface water drought and its impact on public water supplies: 1) reservoir and lake levels, 2) streamflow, and 3) records on the number of communities impacted by deficient water supplies, the types of impacts, and adjustments made to address the drought.

The Water Survey has maintained monthly water level measurements on selected Illinois reservoirs since 1967. The total coverage has gradually increased from 10 reservoirs in 1967 to 38 reservoirs in early 1993. Most of these reservoirs are used for public water supply. Water levels for some reservoirs have been reported periodically in Water Survey memoranda dating back to the 1920s.

The second type of data, streamflow levels, have been recorded at more than 300 locations in Illinois since 1908. Continuous flow records cover periods lasting less than one year to more than 78 years. Approximately 240 gages have at least ten years of record. These gages have been maintained by the U.S. Geological Survey, with cooperation and funding from various state, federal, and local agencies.

The third type of data describe the number of communities impacted by deficient water supplies. Sources for these data include: 1) the ISWS reports on the impacts of individual droughts (Gerber, 1932; Hudson and Roberts, 1955; Changnon et al., 1982; and Lamb et al., 1992), 2) records on the construction of new water supply reservoirs and other water resource projects—actions that typically follow a drought during which supplies are found to be inadequate, and 3) weekly drought newsletters produced by the Illinois Environmental Protection Agency during the 1998 drought, which detail water supply conditions for communities seeking drought assistance.

Reservoir and Lake Levels

Reservoir levels can provide an excellent measure with which to compare the severity of different droughts. For example, table 1 presents the minimum reservoir levels recorded at Lake Decatur during seven different droughts. These measurements suggest that the 1954 drought was by far the most severe on record, followed by those of 1930 and 1940. But changes in water use, reservoir sedimentation, and the addition of other water supply sources can change the relative impact associated with measured water levels. For Decatur, the 1988 drought is believed to have had a more severe impact than the 1930 and 1940 droughts for three reasons: the water use of Decatur had increased threefold by 1988, sedimentation had reduced the storage in the reservoir, and the normal pool elevation of Lake Decatur had been raised in 1958 from 610 feet to 613.5 feet.

Table 1. Minimum Water Levels Reported for Lake Decatur during Seven Droughts

Year	*Water level (ft)*	*Normal pool level*
1930	608.4	610.0
1940	607.6	610.0
1954	605.3	610.0
1964	609.0	613.5
1977	610.9	613.5
1981	612.6	613.5
1988	608.8	613.5

Lake Michigan Water Levels. The major sources of inflow to Lake Michigan are Lake Superior and tributaries located in Wisconsin and Michigan. Precipitation over the lakes is also a major source of water. Illinois contributes only a very small amount of the total inflow to the lake. Thus the lake is most directly impacted by widespread droughts that cover most of the north-central United States, as opposed to droughts that may only impact Illinois. On the other hand, most of the historical droughts that significantly impacted Lake Michigan water levels (1934, mid-1950s, 1963-1964, and 1988-1989) were also severe droughts in Illinois.

Records on Lake Michigan levels have been kept since 1860. Figure 1 shows these levels over the period 1961-1992. This period covers both the lowest and highest water levels measured on Lake Michigan in the 20th century—a low of 575.4 feet above mean sea level in 1964, and 582.6 feet in 1986. Low levels during both the 1926 and 1934 droughts were similarly low (575.6 feet). It is not clear how much the increased diversion from Lake Michigan in the early twentieth century affected these earlier droughts. The 1988-1989 drought was significant—lake levels dropped 4 feet between late 1986 and early 1989.

Though the 1986 Lake Michigan level was the highest recorded this century, higher values were recorded during several years between 1860 and 1886. The maximum lake level is 583.0 feet, recorded in 1886. Given these earlier records, it is not reasonable to suggest a long-term increasing trend in lake levels—perhaps we have merely returned to a period of wet conditions similar to those that existed more than a century ago.

Drought Streamflow

The minimum drought streamflow provides the most direct quantitative assessment of that drought's impact on direct withdrawals from streams. Cumulative streamflow over a critical drought period provides an indirect measure of a drought's impact on withdrawals from water supply reservoirs.

Table 2 ranks droughts for the period 1915-1991 based on streamflow records from six long-term gaging stations. Three droughts—1930-1934, 1952-1955, and 1962-1964—are notable for their severity, duration, and widespread impact. For four out of the six stations, the 1952-1955 drought was the most severe on record. An examination of rainfall records by Knapp (1990)

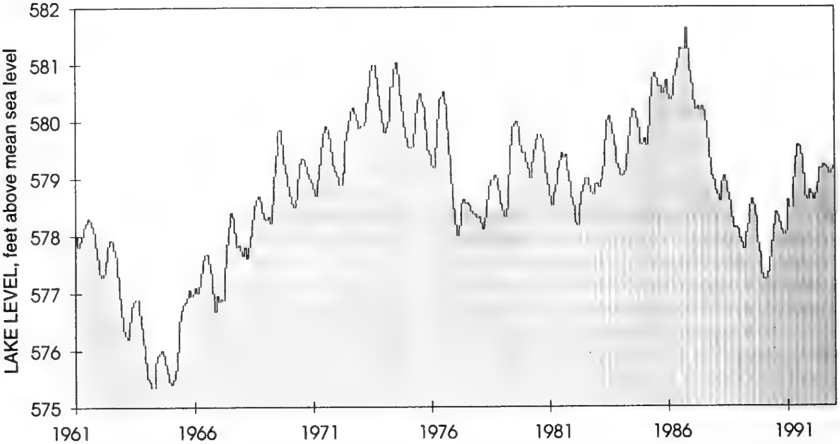

Figure 1. Lake Michigan water level, 1961-1992

indicates that the 1893-1895 drought may have had as extensive an impact as the 1952-1955 drought in many parts of Illinois. However, there are no streamflow records for this earlier drought.

The major difference between a moderate and severe streamflow drought is usually related to the duration of the drought. Since 1965, three shorter droughts are generally considered to have been moderate in nature: 1976-1977, 1980-1981, and 1988-1989. For much of Illinois, the 1988-1989 drought was intense, but lasted less than nine months. But in western and west-central Illinois (the Spoon River at Seville and the LaMoine River at Ripley) this drought started in 1987 and ended late in 1989. For this region of the state, the drought of 1988-1989 was severe, and for several locations it is the drought of record.

Number of Communities Having Water Shortages

The impact of a drought on a surface water supply system depends greatly on the source of the supply as well as the intensity and duration of the drought. Systems that obtain water from a low channel dam or by direct withdrawal from a stream are susceptible to any short, intense drought that causes low flow (up to two months in duration). Reservoirs with a great deal of storage (relative to both the average inflow and water use) are designed to supply water for multiyear droughts, and therefore may not be severely impacted by short, intense droughts. Table 3 describes the drought duration that is most critical for selected reservoirs.

The impact on surface water supplies is usually preceded by a relatively long period of below-normal precipitation. There is no exact definition of when a drought starts, and the drought may be well developed by the time it is recognized. The initial stages of a drought typically have hot and dry weather, promoting increased water use, which then amplifies the impacts of the dry conditions. When the threat to the adequacy of a water supply system is finally recognized, water-use restrictions and conservation measures may be employed to reduce the impact of the drought.

Table 4 lists the number of public water supplies that experienced shortages during selected droughts. Because this table includes estimates from different sources, there is likely some variation in the criteria used to identify a drought shortage. Hudson and Roberts (1955) suggest that a reservoir is suffering a shortage when less than six months of capacity remains in the reservoir by the end of a drought. This may be appropriate except for reservoirs with short critical durations (such as Decatur).

Table 2. Rank of Historical Streamflow Droughts, 1915-1991

PECATONICA RIVER AT FREEPORT

	7 day	6 mo.	12 mo.	18 mo.	30 mo.	42 mo.	54 mo.
1920							
		15	16				
1925		16	14				
1930		17					
	5	4	5	4	7	3	2
	13						
	4	2	7				
1935	16						
	3	12	10	8	4	6	
	14						
	11	18					
1940							
	9	1	2	6	3	2	
		13					
1945							
			12				
1950							
	17						
		8	8	9	9		
1955	18						
	12	10	6	1	1	1	1
	7	6					
	2	5	1	2			
1960							
	10						
	1	7	3	3	5	4	
1965	6						
			15				
		9	11	10	6	4	3
1970		14	13				
1975							
	8	3	4	5	2	5	
1980							
1985							
	15	11	9	7	8		
1990							

KANKAKEE RIVER NEAR WILMINGTON

	7 day	6 mo.	12 mo.	18 mo.	30 mo.	42 mo.	54 mo.
	18						
	9	8					
	14	17	10	4	5		
	4						
1920	10		15				
	8	6	4	5	4	3	2
	5						
		10	7	9			
1925	11	11	8	10			
1930	20						
		2	1	3	2	1	1
		13	13				
	19	1	3	6	6		
1935							
	2	15	11	11			
	6			1			
1940	24	4	6				
	7	5	5	2	3	5	5
	22						
1945		14	20				
	21						
			19				
	23						
1950							
	17	20					
		12	12	8	7	4	3
1955							
	12	16					
		7	9	7			
	16						
1960							
		18	17				
	15						
	13	9					
	3	3	2	1	1	2	4
1965			18				
1970							
		21	16				
1975							
		19	14				
1980							
1985							
	1						
1990							

Table 2. Continued

SPOON RIVER AT SEVILLE

	7 day	6 mo.	12 mo.	18 mo.	30 mo.	42 mo.	54 mo.
		20					
	21						
1920	18	7	8				
	15		9	9	6	2	3
		8	14	6			
1925							
		9		11			
1930							
		5	6	3	5	5	1
	17						
	7	1	2				
1935							
	4	17		7			
	8						
	20						
1940	6	19					
	2	4	3	2	3	3	2
1945							
	19						
	11	16	16				
1950							
	10						
			15	10			
1955							
	13	3	4	5	2	4	4
	9	13	11				
	12						
1960							
		6	10				
	5	10					
	16		5	4	4		
1965							
1970							
	14	11	7	8			
1975							
		15	12				
1980		18	13				
1985							
		14					
	3	12					
	1	2	1	1	1	1	
1990							

SANGAMON RIVER AT MONTICELLO

	7 day	6 mo.	12 mo.	18 mo.	30 mo.	42 mo.	54 mo.
		4					
	21	7	7	7	6	5	
	22						
1920							
			11		10		
	23						
1925		14					
1930							
	5	1	1	3	2	2	2
	10	6	9				
	24						
	8	2	2	6	7		
1935							
	17						
1940	14	9					
	1	5	6	2	3		
1945		13	13				
1950							
	4	17	12				
	3	3	3	1	1	1	1
1955	16						
	13	10	10	10	9		
	14		14				
1960							
	6						
	7	12	4	4	4	3	3
1965							
	20						
1970							
1975							
	11	8	5	9	8		
1980	18	15		8			
	9						
1985							
	19	16					
	1	11	8	5	5	4	
	12						
1990							

Table 2. Concluded

	EMBARRAS RIVER AT STE. MARIE							CACHE RIVER NEAR FORMAN						
	7 day	6 mo.	12 mo.	18 mo.	30 mo.	42 mo.	54 mo.	7 day	6 mo.	12 mo.	18 mo.	30 mo.	42 mo.	54 mo.
	15	12												
		16	6											
1920														
	4													
1925	23								7	11	12	6		
									12	12				
								15T						
1930	9	18						1T	13					
	18	2	2	2	4	5	3	1T	5	3	3	2	5	4
	13	13												
	24	3	3						3	5	15			
1935														
	12		17	11	9			1T	8	7	8			
								15T						
	11							19						
1940		6	8					1T	16	13				
	16	4	4	3	3	3		1T	1	2	2	3	2	3
								21						
	20													
	7	15						1T	11	17	7	9		
1945														
1950														
	19							22						
	6	1	15					1T	9	9				
	1	5	1	1	1	1	1		4	4	1	1	1	1
1955			10					20						
	17									18	9			
			14											
	21													
1960								23						
	14	14	13	10	8			18		15	14	10		
	10							16						
	8		6					1T	15					
	5	8	7	4	2	2	2	15T	14	10	6	4	3	2
1965		17	9	6						16				
	25							10	10	14	13			
1970														
			16	9	6			1T	18	7	11			
								11						
1975														
	3	10	5	5	5			12	19	8	10	8	6	
									17					
								17						
1980		7	11	8				14	2	1	4	7		6
	9													
1985														
								13	6					
	2	9	2	7	7	4			20	6	5	5	4	5
	22													
1990														

Note: 1T indicates these years experienced zero flow.

Table 3. Critical Drought Duration for Selected Surface-Water Supplies

Critical duration (months)	*Public water supply systems*
0-2	Flora, Breese (both direct withdrawals)
7-9	Decatur, Danville
18	Springfield, Marion, Macomb, Bloomington Taylorville, Mattoon, Paris, Vandalia
30	Canton
54	Pana, White Hall, Carlinville

Source: Broeren and Singh, 1989

Another measure of the number of communities experiencing drought can be seen in the steps taken during and after the drought to mitigate or correct water supply deficiencies. Reactions to mitigate the impacts of drought include changes in water treatment, enforced conservation, and short-term additions to the existing storage supply (such as adding wells for emergency supply). More major actions, often following a drought, include raising dam spillways, installation of pipelines, and in extreme cases, developing new reservoirs (Changnon and Easterling, 1989).

The construction of new reservoirs for public water supply use has often followed a major drought, during which the inadequacy of the current system is made evident. The two major periods of reservoir construction in Illinois (see figure 5 in the section on *Water Supply and Use*) were the 1930s and the 1960s, each following major droughts. No new reservoirs for public water supply use have been constructed since 1978. However, other actions have been taken during this time to supplement existing sources or to develop new supplies. Table 5 provides examples of the steps that have been taken to improve surface water supplies since 1972.

Are these public water supplies better equipped to handle drought conditions than in the past? Certainly for specific systems the threat of drought is much less. The development of the Rend Lake Intercities Water System in 1972 provided an abundant supply of water to much of southern Illinois and replaced several existing reservoir systems, many of which were inadequate. Many other communities are now interconnected with larger systems or have developed supplemental supplies that provide a long-range solution to possible water shortages.

But Broeren and Singh (1989) estimate that at present, 25 surface water systems would be inadequate during a 50-year drought without considerable water conservation. Another ten systems would likely have a small amount of supply at the end of the drought, so that they too would be considered to have shortages. Thus it is possible that 35 out of 90 existing systems, approximately 40 percent, would be severely impacted. While this is an improvement over the percentage of systems that had shortages during the 1930-1931 and 1952-1955 droughts, it is not a particularly significant one. The 1988-1989 drought was a moderate one for many areas of the state, yet 18 public water supplies were significantly impacted. What will happen when a longer severe drought occurs? It remains to be seen how helpful lessons learned from the 1988-1989 drought will be.

Table 4. Surface Water PWS Facilities with Drought Shortages

Drought year	*Number of facilities: impacted / susceptible to impact*	*Source of data*
1930-1931	40 / 58	Gerber, 1932
1953-1955	53 / 98	Hudson and Roberts, 1955
1980-1981	12 / 90	Changnon et al., 1982
1988-1989	18 / 91	IEPA public water supply memoranda

Note:
The number of facilities susceptible to impact include all surface water systems except those on Lake Michigan or border rivers.

Table 5. Examples of Steps Taken to Improve Surface-Water Supply Systems since 1972

Type of action	*Public water supplies and year of action*
Construct side-channel reservoirs	Farina (1982), Pontiac (1989), Charleston (1983)
Reservoir dredging	St. Elmo (1986), Carthage (1981), Springfield (1987), Georgetown (1983)
Raising a reservoir spillway	Canton (1972), Carlinville (1981), Waverly (1984), Danville (1988)
Wells added	Canton (1989), LaHarpe (1988), Blandinsville (1988)
Low channel dam built	LaHarpe (1988)
Supplemental pipeline	Centralia (1985), Eldorado (1981)
Additional studies in progress (following the 1988 drought)	Bloomington, Springfield, Decatur, Nashville, Pana, Macomb, Staunton, Waterloo

Impacts on Navigation

The impacts of low flows on barge traffic during the 1988 drought have been well documented by Changnon (1989), whose work is briefly summarized here. In June 1988, insufficient water depth and the creation of shoals severely impeded the movement of barges on the Ohio and Mississippi Rivers. Barge traffic was halted twice in June and July 1988 on the Ohio River near Cairo as well as farther downstream on the Mississippi River so that dredging could clear a navigation channel. Loads were restricted to reduce the draft of the barges, and total river traffic was down by 20 percent (Changnon, 1989).

The conditions that led to the interruptions in barge traffic in 1988 are rare, yet it is estimated that similar or more severe low flows existed on the Mississippi River in the 1930s and 1950s, but the barge industry was not as well developed then as in 1988 (Koellner, 1988). In all three cases (1930s, 1950s, 1988) the low streamflows were preceded by at least 12 months of below-normal rainfall and the drought conditions were widespread, covering the entire Upper Mississippi River basin.

IMPACTS ON GROUND-WATER RESOURCES

Ground-Water Budget

The effects of a drought on ground water are governed by the variables of the ground-water budget. This budget is a part of the general hydrologic budget and assumes that over a long period of time, water gains by a drainage basin will be balanced by water losses within that drainage basin. The ground-water budget for a given watershed can be stated in the form of a simple equation:

$$Pgw = Rgw + ETgw + U + Sgw$$

in which the ground-water recharge within a given basin (Pgw) over time is balanced by ground-water runoff (Rgw), evapotranspiration (ETgw), underflow (U), and change in ground-water storage (Sgw).

Ground-water recharge (Pgw) occurs when infiltrated precipitation exceeds surface evapotranspiration and soil moisture requirements. Most recharge occurs during the spring when evapotranspiration is small and soil moisture is maintained at or above field capacity by frequent rains. Little recharge occurs during summer and early fall, when evapotranspiration and soil moisture requirements normally exceed precipitation. Recharge is also negligible during the winter months when the ground is frozen.

Most of the ground-water recharge will eventually discharge into one of the basin's streams (or other surface water bodies) as ground-water runoff (Rgw), or leaves the basin as underflow (U). Underflow is the net movement of groundwater from the area (or drainage basin) of interest to adjacent areas. The amount of ground-water runoff is a function of the hydraulic gradient (slope) of the water table, the position of the water table relative to the streambed level, and the hydraulic properties of the water-bearing formation.

Ground-water evapotranspiration (ETgw) is the process by which moisture is extracted from below the water table and brought to the near-surface, where it either evaporates or is used by plants in transpiration. Losses to evapotranspiration (ETgw) are greatest during the growing season, May through October, and are particularly great in mid- to late summer. The potential for ground-water evapotranspiration increases as the water table approaches the land surface, where the roots of plants can capture the water and soil capillaries can draw ground water nearer to the surface, allowing warm air to evaporate the water.

Changes in ground-water storage (Sgw) are governed by the processes of recharge, ground-water runoff, underflow, and evapotranspiration. Recharge and evapotranspiration, in particular, have considerable seasonal variation and, as a result, so does the ground-water storage (and thus well levels). Annual changes in ground-water storage, and in particular the changes during drought events, are most closely related to changes in the amount of ground-water recharge. As explained below, this impact may be observed at various times.

Recharge to near-surface deposits can occur at relatively high rates, especially when these deposits contain significant amounts of sand and gravel. However, large areas of Illinois are covered by fine-grained glacial drift, which commonly exceeds 50 feet in thickness. Sand-and-gravel and bedrock aquifers are often deeply buried under this material, which typically has low vertical permeability. In these cases, recharge to many of the deep aquifers is limited to slow leakage through the drift. This recharge and ultimately, storage, are the components of the ground-water budget that are impacted during drought conditions.

Data Sources

The Water Survey maintains a network of 21 observation wells to monitor the natural short- and long-term fluctuations of shallow ground-water levels (i.e., water table conditions) across Illinois. Typically, these wells do not extend into highly productive aquifers; rather, they are constructed in fine-grained glacial materials containing thin lenses of sand. Most are large-diameter (>36 inches), dug or bored wells of the type commonly found in areas where shallow, productive aquifers are not present.

These observation wells are purposely located in areas remote from pumping centers in order to minimize the apparent effects of human activities on ground-water levels. Other influences, particularly those of short duration (e.g., less than one day), are of minimal significance under most circumstances. The ground-water levels experienced in these observation wells are thus representative of conditions beneath nonirrigated agricultural land, and of the water levels found in many shallow, rural domestic wells in Illinois.

The locations of the 21 observation wells are shown in figure 2. Most of these wells have been monitored since the early 1960s, and water levels at four current observation wells have been measured since the early 1950s. Each well is equipped with a Stevens Type F continuous water-level recorder, which contains a 30-day chart. Therefore each well must be visited monthly so the paper chart on the recorder can be changed. The charts are changed and taped readings of ground-water levels are measured at the end of each month.

Drought Impacts on Well Levels

This network of 21 wells, remote from areas of pumping, was used to assess the impacts of drought on shallow ground-water resources across the state. Illinois experienced five noticeable drought episodes over the last 40 years: 1952-1955, 1963-1964, 1976-1977, 1980-1981, and 1988-1989. Each impacted both socio-economic and cultural activities in its own way. The droughts of 1963-1964 and 1976-1977 covered a greater geographic area than the droughts of 1980-1981 and 1988-1989 in terms of their impact on shallow ground-water levels statewide (Wehrmann, 1992). Sufficient data were not available for reliable analysis of the ground-water situation during the 1952-1955 drought.

Lamb et al. (1992) summarized the causes, dimensions, and impacts of the drought of 1988-1989. In regard to ground water, this drought established six new record low ground-water levels in five regions of the state. No other drought event (during the period of record) in Illinois produced this type of historical trend. Figure 2 and table 6 show the network well locations and the historic information associated with these wells, respectively. In addition to the six record lows that were set or tied, ground-water levels were close to the all-time record lows at nine additional locations. They were within 1 foot of record lows at five locations and within 2 feet of record lows at four locations.

Comparison of the patterns of accumulated ground-water level departures from normal (for 12-month periods) for the four major drought periods (excluding 1952-1955) suggests that the magnitude of the accumulated departures for 1988-1989 was greater than for any of the other drought periods. In some instances these departures were more severe for other drought periods,

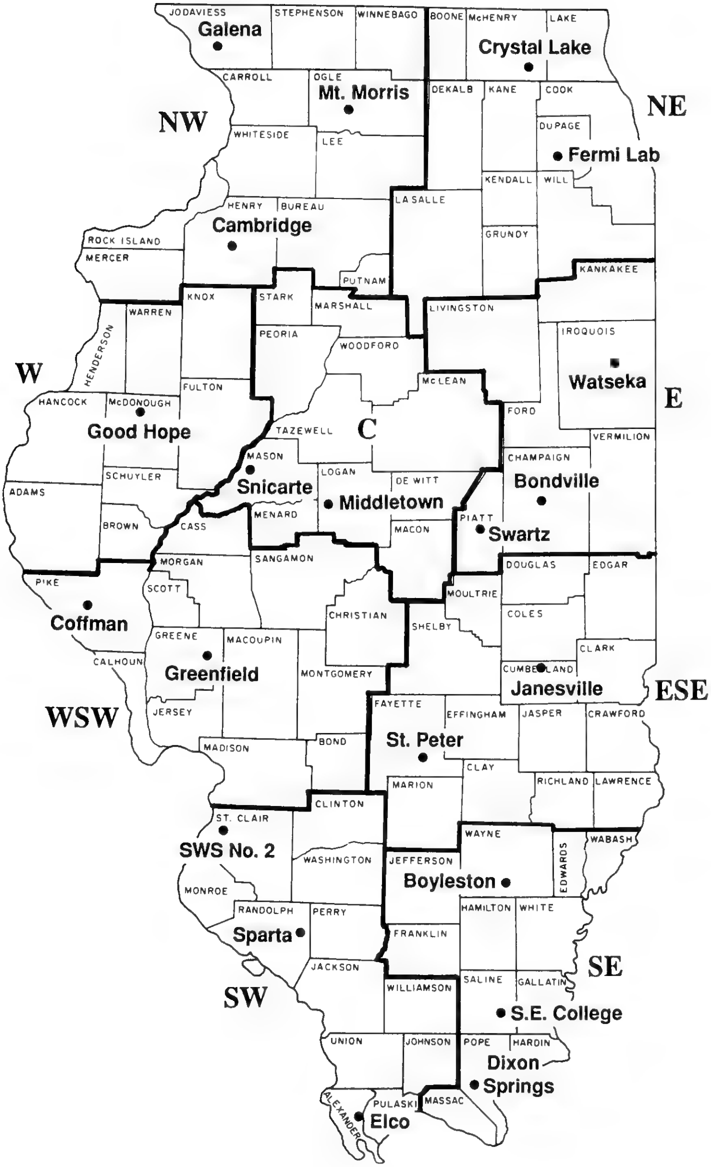

Figure 2. Locations of the 21 active wells in the Illinois shallow ground-water observation well network

Table 6. Record Ground-Water Levels at Network Wells Compared with Lowest 1988-1990 Levels*

	Record high	*Mo/yr*	*Record low*	*Mo/yr*	*1988-1990 low*	*Mo/yr*	*Date records started*
Northwest							
Cambridge	0.20	12/82	21.45	12/88	21.45	12/88	10/61
Galena	13.38	5/74	24.75	12/64	23.88	2/90	9/63
Mt. Morris	1.96	4/73	32.08	3/64	28.02	2/90	11/60
Northeast							
Crystal Lake	1.75	9/72	10.30	2/57	6.68	10/88	9/50
Fermi Lab	0.11	11/85	16.56	7/87	12.86	10/88	4/84
West							
Good Hope	0.45	4/83	22.53	1/90	22.53	1/90	6/80
Central							
Middletown	0.40	7/81	10.50	12/57	9.21	10/88	11/57
Snicarte[a]	31.30	5/85	>40	9/88	>40	9/88	3/58
East							
Bondville	0.06	4.83	7.58	8/83	7.30	10/88	3/82
Swartz	0.77	3/84	12.78	2/64	11.16	11/88	6/54
Watseka	4.33	4/85	19.73	12/63	15.05	10/88	9/52
West-Southwest							
Coffman	0.92	12/82	19.28	10/56	17.80	12/89	3/56
Greenfield	0.75	2/82	21.00	1/81	19.03	12/88	4/65
East-Southeast							
Janesville	0.05	1/73	9.67	10/72	9.02	9/88	4/69
St. Peter	0.10	4/84	7.37	7/72	7.10	9/88	5/65
Southwest							
Elco	0.06	5/86	19.21	11/87	18.72	8/88	3/84
Sparta	0.27	4/83	14.31	2/64	11.38	10/88	11/60
SWS No. 2	6.10	1/73	23.13	12/56	16.77	10/88	1/52
Southeast							
Boyleston	0.43	2/85	10.53	12/88	10.53	12/88	3/84
Dixon Springs[b]	0.01	4/74	>8.44	9/87	>8.44	8/88	1/55
S.E. IL College	0.01	3/86	9.34	10/88	9.34	10/88	8/84

Notes:

* Ground-water levels expressed as depth to water from land surface, feet.

[a] The Snicarte observation well went dry in September 1988 and remained so through April 1989.

[b] The Dixon Springs observation well was dry in September 1987 and went dry again from August to September 1988. These two periods are the only dry periods of record for the well in its 35-year history.

but they were localized to "high-impact" areas of the state where local precipitation was minimal or nonexistent.

Interestingly, for the drought periods of 1963-1964, 1976-1977, and 1988-1989, the greatest accumulated ground-water stage departures all occurred in western and northwestern Illinois. At present, the available data are insufficient to assess precisely why these parts of the state experienced the largest ground-water impacts of drought. Clearly, however, precipitation was deficient in these areas. It is possible that their hydrogeologic systems are especially sensitive to those precipitation deficiencies.

The hydrograph for the Middletown observation well located in central Illinois is presented in figure 3. Records date back to late 1957 for this well, and a record low of 10.5 feet was established in December 1957. The hydrograph for the observation well located in northwestern Illinois near Cambridge (figure 4) in Henry County details water levels since the early 1960s, and shows the full effect of the 1988-1989 drought in this area. The record lows of over 21 feet established in 1988-1989 were more than 2 feet below the previous lows set in 1976-1977. These two hydrographs reveal the severity of the drought of 1988-1989, compared to previous droughts in these two areas.

Based upon available information, the impact of the 1988-1989 drought on ground water persisted substantially longer than the drought's effects on the other components of the hydrologic cycle (precipitation, soil moisture, and surface water).

Ground-Water Supply Shortages

Information on shortages in ground-water supplies is available for three drought periods: 1952-1955, 1980-1981, and 1988-1989. During the 1952-1955 drought, a total of 22 ground-water supply systems experienced shortages (Hudson and Roberts, 1955). Sixteen of these 22 shortages occurred with systems tapping shallow, unconsolidated sand-and-gravel aquifers. The median depth of these wells was only 40 feet. The 1980-1981 drought was intense only in southern Illinois, a portion of the state where most water supply systems use surface sources. Changnon et al. (1982) do not identify any communities impacted by ground-water shortages.

During the 1988-1989 drought the Environmental Protection Agency monitored 23 communities with potential short-term water deficits due to lowered ground-water levels. But in only eight of these communities was the potential shortage severe enough to require actions to relieve the impacts of drought. New wells were drilled for five of these systems (London Mills, Indianola, Dieterich, Newton, and West Liberty-Dundas). A well repair was required in Edinburg. Water hauling was required for a one-month period in Dieterich as a result of pump failure, and Harristown began purchasing water from Decatur. Voluntary conservation measures were adopted in Lincoln and West Liberty-Dundas. In both the 1953-1954 and 1988-1989 drought periods, the number of ground-water systems impacted was considerably less than that for surface water supply systems.

The Illinois State Water Survey constantly receives requests for assistance in evaluating ground-water supplies, and has kept a record of such requests since 1961. Changnon and Easterling (1989) examined the change in the number of requests during three droughts, 1962-1964, 1976-1977, and 1980-1981 and found that during drought conditions, the number of requests increased dramatically. The number of requests for assistance during the 1980-1981 drought was particularly great: 122 percent higher than the average for adjacent years during the most critical six-month period. The average increase in requests during the three droughts analyzed was 82 percent.

