Water Availability and Use Pilot: A Multiscale Assessment in the U.S. Great Lakes Basin

By Howard W. Reeves

Executive Summary

Beginning in 2005, water availability and use were assessed for the U.S. part of the Great Lakes Basin through the Great Lakes Basin Pilot of a U.S. Geological Survey (USGS) national assessment of water availability and use. The goals of a national assessment of water availability and use are to clarify our understanding of water-availability status and trends and improve our ability to forecast the balance between water supply and demand for future economic and environmental uses. This report outlines possible approaches for full-scale implementation of such an assessment. As such, the focus of this study was on collecting, compiling, and analyzing a wide variety of data to define the storage and dynamics of water resources and quantify the human demands on water in the Great Lakes region.

The study focused on multiple spatial and temporal scales to highlight not only the abundant regional availability of water but also the potential for local shortages or conflicts over water. Regional studies provided a framework for understanding water resources in the basin. Subregional studies directed attention to varied aspects of the water-resources system that would have been difficult to assess for the whole region because of either data limitations or time limitations for the project. The study of local issues and concerns was motivated by regional discussions that led to recent legislative action between the Great Lakes States and regional cooperation with the Canadian Great Lakes Provinces. The multiscale nature of the study findings challenges water-resource managers and the public to think about regional water resources in an integrated way and to understand how future changes to the system—driven by human uses, climate variability, or land-use change—may be accommodated by informed water-resources management.

Background and Major Issues

The Great Lakes region has abundant water resources. The Great Lakes are the largest freshwater system on Earth, and groundwater resources are widespread and typically of high quality. The average discharge from the basin to the Atlantic Ocean through the St. Lawrence River makes it the second-largest drainage basin in the United States after the Mississippi River drainage. Diversions of water into and out of the basin are notable for galvanizing discussion of regional water resources, but such diversions actually play a small role in the overall water budget for the basin. Climate variations lead to variations in water delivery (through precipitation) and removal (through evaporation and transpiration). These variations, on seasonal, annual, decadal, and longer timeframes, are crucial in determining lake levels, groundwater levels, and streamflows within the basin. Human interactions with the hydrologic system, other than hydroelectric power generation, represent a small percentage of the overall flow through the system; but drawdown of groundwater levels in the Chicago/Milwaukee area has been as much as approximately 1,000 feet, and the areal extent of the drawdown area is very large (Alley and others, 1999; Reilly and others, 2008). Mapping water withdrawals and return flows by watershed within the basin helps highlight the spatial variation in water use by various economic and water-supply sectors across the basin and illustrates the importance of subregional or local-scale analysis in quantifying the effect of water use on local water resources.

Regional Analysis

Regional water budgets were assembled from existing information. The most notable feature of the regional water budgets is the large storage volume of the surface-water system that is unique to the Great Lakes region compared to most large basins in the United States. Groundwater storage in the U.S. Great Lakes Basin was estimated, and it exceeds the storage of Lake Erie and Ontario. The annual flow through the basin is approximately 1 percent of the volume in storage. Base-flow and recharge estimates were developed from streamgage data for the region and were found to vary according to climate, landscape, and geology. Temporal trends in precipitation, lake levels, and streamflow were investigated. Water-resources development and land-use change have altered the hydrology and hydraulics of the Great Lakes Basin, and control structures on the lakes and connecting channels have dampened some of the natural variability of the system. The large size of the basin, large natural storage of water in the system, and large annual flows through the system buffer the effects of most development, so development has had relatively little overall affect on water availability at the basin scale.

Subregional Analyses

Groundwater resources, surface-water flows, and water withdrawals and returns were studied on a subregional scale in the Great Lakes Basin Pilot.

Lake Michigan Basin Groundwater-Flow Model

A subregional groundwater-flow model for the Lake Michigan Basin was developed to quantify groundwater availability and to simulate system response to changes in anthropogenic and environmental stresses. This subregional model illustrates the source of water to wells and changes in the dynamics of the groundwater system during 1865–2004 in response to development and climate-driven variations in recharge. The model also was used to show the changes in groundwater divides in response to pumping and to analyze the direct groundwater input to Lake Michigan, which is approximately 2 percent of the total groundwater discharge to surface water. The primary discharge of groundwater is to streams and other inland surface-water bodies. Pumping of groundwater produces changes in the estimates of discharge to streams but, because of the scale of the model, it does not distinguish the impact of wells on individual streams.

