6.6 Groundwater Interactions with Lake Michigan

A key objective of the LMB model is to provide a comprehensive account of groundwater interactions with Lake Michigan. The model encompasses the entire lake and simulates shallow and deep flow across its entire shoreline under various stress conditions. The results selected for presentation are intended to summarize the interactions between two important regional water resources, one surface and one subsurface.

A distinction is made between groundwater that enters Lake Michigan directly through the lakebed and indirectly through base flow into streams tributary to the lake. Both groundwater quantities, direct and indirect, contribute to the Lake Michigan budget. Both are influenced by climate variability and by ongoing well withdrawals.

The water-budget analysis presented earlier (fig. 57) indicates that simulated *direct discharge* of groundwater to Lake Michigan under predevelopment conditions (218 Mgal/d) is 1.2 percent of the total simulated inflow for the Lake Michigan Basin (18,318 Mgal/d). In 2005, the direct discharge (216 Mgal/d) is 1.1 percent of the total inflow (19,313 Mgal/d). The *total discharge* (*indirect and direct*) under predevelopment conditions equals the total inflow to the groundwater system because there are no other sinks for groundwater and net lateral flow to the basin is positive. By 2005, the simulated total discharge to the combined features of the Lake Michigan surface-water network (18,720 Mgal/d) captures 96.9 percent of the total groundwater inflow to the basin, whereas most of the remaining 3.1 percent of the inflow is captured by pumping.

According to the model, most of the *direct discharge* occurs near the shoreline. Under predevelopment conditions, 68 percent of the direct discharge occurs within 5,000 ft of the shoreline and 83 percent occurs within first 15,000 ft (table 17). The dropoff with distance into the lake appears to be approximately exponential (fig. 70), in agreement with theory (McBride and Pfannkuch, 1975).

Particle tracking indicates that recharge areas (source areas) of groundwater that discharges within 15,000 ft of the lakeshore extend further from the west and north lakeshores than from the east and south lakeshores (fig. 71). The pattern, although probably influenced by differences in the density of the stream network and by transmissivity of the glacial sediments, could also be partly an artifact of model-grid resolution; this possibility is explored in section 7 (“Alternative Models and Model Sensitivity”).

In parts of NE_WI, SE_WI and NE_ILL, the source areas of direct discharge to Lake Michigan for predevelopment conditions (fig. 71*A*) are somewhat wider than for 1991–2005 conditions (fig. 71*B*). The difference is due to the diversion of groundwater through pumping from shallow wells in the QRNR and SLDV aquifer systems.

Table 17. Predevelopment groundwater discharge to offshore Lake Michigan.

[Values correspond to the confined model, SLMB-C]

Area receiving discharge	Amount of discharge (million gallons per day)	Percentage of total
Total direct discharge to Lake Michigan	217.9	--
Discharge to first 5,000-foot-wide offshore ring	147.9	67.9l
Discharge to second 5,000-foot-wide offshore ring	24.9	11.4l
Discharge to third 5,000-foot-wide offshore ring	7.8	3.6l
Discharge to 15,000-foot-wide offshore ring	180.6	82.9l

Pumping from deep wells also has an effect on groundwater that, in predevelopment times, flowed from Wisconsin and Illinois eastward toward Lake Michigan through the C-O aquifer system and then discharged to the interior of the lake. To quantify the changing shallow and deep components of the system, it is helpful to characterize direct groundwater interactions with Lake Michigan not only in terms of direct discharge into nearshore areas but also by vertically integrating flow that passes under the shoreline toward the lake. The simulated rate of *shoreline discharge* varies appreciably with location; more than that, the rate and even the direction of flow changes as a function of time.

Under predevelopment conditions, flow under the shoreline ranges from less than 0.05 Mgal/d to almost 5 Mgal/d per 5,000 ft linear length (fig. 72*A*), equivalent to a range of 0.08 to 7.7 ft^3/s per mile of shoreline; the average value is 0.22 Mgal/d or 0.35 ft^3/s per mile of shoreline.

The rates simulated by the model are a complicated interplay of local-recharge, stream-density, and hydraulic-conductivity inputs. *Shoreline inflow* induced from Lake Michigan to the predevelopment groundwater system is restricted to peninsulas in the NLP_MI (fig. 72*B*). Maps of shoreline discharge to the lake and induced flow from the lake for 1980 (figs. 72*C*, *D*) show pronounced changes relative to predevelopment conditions, in large measure because of the increase in recharge computed after 1970. The average outflow rate for 1980 increased to 0.23 Mgal/d (0.36 ft^3/s) per 5,000 ft of shoreline. Development also exerted some pressure: for parts of the shore in SE_WI and NE_ILL, shallow and deep pumping caused the direction of groundwater flow to reverse from outflow toward the lake to inflow from the lake. The maps of shoreline outflow and inflow for 2005 (figs. 72*E*, *F*) show some effect on local rates from fluctuations in recharge and recovery of inland water levels with reduced deep pumping in NE_ILL; however, the average outflow rate is again 0.23 Mgal/d (0.33 ft^3/s) per 5,000 ft of shoreline.

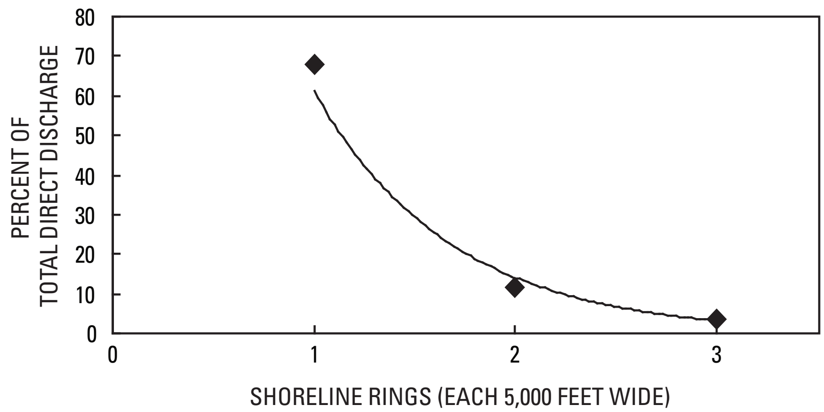


Figure 70. Percentage of total direct discharge to Lake Michigan for nearshore rings. (First nearshore ring extends 5,000 feet from shore. Second ring extends 5,000–10,000 feet from shore. Third ring extends 10,000–15,000 feet from shore. Curve is exponentially declining trendline.)

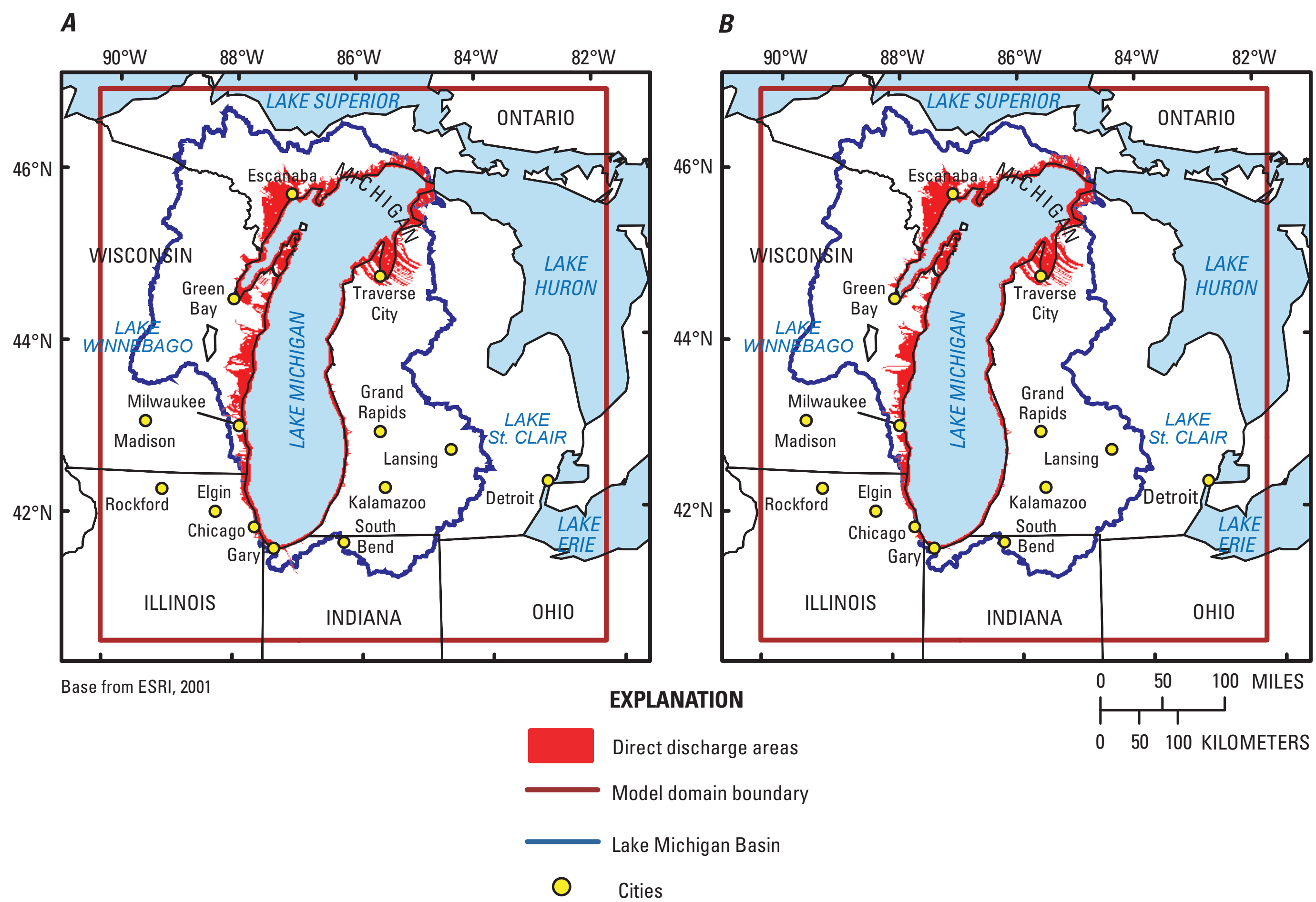


Figure 71. Simulated contributing areas for direct discharge to nearshore of Lake Michigan: *A*, Predevelopment. *B*, 1991–2005.

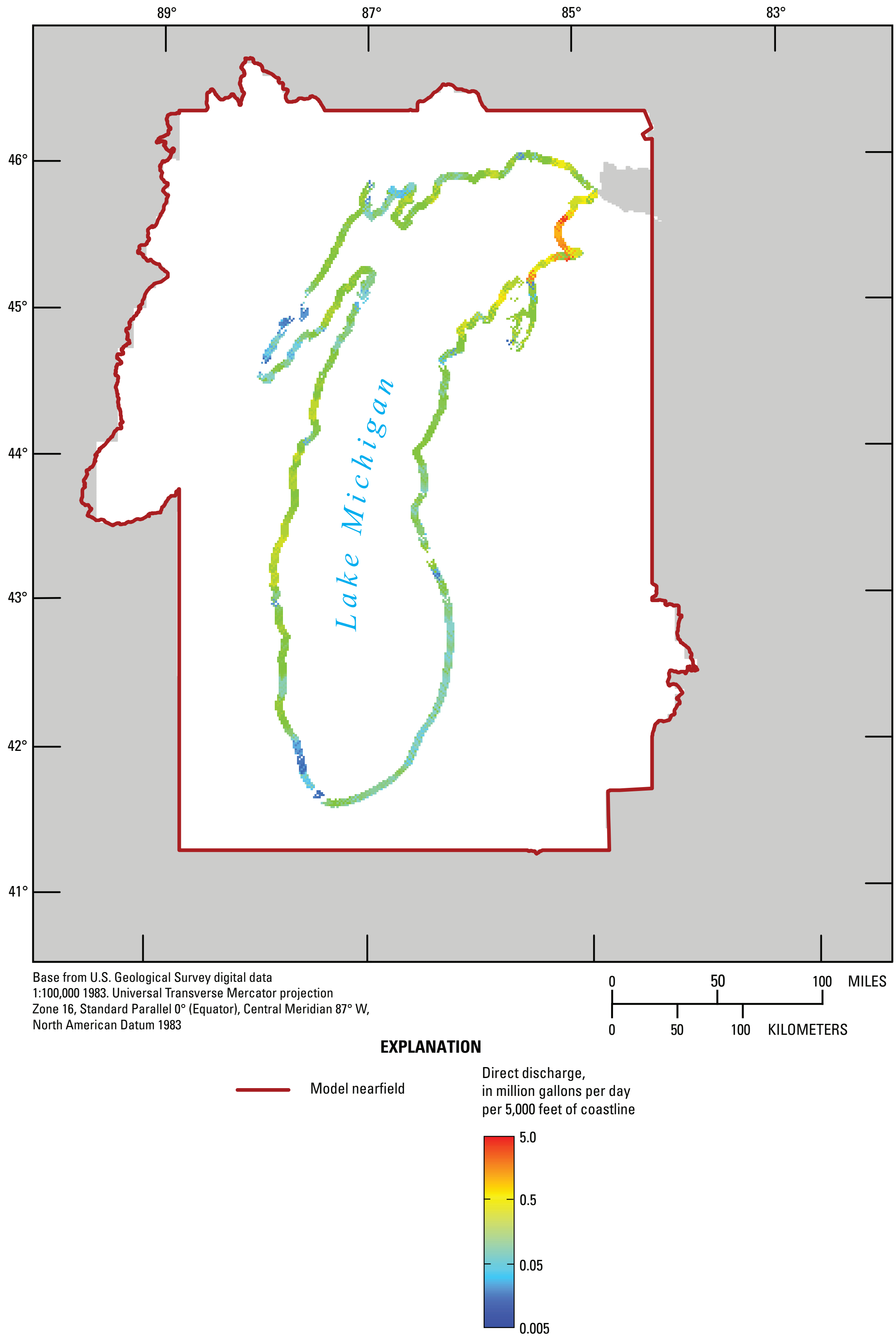


Figure 72*A*. Simulated shoreline outflow (from groundwater to Lake Michigan): Predevelopment.

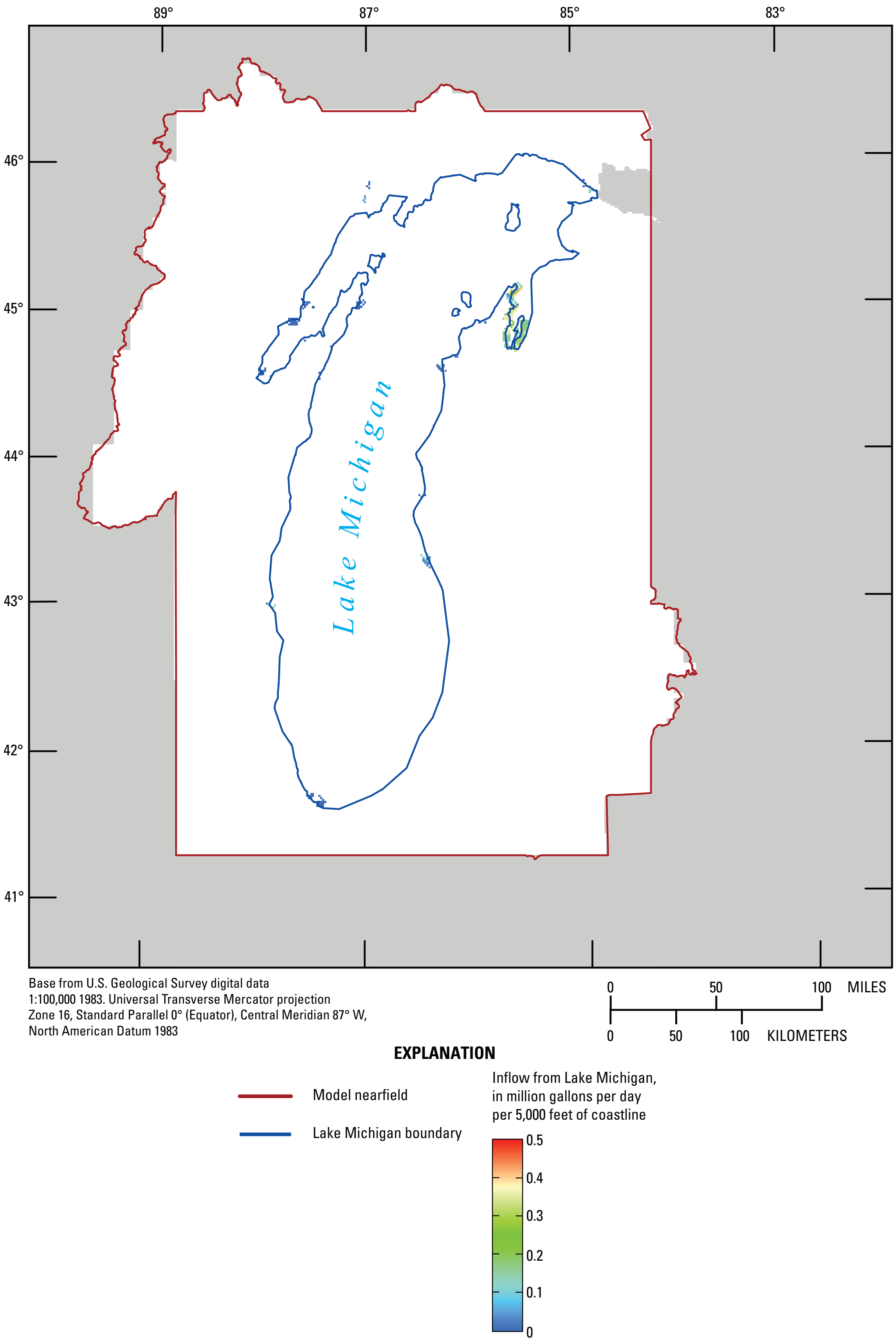


Figure 72*B*. Simulated shoreline inflow (from Lake Michigan to groundwater): Predevelopment.