Discussion

Based on the general hydrologic principles of the ground-water budget, the timing of a drought situation is directly related to the impact sustained by the aquifer system, or its ability to recover. If a drought occurs during the recharge season, it will tend to have a greater impact on ground-water levels than a drought that occurs during the growing season. This is opposite to the impact of a summer drought on agriculture, because little ground-water recharge normally occurs during the growing season. Recovery of ground-water levels from storage removals during the growing season is dependent on excess moisture (recharge) during the subsequent late fall and early spring. If recharge does not occur during this time period, ground-water levels will remain low going into the next growing season and will then fall more rapidly as ground water is taken out of storage by evapotranspiration and ground-water runoff.

Recharge to many of the deep aquifers is limited to slow leakage through the drift. To this end, recharge to deep aquifers is buffered from short-term irregularities in precipitation by the lag time required for reaction to drought conditions. The needed recharge of these

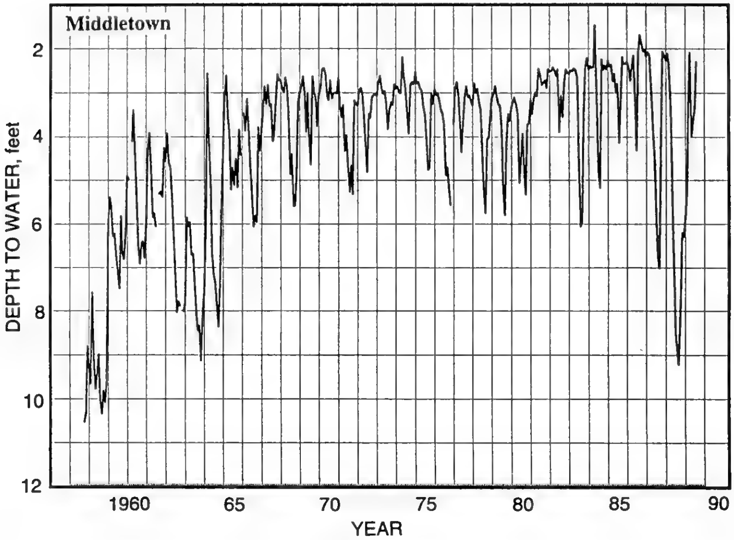

Figure 3. Long-term hydrograph for the Middletown observation well, Logan County, 1958-1989. Data are unsmoothed monthly values.

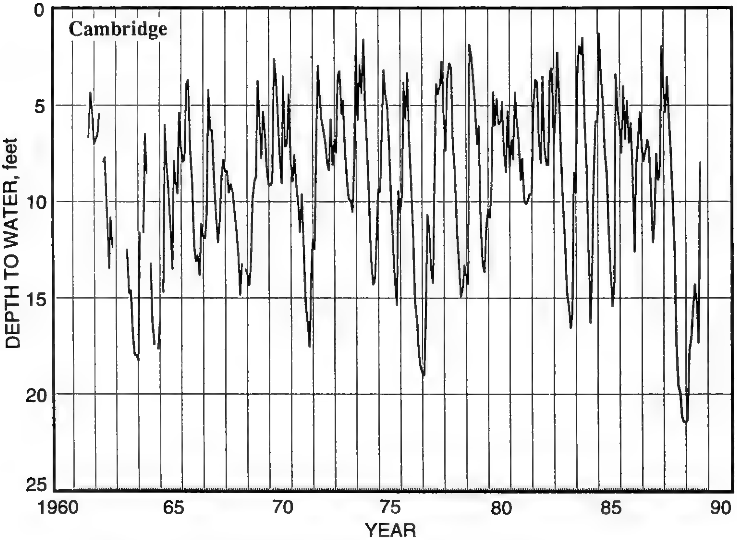

Figure 4. Long-term hydrograph for the Cambridge observation well, Henry County, 1961-1989. Data are unsmoothed monthly values.

systems during nondrought periods is typically sufficient to return them to their previous levels. Currently, the use of ground-water resources to supplement surface water shortages during drought situations is an effective, short-term solution in dealing with a drought condition.

Lack of precipitation is not generally recognized as the underlying cause of ground-water shortages until the resource has declined to a noticeable extent. In recent years, and to some degree now, communities that depend upon ground water often believe that they "run out" of water essentially overnight. Yet a program of regular measurements of depth to water in their wells would alert responsible officials long before the emergency arises (Changnon et al., 1982).

WATER CONSERVATION DURING DROUGHT

Drought plays an important role in prompting water users to secure adequate reserves from alternate sources. The impacts of a drought situation are a strong incentive to develop emergency planning systems to defer the impacts on existing water resources. In 1989, the Illinois Water Inventory Program expanded its Water Use Survey to include questions pertaining to water conservation programs imposed during the drought of 1988. Following are the results of this survey taken from an open file report (Kirk, 1989). This survey indicated that 23.5 percent of the 1,396 public water supplies returning questionnaires requested or imposed water conservation practices in 1988. That is, 21.2 percent of the state's population, or more than 2.47 million people were asked to restrict their water use during this drought year.

For public water supplies not using Lake Michigan water allocations, 1,349 questionnaires were returned out of 1,741 (77.5 percent). These public water supplies reported supplying 3.67 million people with potable water out of the 4.27 million people served by public water supplies without Lake Michigan water allocations (85.9 percent). Of the 1,349 responding facilities, 1,094 responded to the drought questions (81.8 percent). Water conservation was imposed or requested by 22.7 percent of the public water supplies (306), affecting 1.18 million people or about 27.6 percent of the state's population outside of those using Lake Michigan water allocations. Of those affected by the drought, 56.4 percent rely on ground water as their sole source of water.

Of those using water conservation in 1988, 47.0 percent indicated it was due to limited water availability, 14.4 percent indicated limited treatment or distribution capacity, and 38.9 percent listed other causes. The most often-restricted water use was lawn watering, followed by water conservation and car washing.

Water conservation practices were reported successful by 40 percent of all public water supplies that used them. For the public water supplies that responded to the question about the success of their conservation efforts, 92.5 percent reported success. The success of these conservation measures ranged from 0 to 49 percent reduction in water use and the total quantity of water saved, where reported, ranged from 0 to 1.5 million gallons per day. Future plans to expand the public water supplies were indicated by 38.6 percent of those using water conservation measures and 8.9 percent of those without restrictions. Of these, 48.3 percent planned to increase their supply, 16.9 percent planned to increase treatment, and 9.3 percent planned to increase distribution capabilities.

Of the responding public water supply facilities with Lake Michigan water allocations, 11.3 percent asked their users to conserve water, representing 17.5 percent of the approximately 7.37 million people served. Including the 47 public water supplies with Lake Michigan water allocations that responded to the survey, at least 21.2 percent of the state population was asked to conserve water in 1988, totaling about 2.47 million people.

SUMMARY

Illinois has experienced five drought periods over the past 40 years: 1952-1955, 1963-1964, 1976-1977, 1980-1981, and 1988-1989. Each situation created impacts, some major, in both the physical and/or socioeconomic spheres. With each drought, lessons are learned and steps taken to reduce the impact of future droughts. However, severe droughts are very infrequent, and over time water supply systems can develop problems associated with aging facilities, reservoir sedimentation, and increases in water use. A number of facilities, using both surface and ground-water sources, are still not adequate to survive a 50-year drought.

Drought situations impact a large percentage of the state's population and the surface and ground-water resources within the state. Understanding the conditions that produce drought or cause drought conditions may allow us to develop better strategies to help eliminate or reduce its impact. Yet at this point it is apparent that the occurrences of drought still catch us off-guard, and that mitigative measures typically are not begun until the drought impacts become obvious.

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WATER SUPPLY AND USE

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Illinois State Water Survey

INTRODUCTION

Illinois is fortunate that large quantities of both surface and ground water exist within the state, and these water resources have fostered population and industrial growth throughout the state's history. But the quantity of the available resources is limited. Some of the major metropolitan centers, such as the Chicago area, Peoria, Decatur, and Bloomington-Normal, have required the use of both surface and ground water to meet their needs for urban and industrial development and to sustain growth. The regular study of these water resources helps our understanding, and provides the factual basis for management strategies that could avert trends potentially detrimental to the availability of these resources. Monitoring also allows us to recognize the number of facilities and/or individuals dependent upon either surface or ground water that could be impacted by a variety of environmental or human-induced factors.

TOTAL WATER USE AND SOURCES OF SUPPLY

The majority of water use in Illinois falls within three categories: public water supply, self-supplied industry, and hydro- and thermoelectric power generation. In 1991, combined surface water and ground-water withdrawals in Illinois totaled 20,637 million gallons per day (mgd), of which 1,886 mgd was for public water supplies, 614 mgd was for large self-supplied industries, and 18,136 mgd was for power generation. Thus, power generation is by far the leading water use in the state. Separate surface water and ground-water withdrawals were 19,448 and 1,189 mgd, respectively. Excluding power generation, surface and ground-water withdrawals totaled 1,887 and 614 mgd, respectively. Surface and ground-water withdrawals for public water supply were 1,429 and 444 mgd, respectively.

Most types of use return water to nearby streams after being used, regardless of the withdrawal source. In most cases the stream that receives the return flow is in the same major watershed as the point of withdrawal. Two major cases involve an interbasin transfer of water: 1) withdrawals from Lake Michigan are discharged into the Illinois Waterway; and 2) water used for the city of Bloomington is withdrawn from reservoirs in the Mackinaw River basin, but is discharged to the Sangamon River basin. A large percentage of the use is also basically nonconsumptive, meaning that the amount of water returned to streams is virtually the same amount that was withdrawn. Consumptive uses of water include that withdrawn for irrigation and the use of public water supply for watering lawns and gardens.

Table 1 compares 1991 Illinois water use with that for 1965, as given in Water for Illinois: A Plan for Action (ITACWR, 1967). This table indicates that the total water use in the state has risen by 27 percent in 26 years. Self-supplied industry has decreased, while water use for power generation has increased significantly. Public water supply (PWS) use has increased approximately 7 percent, which is less than the population growth (13 percent) during that time. The modest growth in PWS use can be attributed to water conservation, particularly from industrial and commercial users, and some leveling off in residential demand.

Kirk et al. (1979, 1982, 1984, 1985) and Kirk (1987) summarized surface and ground-water withdrawals in Illinois after sending an annual questionnaire to more than 4,000 PWS facilities and self-supplied industries since 1978. The Illinois Water Inventory Program (IWIP) was established to detail water use in Illinois in cooperation with the U.S. Geological Survey. Currently this program is fully funded by the Illinois State Water Survey and is the only statewide collection of these data on a regular basis. The program collects point-source water-use information and groups it within several categories. Collecting these data at the "point-source" level allows its aggregation into any number of environmental or economic categories. Several water-use investigations, including Water Survey Contract Reports 442 (Singh et al., 1988) and 477 (Broeren and Singh, 1989), employ the IWIP data.

Table 1. Increase in Illinois Water Use, 1965 to 1991 (mgd)

Water use	*1965*	*1991*
Power generation	13000	18136
Self-supplied industry	1440	614
Public water supply	1760	1886
Total	16200	20636

Water-use information for selected years between 1900 to 1978 has periodically been reported for individual facilities in unpublished memoranda at the Illinois State Water Survey. Many studies have been developed over the history of the Water Survey that contain water-use information compiled from these data. Two studies used herein are Water Survey Bulletins 21 (Habermeyer, 1925) and 40 (Hanson, 1950).

Trends in PWS Use and Number of Facilities

Table 2 indicates the number of surface and groundwater withdrawal facilities reported during the last 70 years in Illinois. The numbers listed are for supply sources and do not count water supply systems that obtain either raw or finished water from another system. The number of PWS facilities reported has almost tripled, increasing from 497 in 1925 to 1,442 in 1991. Much of the change in the number of facilities results from new water supply practices, consolidation of facilities, organization of individual users into water districts, and to a greater extent, a change in the criteria used to define a PWS. Currently, any facility that serves 25 individuals or 15 properties for 60 days or more in one year is considered a PWS. Development of new surface water sources, such as a major reservoir, can lead to a net reduction in the number of PWS facilities through consolidation. For example, more than 25 communities joined together to form the Rend Lake Conservancy District when that reservoir was built.

To present annual pumpage in this report, only PWS withdrawals >1 mgd were examined. These 162 facilities are the ones most at risk in regard to quantity and quality impacts because of their service to a significant number of people. Figure 1 shows the growth in total water use for these 162 facilities since 1961. The water-use data for individual years show greater fluctuation since 1980, a result of the more complete, detailed records that have been kept since the inception of the Illinois Water Inventory Program. Prior to 1965, much of the increased water use was associated with growth in per-capita consumption. Increases in water use since 1965 are more related to population growth, since the statewide consumption rate has changed only slightly during that time, remaining near 200 gallons per capita per day (gcd). This 200-gcd rate includes water for commercial uses and industry served by public water supplies. Strictly residential water use is approximately 80 gcd.

During drought years, the overall consumption rate may increase. For example, figure 1 shows a 10 percent increase in overall water use in the drought year of 1988. Figure 2 provides examples of the growth experienced since 1911 for three individual facilities: Bloomington, Elgin, and Dixon. Like most facilities in the state, these show consistent growth in water use since the 1940s.

SURFACE WATER

The use of ground water for PWS is usually a preferred option for two reasons: 1) surface water must be treated to a greater degree, primarily for removal of bacteria

Table 2. Number of Public Water Supply Facilities

Year	*Surface water*	*Ground water*	*Total*
1925	74	398	472
1938	172	453	625
1950	111	535	646
1957		640	
1960		771	
1980	118	1045	1163
1985	119	1281	1400
1990	118	1285	1403

Sources: Habermeyer, 1925; Hanson, 1950; and Illinois Water Inventory Program (IWIP).

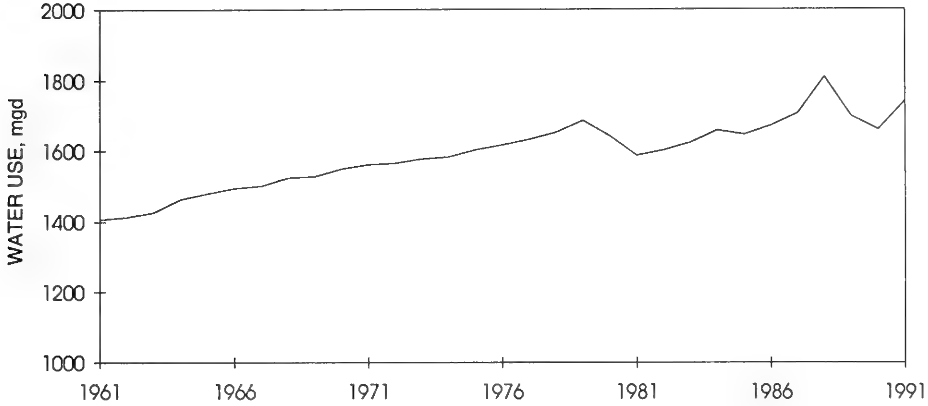

Figure 1. Total water use for the 162 largest PWS facilities

and reduction in turbidity, and 2) unless a community is located near a river with sustained flow, then surface water storage (usually an impounding reservoir) must be created, which requires significant capital expenditure. Nevertheless, in terms of volume, surface water accounts for more than 75 percent of the PWS use in Illinois, and approximately two-thirds of the total population's domestic supply. Surface water supply systems have been developed in cases where the sustainable yield of the available ground-water resources is inadequate to serve the needs of the community. Conjunctive use of surface and ground-water resources is also becoming an increasingly viable option when a community outgrows the yield of their original source of supply.

Sources of Surface Water Supply

For the purposes of this project, four surface water supply sources were defined: 1) Lake Michigan, 2) border rivers, 3) intrastate rivers with sustained flow, and 4) reservoirs (both impounding reservoirs and side-channel reservoirs). Table 3 lists the approximate number of facilities by category for four separate years: 1930, 1954, 1970, and 1992. It is not unusual for the number of facilities in each category to differ from one year to the next, given typical changes in water supply practices. Figure 3 lists the change in overall use from 1961 to 1991 for each of these categories. With the exception of Lake Michigan and the border rivers, most surface water supply systems are located in the southern half of Illinois, where ground-water yields are particularly low. Figure 4 shows the location of all surface water withdrawals used for PWS.

Lake Michigan. The lake is the source for approximately 1.1 billion gallons per day—more than half of the total PWS in Illinois and 75 percent of the portion coming from surface water sources. Since 1985 Lake Michigan water has been reallocated to many communities in DuPage and Cook Counties, which had previously obtained their water supply from the Cambrian-Ordovician aquifer system. These communities do not directly withdraw water from the lake, and therefore are not counted as additional water supply facilities in table 3. Water use from Lake Michigan is part of the total diversion allocated to Illinois from Lake Michigan, and as a budgeted amount, it is not likely to increase significantly.

Border Rivers. Direct withdrawals from border rivers (the Mississippi, Ohio, and Wabash) account for an additional 4 percent of the PWS use from surface waters. Much of the use from border rivers is concentrated in the metropolitan areas of East St. Louis and Rock Island-Moline.

Direct Withdrawals from Streams. Most of the streams and rivers in Illinois with the greatest sustained flow are in northern Illinois. These include the Rock, Kankakee, Fox, Pecatonica, Kishwaukee, and Illinois Rivers. For the most part, their water supply potential has remained untapped, primarily because the same region has abundant ground-water resources. In recent years, two large communities on the Fox River, Elgin and Aurora, have outgrown the availability of high-quality ground water and now obtain most of their

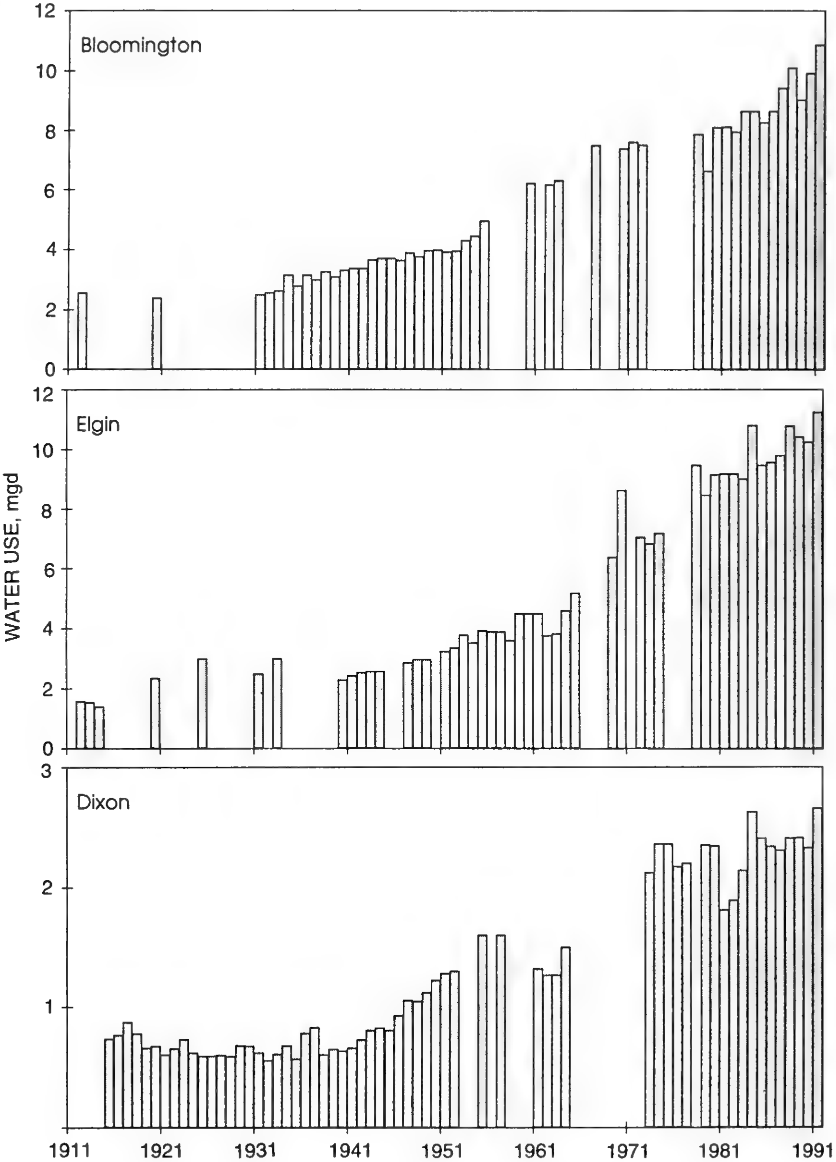

Figure 2. Examples of increases in water use at individual facilities, 1911-1991

Table 3. PWS Facilities in Illinois with Surface Water as Their Primary Source

	1930	*1954*	*1970*	*1992*
Reservoir systems	32	67	85	77
Withdrawals from streams	24	24	15	17
Direct withdrawals from border rivers	14	14	15	15
Withdrawals from Lake Michigan	10	10	14	17
Total	80	115	129	126

Note: Numbers are approximate.
Sources: 1930 from Gerber, 1932; 1954 from Hudson and Roberts, 1955; 1992 from McConkey et al., 1993. 1970 estimated using data from various sources.

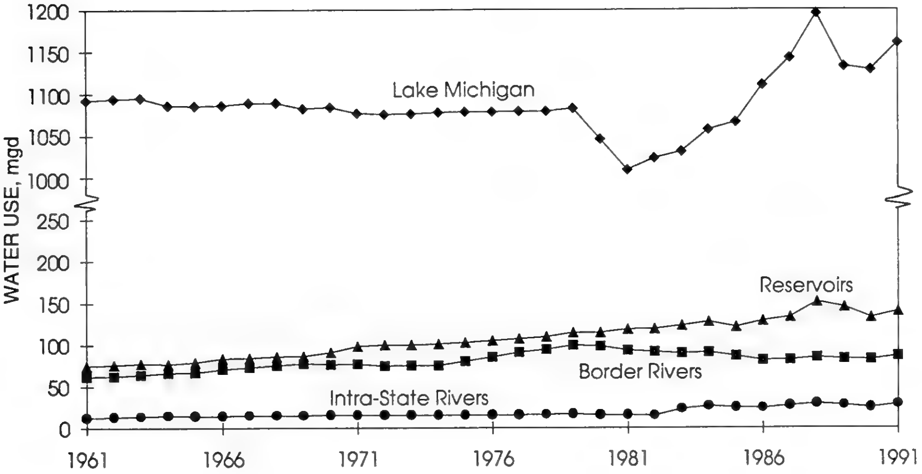

Figure 3. Growth in water use for four categories of surface water supply, 1961-1991

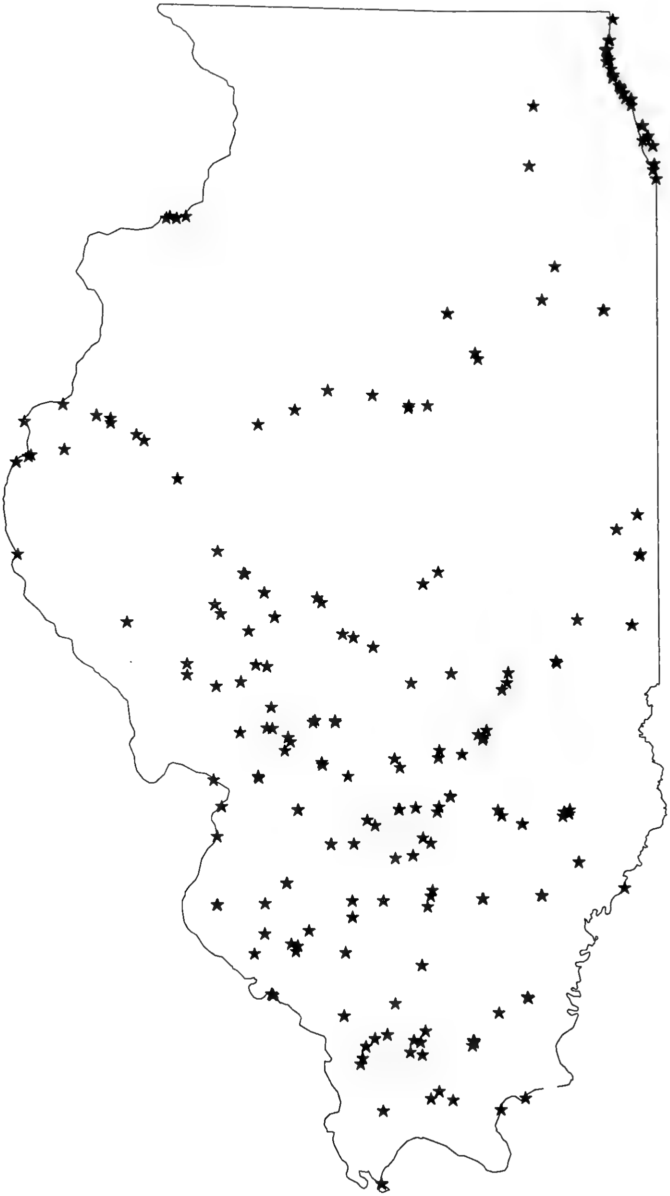

Figure 4. Location of public water supply intakes from surface water sources

water supply from the Fox. The city of Joliet has also mined its ground-water sources and is now evaluating the Kankakee River as a source. The Illinois American Water Company-Peoria, which serves the city of Peoria, now obtains almost 50 percent of its water from the Illinois River. Large rivers in the southern part of the state, specifically the Kaskaskia, Little Wabash, and Big Muddy, have also served as water supply sources for nearby communities.

Reservoirs. Prior to 1920, surface water supplies in the state were few, and most of these were direct withdrawals from streams. These systems' inability to meet increasing water uses started a boom in the construction of water supply reservoirs that continued through the 1930s. The number of new reservoirs constructed during this period is illustrated in figure 5. A second peak in reservoir construction occurred in the 1960s. In many cases, newer reservoirs were built to replace or serve jointly with old reservoir systems that had inadequate storage. The continued construction of reservoirs for water supply came to a halt in the early 1970s, primarily because of environmental concerns and large construction costs associated with reservoir construction.

Table 3 indicates the reduction in the number of water supply reservoirs since 1970. Much of this decrease results from the creation of the Rend Lake Intercities Water System, which serves 12 communities that previously had obtained water from their own reservoirs.

The growth in water use from reservoirs has increased more than 40 percent since the early 1970s, as shown in figure 2. However, during that same period of time no new impounding reservoirs have been constructed for water supply purposes, and only a few side-channel reservoir systems have been constructed. This means that greater demands are being placed on the existing reservoirs. Broeren and Singh (1989) indicate that 25 of these reservoir systems may not be sufficient to supply near-future water demands during a 50-year drought. Presently more than 11 percent of public water supply from surface waters comes from reservoirs, making it the largest source category other than Lake Michigan.

Trends in Surface Water Use

Per-capita use for PWS has not changed appreciably in the last 25 years, remaining near 200 gallons per day per capita (as estimated from present IWIP data and ITACWR, 1967). Future increases are therefore likely to be associated with population increase. Singh et al. (1988) estimated future water use based on population projections for 90 PWS systems using reservoirs and

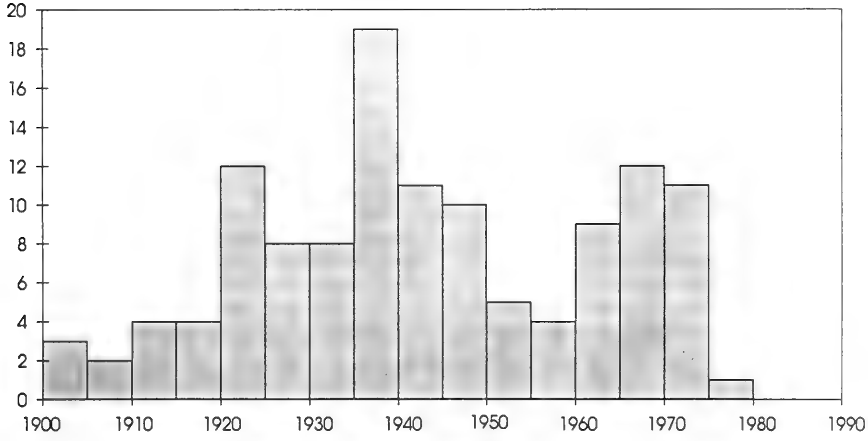

Figure 5. Number of water-supply reservoirs constructed in Illinois, 1900-1990

intrastate rivers as their primary supply source. The values from this study indicate that water use for most of Illinois is likely to increase 10 percent by the year 2020. Broeren and Singh (1989) indicate that 27 of these water supply systems are currently not adequate to supply water demands during a 50-year drought. Prior to 1970, the construction of a new reservoir might have been considered the principal alternative when a community's existing system was becoming inadequate. But one current trend is for these communities to develop smaller supplemental supplies for use either with the existing supply or as an emergency supply during drought conditions. The cities of Bloomington and Decatur, for example, are both evaluating the use of ground water to supplement their reservoir storage. Approximately 18 Illinois communities currently use some combination of surface water and ground water. Of these, eight actively withdraw from both surface and ground water, and ten retain their alternate supply source for emergency purposes only. Other approaches for augmenting supplies are presented by Singh and McConkey-Broeren (1990).

The western suburban fringe of the Chicago area has seen much population growth in recent decades and will likely continue growing. Between 1980 and 1990, major communities along the Fox River increased their total population from 237,000 to 297,000, a combined growth rate of more than 25 percent. High rates of population growth are expected to continue for many decades. The remaining ground-water resources in this portion of Illinois are limited, and continued increase in the use of surface water for PWS is likely.

GROUND WATER

Ground water provides approximately one-third of Illinois' population with drinking water. The sources of this water can be broken down into three major units: 1) sand and gravel, 2) shallow bedrock, and 3) deep bedrock. The principal aquifers of Illinois are shown in figure 2 of the Background chapter of this volume. The majority of the ground-water resources are centered in the northern two-thirds of Illinois. Sand-and-gravel aquifers are found along many of the major rivers and streams across the state and also within "buried bedrock valley" systems. The buried bedrock valleys were created by the complex glacial and interglacial episodes of surface erosion in Illinois. There are also many instances of thin sand-and-gravel deposits within the unconsolidated materials above bedrock. These thin deposits are used throughout Illinois to supply small towns with their water requirements. The shallow bedrock units are more commonly used in the northern third of Illinois, whereas the deep bedrock units are most widely used in the northeastern quarter of Illinois (in and around the Chicago area). The use of these waters is highly variable throughout the state with respect to quantity and use classification. Figure 6 shows the distribution of PWS wells in Illinois.

