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MODELLO DI FLUSSO REGIONALE DELLE ACQUE SOTTERRANEE DEL BACINO DEL LAGO MICHIGAN: PRIMI ELEMENTI

A REGIONAL GROUNDWATER-FLOW MODEL OF THE LAKE MICHIGAN BASIN: PRELIMINARY ELEMENTS

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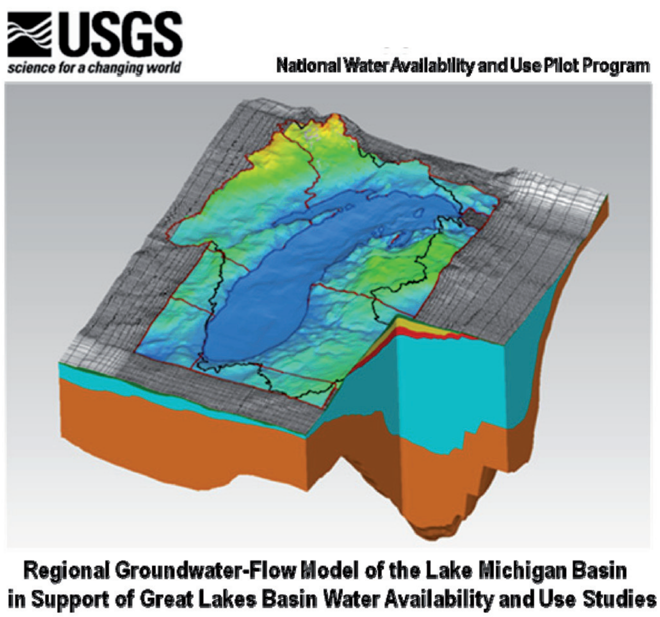
A regional groundwater-flow model of the Lake Michigan Basin and surrounding areas in the northern midwest region of the United States has been developed in support of the U. S. Geological Survey National Assessment of Water Availability and Use Program-Great Lakes Basin Pilot (Feinstein *et alii*, 2010). The transient 2-million-cell model incorporates multiple aquifers and pumping centers with drawdown that extend into deep saline waters. The 20-layer model simulates the exchange between a dense surface-water network and heterogeneous glacial deposits overlying stratified bedrock of the Wisconsin and Kankakee Arches and the Michigan Basin in the Lower and Upper Peninsulas of Michigan; eastern Wisconsin; northern Indiana; and northeastern Illinois. It provides a platform for quantifying the regional sources and sinks of groundwater (including recharge, pumping, and groundwater flow to inland surface water and to Lake Michigan-all elements of the groundwater budget that change with time) and for mapping the direction and magnitude of flows in a series of aquifers (including the source areas for wells and the locations of major groundwater divides at various depths on both sides of Lake Michigan and the migration of the divides in response to pumping).

Five datasets, which were prepared as part of the Great Lakes Basin Pilot to serve as the foundation for model development, are described in separate reports:

- a three-dimensional hydrogeologic representation of aquifers and confining units above the Precambrian basement, with a maximum thickness of 15,000 ft in the middle of the Michigan Basin (Lampe, 2009);
- maps of the coarse fraction of unconsolidated material at depth intervals of 0-100 ft, 100-300 ft, and greater than 300 ft, overlaid on existing interpretations of glacial categories (Arihood, 2009);
- location, depth, and pumping rates of high-capacity public-supply, industrial, and irrigation wells from the early 20th century through 2005 (Buchwald *et alii*, 2010), a compilation that documents generally upward trends in withdrawals and some shifts between deep and shallow pumping;
- maps of recharge derived from a soil-water-balance model that reveals trends in the spatial and temporal distribution of inflow to the water table (Westenbroek *et alii*, 2009);
- maps of salinity in hydrogeologic units that show the three-dimensional boundary between fresh and saline water, as well as the distribution of high concentrations of dissolved solids in the Michigan Basin (Lampe, 2009).

These datasets, along with boundary conditions linked to outlying Great Lakes, hydrologic coverages delineating the surface-water network, and hydrogeologic information relating primarily to hydraulic conductivity provided the input required by the SEAWAT-2000 model to simulate groundwater flow before pumping (steady-state simulation) and after development (transient simulation with 12 stress periods extending from 1864 to 2005). The simulation uses a form of the groundwater-flow equation that takes account of variable density (Langevin *et alii*, 2003). Two versions of the model were calibrated: one for confined conditions and one for unconfined conditions. Multiple target sets developed from observations of head and base flow and inversion methods using the suite of PEST computer programs (Doherty, 2008a,b; Doherty *et alii*, 2010) guided the adjustment of initial inputs. Comparison of



updated parameter values, calibration statistics, and parameter sensitivities demonstrated that the confined and unconfined versions of the model produced solutions similar in most respects.

The output of the calibrated confined model was selected for detailed presentation largely for reasons of numerical stability during inversion and no loss of pumping to dry cells as a result of drawdown. The simulated results, organized laterally into seven subregions and vertically into five aquifer systems, included maps, cross sections and tables of:

- regional predevelopment water table and head conditions at depth in bedrock units;
- changes in water levels (drawdown and recovery) over time, by aquifer system;
- changes in the magnitude and direction of shallow and deep flow;
- water budgets that quantify regional sources (such as recharge and storage release) and sinks (such as base flow to streams and discharge to wells) through time.

Analysis of the results by means of particle tracking, revealed:

- sources of water to shallow and deep wells by subregion;
- the changing configuration of the divides that delineate the Lake Michigan groundwater basin and the postdevelopment groundwater basins around pumping centers; and
- the distribution of direct and indirect discharge of groundwater to Lake Michigan and the modifying effects of pumping on the distribution.