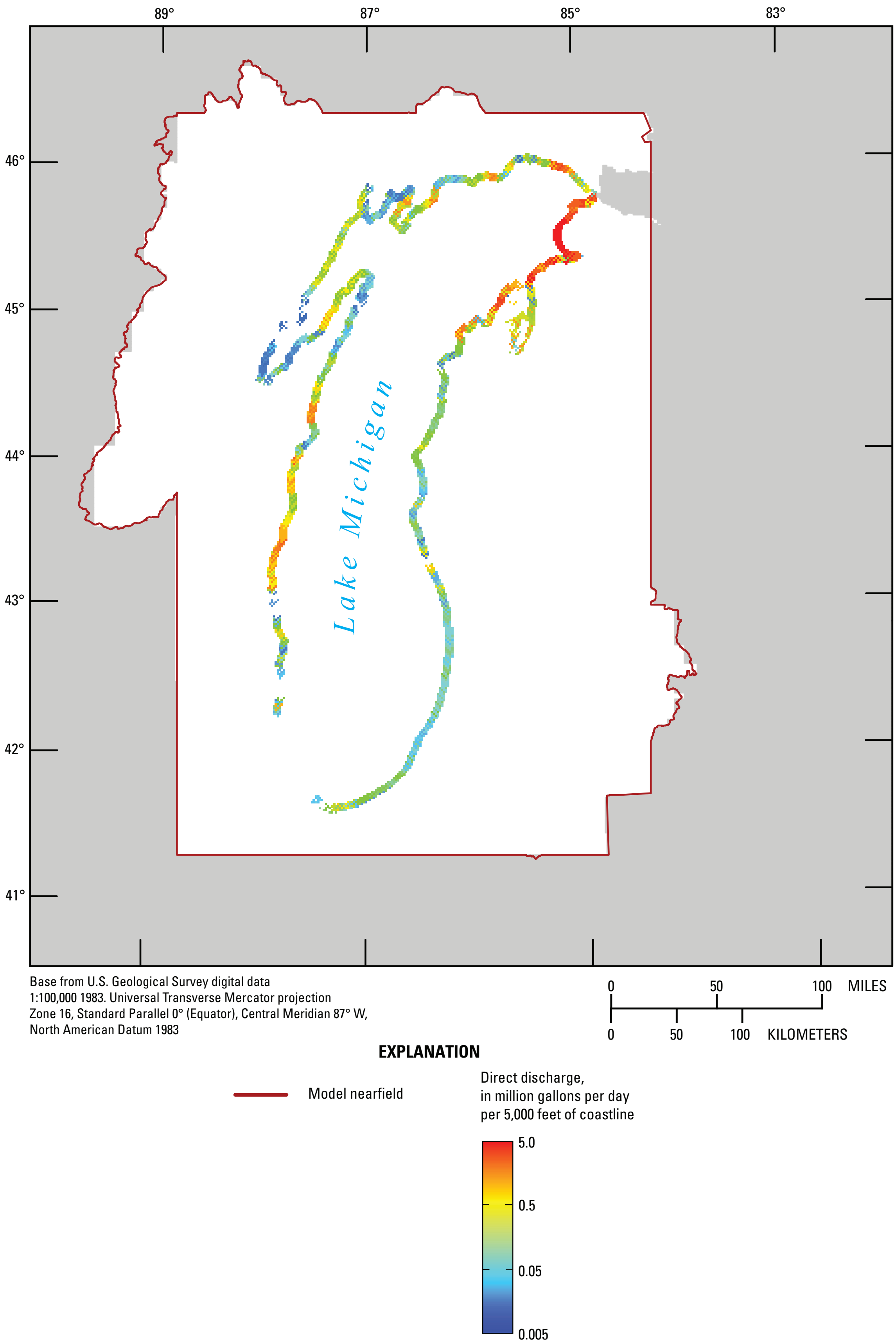


Figure 72*C*. Simulated shoreline outflow (from groundwater to Lake Michigan): 1980.

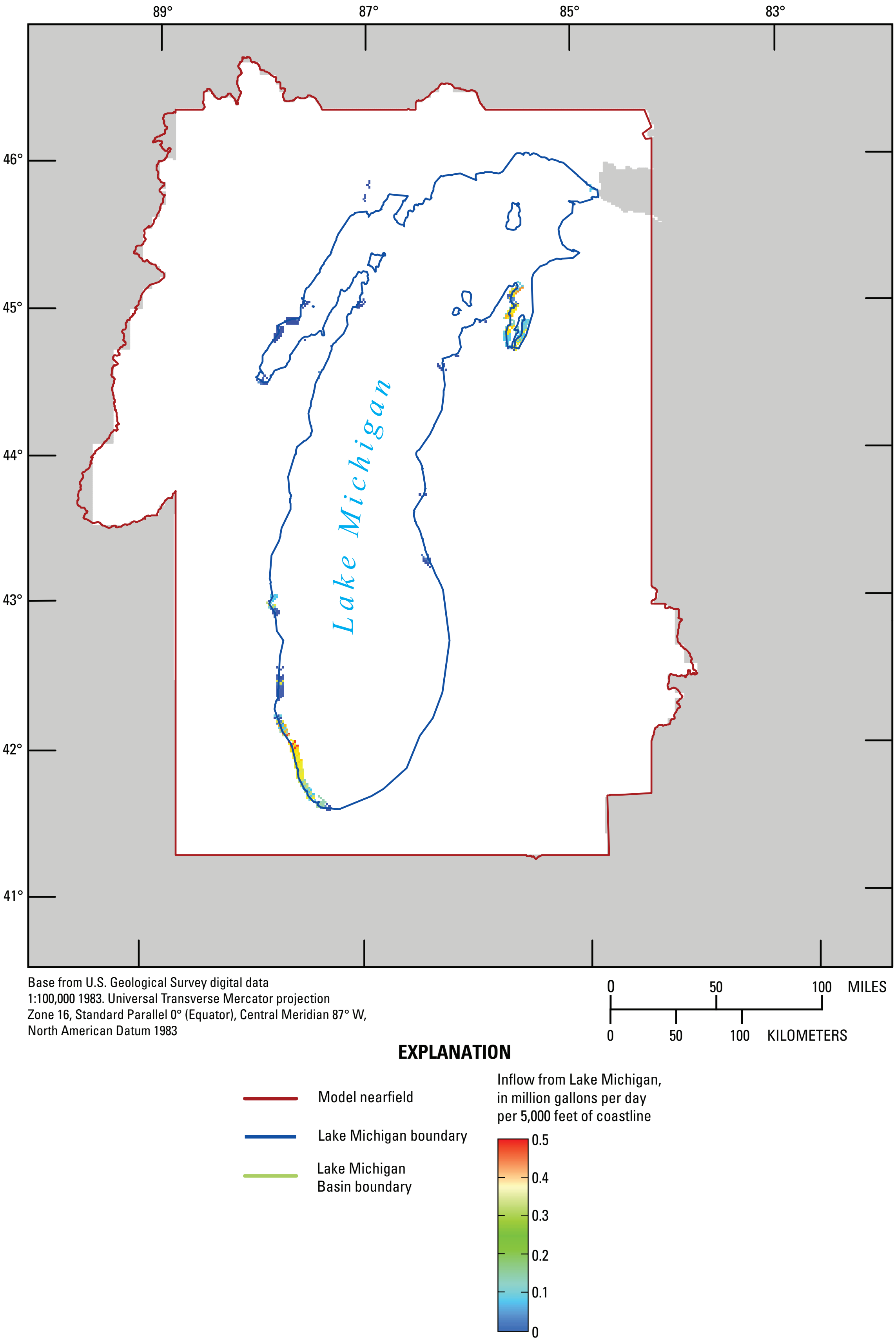


Figure 72*D*. Simulated shoreline inflow (from Lake Michigan to groundwater): 1980.

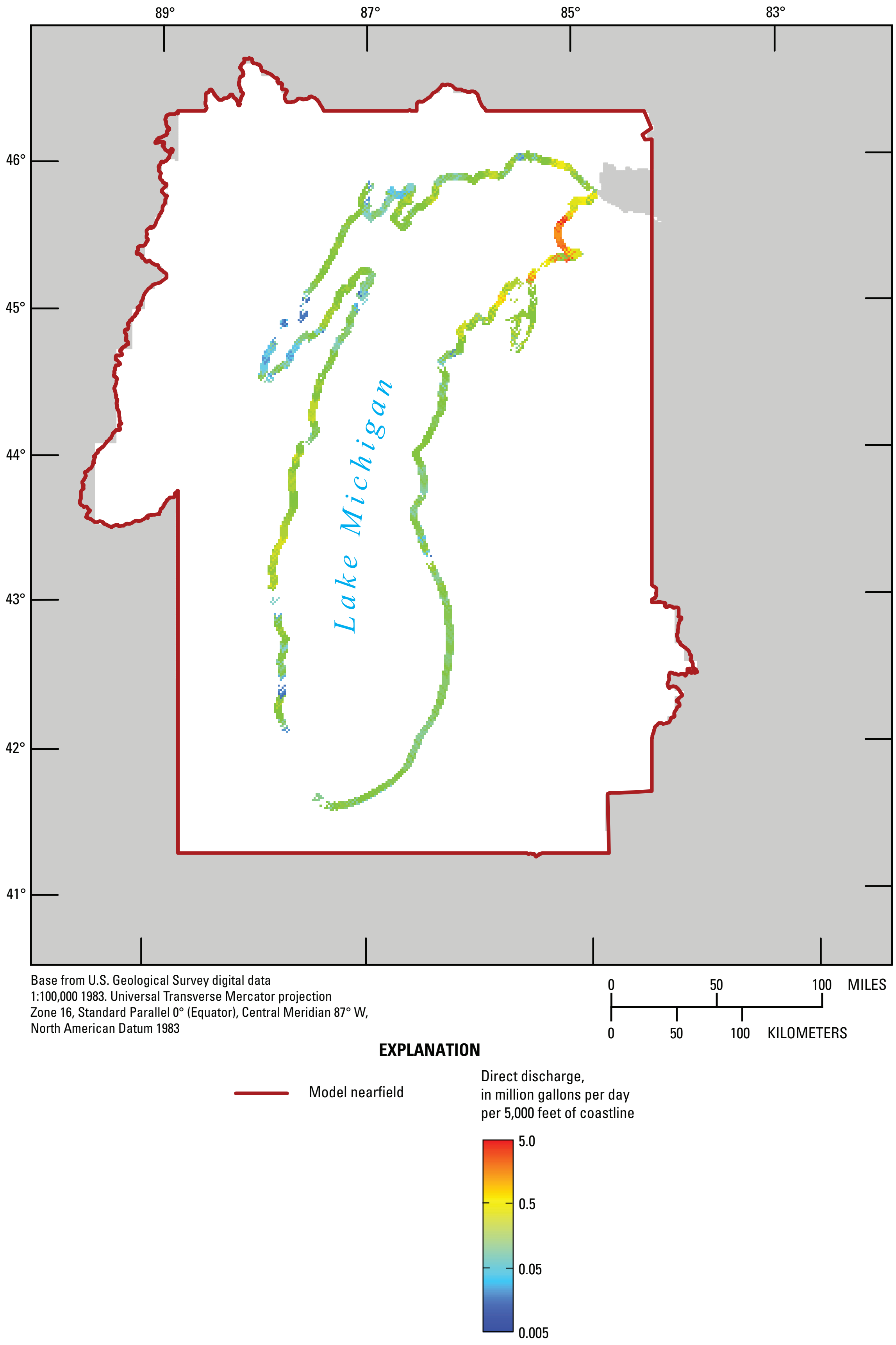


Figure 72*E*. Simulated shoreline outflow (from groundwater to Lake Michigan): 2005.

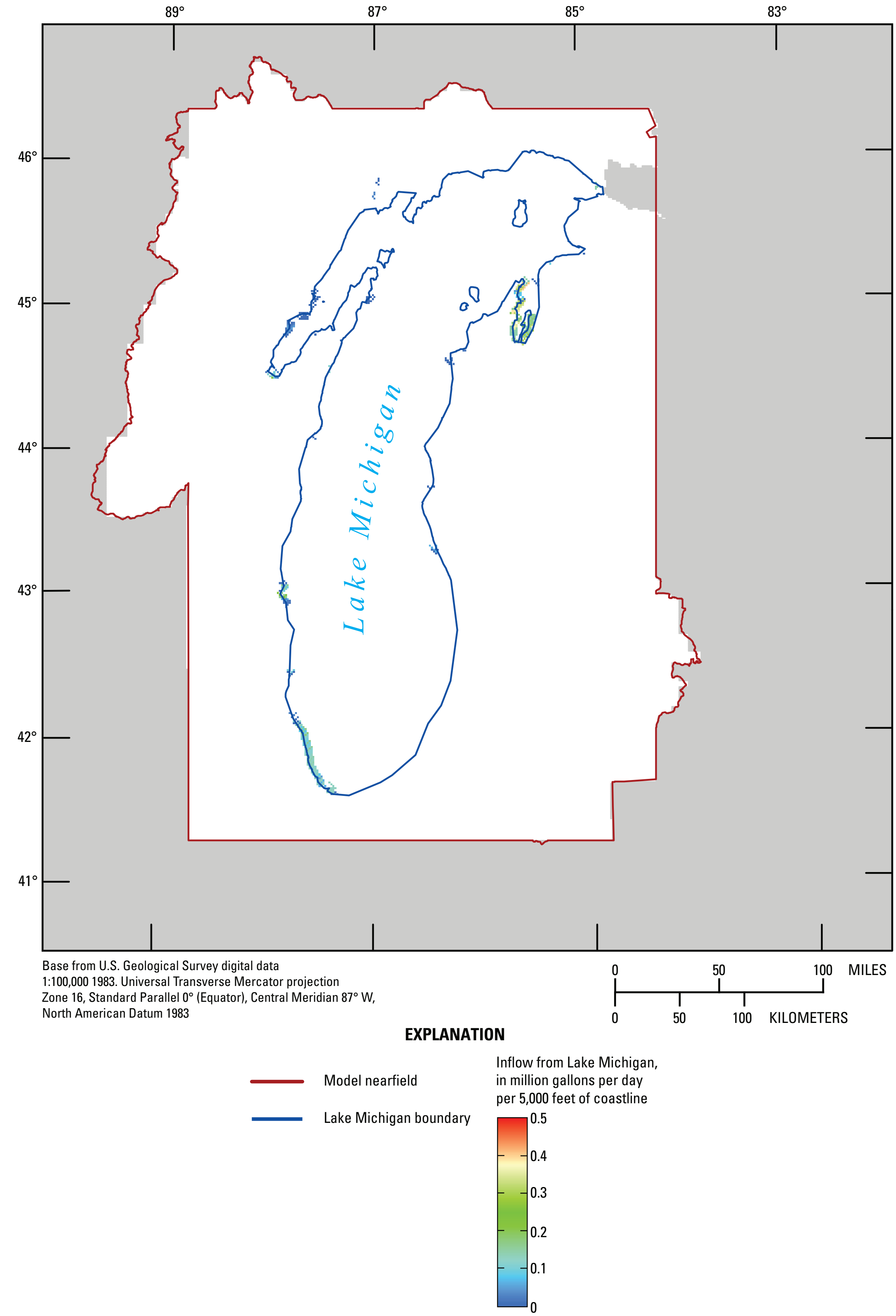


Figure 72*F*. Simulated shoreline inflow (from Lake Michigan to groundwater): 2005.

The same method employed previously to identify the sources of water to wells by comparing water budgets for natural and pumped condition was used to calculate the effect of pumping on direct discharge to the lake. Direct discharge to Lake Michigan is correlated with the trend of groundwater withdrawals from the model nearfield.[31] In 1950, the reduction in direct discharge to Lake Michigan served as a source of water pumped by wells totaling 4.1 Mgal/d, or 2.1 percent of total nearfield withdrawals (table 18). The reduction in discharge increases with time to more than 14 Mgal/d by 2005; however, the relative contribution is lower (1.8 percent of nearfield pumping in 2005) (table 18). When increased induced flow from Lake Michigan is added to the reduced discharge, the lake's relative contribution to well withdrawals becomes slightly larger (last column in table 18). All these findings are subject to an important qualification: the model does not include any return-flow component, such as wastewater-treatment plants that route pumped water after use back to Lake Michigan and possibly neighboring drainage basins. It is possible that most of the simulated reduction in direct discharge and net direct discharge to the lake is, in fact, returned, but at a different time, location, and temperature than would occur in the absence of pumping.

The contribution to pumping derived from *indirect discharge* to Lake Michigan via diverted base flow and induced flow from streams and diverted base flow from inland water bodies is much greater than the contribution attributable to net changes in *direct discharge* alone. The difference is evident when the total contribution (indirect plus direct) to pumping is calculated for the entire surface-water network, including Lake Michigan (last column of table 19). The change in the rate of groundwater interactions with the nearfield surface-water network (that is, the sum of reduced base flow and increased induced flow) accounts in the 1940 to 1985 period for about 75 to 80 percent of water flowing to nearfield wells. Subsequent to Lake Michigan diversions for water supply in NE_ILL, reduced base flow and increased induced flow account for around 90 percent or more of water flowing to nearfield wells. The percentage of nearfield pumping derived strictly from reduced direct discharge to Lake Michigan generally is between 1 and 2 percent. The remaining sources of water (storage release, lateral inflow to the nearfield) provide between 10 and 25 percent of the well discharge depending on the period.

[31] The model nearfield is used in place of the Lake Michigan Basin as the area over which to calculate the effect of pumping on groundwater interactions with Lake Michigan and also with inland surface water. This larger area is used because pumping from outside the Lake Michigan Basin (notably in SE_WI and NE_ILL) has an effect on the exchange between groundwater and the lake.

Table 18. Effect of nearfield pumping on simulated direct groundwater discharge to Lake Michigan.

[Values correspond to the confined model, SLMB-C; Mgal/d, million gallons per day]

Stress period	Date	Net pumping in model nearfield (net of injection) (Mgal/d)	Source: reduced direct discharge *to* Lake Michigan (Mgal/d)	Source: reduced direct discharge *to*, plus increased induced flow *from*, Lake Michigan (Mgal/d)
1	Predevelopment	0.00	0.00	0.00
2	Oct. 1864–Oct. 1900	16.04	.04	.04
3	Oct. 1900–Oct. 1920	56.19	.62	.62
4	Oct. 1920–Oct. 1940	114.62	2.39	2.53
5	Oct. 1940–Oct. 1950	194.16	4.14	4.62
6	Oct. 1950–Oct. 1960	280.43	5.76	6.80
7	Oct. 1960–Oct. 1970	466.98	6.59	7.23
8	Oct. 1970–Oct. 1975	617.10	6.86	8.08
9	Oct. 1975–Oct. 1980	708.37	7.51	9.21
10	Oct. 1980–Oct. 1985	769.31	8.27	10.18
11	Oct. 1985–Oct. 1990	725.49	8.94	11.19
12	Oct. 1990–Oct. 2000	821.38	14.24	16.31
13	Oct. 2000–Oct. 2005	814.37	14.37	16.46

Notes:

1. Net pumping is pumping minus injection. The model simulates injection at only one location (near Kalamazoo, Mich.), where it amounts to about 10 Mgal/d in 2005.

2. Lake Michigan is represented by GHB nodes in the model. The flow to the GHB nodes represents the *direct* discharge to the lake (that is, groundwater flow that discharges directly to the lake rather than indirectly through surface-water bodies that are tributary to the lake.)

3. Because recharge changes between stress periods, it is not possible to use the change in direct discharge to Lake Michigan simulated by the model over time to isolate the effect of changes in pumping on direct discharge. Instead, the effect of pumping is calculated by comparing a simulation *without* pumping to a simulation *with* pumping and computing the difference in the flow to the GHB nodes representing Lake Michigan.

4. Because pumping can induce flow from Lake Michigan landward (that is, out of GHB nodes), it is also possible to calculate the net direct discharge to Lake Michigan (that is, discharge minus induced flow) and the change in the net direct discharge due to pumping. Because the induced flow increases with pumping, the reduction in net direct discharge due to pumping is greater than the reduction in direct discharge.

5. It is important to note that the model does not include any return-flow component such as, for example, wastewater-treatment plants that route pumped water after use back to Lake Michigan. It is possible that most of the simulated reduction in direct discharge and net direct discharge to the lake is, in fact, returned, but at a different time, location, and temperature than under predevelopment (natural) conditions.