Trends in Ground-Water Use

Ground-water pumpage from facilities pumping more than 1 mgd in 1991 are detailed in figure 7. A definite decreasing pumpage trend can be noted for these facilities, primarily due to the reallocation of surface water (Lake Michigan) to the surrounding suburbs in the Chicago area. The current and past ground-water mining situation in northeastern Illinois (see the chapter on Ground-Water Mining) has forced (by law) a reduction in pumpage from the deep Cambrian-Ordovician aquifer system. This pumpage had exceeded the practical sustained yield of this aquifer system (more water was being removed than was being replenished by natural processes) since the late 1950s. Within the last several years, Lake Michigan water has been piped west, replacing ground-water pumpage for many major cities. This trend is further exemplified in figure 8, which shows the pumpage of these facilities within the last 12 years for four major aquifer units: 1) sand and gravel, 2) Cambrian-Ordovician bedrock, 3) Silurian-Devonian limestone, and 4) Pennsylvanian-Mississippian bedrock. Only the Cambrian-Ordovician aquifer system shows a decline in pumpage due to the reallocation of Lake Michigan water to the Chicago region.

RESULTS AND CONCLUSIONS

Water use in the state has increased a modest 27 percent since 1965. Most of that increase is in power generation. Water use for PWS has risen only about 7 percent during that time, less than the concurrent percentage increase in population. The number of public ground-water supply facilities within Illinois has risen significantly during that time, yet the total amount supplied by ground water remains near 25 percent.

A dependable, adequate source of water is essential to sustain the existing and potential population demands and industrial uses in Illinois. Modifications and practical management of the use of both surface and ground water have helped make this vital resource reliable in Illinois. As increases in water use are experienced at individual facilities, innovative alternative approaches to developing adequate water supplies must

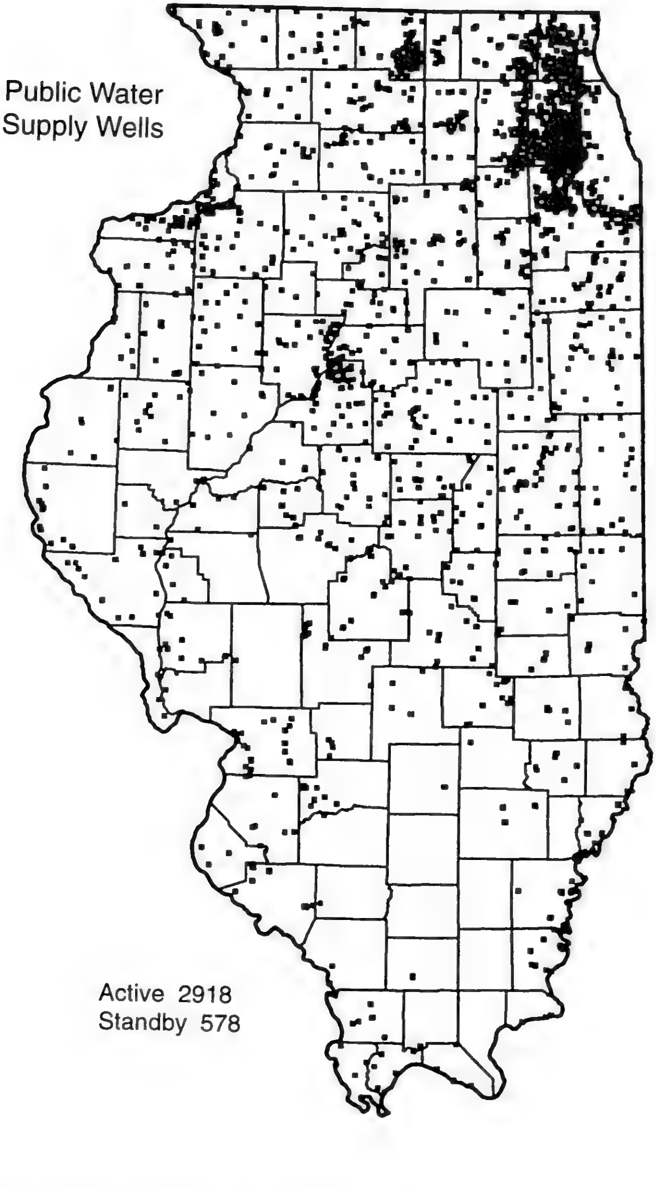

Figure 6. Location of public water supply wells in Illinois, 1990

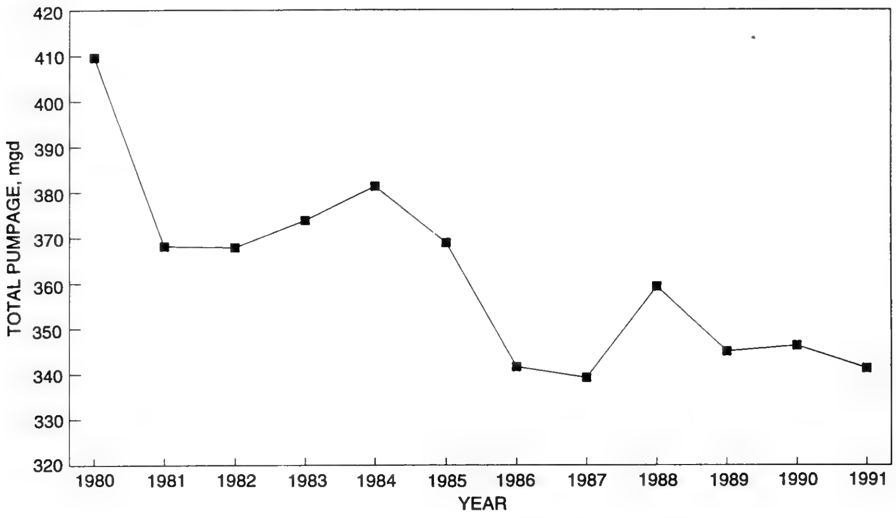

Figure 7. Total ground-water use from facilities pumping 1 mgd or more in 1991

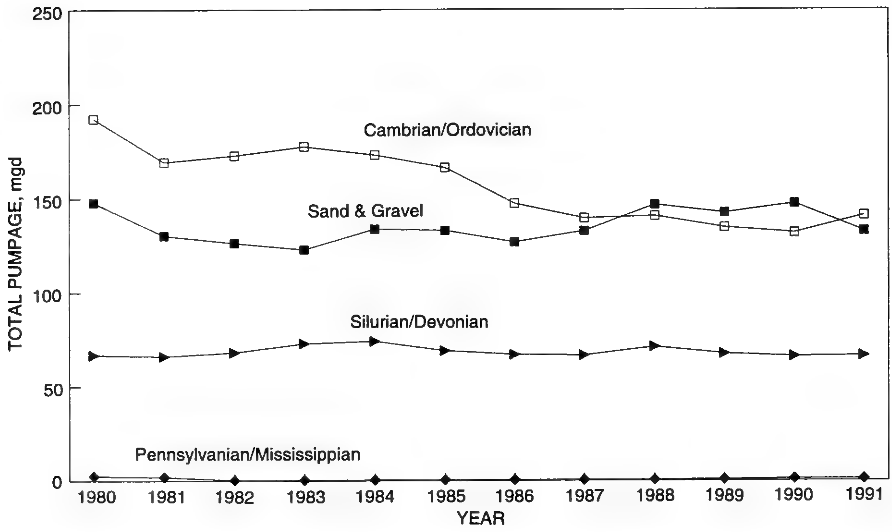

Figure 8. Total ground-water use from major aquifer units by facilities pumping 1 mgd or more in 1991

arise. In particular, this is likely to involve conjunctive use of surface and ground waters. Major metropolitan centers such as the Chicago area, Peoria, Decatur, and Bloomington-Normal have already developed both surface and ground water to meet their needs for development and to sustain growth. The construction of impounding reservoirs has become and will remain economically and environmentally expensive, making it a less common approach.

Proper management of water resources is also necessary to ensure a reliable, high-quality supply for the population. Water conservation practices will become increasingly important to reduce total demand and avoid exceeding available supplies. Both our groundwater resources and surface reservoir storage must be preserved to maintain reliable sources for future generations.

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STREAMFLOW CONDITIONS, FLOODING, AND LOW FLOWS

H. Vernon Knapp
Illinois State Water Survey

INTRODUCTION

Streams in Illinois serve a variety of different uses. They serve as water supply sources for municipal, industrial, and rural needs, and receive wastewater from water treatment plants, thereby incorporating it into the environment. They also provide for recreation, and serve as habitat for fish, water birds, and numerous other types of aquatic life. Often these uses conflict with each other, particularly on streams with high use and/or during drought conditions. As the use of Illinois streams intensifies, it is an increasing challenge to maintain all of the stream functions. Alteration of the flow in streams by natural or artificial means can either facilitate or hinder these uses. Streamflow trends may also signal potential impacts to water quality and changes in the stream ecosystem.

Five factors were identified as having possible, long-term impacts on the amount of flow in streams:

- Climate variability
- Changes in land use (urbanization, reforestation, and removal of wetlands)
- Reservoir construction and operation
- Water use (stream withdrawals and discharges)
- Channelization and other changes in drainage

The objective of this investigation is the analysis of changes in Illinois streamflow conditions, with particular emphasis in relating how the above factors affect the flow regimes of the streams. The identification of trends in streamflow conditions is of great value in analyzing other environmental trends because of the potential impact of flow quantity on water use conflicts, water quality, aquatic habitat, sedimentation and erosion, and stream morphology. In the material presented below, no attempt has been made to further review these potential impacts.

METHODOLOGY

Streamgage Data

All streamgaging records in the state with continuous flow records extending 50 years or more were examined to identify long-term trends in streamflow conditions. Certain locations in the state do not have streamgages with 50-year records, most notably the metropolitan area of northeastern Illinois. For these locations, additional stations with flow records of approximately 40 years or more were added to the dataset. This resulted in a dataset of 79 gaging stations (table 1). Out of this list, individual subsets were created for analyzing the effect of each of the five factors affecting streamflow conditions. For example, in analyzing the impacts of climatic change, it is necessary to choose streamgages with flow records that are relatively untouched by other factors. The streamgages used in analyzing each factor are presented later in this report.

Flow Parameters Evaluated

Each streamflow record contains a minimum of 14,000 values of average daily streamflow. It is impractical to use these data directly to estimate long-term trends in streamflow conditions, primarily because the daily values fluctuate tremendously and are dominated by seasonal differences. Instead, various summary statistics (termed herein as "*flow parameters*") are computed for each year of the record, and trend analysis is performed on the annual series of each flow parameter. The following seven flow parameters were used in the analysis. All flow values are given in cubic feet per second (cfs):

- Annual average flow
- 7-day low flow
- 7-day high flow
- Average winter flow (December-February)
- Average spring flow (March-May)
- Average summer flow (June-August)
- Average fall flow (September-November)

Statistical Analyses

Three types of statistical analyses were employed to identify trends in the annual series for each flow parameters: 1) Kendall Tau-b trend analysis, 2) linear regression analysis, and 3) autocorrelation and spectral density analyses. All three analyses used a null hypothesis test to determine the significance of trends at a 95

Table 1. Correlation coefficients of the Kendall Trend Analysis

			Flow parameter						
REGION Station ID	*Location*	*Years of record*	*Mean flow*	*7-day low flow*	*7-day high flow*	*Fall mean*	*Winter mean*	*Spring mean*	*Summer mean*
SOUTHEASTERN ILLINOIS									
3339000	Vermilion River @ Danville	63	0.1531	***0.3601***	***0.1869***	0.1562	0.1336	0.1060	0.0824
3343000	Wabash River @ Vincennes	61	0.1424	***0.3033***	-0.0396	0.1299	0.0881	0.0746	***0.1842***
3345500	Embarras River @ Ste. Marie	77	0.0376	0.0786	0.0595	0.0321	0.0642	0.0540	0.0226
3346000	North Fk Embarras @ Oblong	51	0.0824	0.0726	0.1357	0.1388	0.1451	0.0823	0.0180
3379500	Little Wabash River @ Clay City	77	0.0451	0.0449	0.0581	0.0034	0.0656	0.0533	0.0027
3380500	Skillet Fork @ Wayne City	63	0.0753	0.0460	0.0937	0.0353	0.0896	0.0364	0.0783
3612000	Cache River @ Foreman	67	0.0402	0.1030	0.0041	-0.0023	0.0692	0.0882	-0.0113
NORTHWESTERN ILLINOIS									
5419000	Apple River @ Hanover	57	0.0739	***0.1857***	0.0990	0.0990	-0.0388	0.0376	0.0326
5430500	Rock River @ Afton, WI	77	0.0849	-0.0032	-0.0056	0.0638	0.1179	0.0232	0.0351
5435500	Pecatonica River @ Freeport	77	0.0191	0.1158	-0.1490	0.0649	-0.0581	0.0226	0.0492
5437500	Rock River @ Rockton	52	***0.2398***	***0.2674***	0.0196	***0.2564***	***0.2172***	0.1418	0.0830
5438500	Kishwaukee River @ Belvidere	52	***0.3228***	***0.2737***	0.1508	***0.2790***	***0.2081***	0.1629	***0.2112***
5439500	S Branch Kishwaukee River @ Fairdale	52	***0.2715***	***0.3255***	***0.1855***	***0.2700***	***0.1931***	0.1523	***0.2278***
5440000	Kishwaukee River @ Perryville	52	***0.2836***	***0.2376***	0.1222	***0.2730***	***0.1936***	0.1599	***0.2368***
5443500	Rock River at Como	61	***-0.1945***	-0.1322	***-0.2741***	-0.1650	***-0.2579***	-0.1126	-0.0874
5444000	Elkhorn Creek @ Penrose	52	***0.2308***	***0.3176***	0.0422	***0.2745***	0.0332	0.1644	0.1372
5446500	Rock River @ Joslin	52	***0.2474***	***0.3004***	0.0603	***0.2564***	***0.2021***	0.1176	0.1508
5447500	Green River @ Geneseo	55	***0.1892***	***0.2020***	0.1354	0.1407	0.0707	0.1111	0.0748
5466000	Edwards River @ Orion	51	0.1090	0.0955	0.0337	0.1200	0.0541	0.0871	-0.0384
5469000	Henderson Creek @ Oquawka	57	0.0564	***0.3286***	0.0075	0.1404	-0.0163	0.0200	-0.0614
KANKAKEE RIVER REGION									
5520500	Kankakee River @ Momence	76	***0.3137***	***0.2252***	***0.2688***	***0.2070***	***0.1846***	***0.2400***	***0.2442***
5525000	Iroquois River @ Iroquois	47	***0.2581***	***0.2174***	***0.2026***	***0.2488***	0.1452	0.1674	0.0028
5525500	Sugar Creek @ Milford	43	0.1384	0.0639	0.1340	0.1916	0.1096	0.1118	-0.0631
5526000	Iroquois River @ Chebanse	68	***0.1703***	***0.2483***	***0.1651***	0.1220	0.0711	0.1422	0.1414
5527500	Kankakee River near Wilmington	76	***0.3558***	***0.2685***	***0.2618***	***0.2190***	***0.2175***	***0.2596***	***0.2856***
5542000	Mazon River @ Coal City	52	***0.1922***	***0.4188***	***0.1843***	***0.3035***	0.1514	0.0588	0.0337
NORTHEASTERN ILLINOIS									
5529000	DesPlaines River @ DesPlaines	51	***0.3474***	***0.6424***	0.0855	***0.3710***	***0.2282***	0.1561	***0.2910***
5531500	Salt Creek @ Western Springs	46	***0.4956***	***0.8040***	0.1382	***0.5285***	***0.2580***	0.1594	***0.4377***
5532500	DesPlaines River @ Riverside	48	***0.4681***	***0.7262***	0.0727	***0.5089***	***0.3280***	0.1755	***0.3865***
5536000	North Branch Chicago River @ Niles	41	***0.3976***	***0.7462***	0.1512	***0.4122***	***0.2585***	0.1561	***0.3220***
5536275	Thorn Creek @ Thornton	43	***0.3134***	***0.5424***	0.0853	***0.3931***	0.1140	0.1185	0.1562
5536290	Little Calumet River @ South Holland	44	***0.2770***	***0.4684***	0.1353	***0.3721***	0.0761	0.0846	0.1860
5539000	Hickory Creek @ Joliet	47	0.1656	***0.2309***	0.0657	***0.2081***	0.1489	0.0583	0.0305
5540500	DuPage River @ Shorewood	51	***0.4055***	***0.6147***	0.1059	***0.3929***	***0.2345***	0.1843	***0.3349***
5546500	Fox River @ Wilmot, WI	49	***0.3588***	***0.4486***	0.1412	***0.3214***	***0.2670***	***0.1905***	0.1752
5550000	Fox River @ Algonquin	76	***0.1979***	***0.2843***	0.0758	0.1467	***0.1790***	0.0702	***0.2035***
5552500	Fox River @ Dayton	67	***0.3152***	***0.4079***	***0.2800***	***0.2393***	***0.1976***	***0.2130***	***0.2953***
SMALL URBAN STREAMS									
3337000	Boneyard Creek @ Urbana	42	-0.1716	***-0.3240***	-0.0742	0.0233	-0.1274	-0.0720	-0.1938
5528500	Buffalo Creek @ Wheeling	39	***0.3171***	***0.4282***	0.1606	***0.4143***	***0.2389***	0.1687	***0.2173***
5529500	McDonald Creek @ Mt. Prospect	39	0.2119	***0.5647***	0.1471	***0.3738***	0.2038	0.0499	0.1795
5530000	Weller Creek @ Des Plaines	41	0.0415	0.1487	***0.2463***	0.1878	-0.0293	-0.0805	0.0073
5532000	Addison Creek @ Bellwood	40	***0.5462***	***0.4791***	0.2103	***0.4718***	***0.3795***	***0.3308***	***0.3641***
5533000	Flag Creek @ Willow Springs	40	***0.5487***	***0.7058***	0.2051	***0.4128***	***0.4769***	***0.3667***	***0.4128***
5534500	North Br. Chicago River @ Deefield	39	***0.3306***	***0.6273***	***0.2578***	***0.4008***	***0.2713***	0.1822	0.2011
5535000	Skokie River @ Lake Forest	40	0.1410	-0.0445	**0.2231**	0.2359	0.1897	0.0923	0.0436
5535500	West Fk. North Br. Chicago River	39	***0.4359***	***0.5932***	***0.2173***	***0.5007***	***0.3036***	***0.2173***	***0.3414***
5536215	Thorn Creek @ Glenwood	42	***0.4448***	***0.3146***	0.1429	***0.3752***	***0.2242***	***0.2149***	***0.2172***
5536235	Deer Creek @ Chicago Heights	43	***0.2824***	0.1336	***0.2735***	***0.3444***	0.1783	0.1539	0.0166
5536255	Butterfield Creek @ Flossmoor	43	0.1694	-0.1266	0.1960	***0.3333***	0.0498	0.0498	0.0011
5536265	Lansing Ditch @ Lansing	43	0.1429	***0.2985***	-0.1849	***0.3200***	0.0410	0.0210	0.1783
5536340	Midlothian Creek @ Oak Forest	41	***0.2561***	***0.3641***	0.1268	***0.3415***	0.1171	0.1073	0.1342
5536500	Tinley Creek @ Palos Park	40	***0.3974***	***0.5978***	***0.2359***	***0.3795***	***0.2410***	***0.2103***	0.1846
5537500	Long Run @ Lemont	40	***0.2538***	***0.6815***	*0.0487*	***0.2202***	***0.2256***	0.1359	0.0513
5550500	Poplar Creek @ Elgin	40	***0.3026***	***0.2578***	***0.3154***	***0.4051***	***0.2205***	0.1410	0.1077

Table 1. Concluded

			Flow parameter						
REGION *Station ID*	*Location*	*Years of record*	*Mean flow*	*7-day low flow*	*7-day high flow*	*Fall mean*	*Winter mean*	*Spring mean*	*Summer mean*
ILLINOIS RIVER									
5543500	Illinois River @ Marseilles	52	***0.2525***	-0.0211	0.1582	0.1814	0.1219	0.1393	0.0987
5568500	Illinois River @ Kingston Mines	52	***0.2685***	***0.3145***	***0.2383***	***0.3213***	***0.2051***	0.1554	0.0996
5586100	Illinois River @ Valley City	51	0.1576	***0.2490***	0.1420	0.1843	0.1372	0.0682	-0.0274
CENTRAL ILLINOIS									
5554500	Vermilion River @ Pontiac	49	0.1616	0.1472	0.1565	***0.2364***	0.1429	0.0391	-0.0867
5555300	Vermilion River @ Leonore	60	0.1642	0.1398	***0.1818***	0.1268	0.0859	0.0871	0.0894
5556500	Big Bureau Creek @ Princeton	55	0.1623	***0.3222***	-0.0263	***0.2040***	0.0330	0.1030	0.0182
5567500	Mackinaw River @ Congerville	47	0.1656	0.1130	0.1711	0.1415	0.0786	0.0657	-0.1748
5569500	Spoon River @ London Mills	49	0.1360	0.1738	-0.0119	***0.2177***	0.0255	0.0697	-0.0867
5570000	Spoon River @ Seville	77	0.1237	0.1193	0.0793	0.0390	0.0232	0.1415	0.0232
5572000	Sangamon River @ Monticello	77	0.0813	0.0225	0.0636	-0.0096	0.0280	0.1005	0.0595
5576000	South Fork Sangamon R. @ Rochester	42	0.1103	-0.1658	0.1498	0.0732	0.1127	0.1730	-0.1405
5578500	Salt Creek @ Rowell	49	0.0561	0.1188	0.0051	0.0765	0.0544	0.0085	-0.0884
5582000	Salt Creek @ Greenview	50	0.1282	0.1735	0.0645	0.1037	0.0678	0.0955	-0.0547
5583000	Sangamon River @ Oakford	52	0.1252	***0.2392***	0.0679	0.1599	0.1342	0.1267	-0.0211
5584500	LaMoine River @ Colmar	47	0.0342	0.0300	0.0879	0.0194	-0.0564	-0.0009	***-0.2063***
5585000	LaMoine River @ Ripley	70	0.0907	0.0426	***0.2108***	-0.0385	0.0037	0.0932	-0.0559
5587000	Macoupin Creek @ Kane	51	0.0196	0.0841	0.0196	0.0667	0.1404	0.0714	-0.1828
SOUTHWESTERN ILLINOIS									
5592000	Kaskaskia River @ Shelbyville	51	0.0620	***0.2669***	***-0.2816***	0.0714	***0.2047***	-0.1184	-0.0259
5592500	Kaskaskia River @ Vandalia	77	0.0800	0.1081	0.0178	0.0697	0.1408	0.0260	0.0602
5594000	Shoal Creek near Breese	46	0.0647	0.0586	0.1633	0.0454	0.1130	0.0666	-0.1536
5597000	Big Muddy River @ Plumfield	77	0.0041	***0.4323***	***-0.1709***	-0.0171	-0.0123	0.0991	0.1094
	@ Plumfield (1915-1969)	55	-0.0626	0.0049	-0.0936	-0.1502	-0.0841	0.0653	-0.0357
5599500	Big Muddy River @ Murphysboro	61	0.1027	***0.5593***	0.0525	0.0973	0.1388	0.0710	0.1508
MISSISSIPPI / OHIO RIVERS									
5474500	Mississippi River @ Keokuk	113	0.1050	***0.2759***	0.0972	0.0648	***0.2335***	0.1092	-0.0136
7010000	Mississippi River @ St. Louis	55	***0.2391***	***0.4228***	0.0896	***0.3670***	***0.3212***	***0.1838***	0.0788
3611500	Ohio River @ Metropolis	57	0.1263	***0.3710***	-0.0363	***0.4499***	0.1379	-0.0073	0.1147

Note: Coefficients in bold & italics indicate significance at the 95 percent level of confidence

percent level of confidence. The results of all three analytical procedures were fairly similar, thus only the Kendall analysis results are reported here.

Table 1 presents the correlation coefficients computed using the Kendall analysis for all 79 gaging stations. The Kendall Tau-b analysis (Kendall, 1975) produces a rank correlation coefficient, which indicates the strength of the trend relative to the overall variability of the flow parameter being analyzed. A coefficient of zero indicates absolutely no trend. Negative values indicate a decreasing trend, and positive values indicate an increasing trend. The strength of the trend increases as the absolute value of the coefficient approaches 1.0 (the maximum correlation). If the natural variability of the flow parameter is particularly great, as with high flows and floods, it may be more difficult to identify a significant trend.

IMPACTS OF CLIMATE VARIABILITY

Weather and climate are the primary driving forces that determine the amount and distribution of streamflow. Variability is a natural aspect of the climatic and hydrologic processes. Annual variability in climate, particularly in precipitation, may result in periods of drought or extended high streamflow. Figure 1 illustrates the considerable variation that can occur with both annual precipitation amounts and the resulting streamflow. The 11-year moving averages of both the precipitation and streamflow are also shown to illustrate their long-term variation. The moving averages indicate that above- and below-normal conditions can persist over a period lasting as long as two decades. When using short streamflow records, it can be particularly difficult to differentiate between this natural variance and a long-term change in overall

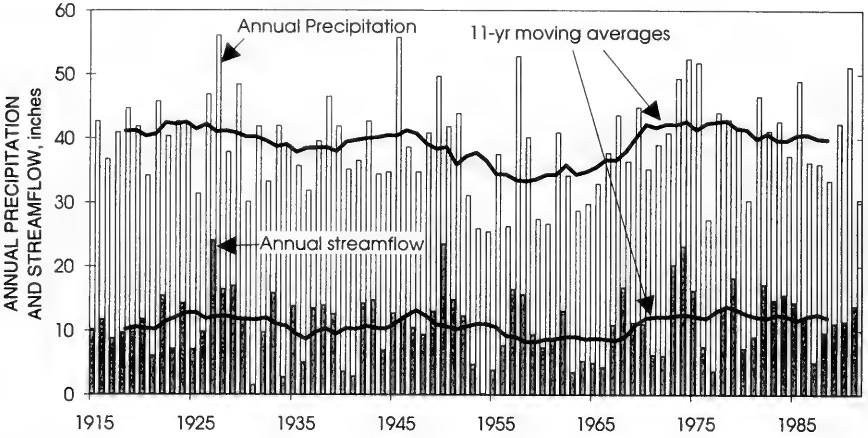


Figure 1. Comparison of annual precipitation and streamflow, Embarras River watershed near Charleston.

climatic conditions. For this reason, it is desirable to use long-term streamflow records to examine trends that may be associated with climatic change.

Previous Studies

Ramamurthy et al. (1989) and Singh and Ramamurthy (1990) examined the increases in average annual flows and peak flows observed on the Illinois River for the period 1941-1985. These studies found that average annual flow on the Illinois River had increased by 20 to 25 percent since 1970, and that annual peak flows had increased about 50 percent. The number of days having high-flow conditions doubled during that time. These studies concluded that the higher flows were caused by concurrent increases in precipitation amounts throughout much of the Illinois River basin.

Changnon (1983) examined trends in the number of flood events and the duration of flood flows for 11 large watersheds in Illinois over the period 1921-1980. Changnon concluded that the number of flood events and flood days generally increased over that period, particularly in the northern and eastern portions of Illinois. Changnon also found an increase in the number of heavy rainfall events during the summer (May to August), which is believed to be one of the causes for the increase in summer floods.

Gaging Records Used in the Analysis

The streamgage records used to analyze the impact of climate variability on hydrology should come from watersheds relatively unaffected by human-induced impacts, including withdrawals, return flows, reservoirs, detention storage, and major land-use changes. Additional gage selection criteria, developed by Slack and Landwehr (1992) for evaluating impacts of climate variability, are the length of the gaging record, its general level of accuracy, and the relative lack of missing or estimated data. Slack and Landwehr identified 36 streamgage records from Illinois as appropriate for the study of climate impacts on streamflow, using a minimum record length of 20 years. For this analysis, a more stringent requirement of 40 years of record was applied, thus eliminating 9 of those 36 records. The gaging record for the Rock River at Afton, Wisconsin, was included since this stream enters Illinois slightly downstream of the gage. Another gaging record, the Fox River at Algonquin, is not without minor influences on its flow, but was included because it provides an important long-term record of average flow conditions in northeastern Illinois. The resulting 29 stations used in the analysis are identified in table 2.

