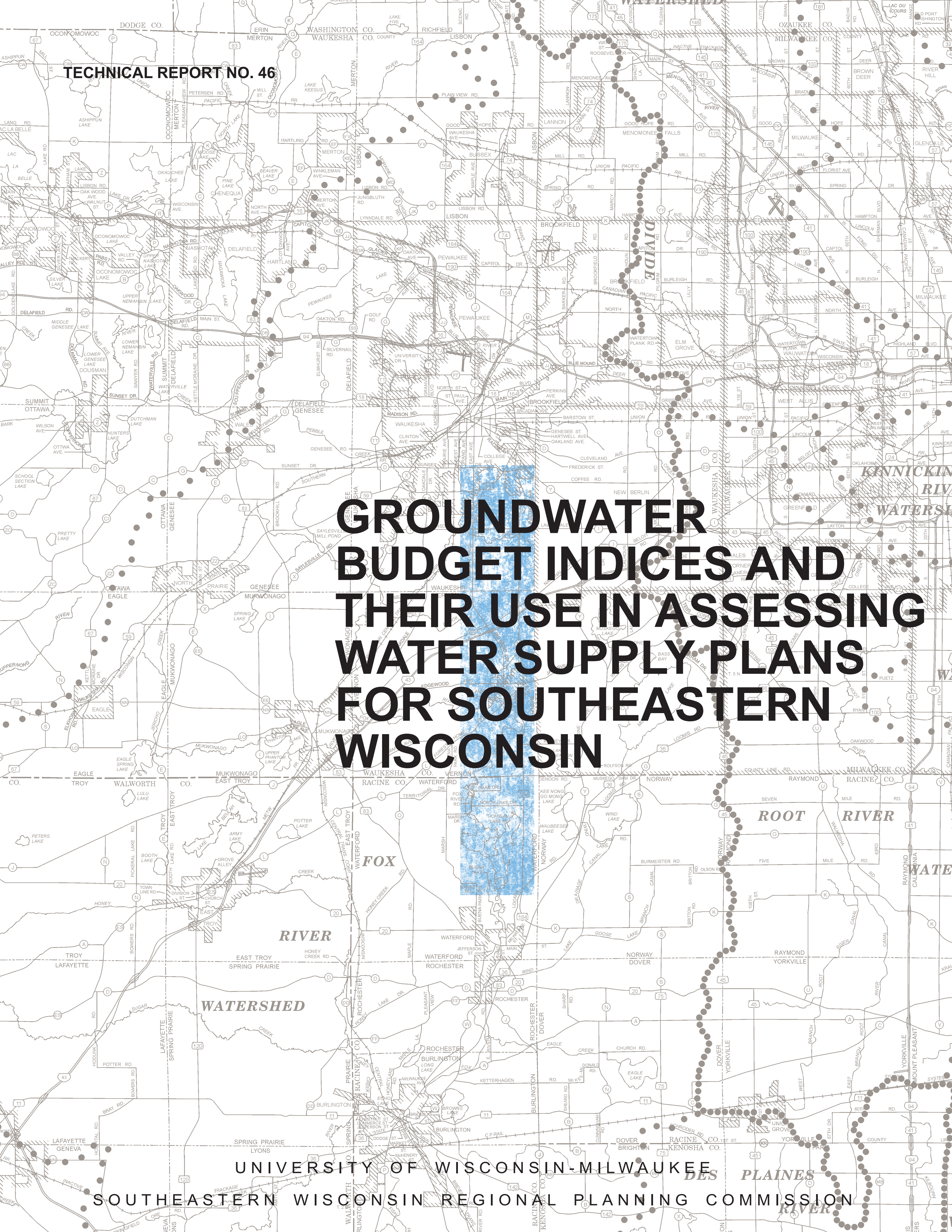
TECHNICAL REPORT NO. 46

GROUNDWATER BUDGET INDICES AND THEIR USE IN ASSESSING WATER SUPPLY PLANS FOR SOUTHEASTERN WISCONSIN



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GROUNDWATER BUDGET INDICES AND THEIR USE IN ASSESSING WATER SUPPLY PLANS FOR SOUTHEASTERN WISCONSIN