Table 19. Effect of nearfield pumping on total (direct plus indirect) groundwater discharge to Lake Michigan.
[Values correspond to the confined model, SLMB-C; Mgal/d, million gallons per day]

Stress period	Date	Net pumping in model nearfield (net of injection) (Mgal/d)	Source: reduced total discharge (direct and indirect) *to* nearfield surface water (Mgal/d)	Source: reduced total discharge (direct and indirect) *to*, plus increased induced flow *from*, nearfield surface water (Mgal/d)
1	Predevelopment	0.00	0.00	0.00
2	Oct. 1864–Oct. 1900	16.04	9.08	9.96
3	Oct. 1900–Oct. 1920	56.19	23.06	27.14
4	Oct. 1920–Oct. 1940	114.62	60.21	70.67
5	Oct. 1940–Oct. 1950	194.16	115.68	139.08
6	Oct. 1950–Oct. 1960	280.43	176.55	218.60
7	Oct. 1960–Oct. 1970	466.98	282.95	373.64
8	Oct. 1970–Oct. 1975	617.10	374.02	464.29
9	Oct. 1975–Oct. 1980	708.37	409.04	539.70
10	Oct. 1980–Oct. 1985	769.31	499.59	621.77
11	Oct. 1985–Oct. 1990	725.49	501.30	642.64
12	Oct. 1990–Oct. 2000	821.38	611.32	781.07
13	Oct. 2000–Oct. 2005	814.37	613.49	785.35

Explanation:

1. Net pumping is pumping minus injection inside the Lake Michigan topographic basin. The model simulates injection at only one cluster of locations (near Kalamazoo, Mich.), where it amounts to about 10 Mgal/d in 2005.

2. Lake Michigan is represented by GHB nodes in the model. Inland surface-water bodies inside the Lake Michigan Basin (streams plus lakes plus wetlands) are represented by RIV nodes. The flow to the GHB and RIV nodes represents the total discharge to the lake (that is, groundwater flow that discharges directly to the lake plus groundwater flow that discharges indirectly through surface-water bodies that are tributary to the lake). All inland surface-water bodies represented in the model inside the Lake Michigan topographic basin are considered tributary to Lake Michigan.

3. Because recharge changes between stress periods, it is not possible to simply use the change in total discharge to Lake Michigan simulated by the model over time to evaluate the effect of changes in pumping on discharges. Instead, the effect of pumping is calculated by comparing a simulation *without* pumping to a simulation *with* pumping and computing the difference in the flow to the GHB nodes representing Lake Michigan and the RIV nodes representing inland surface-water bodies.

4. Because pumping can induce flow from Lake Michigan landward and from surface-water bodes into groundwater (that is, out of GHB nodes and out of RIV nodes), it is also possible to calculate the net total discharge to Lake Michigan (that is, discharge minus induced flow) and the change in the net total discharge due to pumping. Because the induced flow increases with pumping, the reduction in net total discharge is greater than the reduction in total discharge.

5. It is important to note that the model does not include any return-flow component such as, for example, wastewater-treatment plants that route pumped water after use back to Lake Michigan. It is possible that most of the simulated reduction in direct discharge and net direct discharge to the lake is, in fact, returned, but at a different time, location, and temperature than under predevelopment (natural) conditions.

7. Alternative Conceptual Models and Model Sensitivity

Much can be learned about the dynamics of a groundwater-flow system by modifying assumptions built into a selected modeling approach. Some assumptions are linked to the conceptual model of the system, others to imposed boundary conditions and parameters, and yet others to the limitations of the solution algorithm linked to the regional grid spacing. For the groundwater-flow model of the Lake Michigan Basin, the robustness of model results was tested for the following elements of the model design:

- Alternative models—Change conceptual assumptions regarding confined versus unconfined flow, variable density, and fixed salinity concentrations.
- Input sensitivity—Change input assumptions regarding cell-by-cell variation of QRNR hydraulic conductivity, head-dependent and flux-specified farfield boundary conditions, lakebed hydraulic conductivity, and fixed stages of Lake Michigan and other Great Lakes.
- Grid-resolution sensitivity—Change assumptions regarding coarse representation of surface-water network along shoreline of Lake Michigan.

These tests are broad in scope insofar as they show the sensitivity of results not only to key parameter inputs but also to conceptual and geometric assumptions. The simulations, which sometimes involve simplifying model input and sometimes more sophisticated input, show both strengths and weaknesses of the implemented model design.

7.1 Alternative Models

The conceptual model for the calibrated, confined version of the LMB model (the “base” model) has two noteworthy assumptions:

1. Although parts of the flow system are truly unconfined, a confined version that approximates unconfined conditions by scaling inputs to take account of saturated thickness yields an adequate representation of the dynamics of the groundwater-flow system.
2. Although the distribution of salinity and fluid density gradients in the Michigan Basin is in theory subject to change in response to stresses such as pumping, the use of fixed concentration conditions in SEAWAT-2000 yields an adequate representation of the dynamics of the groundwater-flow system.

These sets of assumptions are tested with three alternative models. Each of the alternative models constructed poses advantages for certain types of applications. For this reason they, like the base SLMB-C model version, have been archived and can be distributed for later use.

7.1.1 Unconfined Version of Model

Two versions of the LMB model were calibrated: confined and unconfined. The confined model was adjusted to reflect actual unconfined conditions and employs a linearized version of the groundwater flow equation with concomitant advantages of shorter runtimes, smaller mass-balance error, fully saturated conditions, and no exclusion of pumping because of dry cells. These features facilitated the application of nonlinear regression in the parameter-estimation process. A separate calibration was done by using an unconfined model to generate a version of the LMB model capable of directly simulating unconfined conditions. Such a model version is particularly useful for simulations that focus on water availability in areas with declining saturated thickness and for construction of more finely discretized inset models within the regional model domain to simulate local interactions between shallow pumping and surface.

The unconfined version of the LMB model (SLMB-U) differs from the confined version (SLMB-C) in several ways:

- Storage in unconfined cells (all active cells in layer 1 and cells in underlying layers where the simulated water level is below the top of the cell) is proportional to specific yield rather than specific storage.
- The controlling storage variable is redefined for cells that convert from confined to unconfined—or vice versa—during the simulation.
- Transmissivity in unconfined cells varies during the simulation as a function of saturated thickness rather than remaining constant.[32]

The confined and unconfined models were subjected to the same calibration procedure, although the mass-balance error in the unconfined model was increased to provide manageable runtimes. The mass-balance error in the calibrated unconfined model is approximately twice as great as for the confined model, averaging about 0.2 percent for all time steps. The contribution of target sets to the calibration is similar for the confined and unconfined models (compare table 11*B* to table 11*A*). Both versions of the model were subjected to five regression iterations by using the same estimation techniques discussed in section 5. The model fit as reflected in the final values of the objective function differs little between the two calibrated models: 4.68 E5 confined versus 4.63 E5 unconfined. Comparison of calibration statistics for the two models (table 12) indicates that the agreement between measured and simulated targets is nearly equal, although the quality of the match is better for more target groups in the confined model.

[32] For the confined version of the LMB model, the specific storage and hydraulic conductivity are adjusted to take account of the saturated thickness in unconfined cells based on a trial simulation with initial inputs (see section 5). Also, it is worth noting that the vertical conductance term regulating vertical flow between layers is *not* a function of saturated thickness in *either* the confined or unconfined version of the LMB model.

In addition, when residuals at measured water-level targets are considered, the root mean squares error for the confined model (36.78 ft) is slightly lower than that for the unconfined version (37.57 ft).

The ranking of parameter groups by sensitivity is nearly identical in the two models (compare tables 13*A* and 13*B* and fig. 49*A*, *B*). The specific-yield parameters are relatively insensitive in the calibration of the unconfined model, and the final estimated values for specific yield nearly equal the initial values. The insensitivity of the specific-yield parameters is due to the constraints on the water-table solution imposed by the large number of RIV boundary-condition cells distributed throughout the model nearfield. Specifying a single specific-yield zone for all QRNR deposits probably also contributed to parameter insensitivity.

One way to compare the results of the unconfined model (SLMB-U) to the confined model (SLMB-C) is to inspect the parameter multipliers (appendix table A5–2). In general, the multipliers are very similar, but small differences exist for recharge, hydraulic conductivity, conductance, and storage. Two differences are worth noting:

- Slightly higher recharge in the unconfined model (multiplier on the initial value of 1.060 instead of 1.048 for the confined case).
- Slightly higher riverbed conductance terms in the unconfined model (maximum multiplier on an initial value equal to 2.3 instead of 1.5 for the confined case).

A systematic comparison of the calibration results for horizontal hydraulic conductivity involves computing the central tendency of values for the confined and unconfined models by aquifer system and by subregion (appendix 9). The biggest differences are evident for the K_h for the QRNR system, where the geometric mean is somewhat higher for the unconfined model in UP_MI, NE_WI, and SE_WI and the mean value is slightly lower in N_IND. There are small differences in the other aquifer systems, but in all instances the size of the difference between the two calibrated models is much less than the change from the initial values to calibrated values.

Two general conclusions can be drawn from the comparison of the confined and unconfined LMB models:

1. Even though more unreliable derivatives were fed to inversion routines in the unconfined as opposed to the confined case, the calibration processes produced similar calibration statistics and sensitivities for the two versions.
2. Whereas the calibrated inputs to the two models are not identical, the differences in parameter multipliers and resulting cell values generally are small.

One major difference between SLMB-U and SLMB-C is worth noting: The confined model simulation maintains all pumping input to the model, but the unconfined model loses pumping because of dry cells (where the water table falls below the bottom of a cell containing an active well, turning the cell inactive and eliminating any discharge assigned the cell). For SLMB-U, the loss amounts to about 2 percent of total net withdrawals by 2005 (21 Mgal/d of 1,095 Mgal/d) and 3 percent of 2005 net withdrawals from the Lake Michigan Basin (19 Mgal/d of 580 Mgal/d). The loss is concentrated in two nearfield subregions where withdrawals are predominantly from unconfined aquifers: the SLP_MI (more than 5 percent of pumping) and the NLP_MI (nearly 7 percent of pumping). It is possible that the exclusion of most first-order streams as internal model boundaries eliminates a source of water to wells, which contributes to overestimating drawdown in the unconfined model. It is certain that the coarse representation required by the regional scale results in misfit in some locations; in the *unconfined model*, misfits can result in dry cells and lost pumping, but in the *confined model*, misfits cannot result in lost pumping even though the simulated water level is below the cell bottom. By keeping wells in the affected cells active, the confined model provides a better account of the expected effect of known pumping on base-flow reduction and other water-budget terms, but at the possible cost of maintaining aquifer properties that are unreasonable in the vicinity of the wells.

Shifting from calibration to model results, it is instructive to compare the unconfined and confined versions of the LMB model with respect to the 2005 water budget, predevelopment heads, 2005 drawdown, and water-level hydrographs at pumping centers. Special attention is required to interpret the differences between the models when it is a question of dewatered conditions in the deep flow system.

The 2005 Lake Michigan Basin water budgets for the confined and unconfined models show identical overall patterns with small variations (fig. 73). The total recharge is slightly greater (1 percent) for SLMB-U than for SLMB-C, owing to the larger multiplier estimated for the unconfined model, whereas all the other inflow terms are slightly greater for the confined model, including storage. With respect to the outflow terms, total 2005 pumping is 3 percent lower for the unconfined model due to pumping lost from dry cells (although loss of pumping through 1990 in the unconfined model is less than 0.2 percent), whereas the distribution of discharge among surface-water features shifts slightly in favor of the inland water bodies (lakes and wetlands as opposed to streams) in the unconfined model. Direct groundwater discharge to Lake Michigan is virtually identical for the two simulations. Perhaps the most interesting difference between the model water budgets is the relative size of the storage terms. For stress periods after 1940, the average amount of storage release in the unconfined model is only two-thirds the release in the confined model; the average amount of unconfined storage gain is only about six-tenths the confined gain. It is hard to know the extent to which the smaller storage change in the unconfined case reflects smaller average fluctuations in water levels or, alternatively, smaller storage factors applied to the water-level changes.

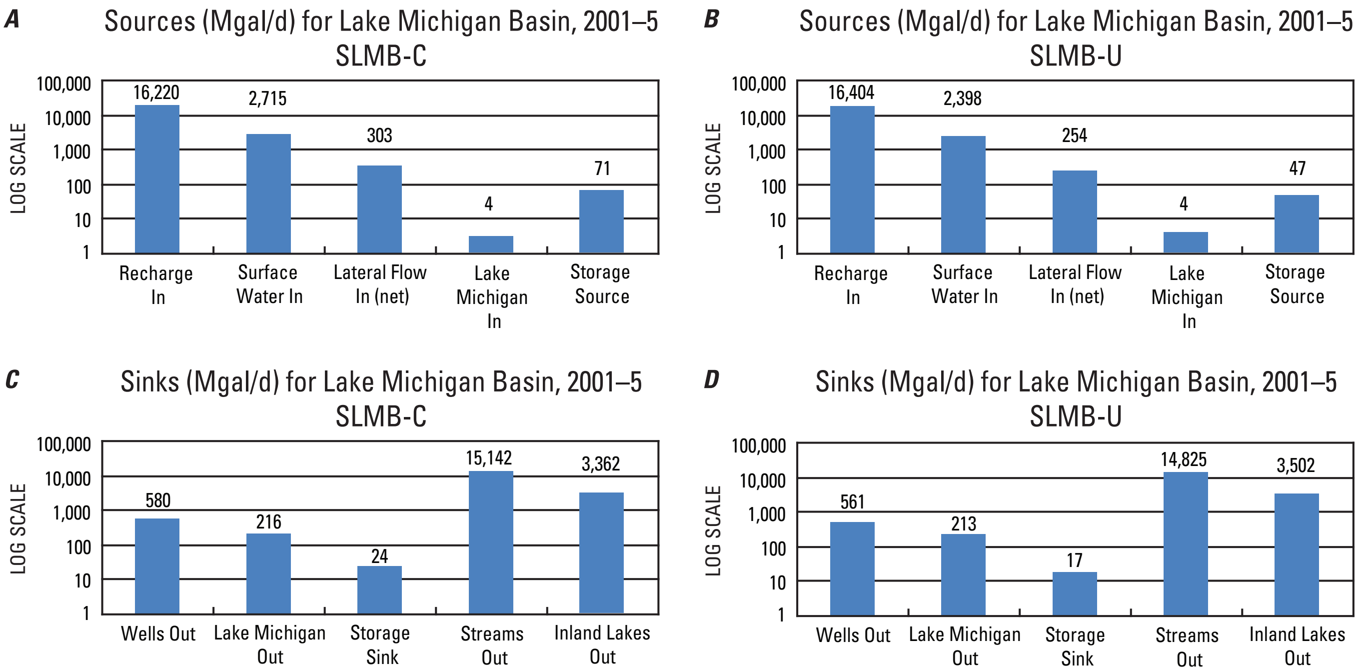


Figure 73. Simulated 2005 water budgets in Lake Michigan Basin: base model (SLMB-C) versus alternative unconfined model (SLMB-U).

Larger differences are apparent in water levels and drawdowns simulated by the two models. To facilitate the comparisons, it is convenient to tabulate by aquifer system the percentage of the model nearfield with differences greater than 20 ft (tables 20 and 21, first data column). This threshold is selected because it is roughly equal to (but less than) the Mean Absolute Error attributable to water-level residuals for the confined model calibration (25 ft). For predevelopment conditions, the unconfined model simulates a higher water table (almost 1 percent of the QRNR system) but lower water levels in some deep system (almost 2 percent of the MSHL system). There are also differences at the 20-foot threshold with respect to 2005 drawdown: the contrast is most marked in the C-O aquifer system, where drawdown in more than 3 percent of the unpinched cells in the unconfined model is lower than in the confined model. Water-level hydrographs at four selected pumping centers (locations shown in fig. 54) provide additional insight into the degree to which the two head solutions diverge. The trends appear very similar for the MSHL pumping center near Lansing, Mich., for the C-O pumping center around Green Bay, Wis., and also for the C-O pumping center in southeastern Wisconsin (compare fig. 74*A* to 74*B*). Drawdowns in northeastern Illinois simulated by the unconfined and confined models are different. Two comments are appropriate in this context. First, calibration statistics (table 12) indicate that the confined model more closely matches observed water levels, drawdown, and recovery for the C-O aquifer system in northeastern Illinois than does the unconfined model. Second, the difference in the slopes in the water-level hydrographs for the confined and unconfined models (compare fig. 74*A* to 74*B*) reflects the storage properties in the two models. In the unconfined model, storage release is small as long as the water column remains saturated because specific storage controls the release of water (equal to thickness multiplied by 1.6 E−7 ft^{-1} once the parameter multiplier of 0.636 is applied to the initial specific storage value of 2.6 E−6 ft^{-1}; see appendix 5, table A5–2). However, once a second water table emerges at depth due to dewatering at the top of the C-O aquifer system at the center of the NE_ILL pumping center, storage release is controlled by the specific yield (equal to either 4.4 E−3 or 4.4 E−2 depending on the unit where the head loss occurs). As a result, for the unconfined model, water-level declines at early times under confined (saturated) conditions are less than declines at later times under dewatered, unconfined conditions. In the confined model, a single storage coefficient, approximated as twice the geometric mean of the specific yield and the product of specific storage and thickness (see discussion of “linearization” in section 5), controls water-level declines. Therefore, the rates of decline in the confined model are less steep than in the unconfined model at early time and greater at late time (compare the NE_ILL pumping center hydrographs in fig. 74*A* and 74*B*), and water levels in the confined model are lower than in the unconfined model in the years before recovery starts in the 1980s.

Table 20. Discrepancy between alternative models and SLMB-C with respect to predevelopment water levels, by aquifer system.

20*A*. Percentage of nearfield active cells in aquifer system with predevelopment water level more than 20 feet HIGHER in alternative models relative to SLMB-C.

	Alternative models		
Aquifer system	**Unconfined SLMB-U (percent)**	**Uniform density MLMB-C (percent)**	**Active transport SLMB-CT3 (percent)**
QRNR	0.80	0.00	0.00
PENN	.06	.00	.00
MSHL	.04	49.50	.00
SLDV	.26	56.49	.00
C-O	.03	51.07	.00

20*B*. Percentage of nearfield active cells in aquifer system with predevelopment water level more than 20 feet LOWER in alternative models relative to SLMB-C.

	Alternative models		
Aquifer system	**Unconfined SLMB-U (percent)**	**Uniform density MLMB-C (percent)**	**Active transport SLMB-CT3 (percent)**
QRNR	0.03	0.00	0.00
PENN	.00	.00	.00
MSHL	1.77	.00	.00
SLDV	.32	.98	.00
C-O	.24	16.71	.00

Table 21. Discrepancy between alternative models and SLMB-C with respect to 2005 drawdown, by aquifer system.

21*A*. Percentage of nearfield active cells with 2005 drawdown more than 20 feet GREATER in alternative models relative to SLMB-C.

Aquifer system	Alternative models		
	Unconfined SLMB-U (percent)	**Uniform density MLMB-C (percent)**	**Active transport SLMB-CT3 (percent)**
QRNR	0.09	0.00	0.00
PENN	.00	.00	.00
MSHL	.00	.00	.00
SLDV	.12	.00	.05
C-O	.25	1.43	20.45

21*B*. Percentage of nearfield active cells with 2005 drawdown more than 20 feet LESS in alternative models relative to SLMB-C.