The Kendall correlation coefficients for each streamflow parameter and each of the 29 stations are

Table 2. Streamgage Records Used to Analyze Impacts of Climate Variability

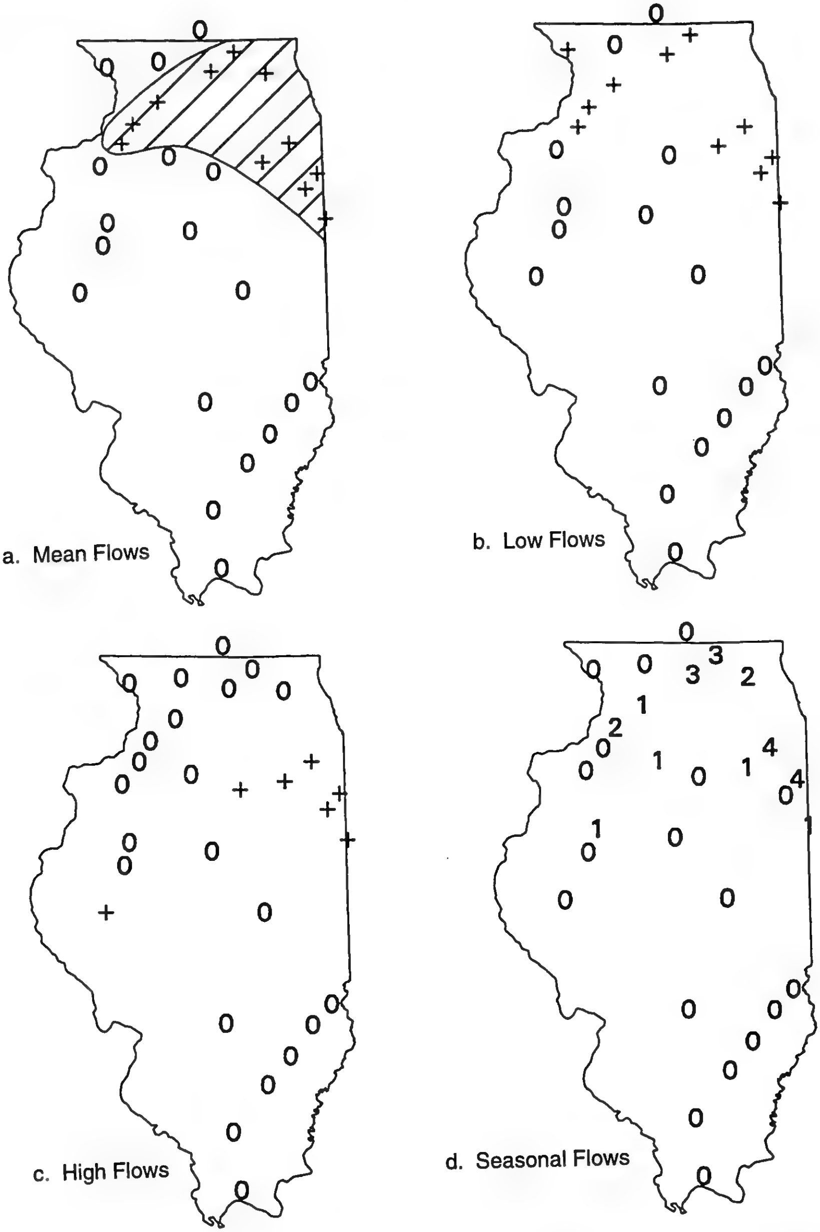
Gage #	*Location*	*Watershed drainage area (mi^2)*	*Period of record*
03345500	Embarras River at Ste. Marie	1,516	1915-1991
03346000	North Fork Embarras near Oblong	318	1941-1991
03379500	Little Wabash River below Clay City	1,131	1915-1991
03380500	Skillet Fork at Wayne City	464	1929-1991
03612000	Cache River at Forman	244	1925-1991
05419000	Apple River near Hanover	247	1935-1991
05430500	Rock River at Afton, WI	3,340	1915-1991
05435500	Pecatonica River at Freeport	1,326	1915-1991
05438500	Kishwaukee River at Belvidere	538	1941-1991
05440000	Kishwaukee River near Perryville	1,099	1941-1991
05444000	Elkhorn Creek near Penrose	146	1941-1991
05446500	Rock River near Joslin	9,549	1941-1991
05447500	Green River near Geneseo	1,003	1937-1991
05466000	Edwards River near Orion	155	1941-1991
05520500	Kankakee River at Momence	2,294	1916-1991
05525000	Iroquois River at Iroquois	686	1945-1991
05526000	Iroquois River near Chebanse	2,091	1924-1991
05527500	Kankakee River near Wilmington	5,150	1916-1991
05542000	Mazon River near Coal City	455	1940-1991
05550000	Fox River at Algonquin	1,403	1915-1991
05555300	Vermilion River Leonore	1,251	1932-1991
05556500	Big Bureau Creek at Princeton	196	1937-1991
05567500	Mackinaw River near Congerville	767	1945-1991
05569500	Spoon River at London Mills	1,072	1943-1991
05570000	Spoon River at Seville	1,636	1915-1991
05572000	Sangamon River at Monticello	550	1915-1991
05585000	LaMoine River at Ripley	1,293	1922-1991
05592500	Kaskaskia River at Vandalia	1,940	1915-1969
05597000	Big Muddy River at Plumfield	794	1915-1969

included in table 1. An examination of these coefficients indicates that most values have a positive correlation, thus we can conclude in general terms that flow conditions are increasing throughout the state. However, most of these coefficients are less than the threshold needed to identify individual trends at the 95 percent level of confidence. Only in certain portions of the state are the trends significantly large to pass this threshold. Figure 2 presents the locations of those stations where statistically significant trends in flow conditions were identified. A description of the flow changes at selected stations and by region follows.

Changes in Mean Streamflow

Most stations throughout Illinois have experienced above-average flow conditions in the last 25 years. This does not necessarily indicate a trend in streamflow conditions, however. Hypothesis tests having a 95 percent confidence level are used to statistically determine which increases are significantly different from zero, thereby suggesting an actual trend rather than natural streamflow variability.

Eleven gaging stations in northern Illinois experienced significant increases in mean streamflow over their



a. Mean Flows

b. Low Flows

c. High Flows

d. Seasonal Flows

Figure 2. Location of streamgages and identification of trends in a) mean flows, b) low flows, c) high flows, and d) seasonal flows.

period of record, as indicated by the hypothesis tests. The hatched area in figure 2a identifies the general region of impact. Records for the remaining 18 locations throughout the state either have no change in mean flow or an amount of change that is not sufficiently different than zero to conclude that a trend exists.

Magnitude of Changes. Figure 3 presents the annual mean discharge for seven streamgages in Illinois with record lengths greater than 75 years. The moving average displays the variation of above- and below-normal conditions throughout the record. All of the watersheds experienced below-normal flow in the 1930s and 1950s, and above-normal conditions in the 1970s and early 1980s. However, two streams—the Fox River at Algonquin and the Kankakee River at Momence—have experienced a particularly high mean flow rate since the late 1960s.

Table 3 compares the percent difference in the mean flow observed at all 29 stations in the last 26 years (1966 to 1991) to the common 51-year period from 1941 to 1991. Also shown is the percent difference from the longer 77-year record of 1915 to 1991.

Kankakee River vicinity. The Kankakee River, in particular, appears to display steady increases in mean flow over its period of record. All three long-term gaging records in the Kankakee River basin show significant increases in mean flow over the last 75 years. The flow in the last 25 years, when compared to that at the start of the period of record, is more than 40 percent greater—an average increase of 0.5 percent per year. The relationship of this increase to changes in the average precipitation of the Kankakee River watershed is examined later.

Northern Illinois. All watersheds in northern Illinois experienced a 13 to 20 percent increase in mean flow in 1966-1991 above the long-term average, with the exception of the northwestern corner of the state—on the Pecatonica and Apple Rivers. The Kishwaukee River at Belvidere and Perryville and the Fox River at Algonquin had particularly high flows during this period, 20 percent above average.

Central Illinois. The watersheds in central Illinois have experienced a 10 to 15 percent increase in mean flows since 1966. While this is a considerable increase, it is not sufficient for the analysis to detect a definite trend in mean flow conditions.

Southern Illinois. Southern Illinois watersheds have experienced little change in mean flow conditions over the last 75 years.

Impact of Period of Record on Analyzing Trends. Examination of the long-term records in figure 3 indicates that the identification of a trend can be partly dependent on the period of record being examined. For example, an evaluation of the Monticello, Seville, and Freeport gage records between 1935 and 1985 would suggest that these locations have experienced steady increases in mean flow. When the full period of record at these stations is examined, however, the existence of a trend is less apparent. Most of the gaging stations being analyzed have a period of record from about 1940 to 1991, or starting from a period where below-normal flows were observed and including the period of above-normal conditions from 1972-1985. It may be expected that some of these shorter records will display an increasing trend when no long-term trend is actually present.

Table 4 lists the Kendall trend coefficients developed for 12 long-term gaging stations in Illinois. Trend coefficients for the entire period of record are compared with partial records containing a shorter period of 50 continuous years. Trend coefficients that exceed the 95 percent level of confidence are presented in bold italics. The coefficients with the highest absolute values represent the strongest trends, whether positive (increasing trend) or negative (decreasing trend). Examination of these values indicates that the shorter 50-year records are much more likely to have greater coefficients than the entire period of record. The exceptions to this are the stations on the Kankakee River, where the trend coefficients for the overall record are as high or higher than any of the partial records. This supports the contention that a significant long-term trend exists on this river.

Table 4 also shows that several gages displayed negative coefficients, indicating decreasing trends in flow, prior to 1973. It is quite possible that 25 years ago there may have been as much concern over decreasing flow conditions as there is today over increasing trends. This brings up an additional question of whether cyclical trends exist on these streams. The possible existence of cyclic trends is briefly examined in the upcoming section: *What is the Nature of the Trends?* But the length of the gaging records under examination is generally not sufficient to identify long-term cyclical trends.

For many of the stations listed in table 4, the trend correlation for the 50-year records ending in 1982 are significantly higher than for either the entire period of record or any of the other 50-year partial records. Some of the previous analyses concerning trends in

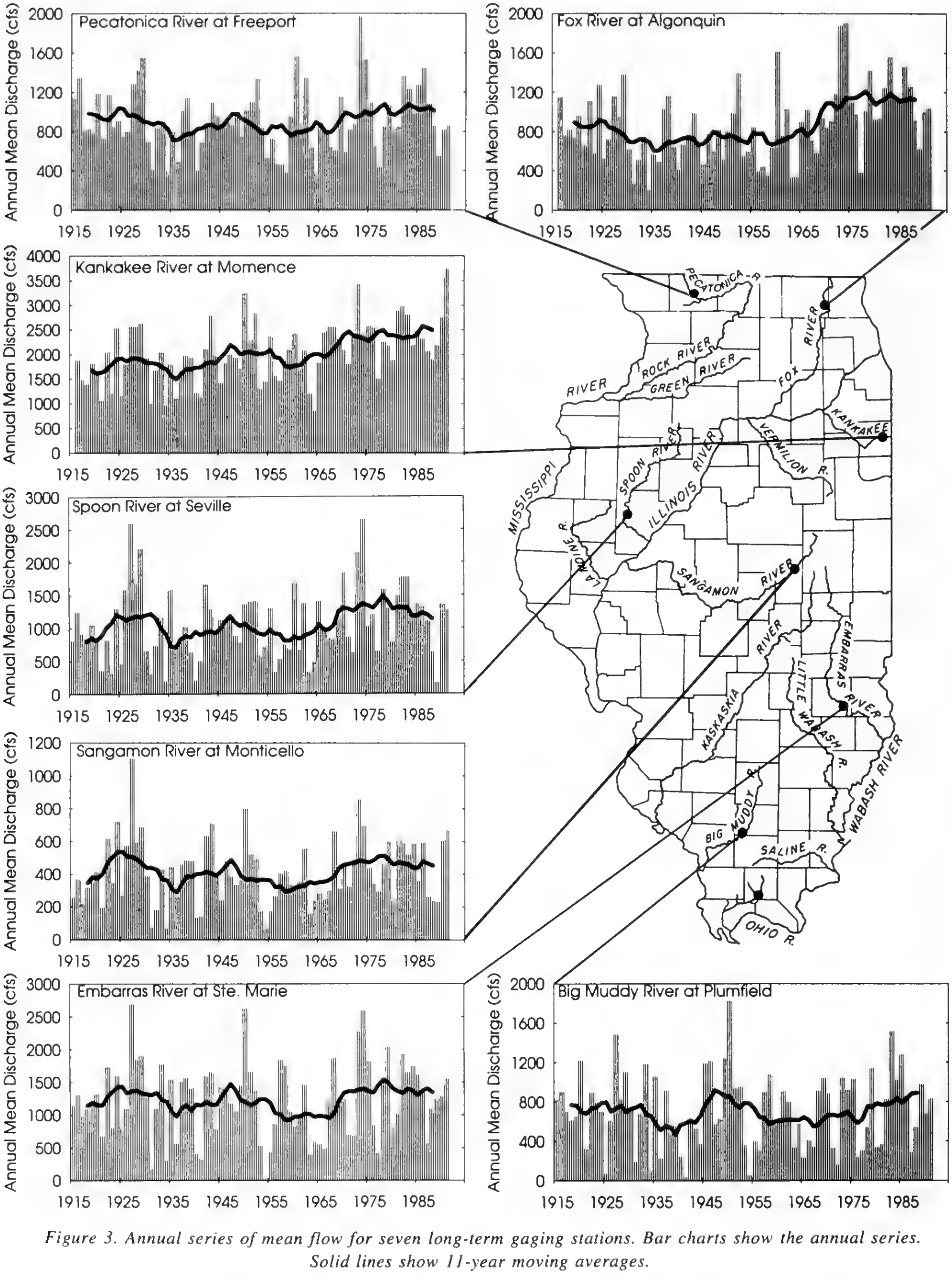


Figure 3. Annual series of mean flow for seven long-term gaging stations. Bar charts show the annual series. Solid lines show 11-year moving averages.

Table 3. Percentage Increase in Mean Streamflow: 1966-1991 Mean Flow Compared to the 1941-1991 and 1915-1991 Means

		Percent increase in mean flows	
Region and gage number	*Location*	*1966-1991 to 1941-1991*	*1966-1991 to 1915-1991*
Kankakee River vicinity			
05520500	Kankakee River at Momence	12.1	20.3
05525000	Iroquois River at Iroquois	11.0	
05526000	Iroquois River near Chebanse	13.0	16.8
05527500	Kankakee River near Wilmington	15.5	26.4
05542000	Mazon River near Coal City	16.1	
Northern Illinois			
05419000	Apple River near Hanover	7.8	
05430500	Rock River at Afton, WI	11.0	12.4
05435500	Pecatonica River at Freeport	5.9	6.5
05438500	Kishwaukee River at Belvidere	21.2	
05440000	Kishwaukee River near Perryville	20.3	
05444000	Elkhorn Creek near Penrose	14.2	
05446500	Rock River near Joslin	13.5	
05447500	Green River near Geneseo	15.2	
05550000	Fox River at Algonquin	19.0	25.0
Central Illinois			
05466000	Edwards River near Orion	11.7	
05555300	Vermilion River near Leonore	15.0	
05556500	Big Bureau Creek at Princeton	15.4	
05567500	Mackinaw River near Congerville	12.6	
05569500	Spoon River at London Mills	11.6	
05570000	Spoon River at Seville	11.3	16.3
05572000	Sangamon River at Monticello	10.7	12.9
05585000	LaMoine River at Ripley	9.8	14.1
Southern Illinois			
03345500	Embarras River at Ste. Marie	9.0	9.0
03346000	North Fork Embarras near Oblong	10.2	
03379500	Little Wabash River below Clay City	7.5	9.1
03380500	Skillet Fork at Wayne City	4.7	
03612000	Cache River at Forman	3.0	2.4
05592500	Kaskaskia River at Vandalia	8.6	12.8
05597000	Big Muddy River at Plumfield	2.3	3.0

Table 4. Influence of Period of Record on Trend Analysis

	Kendall coefficient of trend		
Period of record	*Mean flow*	*Low flow*	*High flow*
Embarras River at Ste. Marie			
1915-1991	0.0376	0.0786	0.0595
1915-1964	-0.0743	-0.1616	-0.0122
1924-1973	-0.1118	0.0425	-0.0286
1933-1982	0.0416	***0.2738***	0.0188
1942-1991	0.0433	0.1395	0.0449
Little Wabash River near Clay City			
1915-1991	0.0451	0.0449	0.0581
1915-1964	-0.0824	***-0.2024***	-0.1102
1924-1973	-0.0514	-0.0408	0.0629
1933-1982	0.0188	***0.2891***	0.0612
1942-1991	0.0449	***0.1990***	0.1102
Sangamon River at Monticello			
1915-1991	0.0813	0.0225	0.0636
1915-1964	-0.0596	-0.0629	0.0220
1924-1973	-0.0661	0.0255	0.0188
1933-1982	0.1184	***0.1939***	0.0890
1942-1991	0.0743	-0.0187	0.0612
Spoon River near Seville			
1915-1991	0.1237	0.1193	0.0793
1915-1964	-0.0563	-0.1360	0.0384
1924-1973	-0.0122	0.0255	-0.0563
1933-1982	0.1755	***0.3708***	0.0400
1942-1991	0.0726	0.1582	-0.0057

Note: Bold italics indicate the Kendall coefficient of trend passes the 95 percent level of confidence

	Kendall coefficient of trend		
Period of record	*Mean flow*	*Low flow*	*High flow*
Pecatonica River at Freeport			
1915-1991	0.0191	0.1158	-0.1490
1915-1964	-0.1167	***-0.2109***	-0.0726
1924-1973	-0.0400	-0.0493	0.0024
1933-1982	0.0629	***0.2517***	0.0824
1942-1991	0.0416	***0.2432***	-0.1722
Rock River at Afton, WI			
1914-1991	0.0849	-0.0032	-0.0056
1915-1964	***-0.1886***	***-0.3350***	-0.1526
1924-1973	0.0106	-0.0255	0.0171
1933-1982	0.1820	***0.2874***	0.0906
1942-1991	***0.1951***	***0.2840***	0.0893
Fox River at Algonquin			
1916-1991	***0.1979***	***0.2843***	0.0758
1916-1964	-0.1599	-0.0957	-0.1667
1924-1973	0.0841	0.1276	0.1200
1933-1982	***0.2702***	***0.4524***	0.1069
1942-1991	***0.3159***	***0.4575***	0.1510
Kankakee River at Momence			
1916-1991	***0.3137***	***0.2252***	***0.2688***
1916-1964	0.0731	0.1879	0.0170
1924-1973	0.1412	0.0289	0.1347
1933-1982	***0.3078***	0.1582	***0.3616***
1942-1991	***0.2310***	0.0476	***0.2816***
Kankakee River near Wilmington			
1916-1991	***0.3558***	***0.2685***	***0.2618***
1916-1964	0.0782	0.1294	0.0714
1924-1973	0.1151	-0.0034	0.0629
1933-1982	***0.3012***	0.1871	***0.1886***
1942-1991	***0.3176***	0.1752	0.1788

streamflow (Changnon, 1983; Ramamurthy et al., 1989) also used streamflow records that extended to the early and mid-1980s. These earlier studies may have results that more strongly suggest trends than the results presented herein, simply because of the period of record used in the analysis. In a similar manner, it should be expected that analyses conducted in the future, using longer gaging records, will also have different results but should present a clearer understanding of long-term trends.

Changes in Low Flows

All 11 stations having an increase in average flow also have an increasing trend in low flows (see figure 2b). Of the remaining 18 stations outside the region, only one has a significant increase in low flows: the Apple River near Hanover.

Figure 4 displays the annual series of 7-day low flows observed at five of the long-term gaging stations. The Fox River at Algonquin is not included because its low flows are noticeably affected by an upstream reservoir. The dark line in each of the plots shown is the 11-year moving median of the low flows. Low flows in the central and southern parts of Illinois (Embarras River, Spoon River, and Sangamon River) were above normal during the 1970s but otherwise show little change over time.

The low flows on the Kankakee River show only a slight trend since 1924, but were consistently below normal from 1916 to 1923. This period of below-normal low flows on the Kankakee River coincides with the period when channelization of that river was being completed (Knapp, 1992), and therefore may have some human-induced impacts. Figure 4 illustrates that the Pecatonica River has experienced an increase in low flows since 1980. But unless future decades show further increase, this is not considered a trend and, in fact, the Kendall hypothesis tests do not identify a significant trend.

Changes in the Number of Low Flow Occurrences. The analysis used to identify trends provides only a comparison of the general magnitude of the annual series of 7-day low flows, and it does not distinguish those years with truly dry conditions from those years where low flows were not severe (or where a low-flow condition did not really exist). In analyzing extreme conditions, such as low flows, it is also necessary to look at the frequency at which these extreme events occur.

Table 5 lists the average number of "significant" low flow events that occurred throughout the gaging records. The "significant" low flows shown in this table are those with magnitudes so low that they occur on average only once in five years. On average, each decade should be expected to have two of these events. This table indicates the change in their frequency of occurrence.

Kankakee River vicinity. In and near the Kankakee River watershed, the frequency of low flows is remarkably consistent from the mid-1920s until 1970. But in the 20-year period 1971-1990, only one severe low-flow event occurred (the 1988 drought). This suggests a definite change in low-flow frequency in the last two decades.

Northern Illinois. The northern Illinois gaging records suggest a recent tendency toward less frequent low flows. The occurrence of low flows in this part of Illinois tends to aggregate in two decades, the 1930s and the 1950s, suggesting a significant interannual dependence between the low flows. The decade of the 1920s, at the beginning of the gaging period, and the period 1971-1990 had significantly low occurrences of severe low flows. This fluctuation in low flow frequency suggests that *if* a long-term trend toward less frequent low flows exists, it is more likely to be cyclical rather than linear in nature. But it is not possible to objectively conclude that a long-term cyclical trend exists given the period of record.

Central and southern Illinois. Low flows in the central and southern portions of the state have occurred with the greatest frequency during three decades: the 1930s, 1950s, and 1960s. There is no apparent trend that the frequency of severe low flow events is changing. In fact, low-flow frequency during the most recent decade, the 1980s, is very indicative of the long-term norm.

Changes in High Flows and Flood Peaks

Only seven stations are identified as having significant increases in high flows, and six of these stations are located in or near the Kankakee River basin in northeastern Illinois (figure 2c). These increased high flows on the Kankakee River may also be the primary cause of flooding increases observed farther downstream on the Illinois River, reported by Ramamurthy et al. (1989) and Singh and Ramamurthy (1990).

Figure 5 displays the annual series of 7-day high flows observed at seven long-term gaging stations. The Kankakee, Fox, Spoon, and Sangamon River gages all experienced increases in high flows, though trends were identified for only the first two of these gages. The stations in southern Illinois (Embarras River and Cache River) show no increase in high-flow conditions.

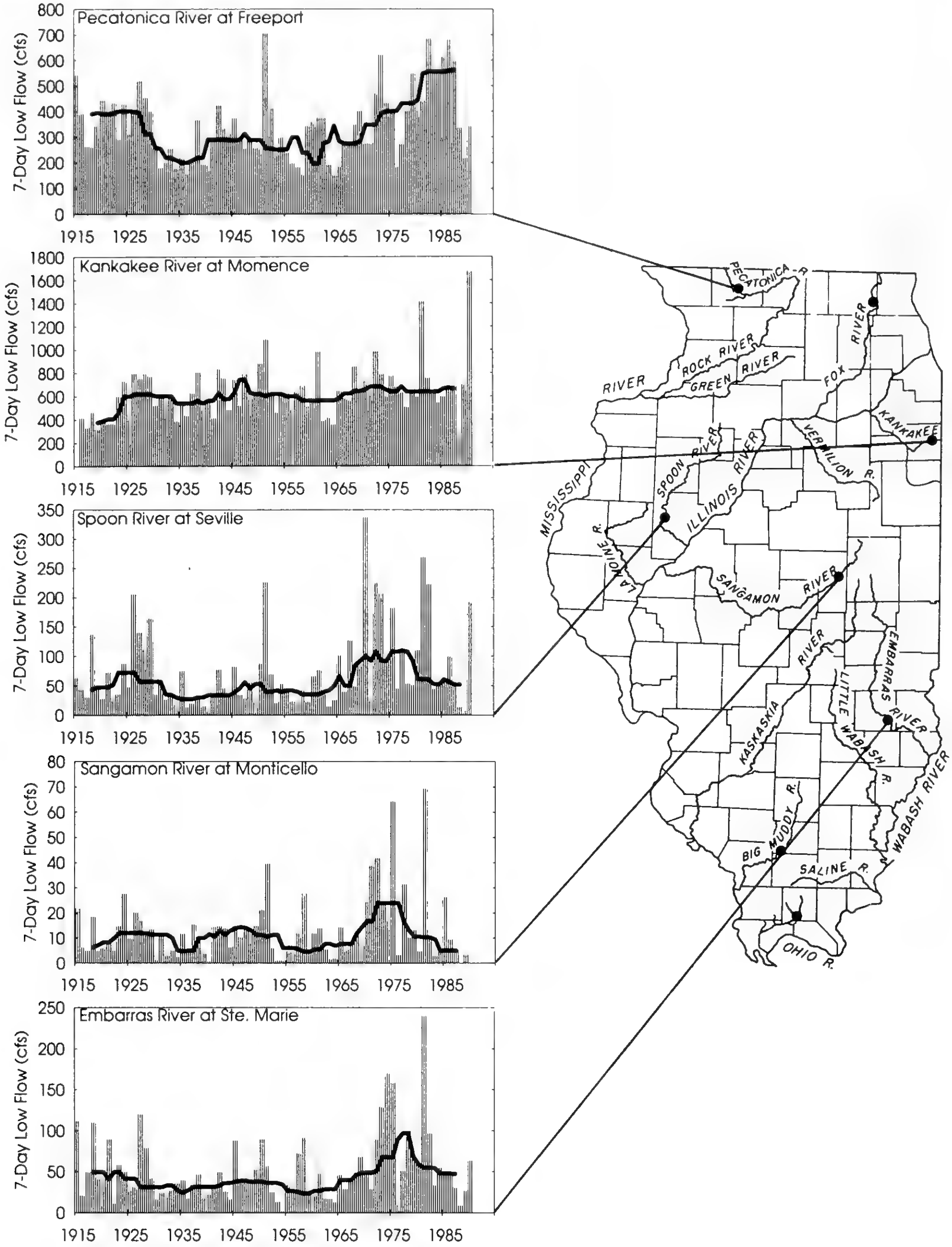


Figure 4. Annual series of low flows for five long-term gaging stations. Bar charts show the annual series. Solid lines show 11-year moving averages.

Table 5. Number of Occurrences of Significant Low-Flow Events

Region and gaging location	*Decade*						
	1920s	*1930s*	*1940s*	*1950s*	*1960s*	*1970s*	*1980s*
<u>Kankakee River Vicinity</u>							
Kankakee River at Momence	3	3	2	2	3	0	1
Iroquois River near Chebanse	2	3	2	1	3	0	1
Kankakee River near Wilmington	3	3	1	3	3	0	1
Mazon River near Coal City	–	–	3	5	1	0	1
Regional Average	2.7	3.0	2.0	2.8	2.5	0.0	1.0
<u>Northern Illinois</u>							
Apple River near Hanover	–	3	1	3	3	2	1
Rock River at Afton, WI	0	8	1	5	3	1	1
Pecatonica River at Freeport	0	7	2	3	1	0	1
Kishwaukee River at Belvidere	–	–	1	2	3	1	2
Kishwaukee River near Perryville	–	–	3	3	2	2	1
Elkhorn Creek near Penrose	–	–	3	4	1	1	0
Rock River near Joslin	–	–	2	4	2	1	1
Green River near Geneseo	–	–	1	5	1	2	2
Regional Average	0.0	6.0	1.8	3.7	2.0	1.2	1.1
<u>Central Illinois</u>							
Edwards River near Orion	–	–	1	4	3	2	2
Vermilion River near Leonore	–	3	0	3	2	1	1
Mackinaw River near Congerville	–	–	–	4	2	0	3
Spoon River at London Mills	–	–	–	3	2	1	2
Spoon River at Seville	1	5	1	4	2	1	2
Sangamon River at Monticello	1	3	0	2	2	1	3
LaMoine River at Ripley	1	3	1	2	1	2	3
Regional Average	1.0	3.5	0.4	3.1	2.0	1.1	2.3
<u>Southern Illinois</u>							
Embarras River at Ste. Marie	2	2	1	2	3	1	1
North Fork Embarras near Oblong	–	–	0	3	3	0	2
Little Wabash River below Clay City	1	3	1	4	2	0	1
Skillet Fork at Wayne City	–	3	2	2	3	0	4
Cache River at Forman	1	3	2	1	2	4	1
Regional Average	1.3	2.8	1.2	2.4	2.6	1.0	1.8

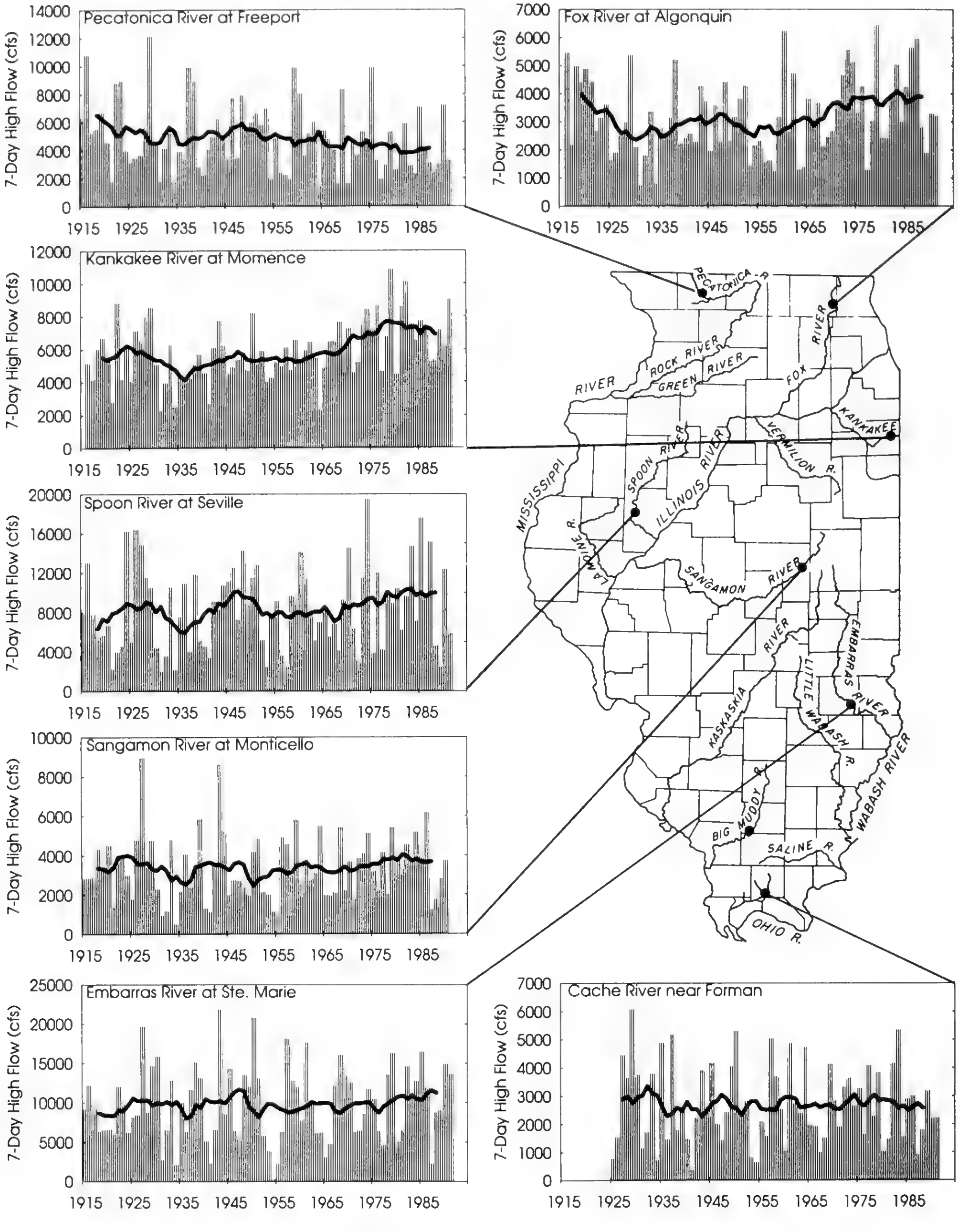


Figure 5. Annual series of high flows for seven long-term gaging stations. Bar charts show the annual series. Solid lines show 11-year moving averages.