Water-use projections were used to develop forecast scenarios to demonstrate the use of the subregional model in predicting changes to the groundwater system in response to projected uses. Changes in pumping in the Cambrian-Ordovician aquifer system on the west side of Lake Michigan produce the most dramatic changes in groundwater levels. Simulations indicate recovery in water levels of more than 100 feet if current conditions are held through 2040; however, additional drawdown of more than 100 feet is indicated under forecast conditions of increased groundwater withdrawal in certain areas.

Analysis of climate change was restricted to the local scale because at the subregional scale, effects of climate change cannot be adequately resolved by the groundwater-flow model. Shifts in long-term recharge rates are quickly compensated for by changes in the estimated base flow to streams such that the regional model response to climate-change scenarios is similar to its response to observed climate during 1864–2004.

Estimation of Streamflows

New methods were developed to improve estimates of surface-water delivery to the Great Lakes and streamflow in ungaged basins. Better estimates of streamflows in the basin are important because the primary discharge of groundwater in the basin is to the inland surface-water system, and surface-water delivery to the Great Lakes from direct runoff and base flow is approximately half of the water supply to the Great Lakes. The effect of water withdrawals on streamflow—especially on the flow required to maintain ecosystem health, termed “ecosystem flows” or “ecological flows”—has gained great interest in the region, and estimates of ungaged flows are an essential part of establishing and understanding ecological flow requirements in any system. A regression-based approach that is constrained to route and conserve flow in the stream network, match observed mean flows at streamgages, and account for specified water withdrawals and transfers was developed into a computer application as part of the pilot. This application also provides the analyst with a suite of tools to interrogate streamflow data, identify anomalies perhaps due to unaccounted-for water use, develop regression models with selected independent landscape and climate variables, and analyze the resulting streamflow estimates. The method was applied to a hydrologic subregion within the Lake Michigan Basin and was shown to be effective in estimating ungaged flows and providing a framework for surface-water accounting.

Water Withdrawals, Return Flows, and Consumption

Water use also was examined at the subregional scale. Seasonal and monthly variations in water withdrawal, return flow, and consumption were documented by using data from Ohio, Indiana, and Wisconsin. This analysis revealed that for all major water-use sectors, water withdrawals increase during the summer months and are lower than the respective annual average during winter months. Peak use is often coincident with or just precedes the lowest summer streamflows, implying that seasonal variation in withdrawals may be important when considerating ecological flows. The implication becomes stronger if ecological flows also have seasonal components; analysis of ecological flows in the region, however, was beyond the scope of this study. Understanding the current status and recognizing trends in water withdrawals, return flow, and consumption will help water managers evaluate ecological flows, instream use, and other constraints that may influence water availability.

Local Analyses

Local analyses focused on water-availability issues that are difficult to quantify on regional and subregional scales. Notably, analyzing groundwater/surface-water interaction and the potential to affect ecological flows in streams by pumping wells are inherently local-scale issues. The local-scale analysis also included examination of the effects of climate variability and methods to estimate uncertainty using surface-water and groundwater models.

Groundwater/Surface-Water Interaction

Understanding the interaction between pumping wells and local streams is a topic of growing interest and concern; however, studies on regional and subregional scales within the pilot project were not able to directly address questions at local spatial scales or short time periods. To illustrate the relation between regional-, subregional-, and local-scale studies, a local inset groundwater-flow model was built within the Lake Michigan Basin groundwater-flow model. The inset model covered a 20-square-mile area and examined the interaction between a single, hypothetical well and the stream network that can be accurately resolved at this local scale. The inset model enables the exploration of pumping-induced effects on streamflow given a set of pumping scenarios, such as withdrawal from different aquifer layers or variations in pumping schedules. For the case studied, streamflow depletion of the closest stream by the introduced pumping well was approximately half the pumping rate of the well. Capture of water from other streams was approximately 40 percent of the pumping rate, and the remaining water delivered to the well was from aquifer storage. The presence of a layer of low hydraulic conductivity between the aquifer being pumped and the stream shifted the distribution, increasing the capture from other streams in the surrounding area and decreasing capture from the closest stream.