Aquifer system	Alternative models		
	Unconfined SLMB-U (percent)	**Uniform density MLMB-C (percent)**	**Active transport SLMB-CT3 (percent)**
QRNR	0.07	0.00	0.00
PENN	.00	.00	.00
MSHL	.01	.00	.00
SLDV	.32	.16	8.72
C-O	3.22	.00	.00

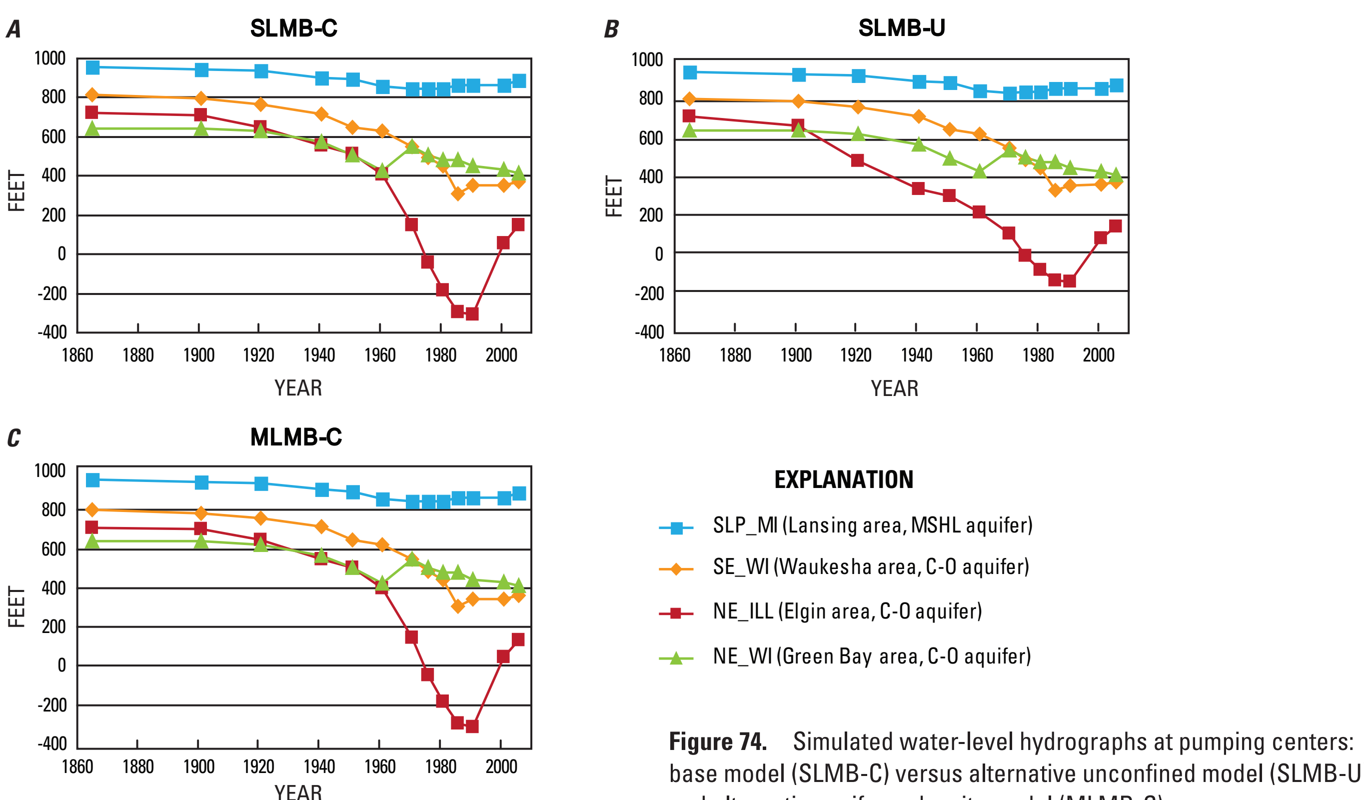


Figure 74. Simulated water-level hydrographs at pumping centers: base model (SLMB-C) versus alternative unconfined model (SLMB-U) and alternative uniform-density model (MLMB-C).

An important finding of the LMB model is that in areas close to large pumping centers with deep wells penetrating the C-O aquifer system, dewatered conditions can exist at the top of the C-O aquifer system, most commonly in the Sinnipee unit. These dewatered conditions manifest themselves in the model in one of two ways:[33] (1) All model layers contain saturated material, but the heads in the Sinnipee are below the top of that unit, implying the presence of a second water table in the dolomite. (2) The simulated head is below the bottom of the Sinnipee and the second water table is present in an underlying unit, such as the St. Peter. The first case is much more prevalent than the second, but both indicate dewatered conditions at the top of the C-O aquifer system and the existence of two saturated systems, one shallow and one deep, separated by a deep water table.

The confined and unconfined versions of the LMB model simulate dewatered areas that form after predevelopment and are attributable to deep pumping. They are found only on the west side of Lake Michigan (fig. 75). In general, the dewatered areas are larger in 2005 than in 1980, although the large dewatered area in northeastern Illinois is slightly diminished due to the switch from groundwater to Lake Michigan as a source of water supply. The agreement between the dewatered areas simulated by the confined and unconfined models is strong, suggesting that the two versions of the LMB model are generally consistent with respect to drawdown patterns and to the pattern of vertical leakage from overlying rocks to the deep C-O units. In this connection, it is worth noting that the dewatered layer for the confined version of the model (SLMB-C) is always treated as fully saturated from the standpoint of horizontal and vertical components of the groundwater flow equation whatever the head level simulated and the implied water-table condition; for the unconfined version (SLMB-U), by contrast, the transmissivity is reduced in proportion to the loss of saturated thickness in dewatered cells and, in addition, the vertical flow calculation across the cell is modified to take account of the presence of unsaturated material (McDonald and Harbaugh, 1988; Harbaugh and others, 2000). Despite these differences in the calculation routines, the results of the two model versions are very similar.

The simulated dewatering at the top of the C-O aquifer system (fig. 75) is supported by a variety of field evidence. There are four main areas where the confined and unconfined versions of the LMB model suggest that dewatering has occurred. In the vicinity of *Green Bay, Wis.*, potentiometric-surface information assembled for 2004 and 2008 indicates that water levels are drawn down to the extent that part or even all of the Sinnipee unit at the top of the C-O aquifer system is dewatered (Luczaj and Hart, 2009) in the same general area where the model simulates the presence of a deep water table for the 2005 stress period. Around *Lake Winnebago in northeastern Wisconsin*, geochemical evidence is favorable to the hypothesis that the top of the C-O aquifer system is dewatered in the same area indicated by the LMB model for 1980 and 2005. Arsenic contamination around Lake Winnebago is attributed to the oxidation of arsenic from a sulfide-bearing secondary cement horizon, which is present at the boundary between the Sinnipee rocks and the underlying unit, generally the St. Peter. Researchers have noted that the elevation of water levels in wells exerts a strong control on the release of naturally occurring arsenic to groundwater; further, they point out that in some areas where arsenic is elevated, heads have been lowered by pumping, so that the present-day levels in wells are open to the Sinnipee and St. Peter units (Gotkowitz and others, 2004). The zone of dewatering near *Waukesha, Wis.*, was noted in an earlier model centered on southeastern Wisconsin (Feinstein, Hart, and others, 2005). This finding led to the installation of nested piezometers at a location within the zone of dewatering simulated by the confined and unconfined LMB models. Water levels measured in 2004 are strong evidence that a second water table is present in the Sinnipee unit (Eaton and Bradbury, 2005). Finally, by far the largest area of simulated dewatering shown in figure 75 corresponds to the pumping centers around *Joliet in northeastern Illinois*. This finding is consistent with results obtained by a model recently constructed by the ISWS for Kane County and surrounding areas (Meyer and others, 2009). In light of these results, the ISWS has compared 2007 water levels in wells that penetrate the top units of the C-O aquifer system to the bottom elevation of the Sinnipee unit at the well locations. They conclude that the large dewatered area simulated by the models and centered on Joliet is consistent in shape and extent with the area where the water levels in the deep wells are either as much as 50 ft below the bottom of the Sinnipee unit (in a restricted zone immediately around Joliet) or at an elevation that falls within the Sinnipee (Wehrmann and others, in preparation). The simulated results of the LMB model agree with the details of this analysis insofar as they show the second water table to be in the St. Peter immediately around Joliet and in the Sinnipee in the larger surrounding area.

[33] See section 5.1 for discussion of the algorithms employed by the SEAWAT code to handle dewatered conditions in unconfined mode and in confined mode.

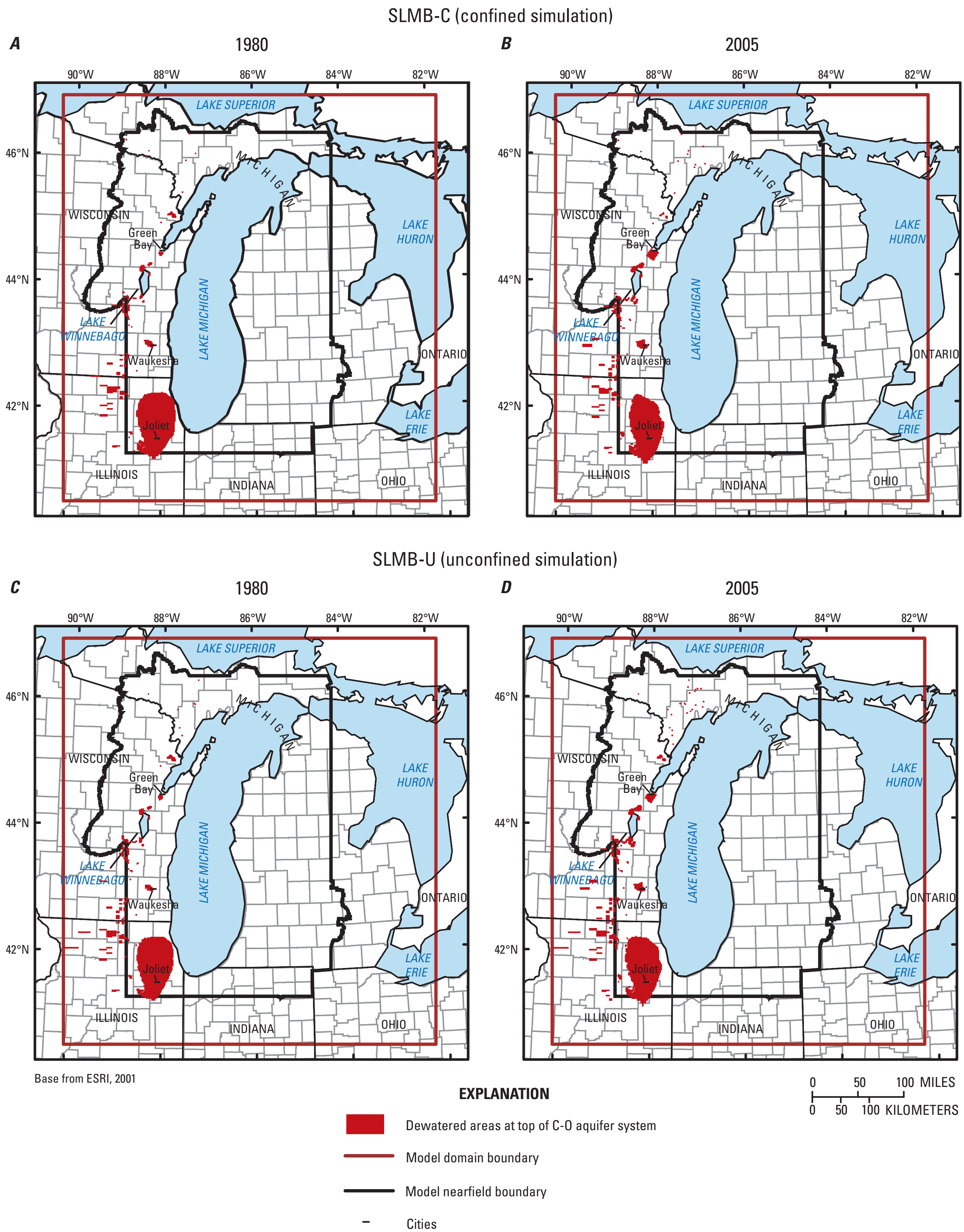


Figure 75. Simulated dewatering at top of Cambrian-Ordovician aquifer system as a result of pumping: base model versus alternative unconfined model for 1980 and 2005.

Pumping is responsible for dewatering at the top of the C-O aquifer system in both Wisconsin and Illinois, but the mechanisms that accompany this dewatering are open to speculation. Multiple water tables at the locations discussed imply that there is shallow saturated system, the top of which is defined by a water table usually in Quaternary deposits and the bottom of which is generally in the Maquoketa hydrogeologic unit. The shallow system is underlain by a deeper saturated system whose top is defined by a water table in the Sinnipee unit or possibly an underlying unit such as the St. Peter and whose bottom is below the bottom of the Mount Simon unit at the base of the sedimentary deposits. It is possible that air enters the intermediate dewatered zone between the two saturated systems by moving through boreholes that penetrate the C-O aquifer system and replaces the water withdrawn from the system. Alternatively, there may not be pathways to allow air to enter the system; in this case, the aquifer material between this second water table and the overlying system would, in fact, remain saturated but under a capillary tension that is above the air-entry pressure required to allow the largest pores to drain. Accordingly, observation wells would indicate the presence of a second, deep water table that is overlain by an intermediate zone analogous to the capillary fringe that is associated with water-table aquifers. However, because the system is not freely open to the atmosphere, the configuration and dynamics of this intermediate zone are likely complex and difficult to predict. Whatever the degree of dewatering, the model findings corroborated by field evidence suggest that pumping from the C-O aquifer system has caused deep water tables to form in the Green Bay, Lake Winnebago, Waukesha, and greater Joliet areas and that this condition occurs mostly commonly in the Sinnipee hydrogeologic unit.

7.1.2 Uniform-Density Simulation

Two alternative models have been devised to test the assumptions that (1) high levels of salinity in the Michigan Basin influence the groundwater flow field in important and detectable ways and (2) this influence can be adequately simulated by assigning fixed concentrations (and, hence, fixed density) levels to model layers in correspondence to unit-dependent maps of the saline body.

Density effects were first tested by preparing an alternative model that substitutes uniform freshwater density for spatially distributed variable density. The exact same model geometry and input used for the calibrated confined saline version of the model (SLMB-C) was applied to a confined version of the model (MLMB-C) without any recalibration. The only difference between the two simulations is that the calibrated saline version is solved with SEAWAT-2000 and the companion freshwater version is solved with MODFLOW-2000. Because SEAWAT-2000 calculations are performed in double precision, MLMB-C is solved with a double-precision version of MODFLOW-2000 to ensure consistency.

As emphasized earlier,

- model findings regarding water availability are sought principally in freshwater areas, and
- model calibration targets are restricted to freshwater areas.

Only the results for the vertical-head-difference target set shows appreciable difference for the two simulations. The statistical similarity indicates that, in freshwater areas, there is little difference between the confined model with variable density and with uniform density in freshwater areas. With respect to the global 2005 water budget for the Lake Michigan Basin, the results also are very similar (fig. 76), which is expected because recharge to the water table is the same in both simulations. The biggest difference is that the MLMB-C simulation yields a 5 percent lower rate of direct discharge to Lake Michigan than the SLMB-C simulation. Large differences are registered in the case of simulated predevelopment heads (table 20*A*, second column). For model cells containing saline water, the heads generated the uniform-density model are higher than the heads generated by a solution that accounts for salinity. The 50 percent or more of cells in the MSHL, SLDV, and C-O aquifer system with more than 20-ft discrepancies are almost all in the Michigan Basin. As far as drawdown is concerned, there is very little difference either within aquifer systems (table 21, second column) or near pumping centers (fig. 74). Closer inspection of the results for the C-O aquifer system shows that, west of Lake Michigan, the drawdown around the NE_WI, SE_WI, and NE_ILL pumping centers is on the order of 5 ft higher for the SLMB-C than the MLMB-C simulation; but east of the lake, drawdown is on the order of 5 ft less. This subtle difference can be attributed to the effect of salinity on water flowing west toward deep pumping centers from the Michigan Basin underneath Lake Michigan. The saline conditions cause more drawdown than otherwise near the pumping centers and under the west side of the lake, where freshwater can be relatively easily moved, and less drawdown than otherwise under the east side of the lake and into the Michigan Basin, where the heavier saline water resists the pull of pumping centers. In effect, the increasing salinity in the direction of the Michigan Basin acts as a kind of boundary that resists the influence of deep wells. Subtle differences also appear in the magnitude and direction of the flow fields generated by the variable- and uniform-density versions of the LMB model (table 22). For the west and east shorelines of Lake Michigan along the latitudes between the cities of Green Bay and Chicago, summation of the lateral flows by aquifer system demonstrates some discrepancies, particularly under 2005 stressed conditions. The SLMB-C simulation shows more movement through the C-O aquifer system from east to west in response to deep pumping centers than does the MLMB-C simulation. Nevertheless, the extent and boundaries of the regional groundwater basins for the freshwater part of the Lake Michigan groundwater basin in the C-O aquifer system are nearly identical for both the variable-density and uniform-density models (figs. 77*A*, *B*).