The 11-year moving average of high flows for the Pecatonica River at Freeport shows a consistent decrease in high flows throughout its period of record. This Kendall trend coefficient for the high-flow series at Freeport is -0.149, which approximates, but does not exceed the threshold used to identify significant trends. (The Kendall analysis was performed on the annual high-flow series, which has a high degree of variability. For these types of series, the trend must be particularly strong to have the coefficient exceed the 95 percent level of confidence.) In a study of a tributary of the Pecatonica River, Potter (1991) suggests that decreasing floods may be the result of land-use changes, particularly soil and water conservation.

Changes in the Number of Flood Events and Flood Days. Table 6 provides the number of significant flood events at several gaging stations by decade. For the purpose of this analysis a significant flood event is one where the expected frequency of the event is less than approximately once every two years. Table 7 provides the number of flood days by decade at the same stations, i.e., the number of days where the average daily flow exceeds the significant flood level. These values are patterned after similar ones presented in Changnon (1983) and were extended to include the years 1981-1990. Changnon (1983) identified an increase in flood events in eastern Illinois and an increase in flood days throughout much of the northern and eastern portions of the state. With ten additional years of data (1981-1990), the existence of a consistent trend in the number of flood events is less clear, and the observed increases were not sufficient for the statistical tests to demonstrate any trends. The number of flood days appears to have increased for the Kankakee River near Wilmington and the Sangamon River at Monticello, but decreases

Table 6. Number of Significant Flood Events

Region and	Decade						
gaging location	*1920s*	*1930s*	*1940s*	*1950s*	*1960s*	*1970s*	*1980s*
Kankakee River Vicinity							
Kankakee River near Wilmington							
winter	3	0	6	2	2	2	5
summer	1	1	2	3	1	4	3
Northern Illinois							
Pecatonica River at Freeport							
winter	6	4	9	4	3	2	2
summer	0	0	1	1	1	0	1
Central Illinois							
Spoon River at Seville							
winter	2	2	5	3	3	4	3
summer	6	1	5	3	2	3	4
Sangamon River at Monticello							
winter	5	2	4	3	4	5	6
summer	2	1	1	1	2	5	5
LaMoine River at Ripley							
winter	3	10	5	5	5	5	3
summer	2	2	6	4	3	4	7
Southern Illinois							
Embarras River at Ste. Marie							
winter	5	4	8	4	4	6	4
summer	2	1	2	2	2	3	1
Cache River at Forman							
winter	8	5	11	4	4	8	4
summer	2	3	0	2	1	1	2

Table 7. Number of Significant Flood Days

Region and gaging location	*Decade* *1920s*	*1930s*	*1940s*	*1950s*	*1960s*	*1970s*	*1980s*
Kankakee River Vicinity							
Kankakee River near Wilmington							
winter	5	0	14	3	6	10	27
summer	0	5	13	8	5	3	6
Northern Illinois							
Pecatonica River at Freeport							
winter	24	20	26	30	7	8	9
summer	0	0	3	5	6	0	5
Central Illinois							
Spoon River at Seville							
winter	3	5	15	11	4	12	9
summer	18	3	12	6	6	10	16
Sangamon River at Monticello							
winter	8	5	8	10	9	11	11
summer	5	3	5	2	5	10	8
LaMoine River at Ripley							
winter	7	22	41	21	17	19	27
summer	6	8	23	10	13	10	22
Southern Illinois							
Embarras River at Ste. Marie							
winter	11	12	26	9	8	20	12
summer	6	3	10	8	8	5	4
Cache River at Forman							
winter	22	15	31	4	8	15	7
summer	5	6	0	8	4	3	7

are noted for both the Pecatonica River at Freeport and the Cache River at Forman.

Changes in Seasonal Flows

The annual series of the mean flow rate for four seasons (March-May, June-August, September-November, and December-February) were examined to identify changes in streamflows by season. Trends in seasonal flows were identified at 11 gaging stations (identified in figure 2d by nonzero values). Ten of these stations are located in the same region identified as having increases in both low and average flows. All 11 stations experienced increased flow during the fall (September-November).

Increases in mean flow rate over all four seasons were displayed by two gaging records: the Kankakee River at Momence and at Wilmington. The two gages on the Kishwaukee River, at Belvidere and Perryville, experienced increased flows for all seasons but the summer (June-August), while the Rock River had increased flows during the winter, and the Fox River at Algonquin had increased flows during the summer.

Comparison of Streamflow Increases and Precipitation Increases

Changes in the Illinois climate were examined in the Atmospheric Resources volume. The period from 1966-1983 experienced greater precipitation and streamflow throughout Illinois than did any other period this century. Precipitation and streamflow records indicate, however, that other wet periods were experienced earlier this century and in the nineteenth century, and standard statistical analysis does not indicate that the latest trends are significantly different. In the past, these wet trends have not lasted more than about 20 years. Were it not for the possible impacts of increased concentrations in greenhouse gases, it might be expected that in future years the climate and streamflow conditions would return to more normal conditions. In most locations throughout the state, the average streamflow in the period since 1985 has, in fact, been much closer to the long-term average.

Ramamurthy et al. (1989) and Singh and Ramamurthy (1990) related the increases in average precipitation and average streamflow in the Illinois River watershed. These studies indicate that average precipitation over northern Illinois has increased by 10 to 14 percent for the period since 1965. These precipitation increases resulted in a 20 to 25 percent increase in the mean flow. This finding is similar to the results of Knapp and Durgunoglu (1993), who simulated the impacts of increased precipitation on a central Illinois watershed using a rainfall-runoff computer model, and found that a 10 percent increase in precipitation produces a 25 percent increase in average runoff.

Northern Illinois. Figure 6 compares the streamflow measured on the Kishwaukee River at Belvidere and the rainfall observed at Marengo. The precipitation increase coincides almost exactly with increased streamflow. The increases in the 1965-1980 precipitation and streamflow over the long-term average are 12 and 24 percent, respectively.

Kankakee River Vicinity. Figure 7 compares the precipitation measured at Kankakee with the streamflow for the Kankakee River near Wilmington. The comparison suggests that a 10 percent increase in average precipitation roughly correlates to a 25 percent increase in average streamflow.

Central and Southern Illinois. Locations in central and southern Illinois also experienced above-normal precipitation during the years 1966-1983 (for example, see figure 1). But the increase is less than 6 percent, and the average streamflow for this period was not substantially greater than at all other times during the period of record.

What is the Nature of the Trends?

The identification of a trend using a statistical test does not necessarily indicate the nature of that trend. For example, an increasing linear trend suggests that changes have been consistent over the period of analysis, and possibly that additional increases will continue. Three hypotheses are briefly examined:

- The trends are linear in nature and suggest similar increases/decreases in the future.
- The trends are cyclic in nature, periodically rising and falling over the period of record.
- When a change in streamflow conditions occurs, it is essentially instantaneous, resulting in a distinctly different set of average flow conditions (step trend).

Three long-term gages that have shown trends in streamflow conditions were examined: the Kankakee River at Momence, the Fox River at Algonquin, and the Rock River at Afton, Wisconsin. For each gaging record linear, cyclic, and step-change functions were fitted to the annual average flow. Parameters for all trend functions were identified by least squares regression techniques. These trend functions are illustrated for each of the three stations in figure 8. The correlation coefficients between the observed annual flows were estimated to determine which trend function most closely approximates the observed changes. The computed correlations are presented in table 8.

Table 8 indicates that in all cases the step trend functions more closely match the series of annual mean discharges. This suggests a distinct change in northern Illinois flows since 1970, although they are not continuing to increase. In fact, the linear trend has the worst correlation for all stations except the Kankakee River at Momence. Figure 8 also shows that since 1985, the mean streamflow at the Afton and Algonquin gages has been closer to the long-term mean than to the 1965-1985 conditions. It is unclear whether this indicates a return to "more normal" conditions. The mean flow at the Kankakee River at Momence has remained above average.

Discussion and Conclusions

Most of the northern third of Illinois shows significant increases in both average streamflow and low flows. Much of northern and central Illinois also received significant increases in average precipitation in the period 1966-1983. The locations that experienced increased average and low streamflows generally experienced precipitation increases >10 percent; therefore the streamflow increases are likely caused by changes in precipitation. Less significant increases in streamflow are also noted in central Illinois, which experienced less change in precipitation. Average precipitation and streamflow since 1984 is close to the long-term average. The locations that show an increase in average flow uniformly show increases in low flows

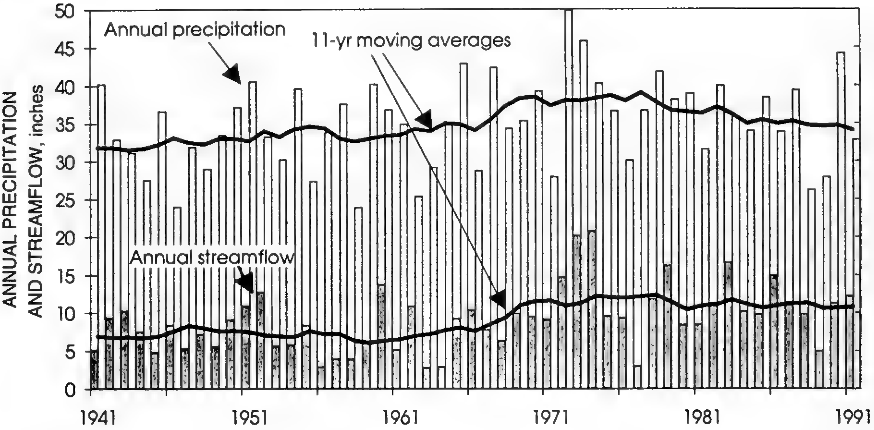


Figure 6. Annual precipitation for Marengo and streamflow for the Kishwaukee River at Belvidere.

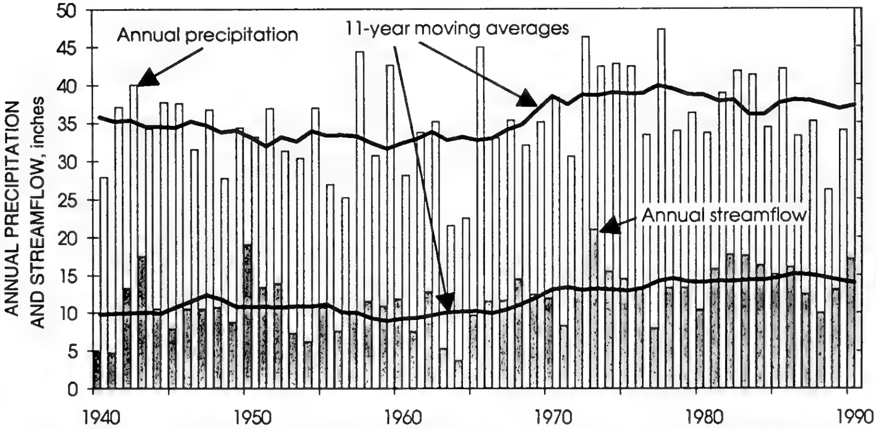


Figure 7. Annual precipitation for Kankakee and streamflow for the Kankakee River near Wilmington.

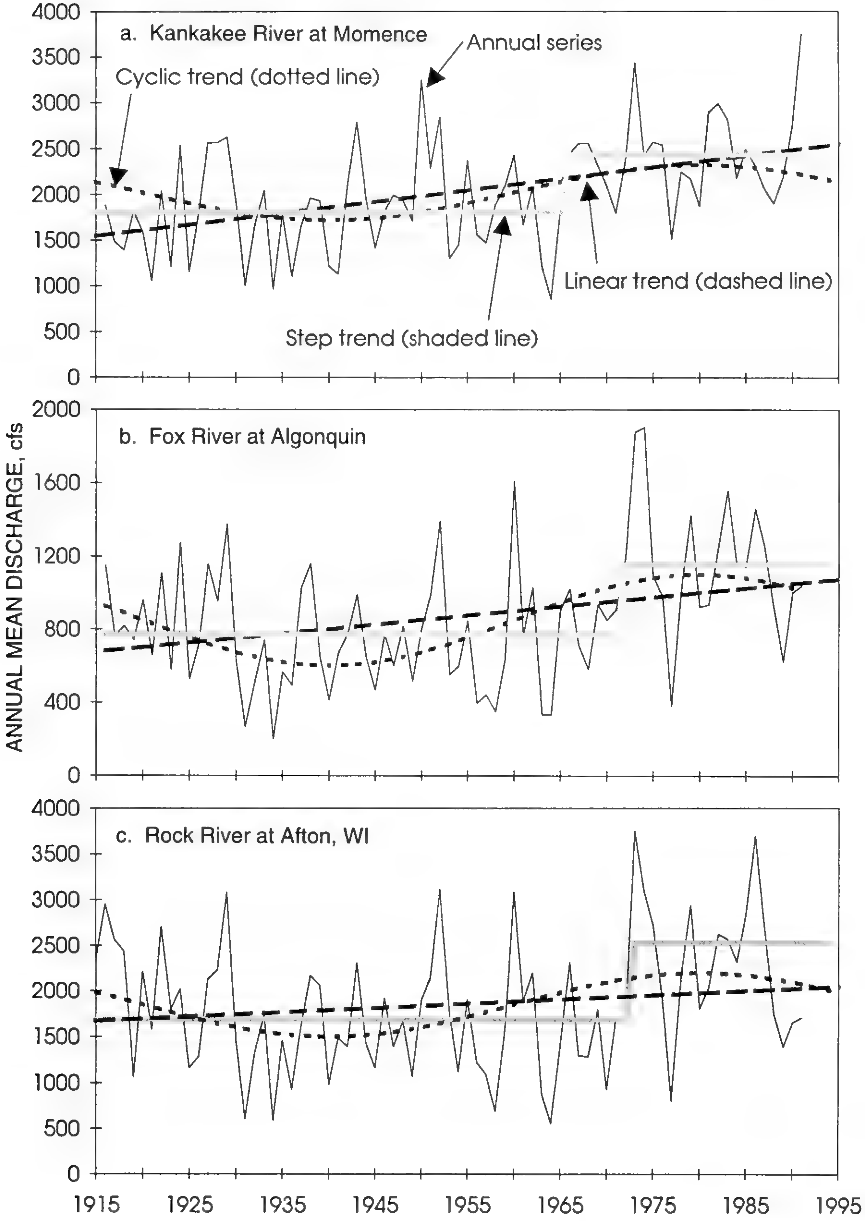


Figure 8. Comparison of the annual mean discharge series to a linear trend, cyclic trend, and step trend on the a) Kankakee River at Momence, b) Fox River at Algonquin, and c) Rock River at Afton, Wisconsin.

Table 8. Correlation of Trend Functions to Annual Mean Discharges

Location	*Linear trend*	*Cyclic trend*	*Step trend*
Kankakee River at Momence	0.3296	0.2689	0.3642
Rock River at Afton, WI	0.1070	0.2450	0.3886
Fox River at Algonquin	0.2239	0.3145	0.3754

and flows during the fall season. High flows have not generally increased, however. The Kankakee River watershed in northeastern Illinois continues to experience anomalous behavior, having continuous increases in precipitation and all streamflow parameters.

The statistical tests identified increasing trends for high flows and flood peaks for the Kankakee River basin. Increases in the number of flooding days have been observed during the last two decades for the Kankakee River. But for most of Illinois, statistically significant increases in high flows and flood peaks do not appear. This is somewhat contrary to the findings of Changnon (1983), who used ten years' fewer data.

IMPACTS OF LAND-USE CHANGE

Urbanization

In the process of urbanization, numerous alterations to a watershed may occur that will cause change in streamflow conditions. The addition of impermeable surfaces, including paved roads, parking lots, roof surfaces, etc., reduces the amount of infiltration and decreases evapotranspiration, thereby increasing both average runoff and storm runoff. More recently, stormwater detention has been added in many watersheds to reduce flood peaks. In most cases, the decreases in infiltration (and hence ground-water recharge) result in a lower ground-water table and less streamflow during dry periods. But for certain urban watersheds, the cumulative effect of a variety of return flows—caused by lawn watering, sump pumping, cooling systems, or other small discharges—may increase low flows.

In the early 1950s numerous gages were located in the Chicago metropolitan area to measure flow from urbanizing watersheds. Table 9 lists the stations in watersheds that have undergone the greatest amount of urbanization since the gages were installed. All watersheds have experienced changes associated with urbanization that affect the flow. Of particular note are the construction of stormwater detention reservoirs, which alter high flows and flooding, and return flows from wastewater treatment facilities, which greatly increase low and medium flows in streams. The presence of these major modifications in each of these watersheds is noted in table 9. The impacts of stormwater detention and wastewater effluents are individually analyzed later in this section.

Analysis of the impacts of urbanization is further complicated in that all of these watersheds are located in northeastern Illinois, which has experienced increased streamflow conditions resulting from climate variability.

Average Flows. No change in the average flow rate has been detected beyond that which may be caused by the impacts of climate change.

Low Flows. The annual series of low flows were examined for the four gaging records listed in table 9 that are not impacted by return flows. Increases in low flows are common, but not universal among these urban streams. This may be partially explained by return flows from lawn watering. The urban area also produces large amounts of wastewater, which must eventually be discharged into the streams. The effect of these return flows is examined in the section on *Impacts of Water Use.*

Flooding and High Flows. Drainage improvements, including storm sewers and channelization, are designed to expedite the flow of water away from urban land. In recent decades, stormwater detention has been added to urban areas to reduce the impact of downstream flooding resulting from these changes. The effects of all these changes on streamflow are well documented in many urban hydrology texts. Of the gages listed in table 9, only three are not affected by stormwater detention (Flag Creek, Tinley Creek, and Long Run). None of these three gage records show an

Table 9. Streamgages Used to Analyze Impacts of Urbanization

Gage #	*Location*	*Watershed drainage area (mi^2)*	*Period of record*	*Additional modifications to watershed*
05528500	Buffalo Creek at Wheeling	19.6	1953-1991	SWD
05529500	McDonald Creek near Mt. Prospect	7.9	1953-1991	SWD
05530000	Weller Creek at DesPlaines	13.2	1951-1991	RF, SWD
05530500	Addison Creek at Bellwood	17.9	1950-1991	RF, SWD
05533000	Flag Creek near Willow Springs	16.5	1952-1991	RF
05531500	Salt Creek at Western Springs	115.0	1946-1991	RF, SWD
05536340	Midlothian Creek at Oak Forest	12.6	1951-1991	SWD
05536500	Tinley Creek near Palos Park	11.2	1952-1991	
05537500	Long Run near Lemont	20.9	1952-1991	RF
05550500	Poplar Creek at Elgin	35.2	1952-1991	RF, SWD

Notes:
RF = major return flows (wastewater treatment facility discharges) to the stream.
SWD = stormwater detention reservoirs affect high flows.

increasing trend in flood peaks, although the Tinley Creek gage displays an increasing trend in the 7-day high flow.

Stormwater Detention. Most urban watersheds in northeastern Illinois have stormwater detention facilities to reduce flood peaks in the watershed. Table 9 identifies six urban watersheds in which stormwater detention reservoirs have been constructed. Trend analysis of the flood peak series indicates that five of these six watersheds have an increasing trend in peak flows. Figure 9 shows that the Addison Creek gage has experienced consistent increases in flood peaks, despite the construction of several detention reservoirs in the watershed. Only Midlothian Creek at Oak Forest displays a reversal in the increasing flood peaks (figure 10).

Reforestation/Deforestation

A considerable amount of forested area in Illinois was converted to farmland more than a century ago, prior to the installation of any streamgages. The trend over recent decades is a small increase in the amount of woodland in Illinois, particularly in the northern and southern extremes of the state. The amount of forest in a watershed must change significantly for these changes to be observed in the streamflow. A 20 percent change in overall runoff may be necessary to separate a trend induced by reforestation from the natural variability in the streamflow record. Since most of the gaging stations in Illinois are located on large streams, it is not possible to evaluate the impact on streamflow of small-scale reforestation.

Experimental catchment studies on the hydrologic impact of deforestation have been conducted in many parts of the nation (e.g., Douglass and Swank, 1972; Patric, 1973; Anderson et al., 1976; TVA, 1955, 1973). All of these studies indicate that deforestation results in increases in average streamflow, low flows, and flooding levels. The amounts of increase vary considerably and depend upon the type of forest cover and various watershed characteristics.

The increase in average flow results primarily from the reduction in watershed evapotranspiration. Increases in flow are particularly apparent the first year after deforestation, before other vegetative growth has a chance to become established. The decreased evapotranspiration also results in higher soil moisture values in unforested areas, which further results in greater baseflow (ground-water flow to streams) during dry periods (Patric, 1973). Flood volumes and peak flow rates often increase after deforestation. However, both Douglass and Swank (1972) and Anderson et al. (1976) indicate that this is usually a result of soil compaction and reduced infiltration associated with the land clearing and development that follows forest harvesting, and *not* by the removal of trees.

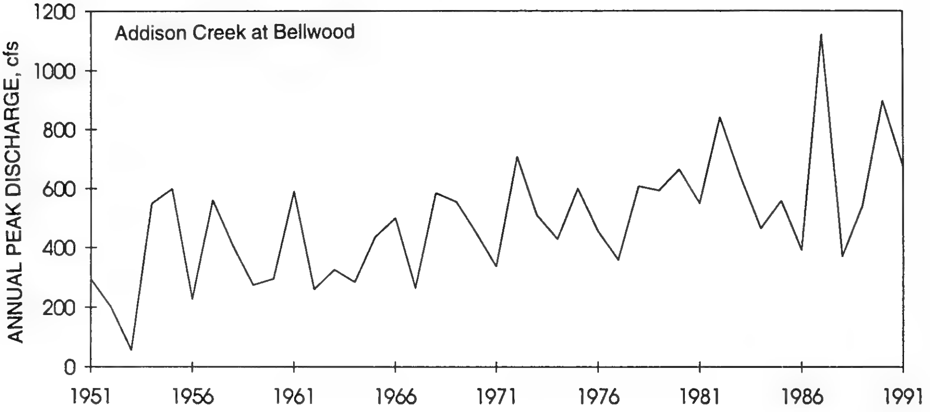


Figure 9. Annual peak discharge series for Addison Creek at Bellwood.

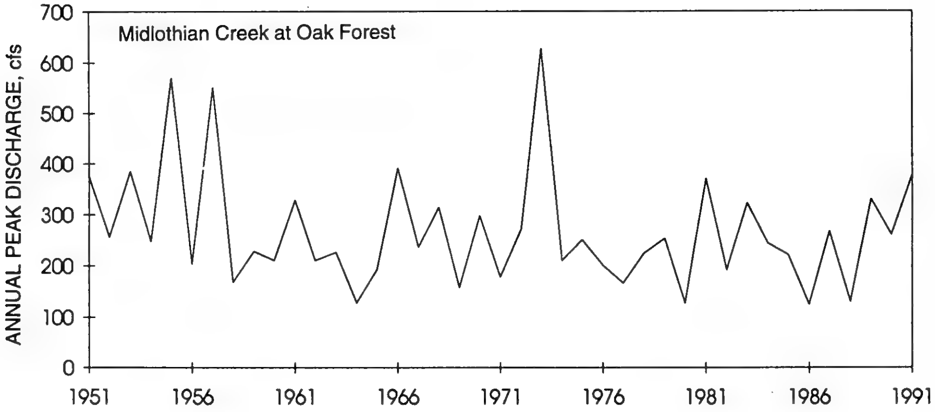


Figure 10. Annual peak discharge series for Midlothian Creek at Oak Forest.

Fewer experimental data are available on the impacts of forest regrowth on streamflow, but the few existing studies indicate that reforestation has a reverse impact and causes decreases in the average flow, low flow, and flooding (Anderson et al., 1976). It may take considerable time to reestablish the same flow conditions that existed prior to the loss of the forest, however.

Removal of Wetland Areas

Illinois has lost an estimated 85 percent of its original wetlands (Dahl, 1990). The impact of the removal of these wetlands on streamflow is not clear. It is often accepted that wetlands reduce streamflow peaks and increase low flows. A review of the scientific literature by Demissie and Khan (1993), however, indicates that this generalized concept may not always be true. Previous studies on the impacts of wetlands are often conflicting: some show that the presence of wetlands causes decreases in peak flows (Novitzki, 1982; Ogawa and Male, 1983), while others suggest an increase or no change in peak flows (Moklyak et al., 1972; Skaggs and Broadhead, 1982). For Illinois, Demissie and Khan (1993) indicate peak flow and floodflow volume are lower in watersheds that have a high percentage of wetland area; but they caution that this relationship could be influenced by other factors. Demissie and Khan also reported increases in low flows with decreasing wetland area, which is contrary to the generally accepted viewpoint. The contribution of other factors to these increases in low flows were not examined.

IMPACTS OF RESERVOIR CONSTRUCTION AND OPERATION

Major reservoirs can produce considerable changes in the flow characteristics of the streams on which they are located. Flood storage reservoirs in large rivers, in particular, are likely to greatly impact the streamflow regime (Kitson, 1984). But the extent to which flow changes occur is dependent upon the purpose, design, and operation of the reservoir. Peak flows and high-flow conditions will be diminished—the extent of the reduction depends on the storage-outflow characteristics of the reservoir. The frequency of medium-flow levels will also usually be slightly increased by a reservoir. Low flows downstream of Illinois reservoirs are usually decreased, although they can be increased if reservoir operation releases a minimum protected flow. The average flow from the reservoir will usually be only slightly reduced, primarily through evaporation from the surface of the reservoir. Knapp (1988) estimates that the loss in average annual flow is approximately 0.3 cfs for every square mile of surface area. Net seepage losses from the reservoir to ground water are usually considered to be small.

Reservoirs on Small Watersheds

Most reservoirs on small watersheds in Illinois have uncontrolled outflow, meaning that outflow occurs over the spillway and no gates are used to regulate the flow. There are no streamgage records for locations directly downstream of such reservoirs to provide examples of their impacts. Knapp (1988) used computer modeling of a reservoir water budget in developing a methodology to roughly estimate the new flow regime downstream. Reservoirs located on small watersheds often have a comparatively large capacity relative to the amount of water flowing into the reservoir, and in these cases there is a greater impact on local streamflow. Figure 11 provides an example of the simulated outflow from a reservoir on a small watershed. If a reservoir with uncontrolled outflow is also used for water supply, the low flows from it are reduced to an even greater extent. The impacts of the reservoir on high and medium flows are usually attenuated downstream of the reservoir—with sufficient distance, the impacts of the reservoir may be difficult to detect.

Major Reservoirs

Table 10 lists the eight streamgages in Illinois located either directly downstream of or sufficiently close to a major reservoir to be affected. Of the gages listed, the Decatur, Shelbyville, Carlyle, and Plumfield gages are located directly downstream of the reservoir.

Mean Flow. None of the gaging stations used in the analysis demonstrate a significant change in mean annual flows.

Low Flows. All of the eight gages listed in table 10 are located downstream of reservoirs that release a minimum protected flow with the exception of the Sangamon River at Decatur. Lake Decatur presents a unique example of possible impacts on low flows because the lake serves a large water supply function. Withdrawals from this lake for water supply far surpass the normal losses from reservoir storage that occur as a result of evaporation and seepage. The impact of Lake Decatur withdrawals on low flows is illustrated in figure 12, which provides the flow frequency relationship at the Decatur gage and the estimated inflow into the reservoir.

Increased low flows in the Fox River at Algonquin, shown in figure 13, result from changes in the

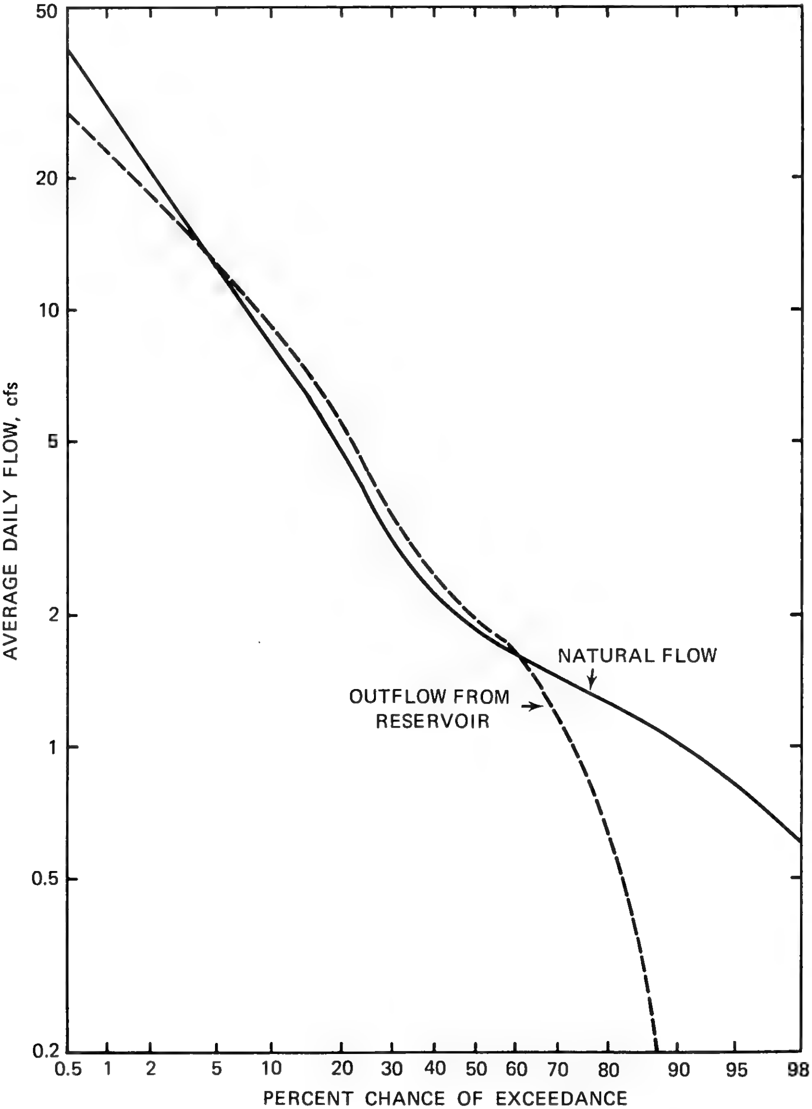


Figure 11. Effect of reservoir storage and evaporation on the outflow of Crystal Lake in McHenry County (from Knapp, 1988).