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Introduction

As part of the assessment of regional ground-water supplies, the Southeastern Wisconsin Regional Planning Commission (SEWRPC) has commissioned the development of four ground-water models for the region and beyond. The first two were developed for historical conditions. A steady state model was constructed to simulate natural, or pre-development, conditions, when human stresses on the ground water system were negligible. This model's function was to generate starting heads for use in the second model, a transient model developed to simulate progressive changes from 1864 to 2000. The steady state and transient models will be referred to as the predevelopment and historical models, respectively, in this report. Both are documented in Feinstein, et al. (2005), although it should be noted that they have been modified since the publication of Feinstein, et al. (2005) to make the models better representations of reality. Inland surface water bodies have been converted from being simulated by the Modflow River software package to simulation by the Modflow Stream software package. The Stream package is more complex and less stable, but it allows a more accurate simulation of ground water/surface water interactions. This modeling package also allows the tracking of how baseflow changes along the length of a channel.

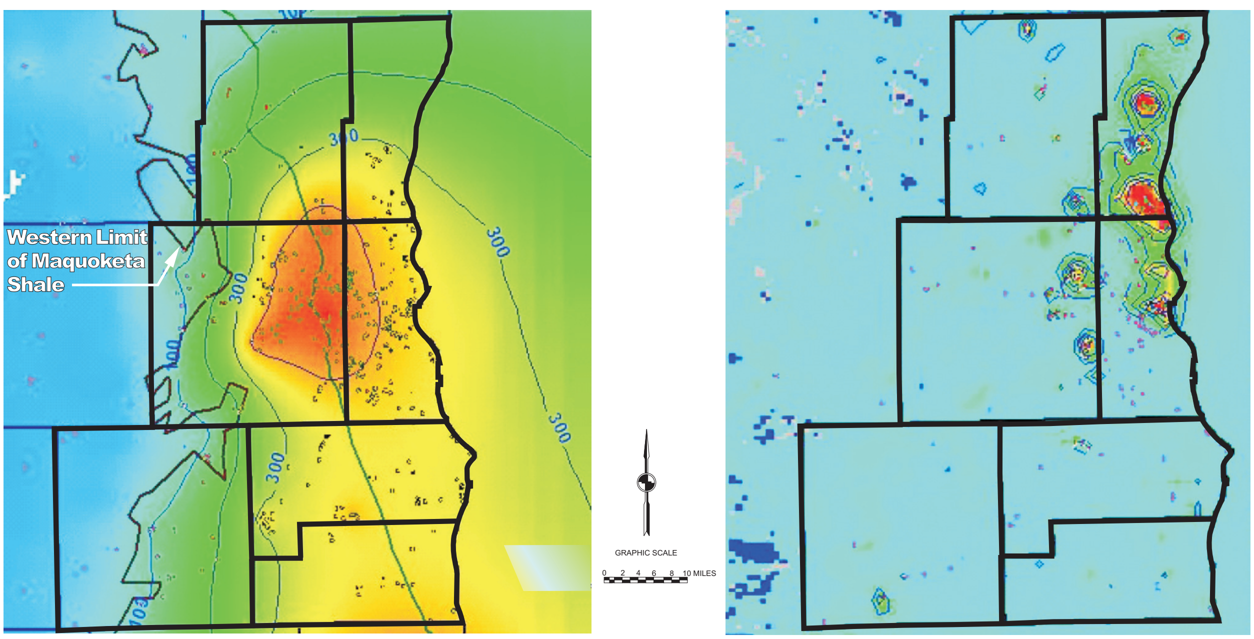
The third model (called the transition model) is designed to start with the 2000 end conditions from the historical model and project forward to 2005. The model is used to generate initial heads for the fourth and final model. That fourth model (called the future model) then starts at the 2005 conditions generated by the third model and projects into the future ground-water system responses to changes in human stresses, ending at design year 2035. The magnitude and location of future human stresses, such as pumping and artificial recharge, have been developed collaboratively by SEWRPC, the U.S. Geological Survey (USGS), the Wisconsin Geological and Natural History Survey (WGNHS), Ruekert and Mielke, Inc., and UW-Milwaukee (UWM). The intent of this model is to allow comparison of ground-water impacts among alternative management scenarios. With the exception of well locations and pumping rates, all other conditions are identical in the four models.