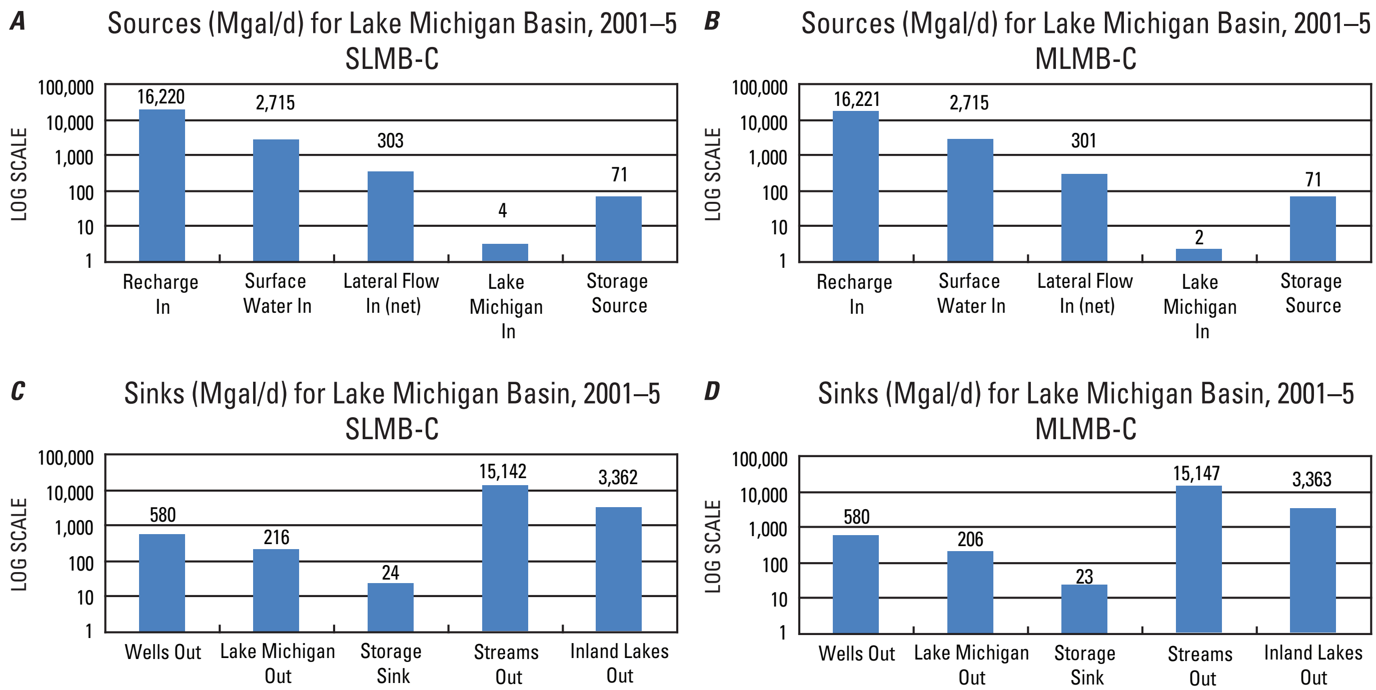
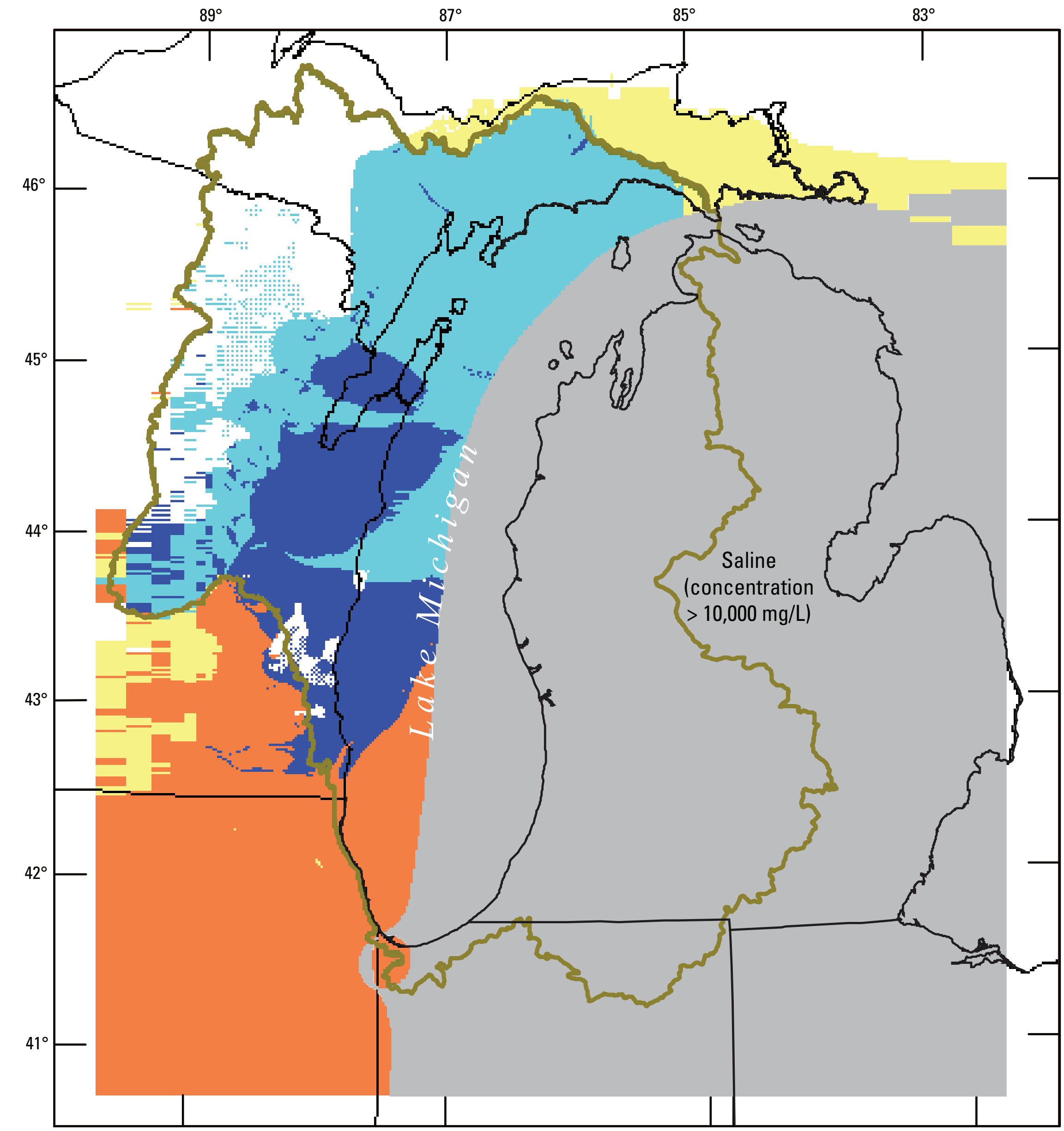


Figure 76. Simulated 2005 water budgets in Lake Michigan Basin: base model (SLMB-C) versus alternative uniform-density model (MLMB-C).

Table 22. East and west components of flow under shores of Lake Michigan between latitude of cities of Green Bay and Chicago: comparison of SEAWAT-2000 to MODFLOW-2000.

Predevelopment conditions			2005 conditions		
SEAWAT-2000 (SLMB-C)			**SEAWAT-2000 (SLMB-C)**		
Aquifer system(s) (layer interval)	**West shore net flow (Mgal/d)**	**East shore net flow (Mgal/d)**	**Aquifer system(s) (layer interval)**	**West shore net flow (Mgal/d)**	**East shore net flow (Mgal/d)**
QRNR (L1-L3)	2.2 toward lake	5.0 toward lake	QRNR (L1-L3)	2.1 toward lake	5.1 toward lake
PENN+MSHL+SLDV (L4-L12)	31.3 toward lake	4.5 toward lake	PENN+MSHL+SLDV (L4-L12)	30.4 toward lake	4.7 toward lake
C-O (L13-L20)	2.6 toward lake	2.4 toward lake	C-O (L13-L20)	7.5 from lake	6.9 toward lake
TOTAL	**36.1 toward lake**	**11.9 toward lake**	**TOTAL**	**25.0 toward lake**	**16.7 toward lake**
MODFLOW-2000 (MLMB-C)			**MODFLOW-2000 (MLMB-C)**		
Aquifer system(s) (layer interval)	**West shore net flow (Mgal/d)**	**East shore net flow (Mgal/d)**	**Aquifer system(s) (layer interval)**	**West shore net flow (Mgal/d)**	**East shore net flow (Mgal/d)**
QRNR (L1-L3)	2.1 toward lake	5.0 toward lake	QRNR (L1-L3)	2.1 toward lake	5.1 toward lake
PENN+MSHL+SLDV (L4-L12)	31.3 toward lake	4.6 toward lake	PENN+MSHL+SLDV (L4-L12)	30.4 toward lake	4.8 toward lake
C-O (L13-L20)	4.5 toward lake	0.2 from lake	C-O (L13-L20)	5.5 from lake	4.4 toward lake
TOTAL	**37.9 toward lake**	**9.4 toward lake**	**TOTAL**	**27.0 toward lake**	**14.3 toward lake**



Base from U.S. Geological Survey digital data
1:100,000 1983. Universal Transverse Mercator projection
Zone 16, Standard Parallel 0° (Equator), Central Meridian 87° W,
North American Datum 1983

EXPLANATION

Plan-view regional divides in freshwater, unpinched cells: predevelopment

- Flow toward surface water (including Lake Michigan) inside Lake Michigan Basin
- Flow toward surface water outside Lake Michigan Basin
- Flow toward pumping wells inside Lake Michigan Basin
- Flow toward pumping wells outside Lake Michigan Basin
- Greater than (>) 10,000 milligrams per liter (mg/L) salinity
- **Lake Michigan Basin**
- **State boundary**

Figure 77*A*. Simulated 1991–2005 groundwater basins for C-O aquifer system: Base model.

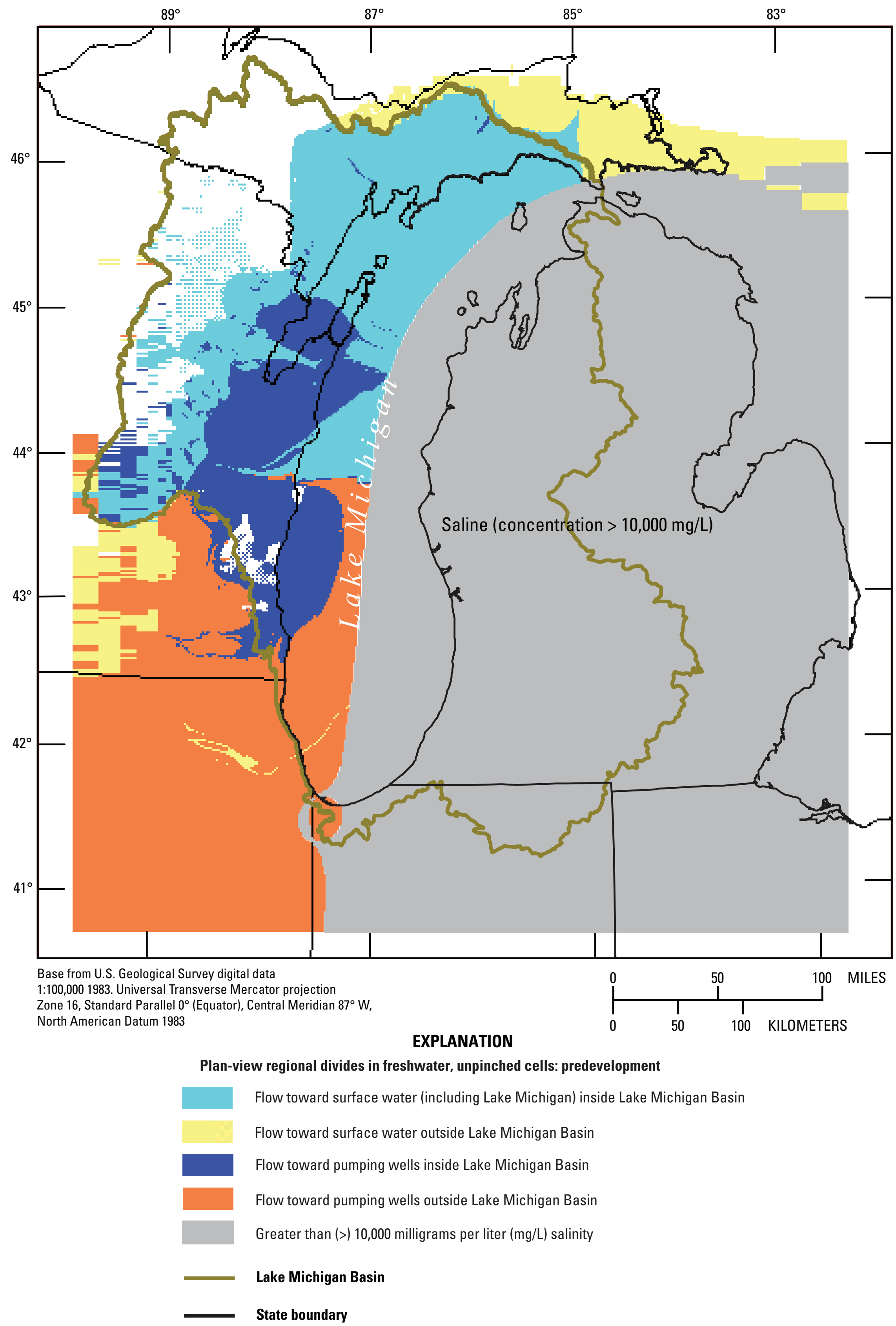


Figure 77*B*. Simulated 1991–2005 ground-water basins for C-O aquifer system: Alternative uniform-density model.

The major differences between the variable-density and uniform-density results relate to the water levels and flow dynamics simulated in the deeper units of the Michigan Basin and under Lake Michigan, where calibration targets are not available. For this reason, it could be argued that there is no basis for preferring the head and flow results of the variable-density solution except on theoretical grounds. Given (1) the extent of the highly saline body in the groundwater system underlying the Lake Michigan Basin and (2) the availability of simulation methods to account for it, a modeling strategy was adopted to consider the effects of variable density rather than neglect the phenomenon. However, comparison of the model versions suggests that, for most applications concerning water-availability issues (for example, mapping regional divides by aquifer system), the uniform-density MLMB-C model can be used in place of the variable-density SLMB-C model for regional analyses of groundwater conditions in freshwater areas.

7.1.3 Active-Transport Simulation

A second way to analyze the influence of saline conditions on the modeling process is to put more, rather than less, weight on the variable-density equation. For ease of input and, especially, to keep runtimes relatively short, the SEAWAT-2000 code was not applied to the calibrated LMB model in normal transport mode, which would permit the saline water body to move by advection and dispersion; instead, the code was executed under the assumption of fixed concentrations. In SLMB-C and SLMB-U, the distribution of spatially variable but time-constant salinities (and the resulting fixed density field) influences the flow system through its effect on hydraulic conductivity and hydraulic gradients, but the saline body itself remains stationary. This assumption can be relaxed with the addition of inputs to the model setup that take account of transport mechanisms.

To test the effect of movement of saline water on model findings, a simple transport simulation was performed for 1864 to 2005 on the basis of the already calibrated SLMB-C model with

- longitudinal, horizontal transverse, and vertical transverse dispersivity set everywhere to 10 ft, 1 ft, and 0.1 ft, respectively;
- molecular diffusion set to 1−E5 ft^2/d;
- porosity (and effective porosity) set everywhere to 0.2;
- a maximum transport time step set to 30 days; and
- an implicit finite-difference solution scheme.

The initial saline concentrations, equivalent to the fixed concentrations in SLMB-C, serve as the only source of salinity in the model. One very small change was made to the calibrated SLMB-C input: in the new model the WEL package, originally restricted to handling input for single-layer wells, also replaces the MNW package for all multilayer wells. This substitution is desirable to simplify the input of sources and sinks in the transport solution, and it is possible because the output of the calibrated SLMB-C model includes the cell-by-cell pumping rates for all stress periods as a function of the transient solution.[34] As a result, it is possible to duplicate the cell-by-cell pumping configuration of the original run with one input package for wells rather than two. However, the translation does promote a small degree of rounding error. To insure a consistent comparison between the transport solution and the fixed-concentration solution, the SLMB-C model was rerun with a single comprehensive WEL package. The corresponding transport run with the same single WEL package is called SLMB-CT3. The runtime of the latter—about 10 hours—is approximately 16 times longer than that of the former.

Mass-balance results (fig. 78), predevelopment water-level results by aquifer system (table 20, third column), 2005 drawdown results by aquifer system (table 21, third column), and hydrographs at pumping centers (fig. 79) all indicate very small differences between simulations without and with transport of saline water. Changes in DS concentration through time are small and reveal no appreciable movement of the saline water in response to pumping. However, drawdown produced from pumping centers in the C-O aquifer system is greater in simulations with transport. The increase is relatively small: the *maximum* change in 2005 between the SLMB-CF3 and SLMB-CT3 models in NE_ILL where wells are in the vicinity of saline water is 28 ft in the STPT aquifer, 23 ft in the IRGA aquifer, and 14 ft in the MTSM aquifer. These changes suggest that added density of the saline water induced to flow toward the pumping centers requires increased drawdown to withdraw groundwater at the simulated rates.

Whereas the comparisons between the fixed and variable concentration simulations demonstrate negligible cost in neglecting transport for most applications, it is conceivable that the SLMB-CT3 version of the LMB regional model might be useful for some problems. Therefore, like the SLMB-U (unconfined) and the MLMB-C (uniform density) versions, its input and output were archived, and the model made available for distribution.

[34] As mentioned earlier, the distribution of pumping between layers for MNW wells is not an input to the model but an *output* based on the total pumping prescribed for the well, aquifer conditions simulated outside the well, and the simulated circulation pattern within the well.

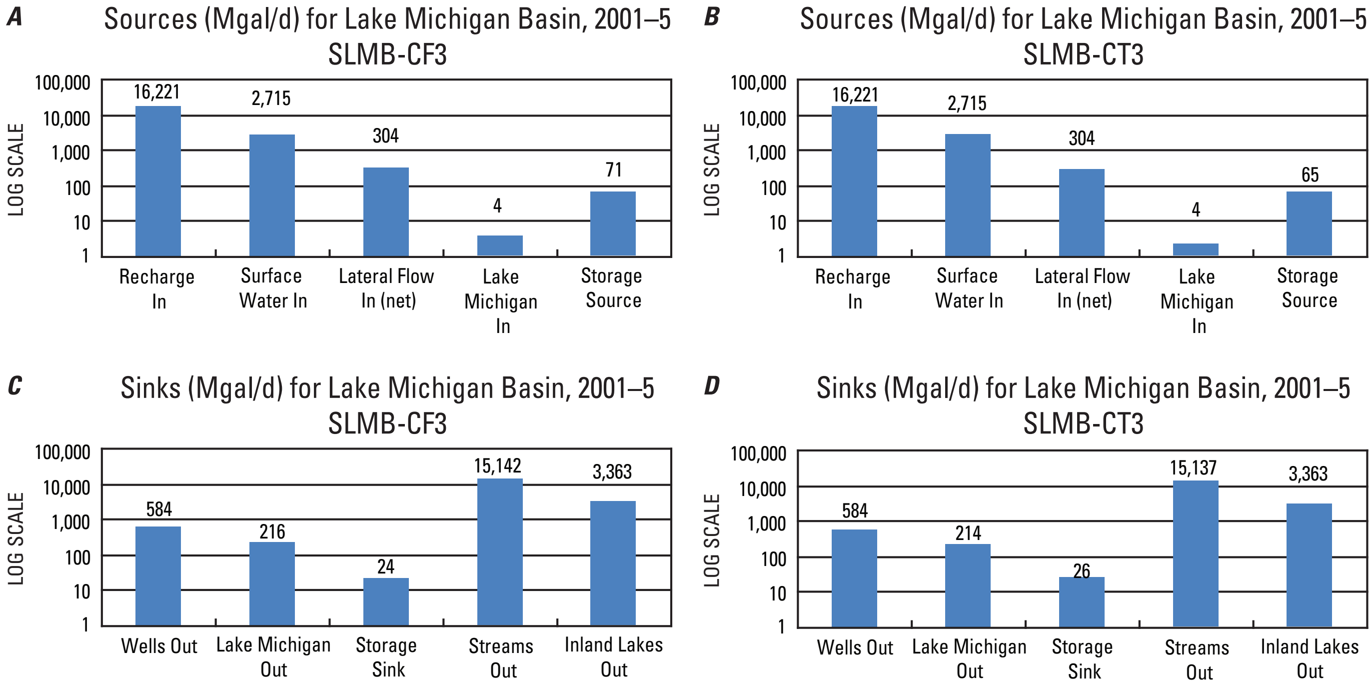


Figure 78. Simulated 2005 water budgets in Lake Michigan Basin: base model (SLMB-CF3) versus alternative active transport model (SLMB-CT3).