Table 10. Streamgages Used to Analyze Impacts of Major Reservoirs

Gage #	*Location*	*Watershed drainage area (mi^2)*	*Period of record*	*Reservoir*
05550000	Fox River at Algonquin	1,403	1915-1991	Fox Chain of Lakes
05573540	Sangamon River at Decatur	938	1982-1991	Lake Decatur
05578500	Salt Creek near Rowell	335	1943-1991	Clinton Lake
05592000	Kaskaskia River at Shelbyville	1,054	1941-1991	Lake Shelbyville
05592500	Kaskaskia River at Vandalia	1,940	1915-1991	Lake Shelbyville
05593000	Kaskaskia River at Carlyle	2,719	1938-1991	Carlyle Lake
05597000	Big Muddy River at Plumfield	794	1915-1991	Rend Lake
05599500	Big Muddy River at Murphysboro	2,169	1931-1991	Rend Lake

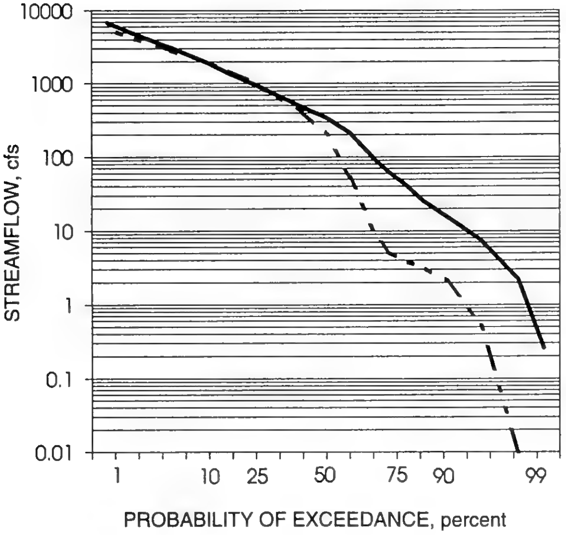


Figure 12. Lake Decatur inflow and outflow.

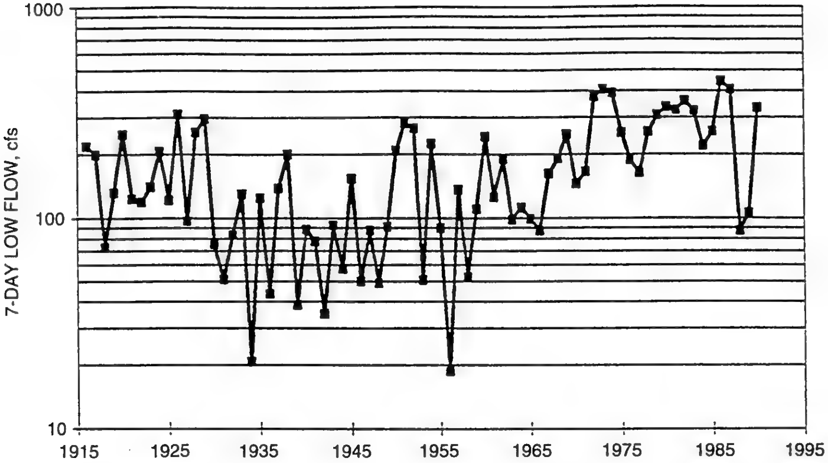


Figure 13. Annual 7-day low-flow series of the Fox River at Algonquin. Increases since the 1940s are caused by changes in reservoir operation from the Fox Chain of Lakes.

operation policy, rather than from any inherent dam characteristics. The gage records from all the other reservoirs demonstrate an increase in low flows after dam construction, all as a result of protected flow releases from the reservoir. Trends in low flows on these streams are therefore subject to changes in policy, as compared to a physical cause-and-effect relationship. The low-flow increases on the Salt Creek near Rowell and the Kaskaskia River gages is moderate, <10 cfs. The gages on the Big Muddy River show substantial increases in low flows, shown in figure 14.

High Flows. Lakes Shelbyville and Carlyle, located on the Kaskaskia River, and Rend Lake on the Big Muddy River were all built primarily for flood control. The three gages directly downstream of these reservoirs (at Shelbyville, Carlyle, and Plumfield) all show significant reductions in flood flows, as illustrated for Lake Carlyle in figure 15. Two gages, at Vandalia and Murphysboro, are located approximately 50 miles downstream of Lake Shelbyville and Rend Lake, respectively. Both of the gages show only slight reductions in flooding, below a level that is detected by the Kendall analysis. In a similar manner, the Rowell gage, located 13 miles downstream of Clinton Lake, shows only a small reduction in flooding. Lake Decatur and the Fox Chain of Lakes, upstream of the Decatur and Algonquin gages, respectively, are not designed to provide much reduction in flooding and therefore show no trend.

Seasonal Flow. Reservoirs do not ordinarily produce a seasonal change in streamflows. However, Lake Shelbyville and Rend Lake change pool levels between winter and summer. The Shelbyville and Plumfield gages both show an increase in average winter flow, resulting from the storage release when the pool level at each of these lakes is lowered in early winter.

IMPACTS OF WATER USE (STREAM WITHDRAWALS AND DISCHARGES)

Streams serve both as sources of water supply and as receptors of wastewater from municipalities and industry (table 11). If the stream is used as a water supply source, the effluent discharge will occur a short distance downstream from the withdrawal. In this case, since the withdrawal and discharge are usually of similar magnitude, there will be an insignificant impact on the flow in the stream, except perhaps over the short distance between the two facilities. More commonly, the municipal water supply is obtained from ground water, and the wastewater discharge to the stream

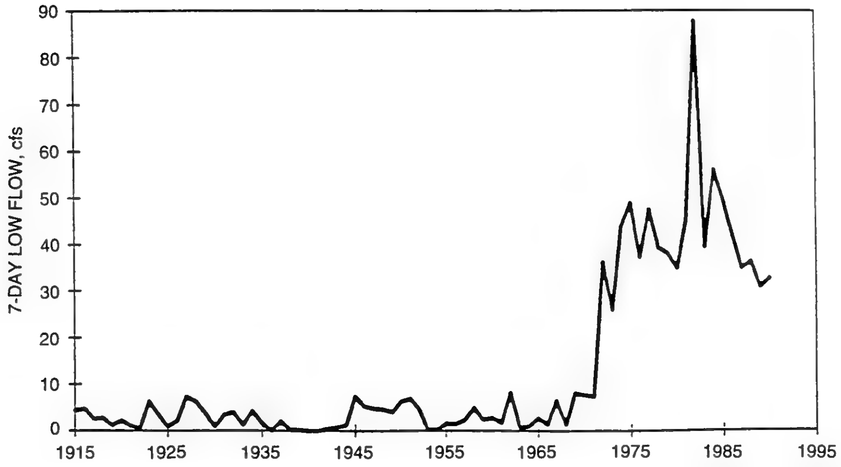


Figure 14. Annual 7-day low-flow series of the Big Muddy River at Plumfield. Increases since 1972 are caused by minimum flow releases from Rend Lake.

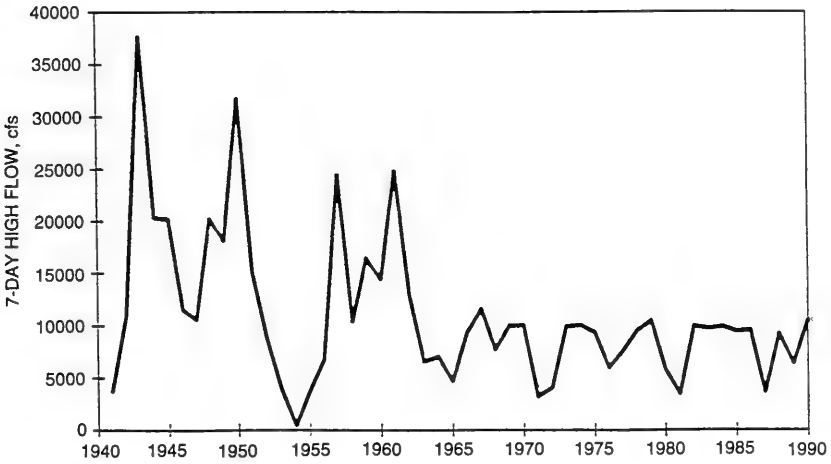


Figure 15. Annual 7-day high flow series of the Kaskaskia River at Carlyle. Reductions since 1967 are caused by flood control from Carlyle Lake.

Table 11. Streamgages Used to Analyze Impacts of Water Use

Gage #	*Location*	*Watershed drainage area (mi^2)*	*Period of record*	*Source of return flows*
WITHDRAWALS				
05554500	Vermilion River at Pontiac	579	1943-91	
05576000	S. Fork Sangamon River near Rochester	867	1950-91	
RETURN FLOWS				
03339000	Vermilion River near Danville	1,290	1929-91	Danville
05439500	S. Branch Kishwaukee River near Fairdale	387	1941-91	DeKalb
05469000	Henderson Creek near Oquawka	432	1935-91	Galesburg
05576500	Sangamon River at Riverton	2,618	1915-56, 1986-91	Decatur
05580950	Sugar Creek near Bloomington	34.4	1975-91	Bloomington-Normal
05581500	Sugar Creek near Hartsburg			Bloomington-Normal
05595200	Richland Creek near Hecker	129	1970-91	Belleville
RETURN FLOWS - URBAN WATERSHEDS				
05530000	Weller Creek at DesPlaines	13.2	1951-91	
05533000	Flag Creek near Willow Springs	16.5	1952-91	Hinsdale
05531500	Salt Creek at Western Springs	115.0	1946-91	MWRDGC
05537500	Long Run near Lemont	20.9	1951-91	Chickasaw Hills, Derby Meadows
05550500	Poplar Creek at Elgin	35.2	1952-91	Streamwood

increases the flow. During normal and high-flow conditions, the magnitude of these discharges is small compared to the ambient streamflow. However, in most cases the effluent discharge is *large* compared to the ambient low-flow conditions in the river, and a significant increase in low flow occurs. In a few cases, there is an interbasin transfer of water, such that a water supply withdrawal reduces the flow in one stream, and returns the wastewater to a different stream.

Mean Flow

Mean flows are affected only with a sizable effluent into a relatively small watershed. The gaging stations that show such an increase are all located in northeastern metropolitan Illinois. Direct withdrawals from streams are typically much smaller than the mean flow, primarily because they are designed to withdrawal no more water than what is available during dry periods. As a result, the impact of withdrawals on mean flow were not detected.

Low Flow

The Kendall analysis did not detect a statistically significant trend in low flows for the two stations downstream of withdrawals, the Vermilion River at Pontiac and the South Fork Sangamon River near Rochester. But in recent years, zero flows have occurred at these gages when they previously did not (see figure 16), suggesting a change in extreme low flows.

Twenty-six gaging stations downstream of return flows demonstrate trends in low flows. These include most stations in northeastern metropolitan Illinois, along with the Vermilion River near Danville, South Branch Kishwaukee River near Fairdale, Bureau Creek at Princeton, Sugar Creek near Hartsburg, Sangamon River at Riverton, and Henderson Creek near Oquawka. The location of all streams, gaged and ungaged, that likely have increased low flows caused by return flows is shown in figure 17. Other locations, such as Richland Creek near Hecker, are impacted by return flows but have not experienced an increase water use over the gage's period of record—thus they show no trend in low-flow conditions.

IMPACTS OF STREAM CHANNELIZATION

Lopinot (1972) reports that approximately 27 percent of the stream mileage in Illinois is channelized. The distribution of channelized streams in Illinois is summarized in Mattingly and Herricks (1991). Channelization is particularly common in the urban northeastern portion of Illinois, and locations where the natural drainage is relatively poor, particularly the east-central portion of the state. Impacts of stream channelization can include increased downstream flooding, a lowered water table, destroyed stream habitat, reduction in stream vegetation, and increased sedimentation downstream. No available research attempts to estimate the change in streamflow conditions in channelized areas, other than applied studies on localized flooding effects. Changes in the flow regime caused by channelization along an established stream are believed to be subtle. To detect the impacts of stream channelization on streamflow, it would be necessary to strategically place gages upstream and downstream of a channelized area. No such set of gages exists with which to conduct an analysis.

SUMMARY

Table 1 provides the results of the Kendall trend coefficients for all stations that were examined. The most common impact on streamflow appears to be that associated with climate change in northern Illinois. Climate change in this portion of the state has produced an increase in average and low flows in streams. There does not appear to be a significant, widespread increase in flooding from climate change, although increased flooding is observed throughout the Kankakee River basin. Water use appears to have the second largest impact on flows in Illinois, primarily from effluent discharges to streams. This results in an increase in low flows for numerous streams in the state. Many urban

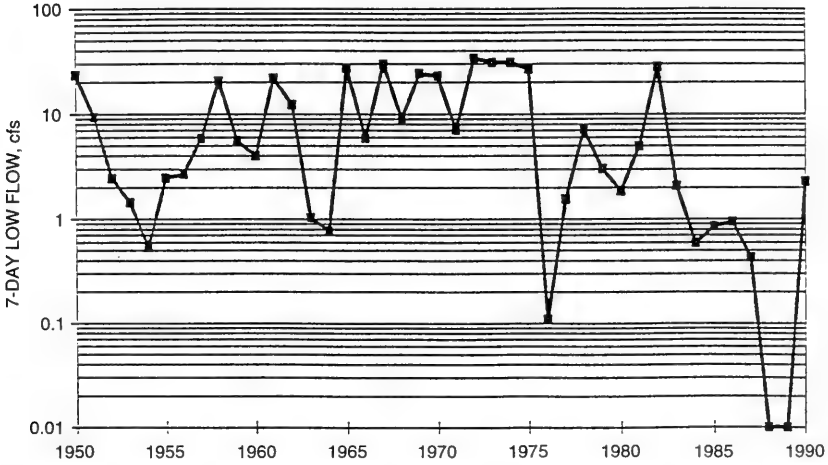


Figure 16. Annual 7-day low-flow series of the South Fork Sangamon River near Rochester. Extreme low flows in 1976, 1988, and 1989 are caused by withdrawals.

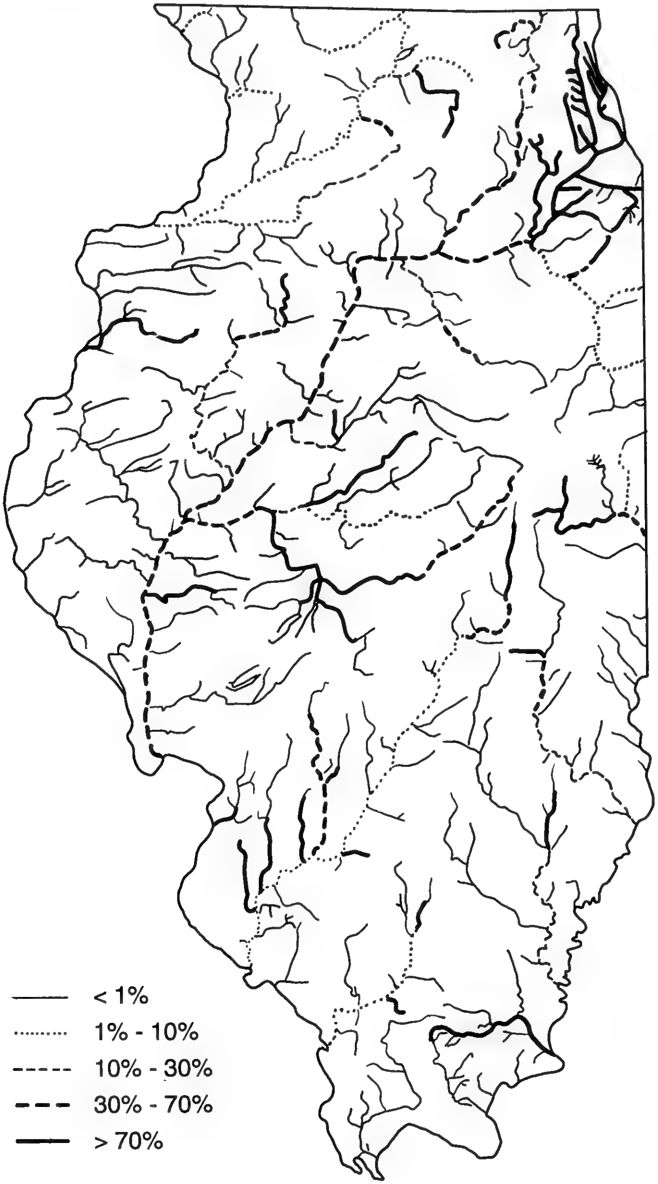


Figure 17. Percentage of the 7-day low flow in Illinois streams that originates from return flows.

streams in northeastern Illinois have considerable increases in high flows, regardless of whether stormwater detention facilities are present.

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INSTREAM FLOW USES, NEEDS, AND PROTECTION

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INTRODUCTION

A fundamental issue in all future water management programs and decisions will be the selection of protected instream flow levels. Suitable and equitable protected streamflow levels must be derived from information on instream flow needs for aquatic habitat, water-based recreation, waste assimilation, and withdrawals for municipal and industrial water supply. These flow levels are required to help maintain: 1) aquatic habitat without being seriously affected by water withdrawals during low-flow or critical periods, 2) water-based recreation and associated streamwater quality and quantity, 3) the assimilative capacity of a stream to receive effluents from wastewater plants without adversely affecting streamwater quality, 4) stream integrity in terms of biodiversity and strength of biotic communities, and 5) water withdrawals for municipal and industrial water supply from flows exceeding the protected flow level and allowable exceptions (if any) during emergency and severe drought conditions. An important part of water resources management is the allocation of water for instream uses.

The quantity of streamflow together with the condition of the instream physical habitat condition influences the quantity of suitable habitat for the target fish species. Hydraulic geometry of riffles and pools in a stream can be studied by making velocity and depth measurements and taking substrate samples along equally spaced transects from one riffle to another. A versatile, basin-wide aquatic habitat assessment model has been developed by Singh and Broeren (McConkey) 1989. This model replaces the hydraulic simulation submodel of the physical habitat suitability model (PHABSIM) developed by the U.S. Fish and Wildlife Service (USFWS). The new streamflow model is based on drainage area-discharge relationships, riffle-pool and stream hydraulic geometries, statistical distribution of depths and velocities in riffle-pool sequences, and adjustment factors to modify stream hydraulic geometry relationships derived from U.S. Geological Survey (USGS) field measurements to those developed from field studies. Desirable low-flow releases from in-channel reservoirs were investigated to meet instream flow needs downstream. The habitat part of the model requires fish preference or suitability data applicable to Illinois, and resolution of concerns regarding the assumption of independence of suitability indexes for depth, velocity, substrate, etc.

INSTREAM FLOW USES

If instream flow is considered as that flow contained within the channel (excluding overbank flow), it may vary from a low value during dry weather or drought conditions to a high value corresponding to about a two-year or median annual flood. Instream flow uses include fisheries and aquatic habitats, recreation, waste assimilation and pollution control, aesthetics, navigation (if natural flow provides navigable water depth without recourse to locks and dams), and hydropower (primarily limited to run-of-the-river plants). In addition, water may be withdrawn from streams for municipal and industrial uses and for irrigating agricultural lands. These uses are termed "off-stream" uses. Water for municipal and industrial uses serves a vital function, and a large part (80 to 90 percent) is returned to the stream as effluents from wastewater treatment plants. Sometimes locks and dams are built to provide year-round navigation in medium- to large-sized rivers; however, these structures adversely impact fisheries and aquatic habitats. To store water for municipal supplies, hydropower generation, or both, dams are built across streams. But they can change the river regime and have some adverse impacts on other uses.

Fisheries and Aquatic Habitats

There is a definite relationship between suitable habitat for various life stages of fish species and magnitude and quality of streamflow. Flows during a period or season, which may be significant for the development of a life stage, can vary from year to year, necessitating the development of seasonal flow duration curves. Using preference or suitability curves for various fish species and their life stages, stream hydraulic geometry relations, and information on substrates and dissolved oxygen conditions, weighted usable areas (WUA) at various seasonal flow durations can be identified for defining suitable streamflow for maintaining aquatic habitats at or above a desired level, without any irreparable loss or stress. WUA is a numerical index used to quantify the available suitable habitat in a stream or river.

Recreation

Water-based recreation includes many activities, such as swimming, fishing, boating, skiing, camping, and sightseeing. All these activities depend on various conditions: weather, season, water quality, surrounding environment, and magnitude of streamflow or stage. The most popular activities include fishing, boating, and swimming. The boating and swimming season generally lasts from mid-April to mid-September, and the fishing season from March to October. Many medium-sized streams and most small streams in central and southern Illinois naturally do not have enough flow during August and September to fully support these recreational activities. Despite voluminous literature on instream flow needs of fisheries and aquatic habitat, not much has been reported on the needs for supporting recreational use.

Wastewater Effluents and Pollution Control

Wastewater effluents from municipal and industrial treatment plants are discharged to receiving streams. The level of treatment at municipal plants is governed by the U.S. Environmental Protection Agency (USEPA) and the Illinois Environmental Protection Agency (IEPA). Complex procedures safeguard the assimilative capacity of streams, while regulatory mechanisms specify acceptable, mixing zone procedures for evaluation of stream assimilative capacities. Presently, basic secondary treatment is mandated for a dilution ratio ≥ 5; the dilution ratio is obtained by dividing the 7-day, 10-year low flow ($Q_{7,10}$) in the receiving stream by the effluent flow (both in similar units). The $Q_{7,10}$ is the mean, lowest consecutive 7-day flow that occurs once in 10 years on the average. The $Q_{7,10}$ is obtained by adjusting for natural flow conditions (i.e., without any water withdrawals or discharge of effluents to the stream) by the recent years' withdrawals and effluent discharges, expected under dry weather conditions. Singh and Stall (1973) developed $Q_{7,10}$ values along all Illinois streams, and recent updates are given by Singh et al. (1988b, 1988c) and Singh and Ramamurthy (1993). Higher levels of treatment are mandated for dilution ratios <5. Treatment of industrial wastes varies according to the type of waste.

Another regulation is mandated for the discharge of effluents containing carcinogenic substances. The criteria for the inclusion of carcinogenic substances in the priority pollutant list of the USEPA were developed by using lifetime exposures to the target substances (IEPA, 1990) in terms of ingesting 2 liters (L) of water and 20 grams (g) of fish each day for 70 years. The average concentration of carcinogens over a lifetime is a function of the harmonic mean flow (Q_{HM}) of the stream.

Aesthetics

Aesthetics is that branch of philosophy relating to the nature and forms of beauty—a study of the mental and emotional response to beauty in the arts, etc. Considering a stream without flow modifications and its environs, the perceived mental and emotional response serves as a benchmark. Flow modifications to accommodate withdrawals from a stream for offstream use may result in a minor to considerable reduction in flow during medium-flow to low-flow conditions, respectively. These flow modifications may adversely affect the aesthetics. If the flow reductions are minor and over small periods, the impacts on aesthetics will be minor. Creation of a navigable waterway (by constructing locks and dams) and a reservoir (to serve multiple purposes) may improve the aesthetics in certain parts of the reach but detract from it in other reaches.

Navigation

There are practically no navigable rivers in Illinois except the boundary rivers: the Mississippi River below Lock and Dam 26 near St. Louis, Missouri, and the Ohio River below Lock and Dam 53 upstream of Cairo, Illinois. These rivers would be navigable without locks and dams to provide a suitable depth of water for barges. Only two intrastate rivers are navigable: the Illinois River and Waterway from Lake Michigan to Grafton near the confluence with the Mississippi River, and the lower Kaskaskia River from Fayetteville to the junction with the Mississippi River. These rivers have locks and dams, which are operated to maintain minimum navigable depths of 8 to 9 feet even during dry weather conditions. During low-flow conditions, the long, near-horizontal pools, created by locks and dams, have very small flow velocities.

Hydropower and Other Plants

The dams in Illinois are primarily low-head dams, and low-head hydropower generation can be economically, environmentally, and institutionally feasible at some of them. Low-head hydropower potential in Illinois is estimated as one percent of all the power required in the state, but only about one-fifth of that potential is presently being generated (Singh, 1987). A study conducted by Wapora, Inc. (Lindsey and Sweeney, 1981), lists six active hydropower facilities in Illinois. Hydropower potential in Illinois is limited because of low hydraulic heads, considerable seasonal variability of streamflow, and high generation costs compared to costs at fossil-fuel plants. Thermal and nuclear power plants require large quantities of water for cooling purposes. Evaporation losses result in reduction of streamflow, while thermal plumes caused by relatively hot water releases from plants cam affect fisheries and aquatic habitats for some distance below these releases. Such impacts and their extent will require further investigation.

QUANTIFICATION OF INSTREAM FLOW NEEDS

Instream flow supports instream uses such as aquatic habitat, water-based recreation, wildlife, waste assimilation, and riparian vegetation. The desirable magnitudes of streamflows that support these uses at various times of the year may be defined as the instream flow needs (IFN). The Federal Fish and Wildlife Coordination Act requires federal agencies to consider instream flow and environmental values in projects under the administrative or regulatory jurisdiction of federal agencies (DWR, 1982). Many states have passed or are in the process of passing laws to control water withdrawals, diversions, and modifications in streamflow, particularly during low-flow periods. Present IFN values are mostly determined for suitable protection of fish and aquatic habitat. The flow needs for other uses such as recreation, waste assimilation, and wildlife are presumed to be covered by those for fish and aquatic habitat. The USFWS has led a well-organized, concerted effort to develop suitable methodologies for assessing seasonal IFN values.

Instream Flow Incremental Methodology

Physical habitat is a function of stream geometry, streamflow, and other relevant factors, such as temperature and water quality. Velocity and depth of flow, channel substrate characteristics, and distribution of riffles and pools influence the diversity and abundance of aquatic insects and benthic communities that sustain fish and stream ecology. The USFWS has collected field data on the relative abundance of various fish species and their life stages, stream geometry parameters (velocity, depth, and width of flow), and channel substrates, at different flows in various streams and rivers in the west. Curves of fish preference or suitability values (varying from 0 to 1) versus values of parameters, such as velocity and depth of flows, were developed for various fish species and their life stages. The developed methodology, known as instream flow incremental methodology (IFIM), has been computerized as PHABSIM, which essentially consists of two submodels—a hydraulic simulation model and a habitat suitability model. Organization and information processing in the IFIM is shown in figure 1.

The basic concept in IFIM (Milhous and Grenney, 1980) is that in any instant of time and in a small surface area of the stream (dA), there exists a function φ(P) that relates physical parameters (P) to the worth of the area as a physical habitat or d(WUA):

$$d(WUA) = \varphi\,(P) \text{ x } dA \qquad (1)$$

Considering stream parameters such as velocity v, depth d, and substrate s,

$$WUA = \sum_{i=1}^{n} P(v)_i \times P(d)_i \times P(s)_i \times \ldots\ldots\ldots\ldots \times dA_i \qquad (2)$$

in which surface area of the stream equals $\sum_{i=1}^{n} (dA)_i$; $P(v)_i$ denotes preference, usability or suitability of a unit area in element i in respect to velocity v_i for the fish species and its life stage under consideration; similarly for depth d_i and substrate s_i, etc. A species of fish will prefer to live in physical conditions (based on v, d, s, etc.) that are most suitable to its present life stage. The parameters are considered as independent variables, based on an extensive literature review by Stalnaker (1980).

Several issues surround the application of the WUA equation: uncertainty about the degree of interdependence among the stream parameters, lack of transferability of results from one stream to others in the region, and questionable assumptions and simplifications in the hydraulic simulation submodel. It is based on uniform flow conditions, whereas during low flows, nonuniform flow conditions prevail because of riffle-pool sequences. Field measurements of velocity and depth can produce significantly biased results in a reach when the transects are not positioned to represent the relative weight of riffle and pool lengths.

The water surface profile (WSP) in the hydraulic simulation submodel does not consider relatively flat pools and steep riffles that act as dams that hold water behind them during low flows. Recent improvements to the submodel, such as IFG4, still use Manning's equation and calibrate the log-log stage discharge relation by adjusting cell roughness without considering surrounding cells. Miller and Wenzel (1984) investigated hydraulic modeling of low flows and found it to be futile in the case of alluvial channels.

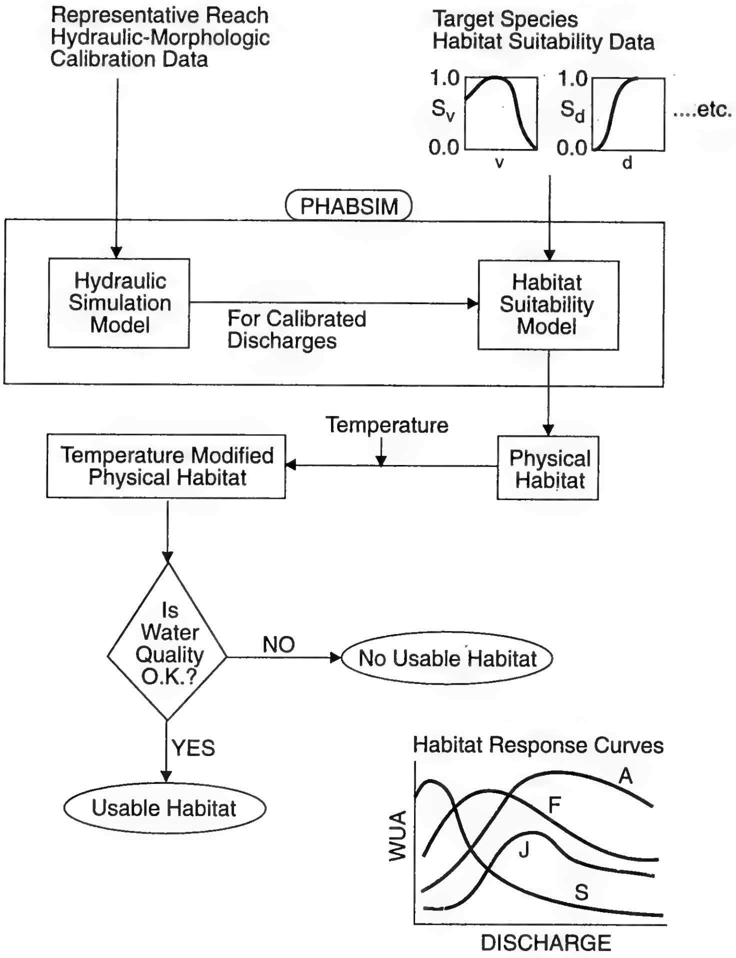

Figure 1. Organization and information processing to develop WUA curves (after Sale, 1980, and Milhous and Grenney, 1980)

Singh and Broeren (McConkey) Method

Natural streams have riffles and pools—the riffles act as dams and hold water in the pools behind them during low flows. As streamflow decreases, the relative differences in depth and velocities in riffles and pools increase. These differences afford suitable habitat for various fish species and their life stages. Leopold and Maddock (1953) have shown that stream characteristics of width, depth, and velocity are related to discharge as simple power functions up to bankfull discharges. Stall and Fok (1968) extended the concept by incorporating flow duration and drainage area in these relationships:

$$\ln(\text{parameter}) = a + bF + c \ln (A_d) \qquad (3)$$

where a, b, and c are coefficients, F is the decimal flow duration, and A_d is the drainage area.