The multiple perspectives provided by the simulated model output portray a regional groundwater flow system that, over time, has largely maintained its natural predevelopment configuration but locally has been strongly affected by well withdrawals. The quantity of rainfall in the Lake Michigan Basin and adjacent areas supports a dense surface-water network and recharge rates consistent with generally shallow water tables and a flow system generally dominated by shallow circulation. At the regional scale, pumping has not caused appreciable disruption of the shallow flow system; but pumping has resulted in decreases in base flow to streams and in direct discharge to Lake Michigan. Comparison of inset models constructed along the Lake Michigan coastline suggests that the regional model because of its coarse grid spacing and coarse representation of surface water underestimates the direct discharge by about 48 percent. When the bias is corrected, the results indicate that about 2 percent of total groundwater flow is directly discharge to the lake at a rate of about 0.5 ft^3/s per mile of shoreline.

Well withdrawals have caused reversals in regional flow patterns around pumping centers in deep, confined aquifers (most noticeably in the Cambrian-Ordovician aquifer system on the west side of Lake Michigan near the cities of Green Bay and Milwaukee in eastern Wisconsin, and around Chicago in northeastern Illinois, as well as in some shallow bedrock aquifers (for example, in the Marshall aquifer near Lansing, Mich.). The shifts in flow have been accompanied by large drawdowns with consequent local decrease in storage (moderated in some areas by metropolitan water-supply projects that substituted Lake Michigan water for groundwater supplies). On the west side of Lake Michigan, well withdrawals have caused a complete reconfiguration of the deep divides. Before the advent of pumping, the deep Lake Michigan groundwater basin boundaries extended to the west of the Lake Michigan surface-water basin boundary, in some places by tens of miles. Over time, the pumping centers have replaced Lake Michigan as the regional sink for the deep part of the flow system.

The regional model results provide a broad picture of the status of the groundwater resource and how it has responded to pumping. However, there are limitations imposed by the relatively coarse grid spacing. Laterally, the finite-difference cells are 5,000 ft on a side in the Lake Michigan Basin and in adjoining areas. At this resolution, the simulation of the water-table response to pumping is severely constrained by the necessity of including enough of the surface-water system in model cells to provide outlets for recharge and, thereby, to avoid spurious simulated water-level mounding. The mounding that occurs when discharge points are neglected can be offset by increasing hydraulic conductivity; but this fix distorts the K_h and K_v fields relative to field conditions. In order to avoid distorting the hydraulic conductivity input, more than half the water-table cells in the Lake Michigan Basin model contain surface-water features, each of which is represented by a boundary condition with a fixed stage. The stage tends to "staple" the water-table solution because there is generally a small gradient between the average groundwater head solved for the cell and the surface-water level assigned to the cell. The regional model by itself cannot overcome this limitation; however, in conjunction with techniques for inset models, it can lay the foundation for any number of applications designed to address local management problems related to optimizing water supply and maintaining ecologic flows. Two promising new techniques-Local Grid Refinement in MODFLOW-2005 and Hybrid Analytic Element/Finite Difference Modeling-could allow enhanced versions of the regional model to simulate groundwater/surface-water interactions in the presence of pumping at the necessary level of refinement while still honoring the regional pattern of flow needed to properly simulate water availability. Research aimed at demonstrating these two methods in a setting characterized by pumping near headwater streams is part of the Great Lakes Basin Pilot project (see Haitjema *et alii*, 2010; and Hoard, 2010).

The construction of alternative versions of the regional model reveals important insensitivities with respect to model design. One is related to variable density. Whereas the specification of salinity dramatically affects groundwater conditions in the deep Michigan Basin and even though the simulated drawdown around pumping centers extends into the highly saline waters, model results indicate that variable density can be neglected with negligible effect on the range of simulated results in *freshwater* areas under either predevelopment or stressed postdevelopment conditions. Relaxing the assumption that saline concentrations are fixed through time also has little effect on model output. A second finding of insensitivity is related to the level of detail appropriate for the values assigned to the hydraulic conductivity of unconsolidated sediments. The availability of geologic descriptions from hundreds of thousands of driller logs for household wells permitted cell-by-cell mapping of hydraulic conductivity in the top three model layers. When this distribution is zoned more broadly on the basis of glacial categories alone (that is, on the basis of material types such as clayey till and coarse outwash), the model results give rise to a somewhat modified water-table solution, but the agreement to calibration targets is only weakly compromised, and the findings are very similar to the more detailed model with respect to the regional drawdown response and the regional water budget.

In summary, the results of this modeling effort have yielded

- improved estimates of the various components of the water budget for the region,
- improved estimates of the various hydraulic properties of the geologic units in the region, and
- a better understanding of the groundwater flow throughout the region.

The regional model is also intended to support the framework pilot study of water-availability and use at the scale of the entire Great Lakes Basin. To that end, an ongoing effort has been undertaken to distill the model's findings using a series of *sustainability indicators* intended to reveal overall patterns in the status of the water resource in terms of the human effect on natural groundwater flows and on groundwater/surface-water interactions. Moreover, the regional model is being applied in *forecasting* mode to shed light on the effects of possible future levels of pumping on the groundwater system and is being used to test hypotheses regarding the effect of *climate variability and change* on water availability. All these aspects, along with a demonstration of the procedures for embedding models and sample results related to ecologic flows, are discussed in detail in a USGS Professional Paper on the comprehensive findings of the Great Lakes Basin Pilot (Reeves, 2010).

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