The future model differs from the historical model in several significant ways. Because it is intended to project future conditions, it cannot be calibrated. The locations of new wells and the pumping rates of all wells can only be estimated. As a result, it is an interpretive model intended to be used for comparison among future management plans. The future ground water levels and fluxes projected by this model can only be as accurate as the placement and magnitude of the future pumping. In addition, this model and the transition model contain estimates of domestic pumping for each stress period. The historical model had domestic pumping added only for the last stress period (2000).

The historical model can be used to calculate water level changes (usually drawdown) between predevelopment periods and 2000 (Figure 1). In the deep aquifer, water levels have declined hundreds of feet (Figure 1A) because most of the aquifer is confined, which limits the availability of water to replace that being extracted. These drawdowns are indicative of a water budget deficit and are also the composite result of pumping throughout both southeastern Wisconsin and also adjacent areas, most notably northeastern Illinois.

In contrast, drawdowns in the shallow aquifer are much smaller despite the fact that nearly twice as much water is being extracted from it (Figure 1B). The reason for the lower drawdowns is that the shallow aquifer is unconfined in most places. It receives direct recharge from precipitation and is also linked directly to surface water bodies. Under natural conditions, most ground water recharge to the shallow aquifer flows through the shallow aquifer and discharges to surface water bodies as baseflow. Pumping the shallow aquifer can reduce the natural ground-water discharge, intercepting it before it reaches surface water bodies and then discharging it to those few rivers that receive wastewater effluent. It is even possible for pumping to reverse the natural ground-water discharge and induce water to flow out of surface waters and into the shallow aquifer. As a consequence, ground-water deficits in the shallow aquifer often do not manifest themselves as large drawdowns. Their effect, instead, is to reduce ground-water baseflow. In fact, in Figure 1B, the large drawdowns all occur where the shallow aquifer is semi-confined by clay-rich glacial till.

Figure 1 Simulated drawdowns for the Region between 1860 and 2000
In Figure 1A, the red color shows areas with drawdown greater than 400 feet.
In Figure 1B, the red zones are drawdowns greater than 50 feet.



In addition to drawdown, the models can also be used to determine the magnitudes of all the components of ground-water budgets (Figure 2 and Table 1) at a variety of scales (regional, county, and community, for example). Because of the complexity of the system being modeled, there are far too many individual terms to report and assimilate. Instead this report groups them into a set of indicator ratios designed to address three questions:

1. How does the quantity of water being removed from an aquifer by wells relate to that aquifer's natural supply?

2. How much have humans altered the ground-water system?

3. What effect does human alteration of the ground-water system have on surface waters?

The indices presented, called demand to supply ratio, human influence ratio, and baseflow reduction index, address the three questions above, respectively. The first two were developed by Weiskel, et al (2007), but have been renamed for this study.

First, this report provides limited historical perspective, using index results from the calibrated historical model. Secondly, it then examines the proposed alternatives for future ground-water usage. Alternative 1 contains the changes from 2005 to 2035 that are anticipated based upon 2035 employment, population, and land use forecasts developed under the recently completed 2035 regional land use plan and continued reliance on groundwater supplies in areas currently using that source of supply. The employment, population, and water demand forecasts are documented in Chapter IV of SEWRPC Planning Report No. 52 (2009). Alternative regional water supply plans 2 through 4 investigate the effects of providing water from alternative sources to selected ground-water using communities in the region. The alternative plans assume the same demand for water and land uses that were developed for Alternative 1. Finally, a preliminary recommended water supply plan has been selected by the SEWRPC Regional Water Supply Planning Advisory Committee, which combines aspects of the four alternative plans.