Singh and Broeren (1989) developed a basinwide flow model to replace the hydraulic simulation submodel of the PHABSIM. Evaluation of the WUA of a habitat suitable for a particular fish species requires knowledge of the local variations in depths and velocities. The model integrates various duration flows and drainage area relationships, stream hydraulic geometry relations developed from USGS flow measurement data, statistical joint distribution of depths and velocities in riffle-pool sequences, and adjustment factors for modifying hydraulic geometry parameters to those derived from field studies.

The first step is the development of relationships among discharges corresponding to various flow durations and watershed parameters such as drainage area and stream length, but mostly drainage area A_d:

$$\log Q(F) = A(F) + B(F) \log A_d \qquad (4)$$

where A(F) and B(F) are regression coefficients. Values of A(F) and B(F) depend on flow duration F. The second step entails development of at-a-station stream hydraulic geometry relations for in-channel flows,

$$\log (VAR) = a_o + a_1 (\log Q) + a_2 (\log Q)^2 + \ldots\ldots \qquad (5)$$

where VAR = velocity (V), depth (D), or width (W). Then the most significant regression equations are derived using calculated values of variables at specified flow durations for all stations within a hydrologically homogeneous region:

$$\log (VAR) = a + bF + (c + dF) \log A_d \qquad (6)$$

The third step involves selection of representative study reaches in various order streams. Each reach must have a minimum of two pools and three riffles. Five transects are equally spaced between riffles, for a minimum of 13 transects in a reach. Six measurements of velocities and depth are taken along each transect. From the set of 78 measurements for velocities and depths, the statistical joint distribution of depths and velocities is determined.

The fourth step deals with development of adjustment factors applicable to stream hydraulic geometry parameters on the basis of values calculated from field studies. The details of all these steps are given by Singh et al. (1986). The integration of this model with the habitat model of the PHABSIM allows basin-wide habitat evaluations and simulations for flow scenarios within the range of discharges corresponding to 10 and 90 percent flow durations.

Streamflow Waste Assimilative Capacity

The IEPA maintains streamwater quality by regulating the level of treatment at wastewater plants so that the effluents entering the stream do not significantly affect water quality. The $Q_{7,10}$ just upstream of the effluent inflow is used in calculating the dilution ratio or the ratio of $Q_{7,10}$ to the effluent inflow. The $Q_{7,10}$ is the lowest average daily flow over a consecutive 7-day period, occurring once in 10 years on the average. For a dilution ratio ≥ 5, secondary treatment is generally required. However, when the ratio is <5, a higher level of treatment is necessary. The $Q_{7,10}$ values are usually in a range of 99 percent flow duration (99 percent flow duration discharge is equaled or exceeded 99 percent of the days over a number of years), which is a very low flow. The protected flows for accommodating inflow needs usually range from 70 to 85 percent flow duration and are much higher than the $Q_{7,10}$.

Another consideration is the Q_{HM} of a stream. This parameter is recommended for regulating carcinogenic waste concentrations in streamwater. The daily average concentration in milligrams per liter (mg/L) is equal to the waste load in milligrams per day (mg/day) divided by Q_{HM} in liters per day (L/day):

$$\begin{aligned} C_{av} &= \frac{1}{n} \sum_{i=1}^{n} \frac{Wasteload, W_i}{Q_i} \\ &= \frac{W}{n} \sum_{i=1}^{n} \frac{1}{Q_i} \qquad \text{; considering constant W} \quad (7) \\ &= \frac{W}{Q_{HM}} \end{aligned}$$

where n = number of days in the flow record and Q is the streamflow.

Withdrawal of water for offstream uses during low and medium flows can significantly reduce the Q_{HM} and thus increase C_{av}. If it increases beyond the permissible value, the waste load to the stream will have to be reduced to lower C_{av}. However, the reduction becomes smaller as the magnitude of protected flow for meeting instream flow needs is increased.

Values of $Q_{7,10}$ (Singh and Ramamurthy, 1993; Singh et al., 1988b, 1988c) and Q_{HM} (Singh and Ramamurthy, 1991) are given in table 1 at USGS streamgaging stations in ten regions (as delineated in figure 2), together with the drainage area in square miles. The information is also available on the Geographic Information System database. Values of $Q_{7,10}$ and Q_{HM} at streamgaging stations in Illinois are shown in figures 3 and 4.

Water-Based Recreation

Only a few studies are available on recreation, and most of them are related to fishing. These studies give results of polls and questionnaire surveys related to what an angler will pay voluntarily to enjoy the fishing activity. Vaughan and Russell (1982) estimated a fishing day's worth at $7 to $24, depending on the type of fish available. Other studies, mostly site-specific, evaluate fishing and some hunting. However, these studies do not take into account the relative abundance of various fish species and associated variations with streamflow changes.

OTHER COMPETING USES

Three main offstream uses that compete with instream flow needs are public and industrial water supply and irrigation. A recent study (Nealon et al., 1989) shows that water supplies can be easily and economically developed from one or more of the three major aquifer systems in a 35-county area in northern Illinois, with the exception of the collar counties around Chicago (Cook, DuPage, Kane, Lake, and Will Counties). In these five counties, Lake Michigan water allocations and some supplies from major rivers are being used to reduce overpumping of deep aquifers. In central and southern Illinois, surface water from streams and rivers meets most of the municipal and industrial water supply needs.

Irrigation of crops is a highly consumptive use of water. The demand, limited to a few months in the summer, varies greatly from year to year, depending on soil moisture deficits, temperature, and precipitation conditions. In areas where sufficient water is not available to fully meet crop irrigation demands, supplemental irrigation may provide some protection against major crop failures. On-farm ponds and storage impoundments can be filled in March, April, or May with withdrawals from streams, aquifers, or both; and they can augment other supplies during critical demand periods for most irrigators. This mode of conjunctive use may lessen water-use conflicts between farmers and others in a region during a dry period or drought year.

Public and Industrial Water Supply

Broeren and Singh (1989) investigated the adequacy of Illinois surface water supply systems to meet future demands up to the year 2020. Ninety such systems serve about 350 towns in central and southern Illinois. Only nine of these systems lie in the northern counties included in the report by Nealon et al. (1989). All 90 systems were inventoried, their water sources identified, and future use estimates developed (Singh et al., 1988a) through the use of the population projections from the Illinois Bureau of the Budget. A new methodology was developed to compute future reservoir storages, allowing for their sediment consolidation with time (Singh and Durgunoglu, 1990). Broeren and Singh (1989) identified ten systems inadequate to meet 1990 demand during a 20-year drought and another ten systems during a 50-year drought. Various mitigatory measures to supplement system supplies have been investigated (Singh and Broeren, 1990). The system inadequacies result mainly from two causes: a decrease in reservoir yield because of continuing sedimentation (mostly due to provision of conventional overflow spillways), and an increase in water demand because of population and industrial growth.

Irrigation

In 1970, 40,000 acres in Illinois were irrigated, but this number has been growing by 9,000 to 10,000 acres per year since then. Of about 240,000 acres irrigated in 1987, Mason County accounted for 36 percent and four other counties (Kankakee, Lee, Tazewell, and Whiteside) accounted for 29 percent (Bowman and Kimpel, 1991). Ground water supplies 96 percent of the area; the rest is served from surface water sources. Most of the irrigated area is in the northern half of Illinois where adequate ground-water supplies can be developed at a reasonable cost. There has been a significant increase in irrigation water use for specialty crops. In some counties with considerable ground-water withdrawals, the lowering of ground-water levels and quality can occur with the continuing increase in withdrawals and seepage of farm water to the aquifers.

Table 1. Gaging Stations, 7-Day, 10-Year Low Flows ($Q_{7,10}$), and Harmonic Mean Flows (Q_{HM})

USGS gage	*Stream and Gaging station*	*Area (mi^2)*	*$Q_{7,10}$ (cfs)*	*Q_{HM} (cfs)*
Region 1				
05414820	Sinsinawa River near Menominee	39.6	5.0	21
05415000	Galena River at Buncombe, WI	125	14.0	60
05415500	East Fork Galena River at Council Hill	20	2.3	6.6
05419000	Apple River near Hanover	247	20.1	92
05420000	Plum River below Carroll Creek near Savanna	230	11.2	70
05420500	Mississippi River at Clinton, IA	86500	13900	37400
05434500	Pecatonica River at Martintown, WI	1034	153	580
05435000	Cedar Creek near Winslow	1.30	0.0	0.0
05435500	Pecatonica River at Freeport	1326	181	720
05437000	Pecatonica River at Shirland	2550	408	1380
05437500	Rock River at Rockton	6363	859	3100
05437695	Keith Creek at Rockford	13.4	0.3	3.0
05438250	Coon Creek at Riley	85.1	2.5	25
05438500	Kishwaukee River at Belvidere	538	35.6	200
05439000	S. Br. Kishwaukee River at DeKalb	77.70	0.2	10
05439500	S. Br. Kishwaukee River near Fairdale	387	12.7	74
05440000	Kishwaukee River near Perryville	1099	69.1	350
05440500	Killbuck Creek near Monroe Center	117	3.1	17
05441000	Leaf River at Leaf River	103	8.6	42
05441500	Rock River at Oregon	8205	1148	4300
05442000	Kyte River near Flagg Center	116	6.0	22
05443500	Rock River at Como	8755	1167	4730
05444000	Elkhorn Creek near Penrose	146	15.0	60
05445500	Rock Creek near Morrison	158	14.0	66
05446500	Rock River near Joslin	9551	1376	5280
05447000	Green River at Amboy	201	5.9	37
05447500	Green River near Geneseo	1003	50.0	275
05448000	Mill Creek at Milan	62.4	0.3	3.0
Region 2				
05527500	Kankakee River near Wilmington	5150	496	2240
05527800	Des Plaines River at Russell	123	0.4	12
05528000	Des Plaines River near Gurnee	232	37.0	100
05528500	Buffalo Creek near Wheeling	19.6	0.3	2.0
05529000	Des Plaines River near Des Plaines	360	55.0	150
05529500	McDonald Creek near Mount Prospect	7.90	0.0	0.0
05530000	Weller Creek at Des Plaines	13.2	0.1	1.2
05530500	Willow Creek near Park Ridge	19.7	40.0	53
05530990	Salt Creek at Rolling Meadows	30.5	0.2	3.8
05531500	Salt Creek at Western Springs	114	38.0	81
05532000	Addison Creek at Bellwood	17.9	2.2	8.0
05532500	Des Plaines River at Riverside	630	139	370
05533000	Flag Creek near Willow Springs	16.5	9.0	15
05534500	N. Br. Chicago River at Deerfield	19.7	0.3	2.0
05535000	Skokie River at Lake Forest	13.0	0.4	3.5
05535070	Skokie River near Highland Park	21.1	0.7	6.4
05535500	W. F. of N. Br. Chicago River at Northbrook	11.5	2.7	7.0
05536000	N. Br. Chicago River at Niles	100	17.0	48
05536195	Little Calumet River at Munster, IN	90.0	6.9	24
05536210	Thorn Creek near Chicago Heights	17.2	0.3	1.5
05536215	Thorn Creek at Glenwood	24.7	16.0	28
05536235	Deer Creek near Chicago Heights	23.1	0.2	2.2
05536255	Butterfield Creek at Flossmoor	23.5	0.0	0.0

Table 1. Continued

USGS gage	*Stream and gaging station*	*Area (mi^2)*	*$Q_{7,10}$ (cfs)*	*Q_{HM} (cfs)*
05536265	Lansing Ditch near Lansing	8.80	0.2	1.2
05536270	North Creek near Lansing	16.8	1.4	2.7
05536275	Thorn Creek at Thornton	104	20.5	48
05536290	Little Calumet River at South Holland	205	29.0	85
05536340	Midlothian Creek at Oak Forest	12.6	0.3	1.0
05536500	Tinley Creek near Palos Park	11.2	0.0	0.0
05537000	Chicago Sanitary and Ship Canal at Lockport	739	1755	2900
05537500	Long Run near Lemont	20.9	0.4	1.2
05539000	Hickory Creek at Joliet	107	4.0	19
05539900	W. Br. Du Page River near West Chicago	28.5	9.0	23
05540095	W. Br. Du Page River near Warrenville	90.4	20.0	52
05540500	Du Page River at Shorewood	324	87.0	185
05543500	Illinois River at Marseilles	8259	3185	7200
05546500	Fox River at Wilmot, WI	868	73.0	380
05548280	Nippersink Creek near Spring Grove	192	21.6	95
05549000	Boone Creek near McHenry	15.5	3.7	10
05550000	Fox River at Algonquin	1403	115	625
05550500	Poplar Creek at Elgin	35.2	0.5	5.4
05551200	Ferson Creek near St. Charles	51.7	1.0	12
05551700	Blackberry Creek near Yorkville	70.2	4.5	27
05552500	Fox River at Dayton	2642	260	1190
05519500	West Creek near Schneider, IN	54.7	6.3	20
Region 3				
05520000	Singleton Ditch at Illinois	220	21.7	80
05520500	Kankakee River at Momence	2294	426	1540
05525000	Iroquois River at Iroquois	686	15.0	130
05525500	Sugar Creek at Milford	446	3.6	40
05526000	Iroquois River near Chebanse	2091	30.0	300
05526500	Terry Creek near Custer Park	12.1	0.0*	2.5
05527500	Kankakee River near Wilmington	5150	480	2240
05542000	Mazon River near Coal City	455	0.2	21
05543500	Illinois River at Marseilles	8259	3180	7200
05554000	N. F. Vermilion River near Charlotte	186	0.0	0.0
05554500	Vermilion River at Pontiac	579	1.2	21
05555300	Vermilion River near Leonore	1251	6.6	99
05559500	Crow Creek near Washburn	115	0.0	0.0
05560500	Farm Creek at Farmdale	27.4	0.0	2.2
05561000	Ackerman Creek at Farmdale	11.2	0.0	0.0
05561500	Fondulac Creek near East Peoria	5.54	0.0	0.0
05562000	Farm Creek at East Peoria	61.2	0.0	4.2
05564400	Money Creek near Towanda	49.0	0.0	0.0
05564500	Money Creek near Hudson	53.1	0.0	0.0
05565000	Hickory Creek near Hudson	9.81	0.0	0.0
05566000	E. Br. Panther Creek near Gridley	6.3	0.0	0.0
05566500	E. Br. Panther Creek at El Paso	30.5	0.0	0.0
05567000	Panther Creek near El Paso	93.9	0.0	1.2
05567500	Mackinaw River near Congerville	767	1.2	40
05568000	Mackinaw River near Green Valley	1089	25.2	170
05568500	Illinois River at Kingston Mines	15819	3050	10900
Region 4				
05466000	Edwards River near Orion	155	1.8	17
05466500	Edwards River near New Boston	445	6.9	66
05467000	Pope Creek near Keithsburg	183	2.0	21

Table 1. Continued

USGS gage	*Stream and gaging station*	*Area (mi^2)*	$Q_{7,10}$ *(cfs)*	Q_{HM} *(cfs)*
05467500	Henderson Creek near Little York	151	0.0*	10
05468000	North Henderson Creek near Seaton	67.1	0.0	3.3
05468500	Cedar Creek at Little York	130	7.7	24
05469000	Henderson Creek near Oquawka	432	8.1	58
05469500	South Henderson Creek at Biggsville	82.9	0.0	0.0
05556500	Bureau Creek at Princeton	196	0.9	13
05557000	West Bureau Creek at Wyanet	86.7	0.0	0.0
05557500	East Bureau Creek near Bureau	99.0	0.0	0.0
05558000	Bureau Creek at Bureau	485	31.0	80
05558500	Crow Creek near Henry	56.2	0.0	0.0
05559000	Gimlet Creek at Sparland	5.70	0.0	0.0
05563000	Kickapoo Creek near Kickapoo	119	0.5	9.0
05563500	Kickapoo Creek at Peoria	297	1.1	21
05568500	Illinois River at Kingston Mines	15819	3050	10900
05568800	Indian Creek near Wyoming	62.7	0.2	7.0
05569500	Spoon River at London Mills	1062	10.4	153
05570000	Spoon River at Seville	1636	22.0	235
Region 5				
05568500	Illinois River at Kingston Mines	15819	3050	10900
05570910	Sangamon River at Fisher	240	0.0*	11
05571000	Sangamon River at Mahomet	362	0.5	21
05571500	Goose Creek near Deland	47.9	0.0	0.0
05572000	Sangamon River at Monticello	550	1.9	38
05572450	Friends Creek at Argenta	111	0.0	0.7
05573540	Sangamon River at Rt. 48 at Decatur	938	0.2	14
05574000	South F. Sangamon River near Nokomis	11.0	0.0	0.0
05574500	Flat Branch near Taylorville	276	0.0	5.0
05575500	South F. Sangamon River at Kincaid	562	1.5	13
05575800	Horse Creek at Pawnee	52.2	0.0	0.0
05575830	Brush Creek near Divernon	32.4	0.0	0.0
05576000	South F. Sangamon River near Rochester	867	0.9	18
05576500	Sangamon River at Riverton	2618	59.5	200
05577500	Spring Creek at Springfield	107	0.0	0.0
05578500	Salt Creek near Rowell	335	6.4	35
05579500	Lake Fork near Cornland	214	2.4	23
05580000	Kickapoo Creek at Waynesville	227	1.2	13
05580500	Kickapoo Creek near Lincoln	306	3.2	25
05580950	Sugar Creek near Bloomington	34.6	15.6	30
05581500	Sugar Creek near Hartsburg	333	15.7	80
05582000	Salt Creek near Greenview	1804	86.0	370
05582500	Crane Creek near Easton	26.5	0.9	8.0
05583000	Sangamon River near Oakford	5093	238	990
Region 6				
05474500	Mississippi River at Keokuk, IA	119000	15260	50300
05495500	Bear Creek near Marcelline	3490	0.1	5.0
05502020	Hadley Creek near Barry	40.9	0.0	0.0
05502040	Hadley Creek at Kinderhook	72.7	0.0	0.0
05512500	Bay Creek at Pittsfield	39.4	0.0	1.0
05513000	Bay Creek at Nebo	161	0.2	4.0
05584400	Drowning Fork at Bushnell	26.3	0.0	0.0
05584500	La Moine River at Colmar	655	2.0	34

Table 1. Continued

USGS gage	*Stream and gaging station*	*Area (mi^2)*	*$Q_{7,10}$ (cfs)*	*Q_{HM} (cfs)*
05585000	La Moine River at Ripley	1293	11.0	100
05585500	Illinois River at Meredosia	26028	3700	14490
05586000	N. F. Mauvaise Terre Creek near Jacksonville	29.1	0.0	0.0
05586500	Hurricane Creek near Roodhouse	2.30	0.0	0.0
05586800	Otter Creek near Palmyra	61.1	0.0	0.0
05587000	Macoupin Creek near Kane	868	2.4	26
Region 7				
05587500	Mississippi River at Alton	171500	21490	73000
05587900	Cahokia Creek at Edwardsville	212	0.5	4.0
05588000	Indian Creek at Wanda	36.7	0.0	0.0
05589500	Canteen Creek at Caseyville	22.6	0.0	0.5
05590000	Kaskaskia Ditch at Bondville	12.4	0.1	1.1
05590400	Kaskaskia River near Pesotum	109	13.0	26
05590800	Lake Fork at Atwood	149	0.0	0.0
05591200	Kaskaskia River at Cooks Mill	473	10.3	43
05591500	Asa Creek at Sullivan	8.10	0.0	0.0
05591550	Whitley Creek near Allenville	34.6	0.0	0.0
05591700	West Okaw River near Lovington	112	0.0	0.0
05592000	Kaskaskia River at Shelbyville	1054	10.0	40
05592050	Robinson Creek near Shelbyville	93.1	0.0	0.0
05592100	Kaskaskia River near Cowden	1330	17.0	90
05592300	Wolf Creek near Beecher City	47.9	0.0	0.0
05592500	Kaskaskia River at Vandalia	1940	39.0	225
05592800	Hurricane Creek near Mulberry Grove	152	0.2	3.0
05592900	E. F. Kaskaskia River near Sandoval	113	0.0	0.0
05593000	Kaskaskia River at Carlyle	2719	50.0	195
05593520	Crooked Creek near Hoffman	254	2.0	11
05593575	Little Crooked Creek near New Minden	84.3	0.0	0.0
05593600	Blue Grass Creek near Raymond	17.3	0.0	0.0
05593900	E. F. Shoal Creek near Coffeen	55.5	0.0	0.0
05594000	Shoal Creek near Breese	735	1.9	19
05594090	Sugar Creek at Albers	124	0.2	2.7
05594100	Kaskaskia River near Venedy Station	4393	68.0	450
05594330	Mud Creek near Marissa	72.4	0.0	0.0
05594450	Silver Creek near Troy	154	0.1	2.0
05594800	Silver Creek near Freeburg	464	1.0	21
05595000	Kaskaskia River at New Athens	5181	99.0	570
05595200	Richland Creek near Hecker	129	5.0	19
05595270	Plum Creek Tributary near Tilden	0.59	0.6	0.0
07010000	Mississippi River at St. Louis, MO	697000	46500	142000
07020500	Mississippi River at Chester	708600	47600	148000
Region 8				
03336000	Wabash River at Covington, IN	8218	756	3880
03336500	Bluegrass Creek at Potomac	35.0	0.0	0.00
03336645	M. F. Vermilion River above Oakwood	432	3.6	47
03336900	Salt Fork near St. Joseph	134	4.1	26
03337000	Boneyard Creek at Urbana	4.50	0.6	1.3
03337500	Saline Branch at Urbana	68.0	2.4	9.9
03338000	Salt Fork near Homer	340	22.7	78
03338500	Vermilion River near Catlin	958	30.2	140
03339000	Vermilion River near Danville	1290	42.2	190

Table 1. Concluded

USGS gage	*Stream and gaging station*	*Area* (*mi^2*)	*$Q_{7,10}$* (*cfs*)	*Q_{HM}* (*cfs*)
03340500	Wabash River at Montezuma, IN	11118	895	4810
03341420	Brouilletts Creek near Universal, IN	331	1.1	18
03341500	Wabash River at Terre Haute, IN	12265	1040	5400
03342000	Wabash River at Riverton, IN	13161	1274	6080
03343000	Wabash River at Vincennes, IN	13706	1337	6440
03343400	Embarras River near Camargo	186	0.5	2.0
03344000	Embarras River near Diona	919	4.9	90
03344500	Range Creek near Casey	7.60	0.0	0.0
03345500	Embarras River at Ste. Marie	1516	16.6	150
03346000	North Fork Embarras River near Oblong	319	0.2	4.5
03346500	Embarras River at Lawrenceville	2333	35.3	222
Region 9				
03343000	Wabash River at Vincennes, IN	13706	1337	6440
03347500	Wabash River at Mt. Carmel	28635	2504	13000
03378000	Bonpas Creek at Browns	228	0.0	0.0
03348500	Wabash River at New Harmony	29160	2634	13340
03378635	Little Wabash River near Effingham	240	0.0	0.0
03378900	Little Wabash River at Louisville	745	0.6	8.0
03379500	Little Wabash River below Clay City	1131	1.4	15
03380350	Skillet Fork near Iuka	208	0.0	0.0
03380475	Horse Creek near Keenes	97.2	0.0	0.0
03380500	Skillet Fork at Wayne City	464	0.1	2.7
03381500	Little Wabash River at Carmi	3102	6.8	90
Region 10				
03382000	Middle Fork Saline River near Harrisburg	198	0.7	2.0
03382100	South Fork Saline River near Carrier Mills	147	2.3	13
03382170	Brushy Creek near Harco	13.3	0.0	0.0
03382500	Saline River near Junction	1051	4.2	25
03382510	Eagle Creek near Equality	8.51	0.0	0.0
03384450	Lusk Creek near Eddyville	42.9	0.0	0.0
03384500	Ohio River at Dam 51 at Golconda	143900	14610	66000
03385000	Hayes Creek at Glendale	19.1	0.0	0.0
03385500	Lake Glendale Inlet near Dixon Springs	1.10	0.0	0.0
03386000	Lake Glendale Outlet near Dixon Springs	1.98	0.0	0.0
03386500	Sugar Creek near Dixon Springs	9.70	0.0	0.0
03611500	Ohio River at Metropolis	203000	53820	141000
03612000	Cache River at Forman	244	0.0	3.8
05595500	Marys River near Sparta	17.8	0.0	0.0
05595730	Rayse Creek near Waltonville	88.0	0.0	0.0
05595800	Sevenmile Creek near Mt. Vernon	21.1	0.0	0.0
05596000	Big Muddy River near Benton	502	32.0	64
05596500	Tilley Creek near West Frankfort	3.87	0.0	0.0
05597000	Big Muddy River at Plumfield	794	37.0	90
05597500	Crab Orchard Creek near Marion	31.7	0.0	0.0
05598500	Beaucoup Creek near Pinckneyville	231	0.0	0.4
05599000	Beaucoup Creek near Matthews	292	0.0	1.6
05599500	Big Muddy River at Murphysboro	2162	55.0	270
05600000	Big Creek near Wetaug	32.2	0.0	2.6
07020500	Mississippi River at Chester	708600	47600	148000
07022000	Mississippi River at Thebes	713200	48610	151500

Notes: $Q_{7,10}$ values for all regions except region 2 are based on discharges and effluents up to 1984, and for region 2 up to 1990; values are rounded to the first place of decimal. Q_{HM} values for all regions based on discharges and effluents up to 1990.

* $Q_{7,10}$ value is positive but < 0.05 cfs.