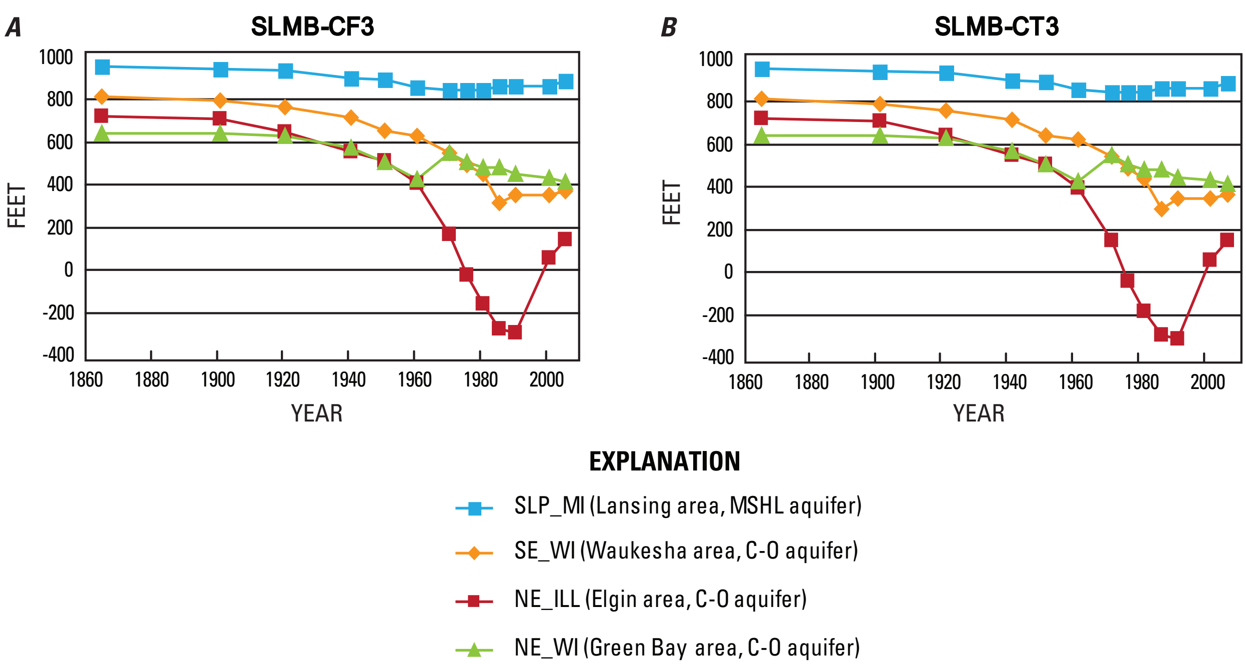


Figure 79. Simulated water-level hydrographs at pumping centers: base model (SLMB-CF3) versus alternative active transport model (SLMB-CT3).

7.2 Model Sensitivity

Model sensitivity analysis consists of modifying a single type of input in each sensitivity simulation. Selected sensitivity simulations test inputs falling into three categories: farfield boundary conditions, parameter values, and grid resolution. All the tests were done on the calibrated confined variable-density model, SLMB-C, which is considered the base model.

7.2.1 Farfield Boundary Conditions

As discussed in section 4 (“Model Construction”), the boundary conditions at the edge of the model (first or last row, first or last column) consist of two types:

- GHB (head-dependent) cells representing Great Lake stages or CHD (constant-head) cells representing surface-water stages in the highest active cell at a row/column location, with underlying cells set as no-flow boundaries at their outside edge (see figs. 26 and 27).
- WEL (constant-flow) cells representing time-dependent inflow or outflow to the bedrock across the southwestern model edge of the LMB model domain, derived from a published regional model centered on northeastern Illinois (see fig. 27).

Both conditions were modified to test sensitivity. In the first case, the lake stage and water-table values for the farfield boundary cells at the sides of the model were propagated downward as CHD cells, thereby replacing the vertical no-flow boundaries at the sides of the model with constant-head boundaries (simulation SEN1-CHD). In the second case, the time-dependent flow constituting the boundary condition in bedrock layers along the southwestern edge of the model domain were either halved (simulation SEN2-HAF) or doubled (simulation SEN3-DUB) in magnitude. The effects of the three sensitivity runs on the original SLMB-C output are presented in terms of the percentage of cells in each aquifer system that differ more than 20 ft from simulations using predevelopment heads (table 23, first three columns) and with more than 20 ft of difference with respect to 2005 drawdown conditions (table 24, first three columns). A threshold of 20 ft was selected because it is roughly the magnitude of the mean absolute error for calibrated water levels. For predevelopment water levels, the changes in excess of 20 ft, positive and negative, are concentrated in the C-O aquifer system. These discrepancies occur almost exclusively in the deep part of the Michigan Basin, which is devoid of calibration targets. Farfield boundary conditions appear to have very little effect on the drawdown distribution simulated for 2005. When the focus is on freshwater areas of the model, the effects of modifying farfield boundary conditions on both initial heads and drawdown are very small. At the selected pumping centers (see fig. 54), graphs showing the predevelopment water levels for the farfield boundary condition in sensitivity runs are similar to those showing levels for the base model, SLMB-C (fig. 80). Simulated drawdowns in 1960, 1980, and 2000 for the farfield boundary sensitivity runs are also similar to those simulated by the base model (fig. 81). For the drawdown graphs, it is interesting that the base and sensitivity runs all produce the same pattern: drawdown increases over time at the SE_WI pumping center, but the NE_ILL and SLP_MI centers both show recovery of water levels between 1980 and 2005 as a result of reductions in withdrawals, whereas the NE_WI center shows recovery between 1960 and 1980.

7.2.2 Parameter Values

Three simulations were done to test the sensitivity of model outcomes to parameter values. Clearly, a virtually unlimited number of such simulations could be devised. The ones selected bear on two important aspects of the model design: the handling of glacial heterogeneity and the treatment of groundwater exchange with Lake Michigan.

The reader may recall that the assignment of hydraulic conductivity to the inland QRNR deposits (mostly glacial in origin) in the model depends on two databases, one of which assigns glacial categories (types of tills and stratified deposits) to cells and the other of which assigns the cells a number representing coarse fraction (the proportion of sands and gravels as opposed to the proportion of silts and clays). The result is cell-by-cell variation of K_h and K_v wherever inland QRNR deposits are present in the top three model layers. The questions arise, “Given the regional scale of the model and the constraints on the solution posed by internal boundary conditions, are model results largely insensitive to the heterogeneity generated by this method, and could a simpler version of the model based on zoned input to the QRNR layers produce a similar fit to calibration targets?”

To address these questions, delineation of K zones was based on the extent of glacial categories in each QRNR layer (see fig. 36), and zoned values were based on the geometric means consistent with calibrated values in the SLMB-C model (see appendix 6*A*, layers 1, 2, and 3 for K_h input and appendix 6*B*, layers 1, 2, and 3 for K_v input). Apart from this change, the sensitivity simulation, called SEN4-QRN, is identical to the base SLMB-C run. In general, it produces water-level and flux results that are similar to those from the base run. For example, comparison of the residuals generated at targets by the two runs show only minor increase in the overall misfit for the run with the simplified QRNR input (the objective function increases by 2 percent), limited largely to a few target subsets. The residual differences that occur correspond mostly to differences in the simulated water-table surface. Inspection of table 23 shows that, for the sensitivity simulation, there are a fairly large number of shallow (that is, QRNR or PENN aquifer system) cells with more than 20 ft higher water levels than in the base run, owing to the simplified zonation, but an even greater number of cells with more than 20 ft lower water levels. These discrepancies are distributed throughout all subregions, but they are largest in the NLP_MI.

Table 23. Discrepancy between model-sensitivity simulations and SLMB-C with respect to predevelopment water levels, by aquifer system.

[FF, farfield; *K*, hydraulic conductivity]

23*A*. Percentage of nearfield active cells in aquifer system with predevelopment water level more than 20 feet HIGHER in model sensitivity simulations relative to SLMB-C.

Aquifer system	Model-sensitivity simulations					
	Modified FF no-flow boundaries SEN1-CHD (percent)	FF boundary fluxes halved SEN2-HAF (percent)	FF boundary fluxes doubled SEN3-DUB (percent)	Simplified *K* input to QRNR SEN4-QRN (percent)	Lake Michigan bed *K* increased by 10× SEN5-BED (percent)	Variable stage in each Great Lake SEN6-GLS (percent)
QRNR	0.00	0.00	0.00	1.65	0.00	0.00
PENN	.00	.00	.00	2.81	.00	.00
MSHL	.00	.00	.00	.08	.00	.00
SLDV	10.59	.00	.00	.04	.00	.00
C-O	51.16	.00	18.92	.06	.00	.00

23*B*. Percentage of nearfield active cells in aquifer system with predevelopment water level more than 20 feet LOWER in model sensitivity simulations relative to SLMB-C.

Aquifer system	Model-sensitivity simulations					
	Modified FF no-flow boundaries SEN1-CHD (percent)	FF boundary fluxes halved SEN2-HAF (percent)	FF boundary fluxes doubled SEN3-DUB (percent)	Simplified *K* input to QRNR SEN4-QRN (percent)	Lake Michigan bed *K* increased by 10× SEN5-BED (percent)	Variable stage in each Great Lake SEN6-GLS (percent)
QRNR	0.00	0.00	0.00	7.61	0.07	0.00
PENN	.00	.00	.00	2.74	.00	.00
MSHL	.00	.00	.00	1.92	.00	.00
SLDV	.00	.00	.00	.24	.00	.00
C-O	.00	6.84	.00	.08	.00	.00

Table 24. Discrepancy between model-sensitivity simulations and SLMB-C with respect to 2005 drawdown, by aquifer system.

[FF, farfield; *K*, hydraulic conductivity]

24*A*. Percentage of nearfield active cells in aquifer system with 2005 drawdown more than 20 feet GREATER in model sensitivity simulations relative to SLMB-C.

	Model-sensitivity simulations					
Aquifer system	**Modified FF no-flow boundaries SEN1-CHD (percent)**	**FF boundary fluxes halved SEN2-HAF (percent)**	**FF boundary fluxes doubled SEN3-DUB (percent)**	**Simplified *K* input to QRNR SEN4-QRN (percent)**	**Lake Michigan bed *K* increased by 10× SEN5-BED (percent)**	**Variable stage in each Great Lake SEN6-GLS (percent)**
QRNR	0.00	0.00	0.00	0.16	0.00	0.00
PENN	.00	.00	.00	.00	.00	.00
MSHL	.00	.00	.00	.01	.00	.00
SLDV	.00	.00	.00	.00	.00	.00
C-O	.00	.00	.00	.00	.00	.00

24*B*. Percentage of nearfield active cells in aquifer system with 2005 drawdown more than 20 feet LESS in model sensitivity simulations relative to SLMB-C.

	Model-sensitivity simulations					
Aquifer system	**Modified FF no-flow boundaries SEN1-CHD (percent)**	**FF boundary fluxes halved SEN2-HAF (percent)**	**FF boundary fluxes doubled SEN3-DUB (percent)**	**Simplified *K* input to QRNR SEN4-QRN (percent)**	**Lake Michigan bed *K* increased by 10× SEN5-BED (percent)**	**Variable stage in each Great Lake SEN6-GLS (percent)**
QRNR	0.00	0.00	0.00	0.02	0.00	0.00
PENN	.00	.00	.00	.00	.00	.00
MSHL	.00	.00	.00	.00	.00	.00
SLDV	.00	.00	.00	.00	.00	.00
C-O	.00	.00	.55	.00	.00	.00

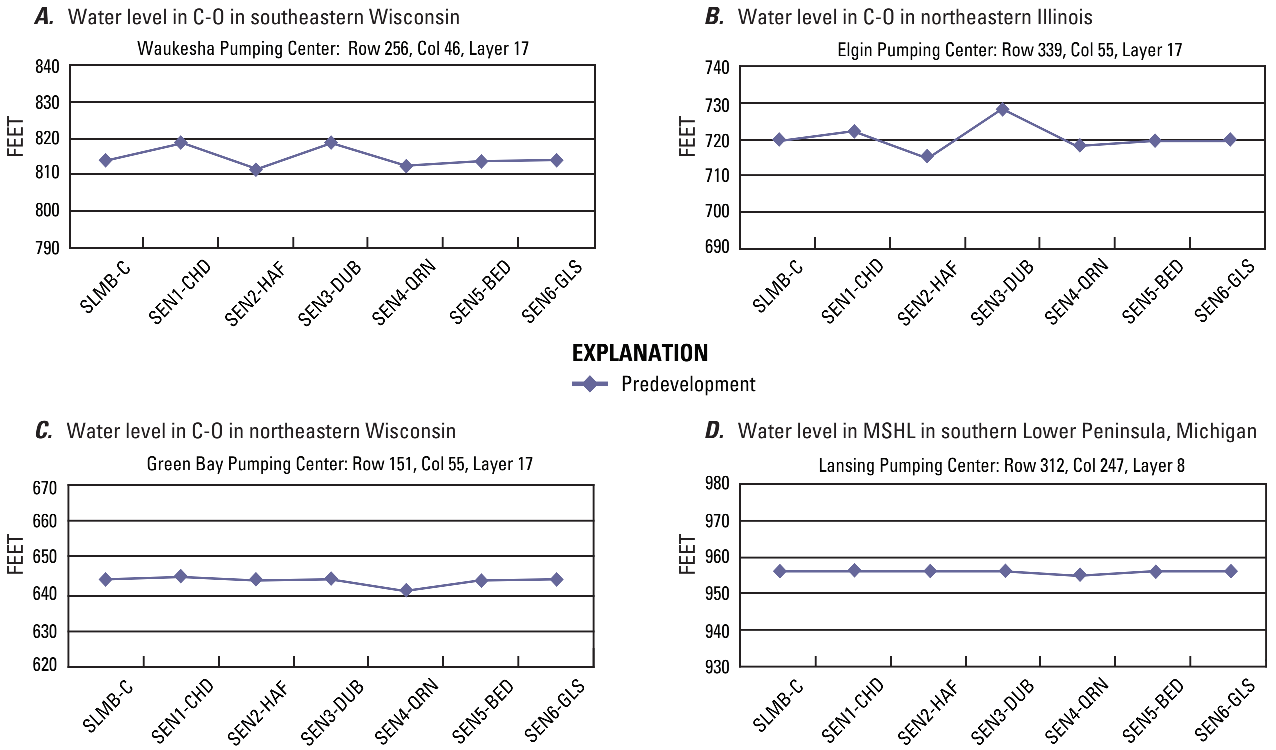


Figure 80. Comparison of simulated predevelopment water levels at selected pumping centers: base model versus sensitivity models.

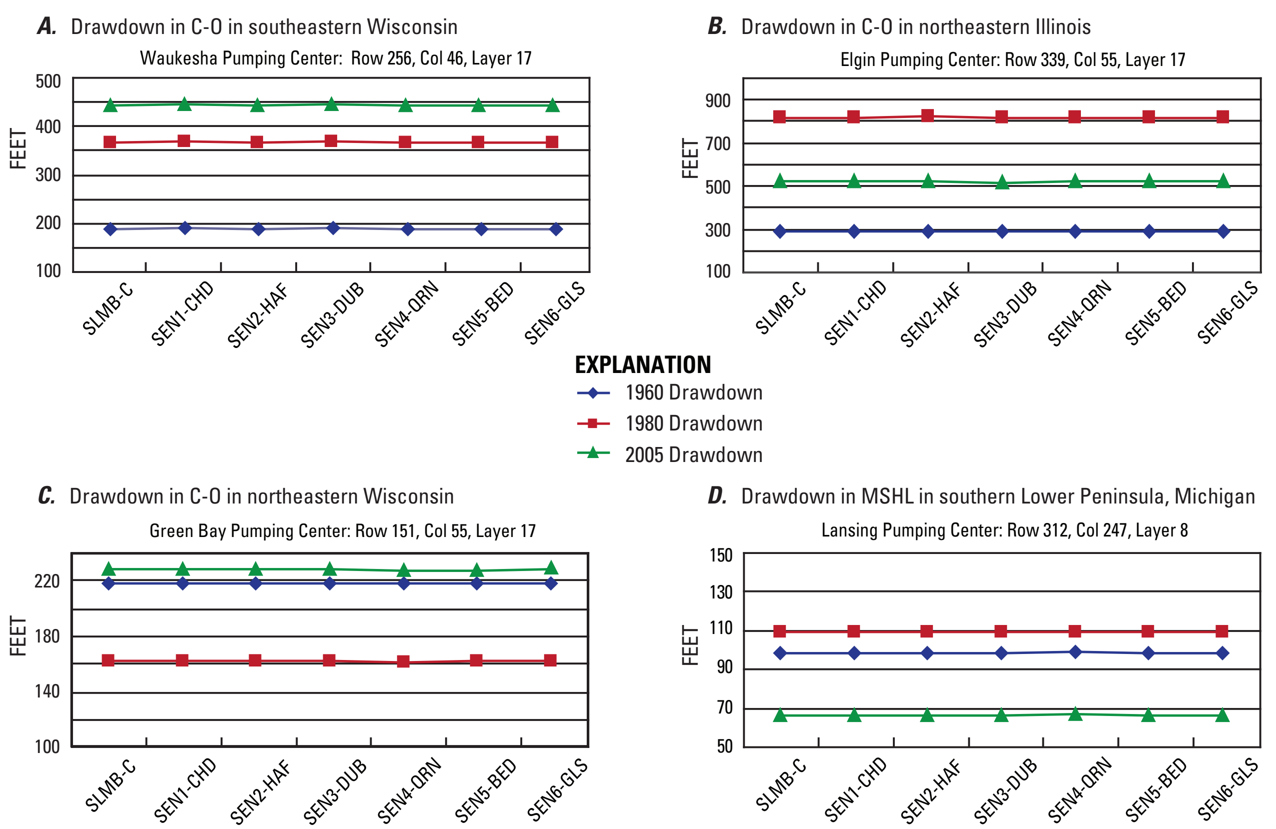


Figure 81. Comparison of simulated drawdown at selected pumping centers: base model versus sensitivity models.

Inspection of table 24 shows that drawdown results in all aquifer systems are much less affected by the simplified QRNR *K* zonation than are water levels. The effect of the simplification is extremely small at the selected pumping centers (as evident in results for SLMB-C and SEN-QNR water levels in fig. 80 and drawdown in fig. 81), which is expected because none of the centers features QRNR wells.

On the whole, it appears that the simplified *K* representation produces a water-table solution that is distinct from the solution with cell-by-cell *K* variation but simulates a very similar response to shallow pumping. The magnitude of drawdown simulated at the water table by either the base or sensitivity model is constrained by the presence of fixed head-dependent boundaries in roughly half the inland water-table cells. Although this structural element of the regional model limits the extent to which the detailed QRNR hydraulic-conductivity database is able to improve regional model results when compared to a simplified approach, the availability of the database is intended to be a product that, by itself, is a useful starting point for future studies involving the shallow groundwater-flow system in and around the Lake Michigan Basin.