Figure 2: Graphical depiction of the ground water components used in this study. Blue arrows are for the shallow aquifer, orange arrows are for the deep aquifer, and red arrows are exchanges between the two aquifers. The abbreviations are defined in Table 1.

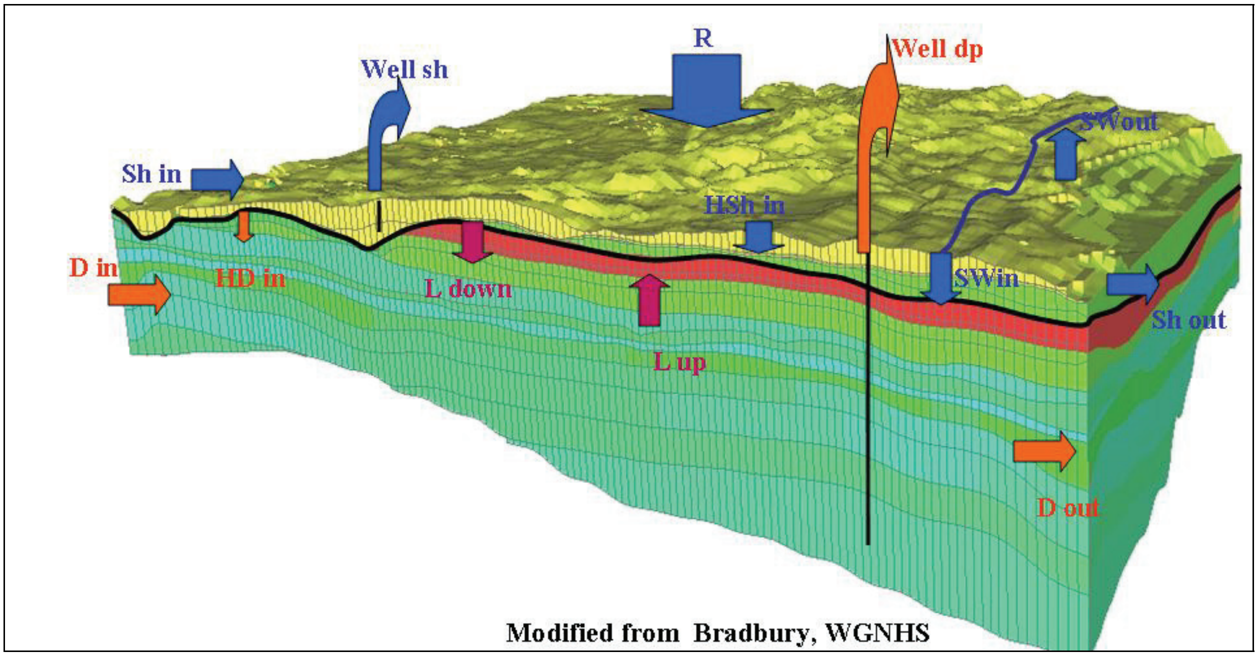


Table 1 Definition of the flow and storage terms shown in Figure 2[1]

	Inflows	Outflows	Storage
Shallow Aquifer	R = recharge		Volume of water in the aquifer below the water table and above the top of the Maquoketa Shale
	SW in = flow from surface waters	SW out = discharge to surface waters (baseflow)	
	Sh in = lateral inflow through the aquifer	Sh out = lateral outflow through the aquifer	
	L up = leakage up from deep aquifer	L down = leakage down to deep aquifer	
	H_{Sh} in = human inputs (septic system return)	Well sh = pumpage from shallow aquifer wells	
	Inflows	Outflows	Storage
Deep Aquifer	D in = lateral inflow through the deep aquifer	D out = lateral outflow through the deep aquifer	Volume of water in the aquifer below the top of the Maquoketa Shale and above the base of the deep aquifer
	L down = leakage down from shallow aquifer	L up = leakage up to the shallow aquifer	
	H_D in = human inputs = 0	Well dp = pumpage from deep aquifer wells	

[1] *For additional detail in the derivation of the terms from the groundwater modeling output, see Appendix A.*

Historical Distribution of Ground-Water Budget Indices in Southeastern Wisconsin.