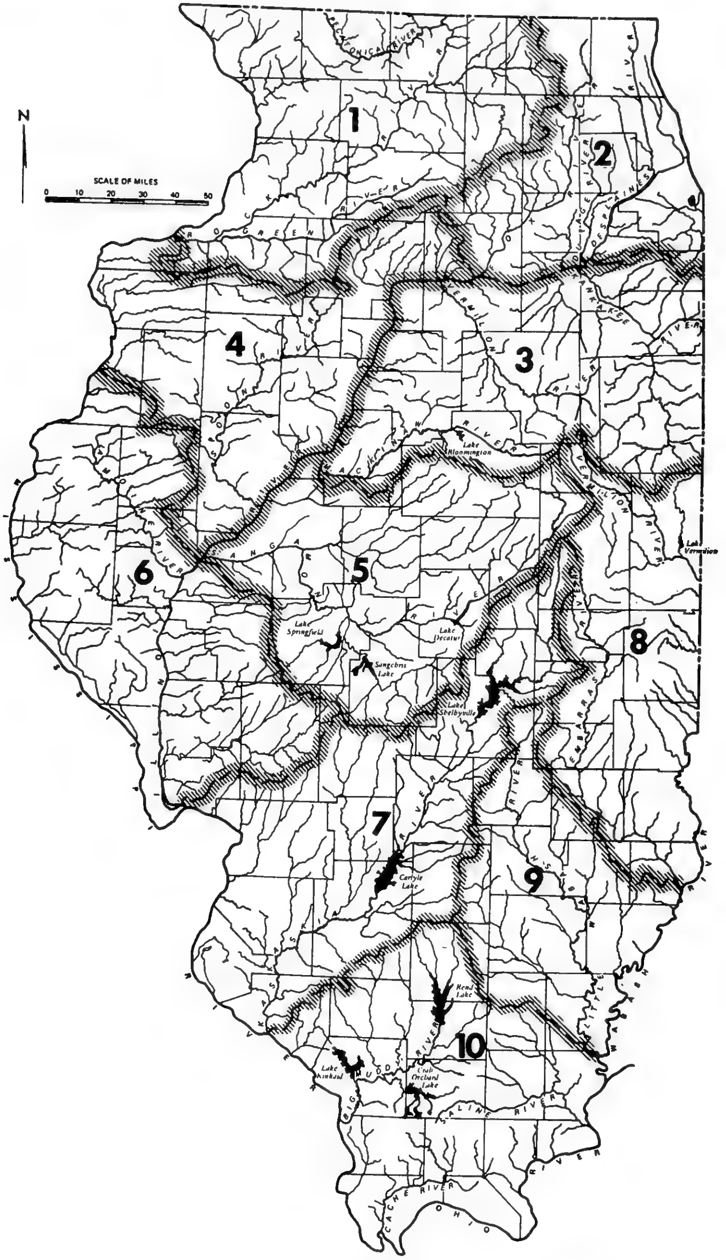

Figure 2. Regions for developing $Q_{7,10}$ and Q_{HM} maps

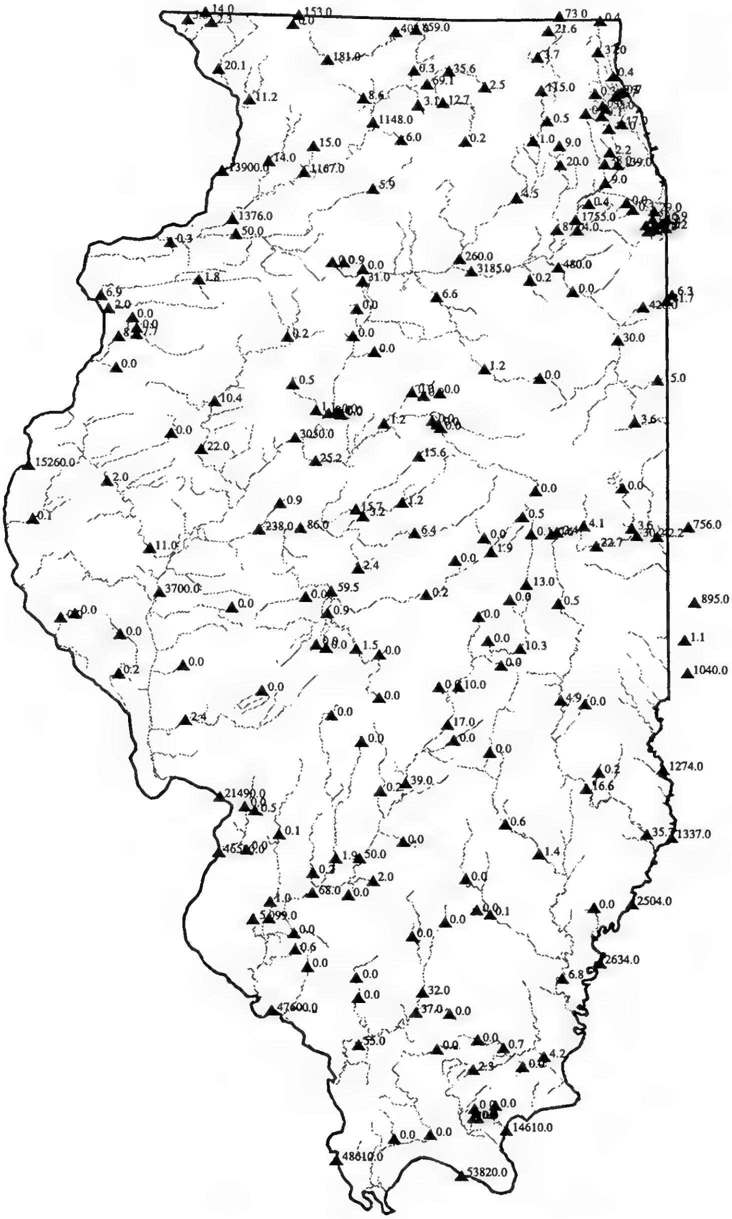

Figure 3. 7-day, 10-year low flows, $Q_{7,10}$ for Illinois streams

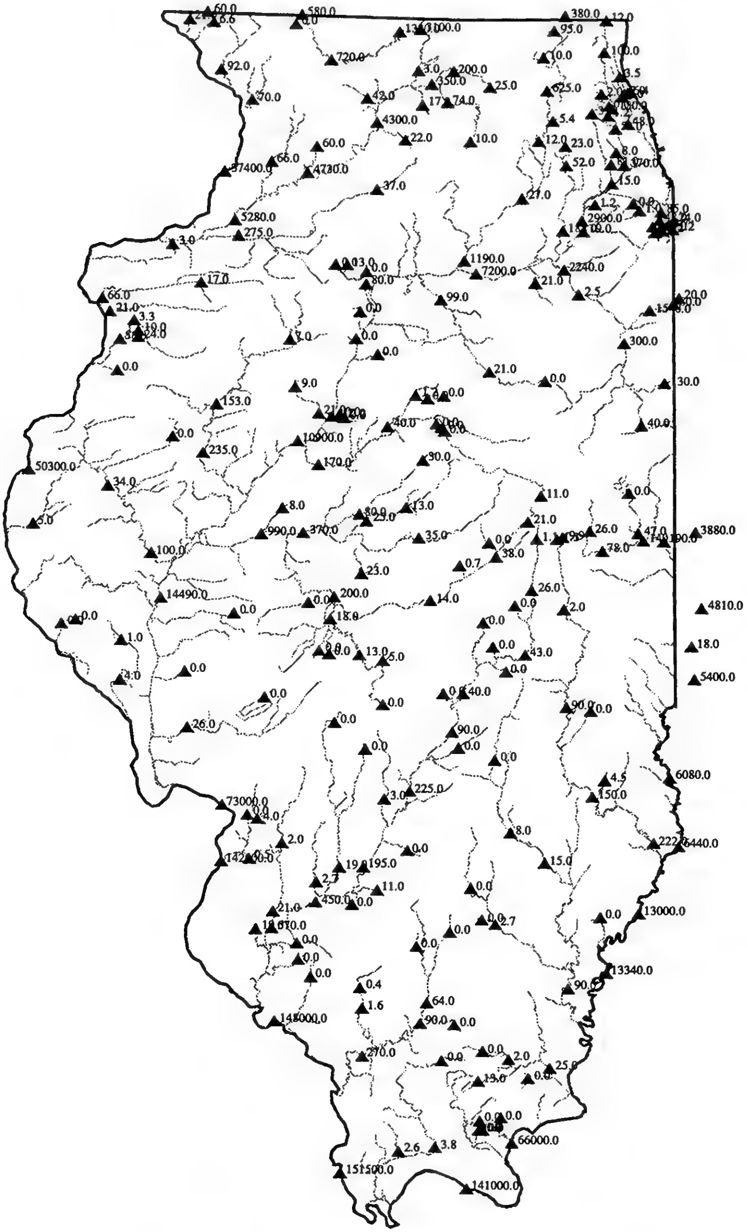

Figure 4. Harmonic mean flows, Q_{HM}, for Illinois streams

The cost of irrigation water varies considerably. Simple diversion from a river with substantial and sustained low flows is the most economical way to provide irrigation under favorable conditions. The need for storage impoundments raises the cost and raises environmental concerns. Irrigation from wells is an economical alternative depending on well depth and aquifer capacity. Irrigation may be required for four to ten weeks during a dry year. Thus the annual capital cost component forms a large part of the overall cost. Irrigation is more costly than precipitation in supplying crops with water. Nonetheless, production from irrigated agriculture is less variable than from rain-fed agriculture (CAST, 1982). Water conservation in irrigation implies more crop productivity per unit of water used. Overdraft of stored ground-water resources should be restricted to prolong their useful life for future generations.

INSTREAM FLOW REGULATION AND MANAGEMENT

The philosophy of desirable management programs for protecting instream flow needs is very well expressed in the report prepared by the Illinois Instream Flow Protection Committee (1991):

> The protection of minimum instream flows within the rivers and streams of Illinois is a significant water resources management issue that has been widely recognized since the mid 1970s. With each new drought and burst of economic development and growth in Illinois, numerous additional demands for the offstream use of the State's surface water resources occur. The development of these resources occurs across the State and can cause significant negative impacts to streams of any size and at any location. Without provision for the protection of some levels of minimum streamflows, the resource values, uses and benefits of these aquatic resources are significantly impaired. In addition, it is now becoming recognized that most of the streams in Illinois cannot meet the demands of all users at all times. Therefore, developers of the surface water resources of the State of Illinois must recognize the need to cease withdrawals at various times to protect the values of instream uses. They must also recognize that most water supply developments in Illinois will require that additional storage or alternative sources of supply be developed as a necessary part of any secure water resource development project. (p. 11).

Background

During the last two decades, the energy crisis and droughts have made many Illinois state agencies conscious of the need to protect instream flows from unrestricted and increasing water withdrawals from streams and rivers. The agencies have initiated research, investigations, and evaluation studies for instream flow protection through cooperative programs with the University of Illinois and the Illinois Natural History and Water Surveys. A State Water Plan Task Force (SWPTF) was created in 1980 to consider 18 water issues, including instream flow protection, and to prepare a new state water plan.

The SWPTF instream flow group made recommendations after the 1982 workshop, and they adopted the following policies: 1) the aesthetic qualities and the recreational potential of the rivers of Illinois are substantially dependent on the protection of reasonable flows in the rivers of Illinois, 2) the protection and maintenance of such flows is in the public interest, and 3) the protection of reasonable instream flows must be pursued through appropriate regulatory, planning, and advisory authorities of the state. An interim protected low-flow planning standard was developed, based on the $Q_{7,10}$ and 75 percent flow duration discharge, for defining the amount of water withdrawals permissible for offstream uses.

Regulation and Management Problems

The selection of protected instream flow levels is still beset by various concerns and problems, such as 1) clear regulatory authority to require protection of instream flows, 2) lack of agreement or results from various IFN methods, 3) lack of agreement regarding protected flows based on monthly, seasonal, and annual flow durations, 4) unwillingness of water users to pay for instream flow protection assessment studies, 5) conflicts in vested interests of upstream and downstream users, 6) problems with monitoring withdrawals within the mandates, and 7) development of a comprehensive allocation, monitoring, and regulatory system.

Seasonal Protected Flow Levels

It is generally accepted that certain instream flow levels need protection for the preservation of aquatic habitats and stream ecology, but there is not much consensus about the desirable levels of protection, considering both IFN and municipal and industrial water use. Healthy maintenance of various life stages of different fish species requires particular flow levels from month to month, season to season, or both. For ease of mandating, monitoring, and regulating, the general tendency is to relate the desired protected flow level to streamflow duration. However, use of monthly or seasonal flow durations can provide diversity in protected flow levels, some modifications to meet particular fish species' needs, such as for spawning, and maintain temporal variation in streamflow.

Singh and Ramamurthy (1987a) developed flow values corresponding to 85 percent and 75 percent flow durations, both on a monthly and annual basis. The relevant flow values for some stations in three selected basins are given in table 2. Protected flows corresponding to a particular annual flow duration have a single value for all the months of the year, whereas protected flows corresponding to a particular monthly flow duration change from month to month. Monthly protected flows for January through July can be up to ten times those from the annual flow duration, but as low as one-third of the annual flow duration for the remaining months. A desirable level may be the maximum protected flow corresponding to annual and monthly protected flow durations, with a proviso for flushing flows to improve the channel substrate characteristics.

Flow Releases below Dams

Modification of river flows resulting from the construction and operation of a dam or impounding structure causes significant water quality and aquatic habitat problems downstream. These problems can be mitigated to some extent by requiring desirable, minimum flow releases from the reservoir to protect the natural stream environment downstream. Public Law 92-500 makes provisions for minimum flow releases when projects are constructed or licensed by federal agencies.

Singh and Ramamurthy (1981) conducted extensive analyses on the costs of providing low-flow releases at various levels from impounding reservoirs, assumed at each of the 123 relatively long-term gaging stations on intrastate streams in Illinois (excluding those on the Illinois River). These reservoirs were designed to provide supplies equal to 2, 5, 10, and 20 percent of the mean flows of the impounded streams. The reservoir design storage capacities and associated costs were calculated assuming low-flow releases corresponding to zero and eight protected flow levels, for both 25- and 40-year droughts. Suitability or preference indexes for nine target fish species were considered in defining the average suitability index. Geometries of riffles and pools were estimated from stream hydraulic geometry and a literature search. The information developed on the percentage of increase in reservoir cost to accommodate various flow releases corresponding to protected flow levels can help in selecting the optimal protected flow, that is, the flow that not only substantially protects instream flow uses, but also allows municipal and industrial water supply at no more than 10 to 30 percent increased cost.

Some obvious impacts of damming and regulating rivers include possible habitat alteration because of changes in the temperature regimen of the water released, and changes in turbidity and water chemistry. Temperature effects can be moderated by providing multiport release mechanisms. The delayed impacts are not well understood but may be caused by changes in flow duration and suspended solid concentrations, and by the introduction of new species. Many of these impacts can be reduced by environmentally acceptable design, construction, and operation of the reservoirs.

INSTREAM FLOW PROTECTION

The development of protected-streamflow standards is essential for the most desirable, equitable use of streamwaters for aquatic habitats, recreation, waste assimilation, and municipal and industrial water supply. The demand for offstream water uses increases in the long term with economic development and in the short term during droughts. Without protecting some level of minimum streamflow, the values, uses, and benefits of aquatic resources will be significantly diminished. Development of surface water resources in Illinois must consider no water withdrawals from streams when the flows fall below certain protected levels, as well as the need for additional storage or alternative sources of supply.

Relevant Studies

The main conclusions drawn from a review of relevant studies (Bertrand et al., 1991) performed in Illinois are: 1) habitat area and habitat diversity are generally positively related to stream size, 2) smaller streams have considerably greater variability in flow than larger streams, 3) during summer, low-gradient streams have significant diel fluctuations in dissolved oxygen (DO) concentrations, 4) night-time sag in DO concentrations may correspond to the absence of several important game and nongame fish species, 5) IFIM is poorly suited to Illinois' low-gradient streams, 6) preference or suitability curves must be developed for Illinois fish species, and 7) some fish species can tolerate periods of zero flow for a month or two by taking temporary

Table 2. Average and 85 and 75 Percent Duration Flows (F85 and F75) at Stations for Three Selected Basins (North to South)

Flow	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Year*
Northern													
Station No. 05437500 (Rock River at Rockton) with a drainage area of 6363 sq mi and a 52-year period of record (1940-1991)													
Avg	2977.8	3324.2	3050.3	3080.0	3580.5	7273.6	7190.5	4931.9	3835.3	3173.9	2573.3	2719.4	3975.7
F85	1118.39	1400.00	1327.51	1297.80	1403.24	2654.73	3240.00	2236.20	1760.00	1358.24	1218.24	1120.00	1399.82
F75	1297.59	1670.00	1596.63	1597.11	1735.10	3507.47	4320.00	2774.22	2110.00	1666.39	1397.83	1330.00	1799.63
Station No. 05438500 (Kishwaukee River at Belvidere) with a drainage area of 538 sq mi and a 52-year period of record (1940-1991)													
Avg	241.4	276.6	291.3	275.4	379.4	693.9	607.9	445.3	369.2	256.5	214.2	245.1	357.7
F85	60.93	71.00	67.88	63.82	75.29	179.58	206.00	162.71	123.00	80.85	61.93	54.00	77.98
F75	70.83	87.00	89.71	100.61	104.48	239.23	269.00	208.42	157.00	98.78	74.83	62.00	107.97
Station No. 05444000 (Elkhorn Creek near Penrose) with a drainage area of 146 sq mi and a 31-year period of record (1961-1991)													
Avg	73.1	80.7	84.4	99.2	122.9	192.2	138.7	134.9	132.1	88.3	80.3	77.3	108.6
F85	32.01	31.94	34.01	32.01	34.91	50.03	55.75	47.02	41.75	39.01	31.01	29.91	35.00
F75	36.02	40.80	41.02	37.02	39.94	66.02	69.69	62.04	56.64	45.02	36.01	34.90	43.00
Station No. 05446500 - Rock River near Joslin with a drainage area of 9549 sq mi and a 52-year period of record (1940-1991)													
Avg	4407.7	4939.8	4748.2	5088.6	5976.4	10802.7	10599.1	7862.1	6372.7	5109.7	4013.9	4038.1	6161.0
F85	1677.51	2060.00	1997.07	1995.61	2205.40	4161.66	5060.00	3683.12	2880.00	2307.07	1918.10	1690.00	2179.69
F75	1946.63	2440.00	2394.46	2395.18	2709.00	5384.34	6270.00	4480.36	3600.00	2675.66	2185.66	2000.00	2759.47
Central													
Station No. 05572000 - Sangamon River at Monticello with a drainage area of 550 sq mi and a 51-year period of record (1941-1991)													
Avg	156.4	226.7	370.4	391.4	581.8	679.7	801.1	720.3	543.0	299.2	158.0	77.0	415.9
F85	6.10	9.45	12.01	21.02	29.00	138.08	213.08	175.06	95.65	35.02	13.00	7.36	17.01
F75	10.01	16.84	22.02	41.09	68.00	207.12	280.89	230.07	137.24	56.04	18.01	10.96	32.03
Station No. 05582000 - Salt Creek near Greenview with a drainage area of 1804 sq mi and a 50-year period of record (1942-1991)													
Avg	506.3	729.5	1026.4	1075.6	1690.0	2087.2	2427.7	2246.5	1763.8	1133.4	633.2	357.0	1303.3
F85	105.64	113.00	107.77	119.64	184.87	468.20	770.00	637.91	440.00	250.80	141.54	106.00	142.01
F75	123.72	133.00	130.59	217.81	352.12	750.47	1040.00	821.66	575.00	353.22	181.37	132.00	208.03

Table 2. Concluded

Flow	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Year*
Station No. 05583000 - Sangamon River near Oakford with a drainage area of 5093 sq mi and a 52-year period of record (1940-1991)													
Avg	1328.1	1758.6	2761.7	3006.6	4589.9	5539.2	6396.5	6059.9	4797.1	2911.6	1650.7	925.7	3468.7
F85	261.56	282.00	274.58	299.33	396.89	1384.29	1800.00	1676.93	1160.00	616.82	394.89	285.00	367.93
F75	311.42	330.00	347.82	448.36	656.25	1942.53	2370.00	2094.22	1580.00	916.53	508.75	354.00	539.82
Southern													
Station No. 03378635 - Little Wabash River near Effingham with a drainage area of 240 sq mi and a 25-year period of record (1967-1991)													
Avg	50.4	110.4	300.5	217.4	338.5	381.3	331.5	204.2	151.7	77.1	56.3	53.5	188.6
F85	0.00	0.00	4.45	8.91	20.36	37.83	37.69	17.90	4.63	0.34	0.00	0.00	1.60
F75	0.10	2.84	19.71	19.81	43.53	55.74	58.31	26.84	10.70	3.15	0.97	0.00	7.88
Station No. 03378900 - Little Wabash River at Louisville with a drainage area of 745 sq mi and a 17-year period of record (1966-1982)													
Avg	61.5	170.3	749.8	729.4	1103.7	1378.7	1098.3	560.1	532.4	310.4	192.9	154.2	583.7
F85	8.04	8.89	18.38	25.45	43.00	100.83	88.89	54.38	26.33	14.19	15.07	8.92	17.03
F75	10.20	13.64	36.41	50.67	80.00	148.16	160.79	80.94	45.29	23.27	19.13	14.73	31.06
Station No. 03379500 - Little Wabash River below Clay City with a drainage area of 1131 sq mi and a 26-year period of record (1966-1991)													
Avg	175.9	593.9	1624.7	1209.0	1948.1	2022.7	1844.2	1013.7	619.3	388.8	316.9	231.4	993.8
F85	9.04	13.00	26.30	60.43	79.53	167.79	130.00	68.34	36.00	20.13	14.09	7.90	21.99
F75	13.12	25.00	61.92	98.50	191.54	243.27	222.00	101.81	60.00	32.23	22.12	12.00	41.98
Station No. 03381500 - Little Wabash River at Carmi with a drainage area of 3102 sq mi and a 26-year period of record (1966-1991)													
Avg	500.5	1404.2	3813.4	3659.2	4897.3	5798.4	6052.5	3795.4	2018.4	1086.2	765.0	464.2	2843.4
F85	30.21	37.00	100.66	211.93	306.42	638.92	510.00	243.20	159.00	82.51	55.24	32.00	76.97
F75	46.31	62.00	208.15	368.62	706.81	1004.23	858.00	360.73	236.00	124.00	74.58	46.00	154.91

refuge in the pools. As pointed out by Singh and Broeren (1989), the IFIM's hydraulic submodel is based on many untenable assumptions, in addition to shortcomings in the habitat submodel regarding independence of fish preferences for velocity, depth, substrate, etc.

Flow Regime Changes

If the protected flow levels are to correspond to some flow duration, the series of daily flow values observed at a gaging station should be free from time trends. However, a streamflow regime can change with urbanization in the drainage basin, regulated flow from reservoirs, water withdrawals from streams as well as effluent discharge to streams, and climate change such as the cooler, wetter climate in northeastern Illinois during 1966-1985. It is important to ensure that the protected flow statistics represent existing conditions. Necessary modifications and adjustments are discussed by Singh and Ramamurthy (1987b).

Seasonal Protected Flow Levels

Maintenance of fish-spawning habitat may require high flows in early spring. Improvement in water quality and avoidance of fish crowding during summer can be achieved by keeping satisfactory protected flow levels. A relatively lower protected flow level in winter is tolerable if the pools have sufficient depth of flow.

Average (Q), 85 percent duration (Q_{85}), and 75 percent duration (Q_{75}) flows are plotted in figure 5 for the northern (Rock River), central (Sangamon River), and southern (Little Wabash River) basins. The average flow increases slightly from north to south because of increase in precipitation, but the Q_{85} and Q_{75} flows decrease greatly. Curves of Q_{85} and Q_{75} versus drainage area are quite steep for basins in central and southern Illinois, indicating a greatly reduced flow as the drainage area decreases.

As an example, the ratios of monthly Q_{75} to annual Q_{75} flows are shown in figure 6 for one sub-basin each in the Rock, Sangamon, and Little Wabash River basins. These ratios represent the relative streamflow variability during the year. Low values in the Rock River basin denote less streamflow variability, and high values for the Sangamon and Little Wabash Rivers denote high streamflow variability. The values of the ratio generally decrease with increased drainage area in a region, and with reduction in flow duration for a basin. The habitats have adjusted to this variability over the past historic flows, and it is rational to base this variability in protected flow levels on monthly or seasonal flow durations. The use of a particular statewide or regional flow duration is governed by exhaustive instream flow analyses, as well as water supply needs, recreation, and waste assimilation studies for various parts of Illinois. For the months in which the ratio of monthly to annual flow duration discharges is <1.0, the protected flow level may be set at the annual flow duration values. Some months with ratios >1.0 can be combined so that fewer protected flow levels are specified during the year, over periods in months (maybe resembling the seasons) for ease of monitoring and regulation.

Regulatory Structure

Instream flow protection through federal licensing proceedings (Clark, 1991) is covered to some extent by the Federal Power Act, the River and Harbors Act, and the Clean Water Act Dredge and Fill Program. Protection is also provided through special provisions of the National Environment Policy Act, the Fish and Wild-life Coordination Act, the Endangered Species Act, and the Wildlife and Scenic River Act. In Illinois, the Department of Transportation has authority under the River, Lakes, and Streams Act over the public waters of the state and must supervise every use of public waters to protect navigation, aquatic life, and other instream public uses.

About 15 eastern and midwestern states have laws to establish minimum streamflows (Clark, 1991). The implementation of controversial statutory instream flow programs has been progressing well in the western states. Indiana requires water-use registration. Iowa sets water-use priorities by statute and takes into account water conservation and emergency restrictions when needed. Minnesota has set protected flows on many streams using methods such as 90-95 percent flow duration (the Montana method), with 70-75 percent monthly flow duration for August. Wisconsin has a permit system for water withdrawals. What is lacking in all of the states mentioned, however, are regional, seasonal protected flow levels based on hydraulic and habitat simulation, water quality, water supply, and waste assimilative capacity, together with vital economic considerations. Development of such information will be in the best interests of the public, future generations, aquatic habitats, stream ecology and quality, aesthetics, intergenerational equity, etc.

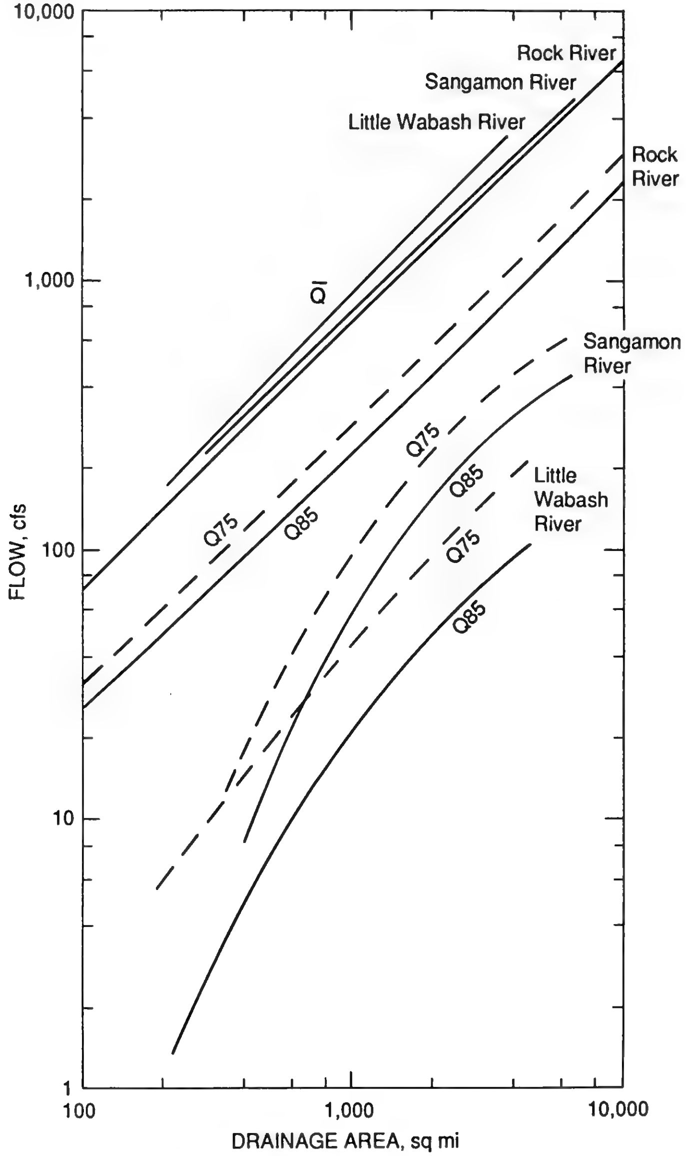

Figure 5. Average flows and 75 and 85 percent duration flows ($\bar{Q}$, Q75, and Q85) in the Rock, Sangamon, and Little Wabash River basins (see table 2)

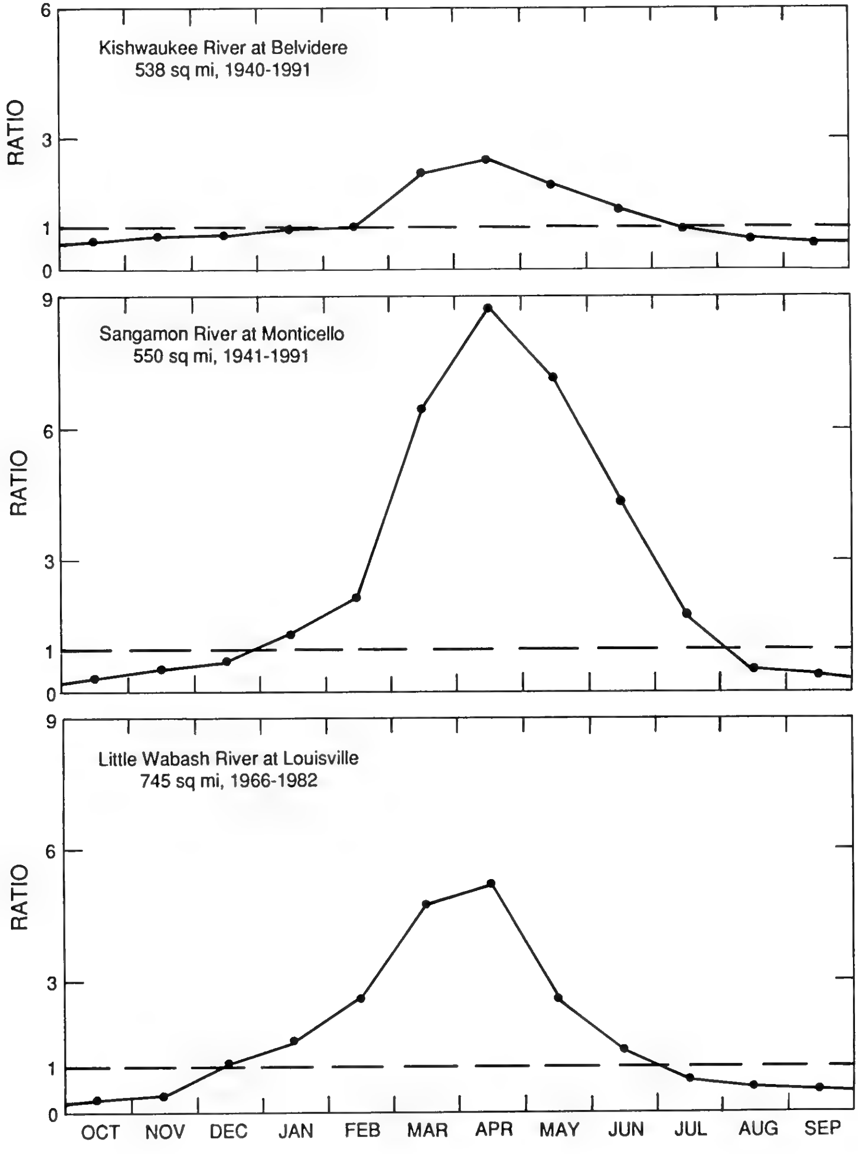

Figure 6. Ratio of 85 percent monthly duration flows to 85 percent annual duration flows in the Kishwaukee, Sangamon, and Little Wabash Rivers

SUMMARY

The protection of instream flows has been under serious consideration by the state natural resource agencies for the last two decades. The absence of suitable habitat assessment models (in terms of hydraulic and habitat simulations) and the lack of financial support for an integrated statewide study of desirable protected flow levels have seriously hindered instream flow regulation and the development of an associated infrastructure. Protected streamflow standards are essential for the most desirable, equitable use of streamwaters for aquatic habitats, recreation, waste assimilation, stream integrity in terms of diversity and strength of biotic communities, and municipal and industrial water supply.

The adoption of a protected flow standard involves consideration of conflicting goals and needs. Both tangible and intangible benefits are associated with a protected flow level, and these benefits vary with the level of protection. There is also an associated cost for adopting and maintaining a protected flow level in a stream. A cost-benefit approach will provide a framework for analyzing the economics of objectively selecting and adopting a particular protected flow level to meet various needs.

The Instream Flow Incremental Methodology commonly used for aquatic habitat assessment, has two submodels: hydraulic simulation and habitat simulation. The Singh and Broeren (McConkey) flow model can replace the IFIM hydraulic simulation model, overcome various shortcomings, and provide a rational, basin-wide application. The habitat submodel will require the development of preference or suitability curves for various Illinois fish species and their life stages, together with some consideration of stress levels (in low-flow or drought periods) from which the fish can recover without irreversible damage. A statewide five- to seven-year effort will be necessary to develop basic data on instream flow needs for Illinois streams of various sizes and orders. Another three-year economic and system study will be necessary to develop specific protected flow values along the streams, regulatory and monitoring structures, and procedures for dealing with sensitive areas. A state commitment to achieve these objectives will greatly improve the environment and welfare of the people in Illinois.

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