Little information, either from field tests or calibration targets, is available to quantify or update the hydraulic conductivities assigned the Lake Michigan bed deposits in layers 1, 2 and 3. For this reason, a second sensitivity run, called SEN5-BED, was constructed in which the K_h and K_v of the lakebed zones were increased by 10 times with respect to the value in the base run, SLMB-C. The effect on this change is minimal on calibration target residuals, predevelopment water levels (table 23), 2005 drawdown (table 24), or conditions at pumping centers (figs. 80 and 81). In order to detect a difference, it is necessary to compare the SLMB-C and SEN5-BED water budgets. The base simulation yields a predevelopment rate of direct discharge to Lake Michigan equal to 218 Mgal/d (see fig. 57). The SEN5-BED run yields a predevelopment rate of 279 Mgal/d. The order-of-magnitude increase in *K* produces about a 30-percent increase in discharge, and this sink increases from 1.3 percent of the Lake Michigan Basin outflow budget to about 1.7 percent of the budget. Given the uncertain nature of the bed properties, an error term on the order of plus or minus 30 percent for the discharge term is not unexpected. More attention will be given in the next subsection to consideration of possible bias in the model estimate of this flux term.

The final sensitivity run, SEN6-GLS, involved time-dependent treatment of the stages assigned Lake Michigan and the farfield Great Lakes. Lake stage measurements compiled by the U.S. Army Corps of Engineers, Detroit District (2006) were averaged over stress-period intervals to modify the GHB input from the SLMB-C model. For example, the monthly excursion in the Lake Michigan/Lake Huron level recorded by the U.S. Army Corps of Engineers between 1918 and 2005 ranges from 576.04 to 582.32 ft above lake datum, with a median value of 578.86 ft. When averaged by stress-period interval, the range is from 577.52 ft in 2001–5 to 580.59 ft in 1971–75. The effect on model results of varying stage by stress period in Lake Michigan, Lake Superior, Lake Huron, Lake St. Clair and Lake Erie is extremely small (tables 23 and 24; figs. 80 and 81). Perhaps the biggest effect is on the direct discharge term to Lake Michigan. The 2001–5 rate of direct discharge to Lake Michigan changes from 216 Mgal/d in the base model to 219 Mgal/d in the sensitivity run, an increase of only 1 percent. The reason for the insensitivity of overall results to variable Great Lake stage is that most of the groundwater outflow in the model occurs not to the Great Lakes but to inland surface-water features. Owing to lack of data for the SEN6-GLS run, as for the SLMB-C run, the stages of streams and water bodies were fixed for the entire duration of the simulation; consequently, the true effect of temporal variability in surface-water levels on model results is not represented.

7.2.3 Grid Spacing

A regional finite-difference groundwater-flow model is generally characterized by a large domain discretized into a grid that is coarse relative to the density of features such as surface-water discharge zones. Among all the possible tests of the sensitivity of LMB model results to its 5,000-ft nearfield grid spacing, one was selected that centers on a key outcome of the model simulation: the rate of groundwater direct discharge to Lake Michigan. The objective was to determine how the grid resolution affects the partitioning of flow near the Lake Michigan shoreline between inland surface water (indirect discharge) and the lake (direct discharge)—that is, whether the coarse grid spacing introduces a systematic bias into the relative discharge rates simulated by the regional model.

The sensitivity analysis of discharge near the shoreline requires the use of inset models (a smaller model "inset" into the larger model, using the larger model results as boundary conditions for the smaller model) as a way of contrasting results from refined as opposed to coarse grid spacing; use of inset models in this context also demonstrates the utility of the regional model in construction of local-scale models, one of the goals of this study. Eight inset models of roughly equal area were constructed, all within the Lake Michigan Basin (fig. 82). Each nearfield subregion contains one inset model except for the NLP_MI subregion, which contains two. A telescopic mesh refinement (TMR) approach available through the Groundwater Vistas interface (Rumbaugh and Rumbaugh, 2007) allows models with refined grid resolution to be automatically constructed such that the imposed boundary conditions (CHD, RIV, and GHB) at the edges of the inset domain honor the water-level conditions simulated by the regional model. For TMR construction, the boundary heads correspond to predevelopment conditions (no pumping wells). The layering and property values specified for the inset models correspond exactly to the base regional model, SLMB-C.

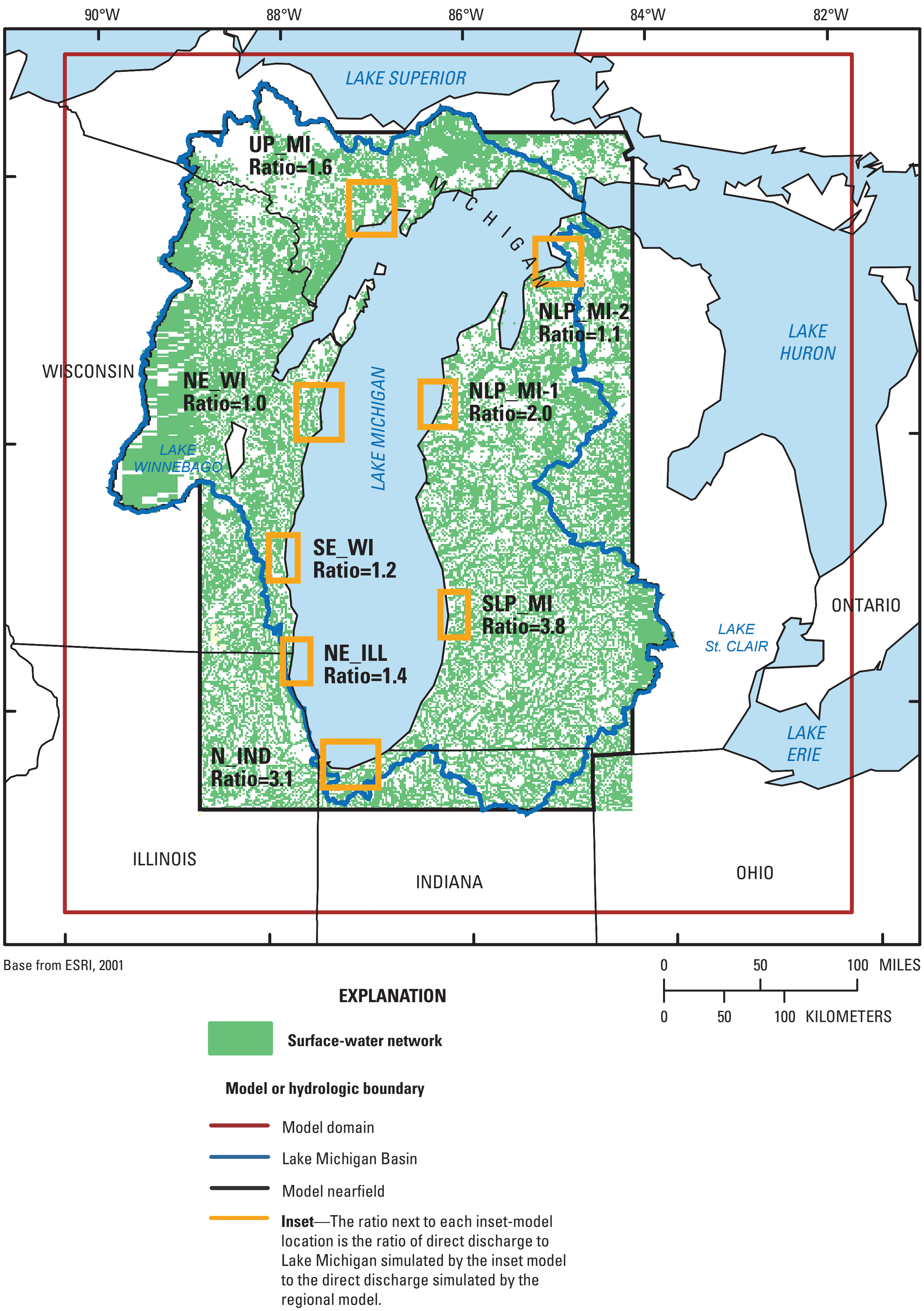


Figure 82. Locations and results for shoreline inset models.

However, the grid spacing for each inset model is smaller, producing cells 500 ft on a side with an area 1/100th the size of a regional model cell. The areal extent of the RIV cells in the inset model is the same as for the base model. (See figs. 83*A* and *B*, which contrast the grid spacing and compare the RIV cell distribution, shown in green, for the regional and inset models for the TMR in SLP_MI.) Conductance terms of the RIV cells internal to the inset domains were adjusted to ensure that the flow into and out of the inset model domain is virtually identical to the flow through the regional model for the same area. In this way, it is possible to directly compare the partitioning of a single amount of outflow between the two competing sink types, inland surface water and Lake Michigan, at two very different grid resolutions.

The assumption underlying the comparison is that the refined spacing of the inset models allows for a more accurate simulation of gradients near discharge areas, and, therefore, a more accurate account of the fate of groundwater. The theoretical basis for this understanding is discussed in appendix 2. In that discussion reference is made to a "leakage factor" symbolized by λ, which indicates the degree of grid refinement needed to accurately simulate discharge patterns around surface-water features as a function of the distribution of horizontal and vertical hydraulic conductivity and layer thicknesses (Haitjema and others, 2001). Calculation with LMB model inputs of the average value and range of values for λ around the Lake Michigan shoreline indicate that the 500-ft spacing of the inset models is generally adequate to simulate discharge without introducing numerical inaccuracies.

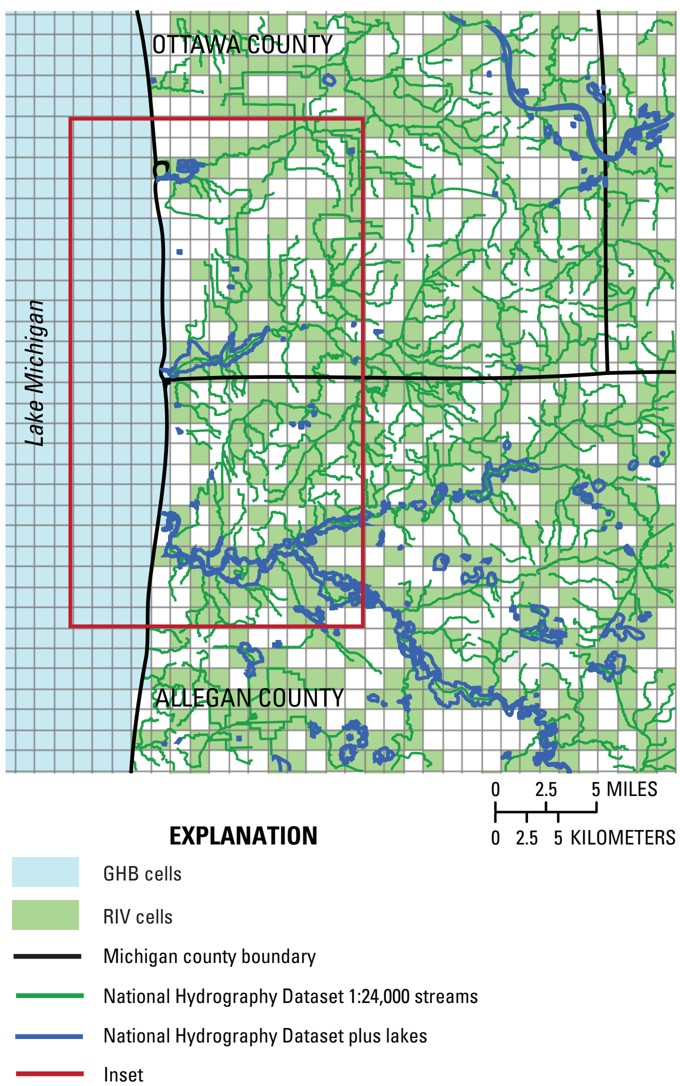


Figure 83*A*. Representation of inset area in SLP_MI: regional model.

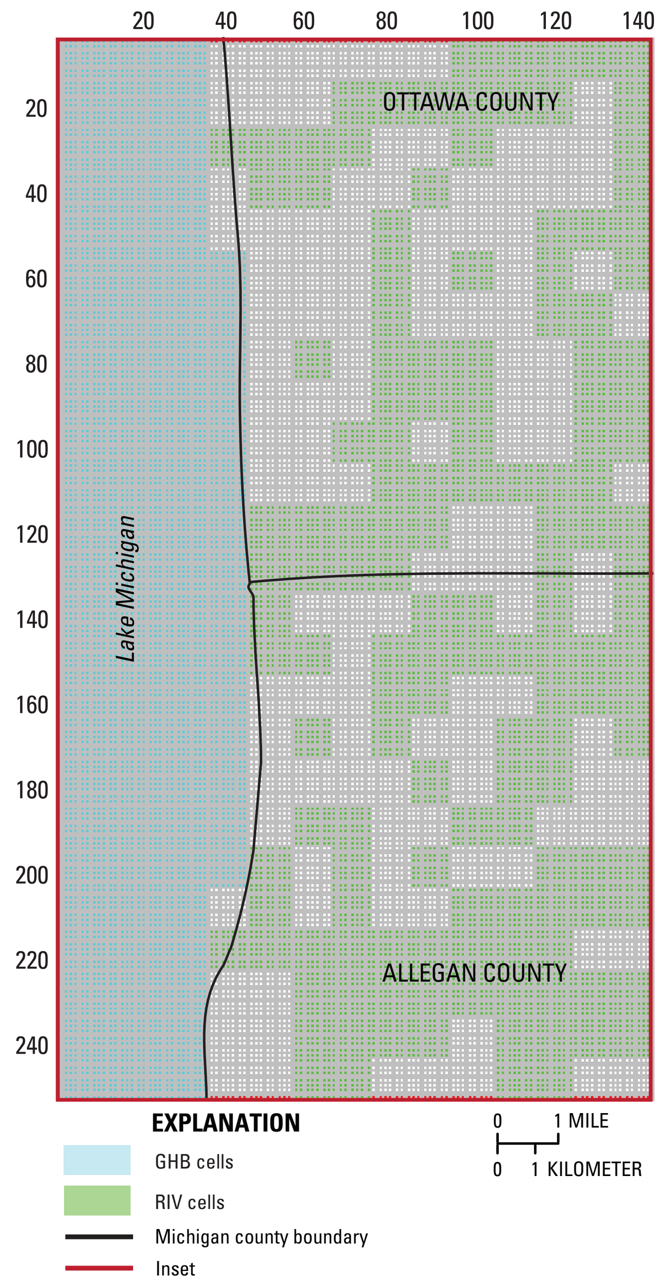


Figure 83*B*. Representation of inset area in SLP_MI: inset model with refined grid.

The results of the sensitivity analysis are presented in terms of the ratio of direct predevelopment Lake Michigan discharge simulated by the inset model relative to the regional model. A value greater than 1 indicates that the inset model yields a higher rate of discharge to the lake than does the regional model. For all eight inset areas, the ratio is greater than 1, although the value ranges from 1.02 in NE_WI to 3.81 in SLP_MI (fig. 82). The systematic discrepancy suggests that the finer resolution is needed to accurately simulate the hydraulic gradients toward Lake Michigan along its shoreline. The average ratio is 1.9; but when the total direct discharge is summed across all eight areas for the two grid resolutions, the global ratio is equal to a lower value, 1.27. This calculation suggests that the regional model, due to its coarse grid spacing, systematically underestimates the discharge to Lake Michigan by a factor on the order of 30 percent.

The coarse grid resolution of the regional model gives rise not only to inaccuracies in local gradients but also to blocky and, therefore, inaccurate representation of the elevation and geometry of surface-water features. The misrepresentation of the surface-water geometry can be compensated for by the conductance term, which incorporates the length and width of the stream segments or lake areas represented by the RIV cell. However, some distortion still arises from the grouping of multiple surface-water features in a single cell (see appendix 2). The effect of grouping multiple features was assessed by using an inset model constructed for the SLP_MI. In this case, the inland surface-water network is recast from the original blocky input (fig. 83*B*) to input that more accurately reflects the true geometry of streams and water bodies (fig. 83*C*) by matching surface-water features directly to the finer mesh. The sum of the conductance terms for each segment of surface water represented by the two sets of RIV cells is identical. This refined-grid inset model simulates greater discharge to Lake Michigan than the original inset model with a refined grid and blocky RIV input. The factor *increases* by 14 percent, changing from 3.8 to 4.3 times the regional model discharge.

The foregoing analyses suggest that bias arising from coarse grid resolution is large enough to justify a correction of the overall estimates of groundwater interactions with Lake Michigan generated by the regional LMB model. It is instructive to combine the average increase simulated by the inset models due to a refined grid alone (1.27) with the increase simulated arising from refining the surface-water network in the one case tested (1.14). If the resulting value, 1.45, is applied generally to the regional model results, it implies that

- the proportion of (predevelopment) groundwater inflow to the Lake Michigan Basin that discharges directly to Lake Michigan, rather than to competing sinks, should be increased from 1.3 percent to almost *2 percent of the overall water budget*, and
- the average rate of (predevelopment) direct groundwater discharge to Lake Michigan should be increased from the calculated value of 0.33 ft^3/s per 5,000 ft of shoreline to 0.48 ft^3/s per 5,000 ft of shoreline or, in other terms, *0.50 ft^3/s per mile of shoreline*; this corrected average rate is at the low end of the range of 0.5 to 2.0 ft^3/s per mile of shoreline estimated by Neff and Nicholas (2005).

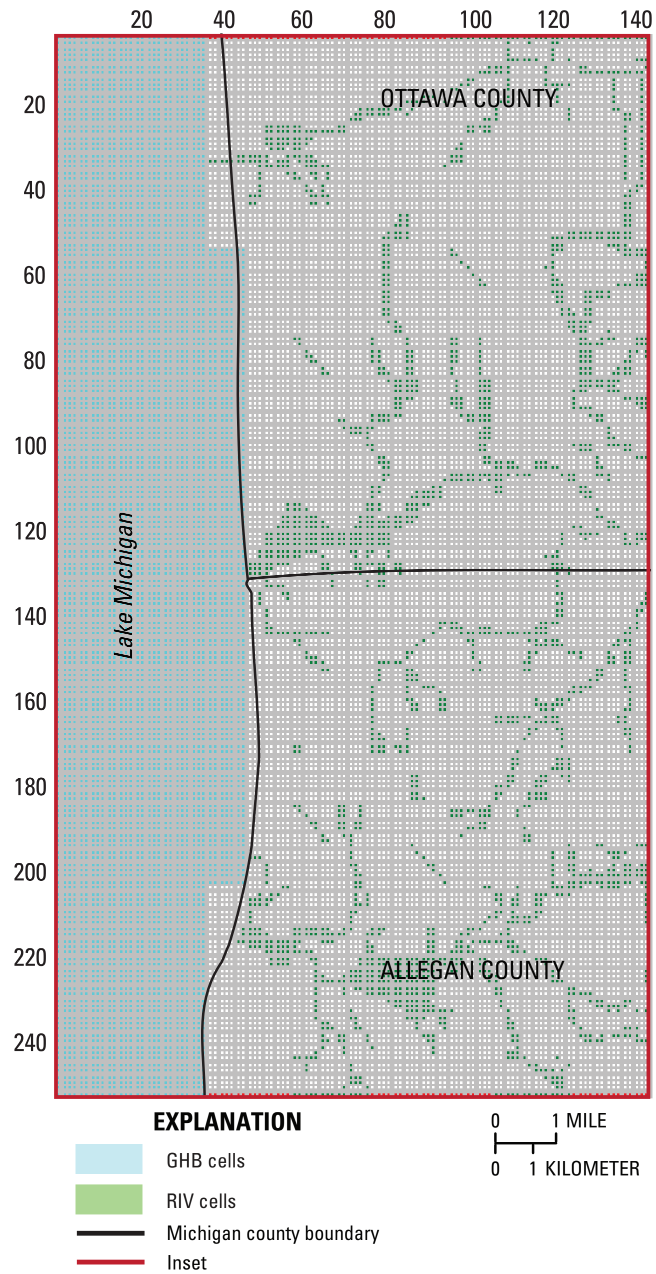


Figure 83*C*. Representation of inset area in SLP_MI: inset model with refined grid and refined surface water.