Demand to Supply Ratio (DSR)

One measure of an aquifer's ground water budget comes from comparing the net amount of water humans are extracting (volume pumped) to how much water is replenished at a given point in time. It can be expressed as:

$$\text{Demand/Supply} = (\text{Well out} - \text{H in})/(\text{Sum of natural inflows}), \qquad (1)$$

where the terms are defined in Figure 2 and Table 1.

The net extraction (outflows induced by humans pumping wells minus any human returns to the same aquifer) is used as an indicator of human stress on the aquifer. The only human return occurring in the model is treated wastewater, returned almost exclusively by private, onsite treatment systems (septic systems or equivalent). One exception is the City of Lake Geneva in Walworth County, which pumps its water from the shallow aquifer and returns its treated wastewater to the same aquifer through infiltration basins.

Neither the net extraction nor the net inflow to a given area (county or community) is effected by changes outside that area. Therefore, the value of the DSR is not influenced by ground water conditions in surrounding areas. The DSR will only change when pumping in the area of interest changes.

The natural inflows include recharge, leakage, flow from surface water bodies and lateral flow through the aquifer. Values from the 1900 simulation have been used for this purpose, because there was very little human impact at the time. These natural, or predevelopment, inflows are used rather than present-day inflows because the current ground water system has responded to the stress of modern pumping. Consequently, water is flowing toward the pumping centers via leakage, lateral flow and capture from surface waters. This water is being "borrowed" or appropriated from other areas at present. As such it represents a potentially temporary source, dependent upon the absence of pumping in surrounding areas or in there being no objection to its redirection from surface waters. Including the "borrowed" water as a permanent source would be misleading as it would overestimate the supplies in a given location's water balance.

The DSR values are open-ended, but typically range up from 0. A value of 0 indicates that the ground water budget remains in the same balance as it did before human influence. When ratio values become increasingly positive, the indication is that pumping is moving the water budget out of its natural balance. When a value of 1 is reached, net pumping is extracting the same amount of water as would be naturally replenished. Values greater than 1 indicate that pumping has moved the aquifer into ground water budget deficit, and the farther the ratio is above 1, the farther out of balance the ground water budget deficit becomes. This situation is not sustainable in perpetuity.

Figures 3 and 4 show the spatial distribution of the DSR in 2005 in the deep and shallow aquifers, respectively. These maps are derived from the transition model. They include the effects of domestic pumping in addition to those from high capacity wells. The maps are intended to show general patterns and not the specific values at a given location. They've been generated by contouring the ratio values for all communities as if they occur at each community's centroid (midpoint).