Assessment of Climate-Change Effects

The potential effects of climate change and variability were simulated by varying the recharge imposed on the subregional groundwater-flow model through the use of a soil-water-balance estimate. To demonstrate the technique, input to the soil-water-balance recharge estimate was from a scenario generated by an atmosphere-ocean coupled general circulation model, and base-flow changes in the system in response to a 2000–40 scenario are presented. For the scenario tested, base flow increases for part of the scenario and then decreases after approximately 2015. The simulated base flow was zero for several years in the prediction scenario showing the sensitivity of the headwater stream to relatively modest changes in estimated recharge at the local scale.

Assessment of Uncertainty of Flow, Water-Level, and Base-Flow Reduction Estimates

Much of the analysis performed in the Great Lakes Basin Pilot relied upon USGS streamgage data. In addition, the groundwater-flow model relies on groundwater-level data. For the surface-water network, the importance of streamgage stations to the uncertainty in flow estimates was studied for a watershed in southwest Michigan/northwest Indiana. At a 20-percent reduction of streamgage observations, the probability of the estimated flow being within 10 percent of measured flow at a gage was between 85 and 90 percent. This range of probability decreased dramatically to between 60 and 75 percent if half the streamgage observations were removed from the analysis.

For the local groundwater-flow model, the most effective location for future data collection to reduce uncertainty in water level and base-flow reduction estimates for hypothetical pumping within the inset model area was studied. Use of numerical techniques that estimate prediction uncertainty and sensitivity to observations were very sensitive to the conceptual model used to develop the local-scale model. A highly parameterized approach was shown to be effective in identifying locations for additional observations that would decrease prediction uncertainty. Approaches with similar structure to the underlying aquifer characterization but with fewer parameters did not clearly identify locations where additional observations would be productive. These results indicate that local inset models should have a refined spatial distribution and be highly parameterized if these types of analyses are desired.

Challenges and Lessons Learned

The Great Lakes Basin Pilot identified several challenges and lessons learned:

- Studies summarizing water use highlight inconsistencies in water-use data collection and reporting across the region. Much of the reported water use in some sectors relies heavily on estimates, and the estimation procedures may vary from state to state. Resolving these inconsistencies and developing methods to improve estimates for the broad water-use sectors and for specific categories within the broader sectors remains a challenge.

- Estimation of surface-water characteristics across the basin was hampered by the requirement that all streams in the geographic dataset used for the analysis be routed through the stream network. Existing datasets are quite well constructed in this respect, but there remains a small percentage of streams that are disconnected or improperly routed; correcting even these few problems is labor intensive and time consuming.

- The tension between developing a regional groundwater-flow model capable of representing regional hydrologic dynamics and the desire to address problems of local interest is a challenge for regional water-availability studies. Methods to allow regional models to be used to address local questions, such as the illustrative inset model discussed previously, provide insight into the potential local response in water levels and base flow to groundwater withdrawals. For site-specific questions, more refinement of the hydrogeologic characteristics would be needed to better address local issues.

One other issue that remains a challenge to both the subregional- and local-scale groundwater-flow models is that traditional models do not account for potential changes in recharge to the aquifer system in response to changes in pumping, return flow, or other specific changes to the environment. This separate treatment may be valid on the subregional scale; but as questions become more site specific, the potential for pumping to modify recharge to the local aquifer should be included in the simulation. For situations where recharge can be influenced by pumping, coupled groundwater-surface water models that generate recharge to the groundwater system as part of the simulation would be required.

Water availability is a function of water quantity and a range of other factors including water quality, physical infrastructure, water law and regulations, and economic considerations. Social decisions regarding desired instream flows for recreation, transportation, ecological support, or aesthetics may constrain water availability, and current societal decisions pertaining to water availability can be further complicated by changes in social norms with time. The legal framework for existing water use may override other considerations by granting primacy for use to senior water-rights holders or preventing any development near certain designated streams. These constraints were not studied as part of this effort.

The underlying framework controlling water availability is the interplay between storage of water in the system, flux of water through the system, and human and ecological uses of water. Understanding this underlying framework is paramount to developing estimates of water availability given the constraints that are recognized today or that may be imposed in the future. This study summarizes regional estimates of water in storage and the fluxes of water through the system. Subregional and local analyses that were part of this study quantified various aspects of the water resources, demonstrated tools and techniques capable of assessing subregional and local issues, and helped provide the requisite information to inform regional, subregional, and local water-availability decisions.

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