8. Model Limitations and Suggestions for Future Work

Model limitations stem from the regional scale of the study, gaps in available data, model conceptualization, and unaccounted-for processes. They are summarized below. In some cases, more detail is contained in companion reports that describe the methods and datasets used to estimate model stratigraphy and salinity (Lampe, 2009), the distribution of glacial texture (Arihood, 2009), water use (Buchwald and others, 2010), and recharge (Westenbroek and others, 2010).

Grid spacing—The 5,000-ft grid spacing in the model nearfield and the 20 layers employed to accommodate multiple aquifer systems yield a model with more than 2 million cells and approximately 100,000 cells per layer. A more finely discretized model would produce too many cells to efficiently manage with respect to input and output with the tools employed. Throughout this report, attention has been paid to the problems that arise from overlaying the dense surface-water network characteristic of the areas around the Great Lakes on the regional grid spacing. (See in particular the discussion of the conceptual model in section 3. See also the final subsection of appendix 2; there, a schematic model is presented to demonstrate that the coarse grid spacing in the regional model introduces errors in the simulated rate of exchange between groundwater and surface water, which, especially in areas of fine-grained sediments, can be on the order of 50 percent or more.) The coarse spacing restricts the magnitude of the water-table response to transient stresses, limits the value of calibration targets in the shallow flow system in estimating parameters, and distorts the partitioning of discharge among surface-water sinks. It also precludes the model from simulating flow paths shorter than 5,000 ft and limits the precision with which point features (especially pumping wells) can be located. Similarly, the large thickness of many of the bedrock layers causes pumping stresses from partially penetrating wells to sometimes be assigned too shallow or too deep.

Time stepping—Not only the spatial resolution but also the temporal resolution of the model affects the dynamics of the system and the spectrum of results. Each stress period in a MODFLOW-2000/SEAWAT-2000 simulation has its own imposed conditions, such as recharge and pumping. The conditions are updated at the beginning of a stress period and held constant for the duration of the stress period; they do not evolve continuously over the course of time. The *modeled* system responds to the stepwise changes in these conditions first through changes in water levels, which are reflected in the storage term, and then through changes in the fluxes between the groundwater system and external features, such as surface water. The rate of removal (or addition) of water from (or to) storage is highest in the first time step, immediately after the imposed stepwise changes in stresses when the rate of change of water levels is greatest, and lowest for the final time step, when water levels have had time to stabilize and external inflows and outflows have had time to adjust. Conversely, the change in flux to and from surface-water features is at its highest value for the final time step because the accumulated response to variations in pumping or recharge is greatest at the end of the stress period. All the source and sink results presented in this report correspond to the last time step in the stress period. The tabulated values for storage flux can be taken as minimum contributions for a stress period, and tabulated values for lateral flow or exchange with surface water can be taken as maximum contributions for the period.

The difference between the beginning and ending storage rates in a stress period can be large, amounting often to a reduction of more than half. For the SLMB-C simulation in the 1976–80 stress period, the storage release in the model nearfield after the first time step (60 days from the step change) is 1,926 Mgal/d, but it is only 522 Mgal/d for the last time step (2.5 to 5 years from the step change). For the 2001–5 stress period, the nearfield reduction is from 217 to 98 Mgal/d. When recharge effects are filtered from the results and only the storage fluxes associated with changes in pumping are compiled, it is possible to compare the storage contribution to wells as a function of the time step selected within a stress period. For the SLMB-C simulation in the 1976–80 period, net storage release during the first time step accounts for 26 percent of the water diverted to nearfield wells but for only 17 percent during the last time step. It is not clear which value is more representative of the overall role of storage as a source of water to wells. It is important to recognize that the results presented in figures and tables represent the low end of a range for the storage contribution and that the high end could be even 2 times greater. However, because changes in pumping are, in reality, gradual rather than stepwise, all the storage contributions simulated by the model are necessarily approximate. Because the reported changes in base flow to surface water represent maximum values for the stress period, they can be considered “conservative” estimates of the effects of pumping or recharge changes on surface-water/groundwater interactions.

Dewatering—The LMB model results are consistent with field evidence in showing that some cells at the top of the Cambrian-Ordovician aquifer system that were confined under predevelopment conditions become unconfined between 1864 and 2005. The timing of dewatering and formation of a deep water table varies from location to location. This dewatering phenomenom requires adjustments to the input of the confined version of the LMB model. For the SLMB-C simulation, the hydraulic-conductivity values of the dewatered cells are adjusted to reflect the loss of saturated thickness and yield an effective transmissivity more reflective of pumped conditions. Because MODFLOW allows only one storage parameter for a model simulated in confined mode, cells in deep aquifers that become unconfined at some time during the simulation are represented with a “compromise” value of specific storage, which is inserted for the entire simulation period and, when multiplied by cell thickness, is smaller than the specific-yield value appropriate for unconfined conditions but larger than the storage-coefficient value appropriate for confined conditions. The methods adopted to quantify the adjusted values of hydraulic conductivity and storage parameters are discussed in section 5.1. The use of these adjusted terms introduces some error in the simulated conditions around deep pumping centers for the confined version of the LMB model. In contrast, the input to the unconfined version of the model, SLMB-U, requires no adjustments because the transmissivity is automatically a function of saturated thickness and the correct storage term is automatically selected as a function of water-level conditions. Thus, SLMB-U is not affected by the same limitations with respect to deep unconfined conditions as is SLMB-C. Comparison of their results shows that the maximum drawdown patterns for the two simulations are very similar in the areas of deep dewatering and suggests that distortions arising from the confined transmissivity and storage adjustments for SLMB-C are not large (see fig. 75). However, comparison of water-level hydrographs shows that the early drawdown history is different for the two simulations and indicates that some caution must be exercised in using the results of the confined version of the model that pertain to the rate of water-level change (see section 7.1 and fig. 74). It is also possible that the particle-tracking results discussed in section 6, particularly in relation to the contributing areas of deep Cambrian-Ordovician wells, are influenced by the assumption of fully saturated conditons implicit in the confined version of the model, which allows for vertical and horizontal flow across cells even if the simulated water level is below the cell bottom.

Data gaps—Beyond the limitations posed by the model's spatial and temporal discretization and by model assumptions, data gaps add uncertainty. Notable examples are the following:

- Zonation of subsurface properties (on the basis, for example, of scattered aquifer tests).
- Surface-water stages based on interpolation of land-surface data rather than on local stage measurements (which probably introduces a bias, given that the gridded land-surface data used to compute the stages tend to overestimate the elevation of incised channels).
- Fixed surface-water stages do not reflect variations in stage that have occurred in time as a result of wetter and drier periods.
- Absence of domestic pumping from model input (withdrawals largely but not entirely balanced by return flow through septic systems to the same shallow aquifers from which the groundwater was withdrawn).
- Absence of farfield high-capacity pumping in the farfield areas of Michigan and Indiana (an omission that probably has little effect on nearfield results because most of the missing farfield pumping is shallow and its lateral influence is buffered by surface water).
- Uneven distribution of calibration targets (for example, vertical-head-gradient targets are largely limited to the western side of Lake Michigan; even more important, although there are data against which to match the simulated rebound in NE_ILL of deep water levels after 1980, data are scarce that relate to drawdown between 1940 and 1980, making it difficult to evaluate the parameters affecting the slope of the drawdown curve).
- Uncertainty about the distribution of effective porosities (equated in this study with the distribution of calibrated specific-yield values), especially due to the effect of unknown preferential flow paths; for example, those associated with gravel beds in unconsolidated deposits or with joints and partings in bedrock units. Effective porosities are not an input to SEAWAT-2000 and therefore have no effect on simulated water-level and flux results, but they are an input to MODPATH and therefore affect particle-tracking results, notably the estimated traveltimes of flow to pumping wells.

Unrepresented processes—The modeled areas shown in this report were conceptualized in a way that was consistent with the observed data. However, alternative conceptualizations could be used to model this area. Several of these alternative conceptualizations were presented in this report, but that should not preclude other conceptualizations that fit the observed data. In particular, the fact that some processes were approximated or neglected in the conceptualization adds uncertainty to model outcomes. For example, the contribution of vertical flow through abandoned, unsealed boreholes to the downward leakage between shallow and deep aquifers is not well understood. A study of this issue as it pertains to the shallow and deep aquifers separated by the Maquoketa hydrogeologic unit in southeastern Wisconsin (Hart and others, 2008b) concluded that abandoned boreholes could potentially transmit an appreciable amount of downward leakage to the deep part of the flow system, rivaling the downward flow through the Maquoketa itself, but it is not known whether conditions around the boreholes generally allow water to readily enter or exit in order to take advantage of the open conduits. The assumption that the bedrock at the regional scale acts as an equivalent porous medium (see section 3.1, discussion of preferential flow) is a recognition that the LMB model is not capable of simulating the local effects, for example, of fractures and bedding planes on the drawdown pattern around individual wells.

The chief source of inflow to the LMB model is recharge. The soil-water-balance model (see section 4, "Model Construction") devoted to estimating the spatial and temporal distribution of recharge is a sophisticated tool, but some processes influencing the transfer of water from the surface to the water table are not considered in the way the algorithm was applied for this study. Among the unrepresented processes are overland routing of surface runoff to account for focused recharge in low-lying areas (an effect that is probably secondary at the 5,000-ft nearfield grid spacing) and irrigation as a source of recharge (it was assumed that all but a very small proportion is consumed by evapotranspiration, which might not always be true). Other limitations affect the ability of the estimated cell-by-cell recharge distribution to be updated during the calibration process. Limitations might have been introduced by the use of partly overlapping base-flow target sets to calibrate both the SWB model and the LMB groundwater-flow model, by the routing of all the water entering surface-water features to the target locations (even from wetlands, which might lose at least part of their base flow to evapotranspiration), and by estimating only a single multiplier for recharge on the basis of conditions at the end of the model simulation and then applying that same multiplier to all earlier stress periods rather than estimating recharge independently for different periods.

Other unrepresented processes might affect the ability of the model to serve as a forecasting tool. In principle, the flux boundary in the southeastern corner of the model should be updated to reflect future flow into and out of the domain. However, sensitivity analysis suggests that the effects of neglecting variations in this flux on model results are small except in some cases for the C-O aquifer system (see section 7). Upconing of saline water around pumping centers (for example around Joliet in NE_ILL, where DS concentrations have risen in well discharge) could be simulated by running the model in transport mode, but preliminary analysis suggests that the coarse grid spacing—and, especially, the thickness of the layers—blunts the model's ability to simulate local movement of the saline body (see section 7). More generally, it must be emphasized that the LMB models (that is, both the SLMB-C and SLMB-U simulations) do not fully reflect the processes that control flow in the Michigan Basin where saline conditions are most prevalent. Variations in density are grossly estimated across the more than 10,000-ft thickness of the basin, and the influence of temperature gradients, viscosity distribution, and any lingering effect on the flow field of overpressurization due to glacial unloading (discussed, for example, by Bahr and others, 1994) are neglected. In this sense, it is probably most fitting to consider the saline body more as a boundary condition that influences conditions at the edges of the freshwater body. LMB model results simulated within the saline body—water levels and flow patterns alike—should be considered approximate.

Limited precision—Regional model results are inherently inprecise. An important example involves the simulated locations of groundwater divides. The simulated locations are uncertain because they vary with depth, they change through time, and they are very sensitivite to pumping rates as well as model inputs (such as the hydraulic-conductivity distribution) and model geometry (such as the coarse grid spacing). For all these reasons, if precise knowledge of the location of shallow or deep groundwater divides were needed for management decision-making purpose at the local scale, additional data and analysis would be needed to refine the regional results.

Most of the limitations discussed above may be considered avenues for future work. Two areas of possible future study are discussed here. The most recent version of the SEAWAT-2000 code (Langevin and others, 2008) is able to simulate temperature gradients and viscosity conditions. In principle, it could also be used to simulate overpressurization in the Michigan Basin by means of imposed areas of high head and possibly even the action of sources of salinity (for example, in the Salina Group) by means of concentration source cells. The LMB model could be used as a starting point for future models aimed at a more rigorous study of variable-density conditions in the Michigan Basin. Versions of the model with refined lateral spacing and layering might help to increase understanding of the role of pumping on movement of saline water; for example, in the MSHL aquifer system in Michigan and the C-O aquifer system in northeastern Illinois (for an example application of this type, see Lahm and Bair, 2000).

The regional model is partially designed to be a platform for inset models, which address local water-resource issues at a finer grid resolution. Two recent methodological advances have enhanced the flexibility and power of the connection between the regional model and the local refined model embedded in it. The first, called Local Grid Refinement (Mehl and Hill, 2005), allows changes in the parent regional model to influence the child local model, and the reverse is true. This advance is particularly important for maintaining proper boundary conditions for the refined inset model as stresses are added inside it or around it. For example, the gradual expansion of drawdown in the regional model due to a pumping center at some distance from the local model automatically influences conditions at the boundary and inside the local grid, something that does not occur automatically with an inset model with fixed boundary conditions. The second approach, called hybrid finite-difference/analytic-element modeling, replaces the upper layer of the MODFLOW-2000 or SEAWAT-2000 model with a gridless analytic-element layer on the basis of techniques discussed by Haitjema (1995); this substitution allows the problems associated with superimposing the surface-water network on the finite-difference grid to be largely overcome without any alteration of the original horizontal or vertical grid spacing in the layers below the top layer. The possible advantages of this approach for simultaneously simulating with enhanced accuracy shallow and deep flow conditions is the subject of ongoing research (Haitjema and others, 2010). A study area was selected within the LMB model domain—shown in figure 84—to test the new Local Grid Refinement and Hybrid methods on a single problem involving the effect of pumping near a headwater stream on low-flow surface-water discharge (Hoard, 2010).

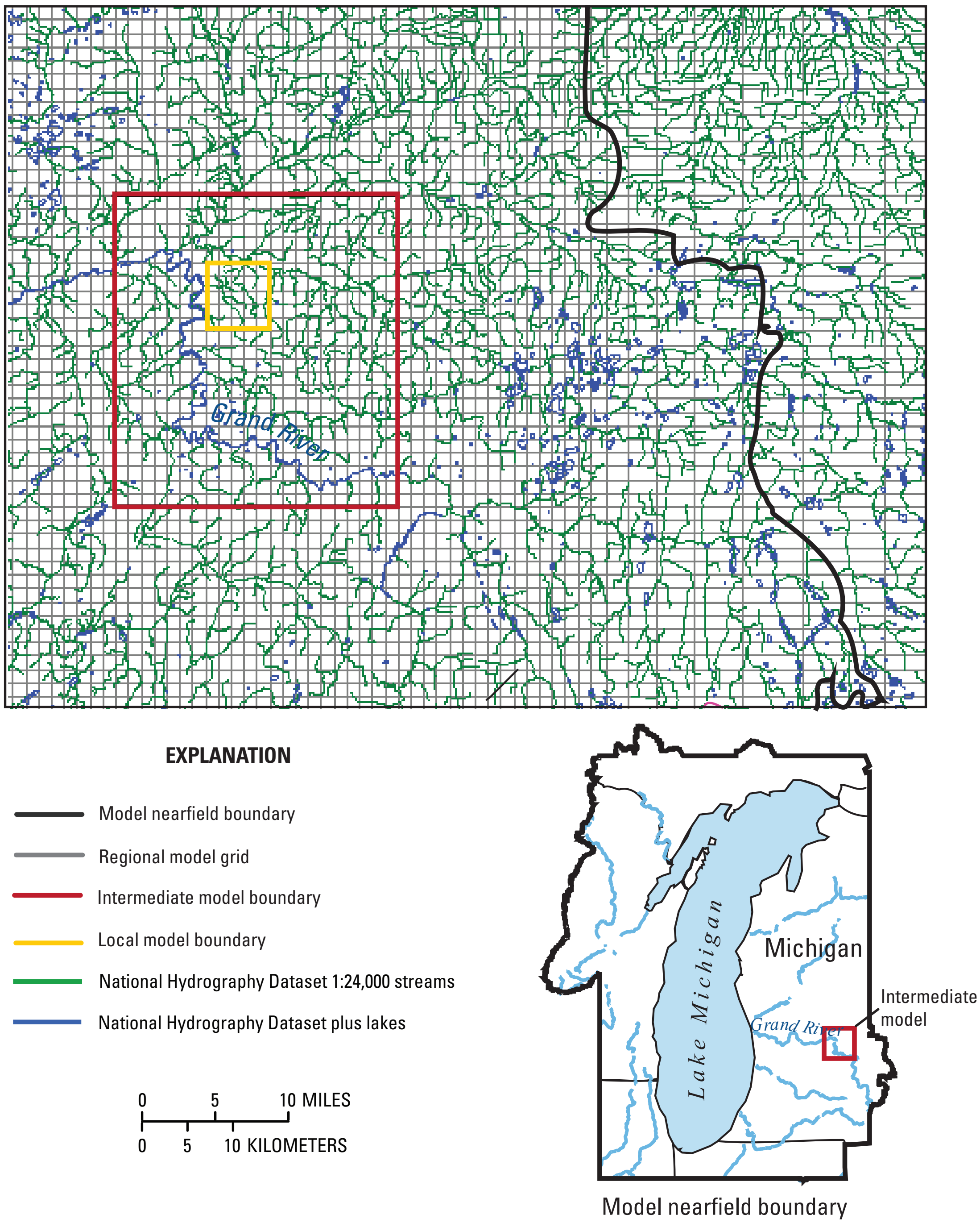


Figure 84. Demonstration area for inset models with grid refinement.

9. Summary and Conclusions

A regional groundwater-flow model of the Lake Michigan Basin and surrounding areas has been developed in support of the USGS National Assessment of Water Availability and Use—Great Lakes Basin Pilot. 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 and others, 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 and others, 2010); and
- 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 (see section 4), hydrologic coverages delineating the surface-water network (see appendix 2), and hydrogeologic information relating primarily to hydraulic conductivity (see appendix 4) 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 and others, 2003). Two versions of the model were calibrated: one for confined conditions (SLMB-C) and one for unconfined conditions (SLMB-U). 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 and others, in press) guided the adjustment of initial inputs. Comparison of updated parameter values, calibration statistics, and parameter sensitivities demonstrated that SLMB-C and SLMB-U 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; and
- 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 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; however, 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 discharged 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, as discussed in section 3, 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 maintaining 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 and others, 2010; and Hoard, 2010).

The construction of alternative versions of the regional model reveals important *in*sensitivities 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 only very small 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 findings using a series of *sustainability indicators***.** These are 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. Ongoing work includes application of the regional model in *forecasting* mode to shed light on the effects of possible future levels of pumping on the groundwater system, and the model is being used to test hypotheses regarding the effect of *climate variability and change* on water availability. 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 Project (Reeves, in press).

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