Figure 3 Demand/Supply Ratio in Deep Aquifer - 2005

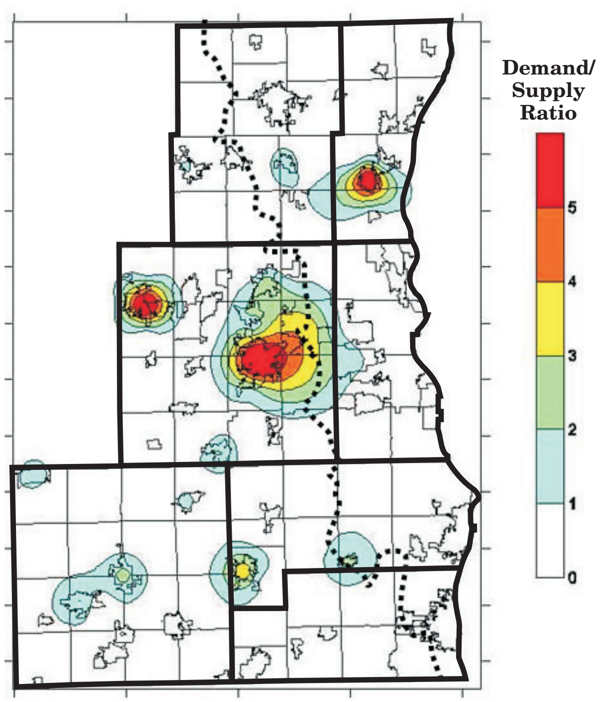
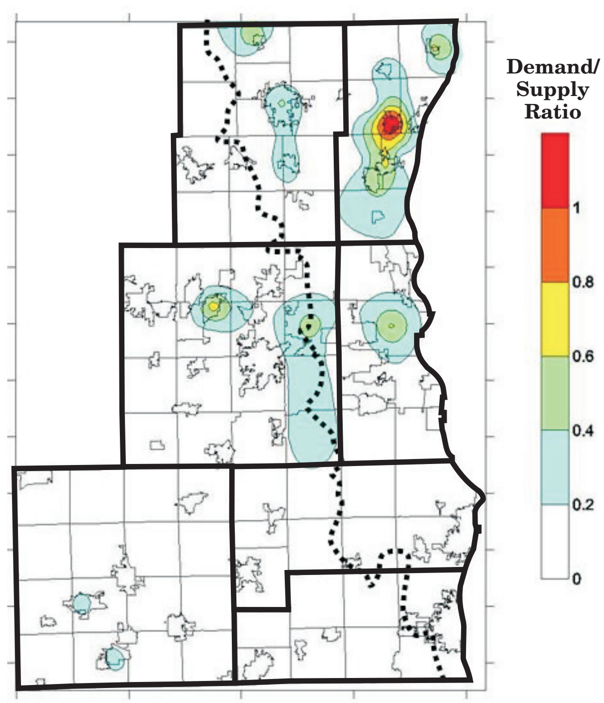


Figure 4 Demand/Supply Ratio in Shallow Aquifer - 2005



In the deep aquifer, the color-filled areas are those in ground water budget deficit. The primary area of concern is eastern Waukesha County. Other areas of concern are located in the Cities of Cedarburg and Oconomowoc. The City of Waukesha is removing over five times more water from the deep aquifer than was being naturally replenished in 1900. At present, there is no immediate water shortage in these areas, because ground water is flowing in from under surrounding areas and as leakage from the shallow aquifer. Instead, the color-filled areas should be interpreted as the focus of where ground water supply problems are developing. The southern areas of color on Figure 3 are areas in the vicinity of the Village of Union Grove and the Cities of Burlington, Elkhorn and Delavan.

In the shallow aquifer (Figure 4), a very different color scale has been used, because only the Village of Saukville has a DSR exceeding 1.0. Other color-filled areas on the map indicate regions where the ground water budget is impacted but is not yet in budget deficit. The reason for the much smaller ratios in the shallow aquifer is because there is much more inflow available (primarily as recharge), so the supply is greater. The green spot in the central part of Milwaukee is the effect of the Milwaukee Metropolitan Sewerage District's deep tunnels, which are constructed in the shallow aquifer and act as ground water sinks (demands) most of the time. The City of Brookfield and the Villages of Kewaskum, Belgium, Grafton and Hartland are stressing the shallow aquifer relatively hard (ratio values are greater than 0.4)

The City of Lake Geneva, on the other hand, returns treated wastewater to the shallow aquifer. When this is accounted for, that community's DSR drops to 0.07 (Figure 4) from the 0.93 it would be without the return.

Comparing Figure 3 to the drawdowns in the deep aquifer (Figure 1A) shows that the DSR pattern has some similarities but also significant differences. First, drawdown is a composite of historical water level changes and is also affected by outside factors, such as pumping in northeastern Illinois. In contrast, the DSR map (Figure 3) indicates where water budget deficits were located in 2005 only.

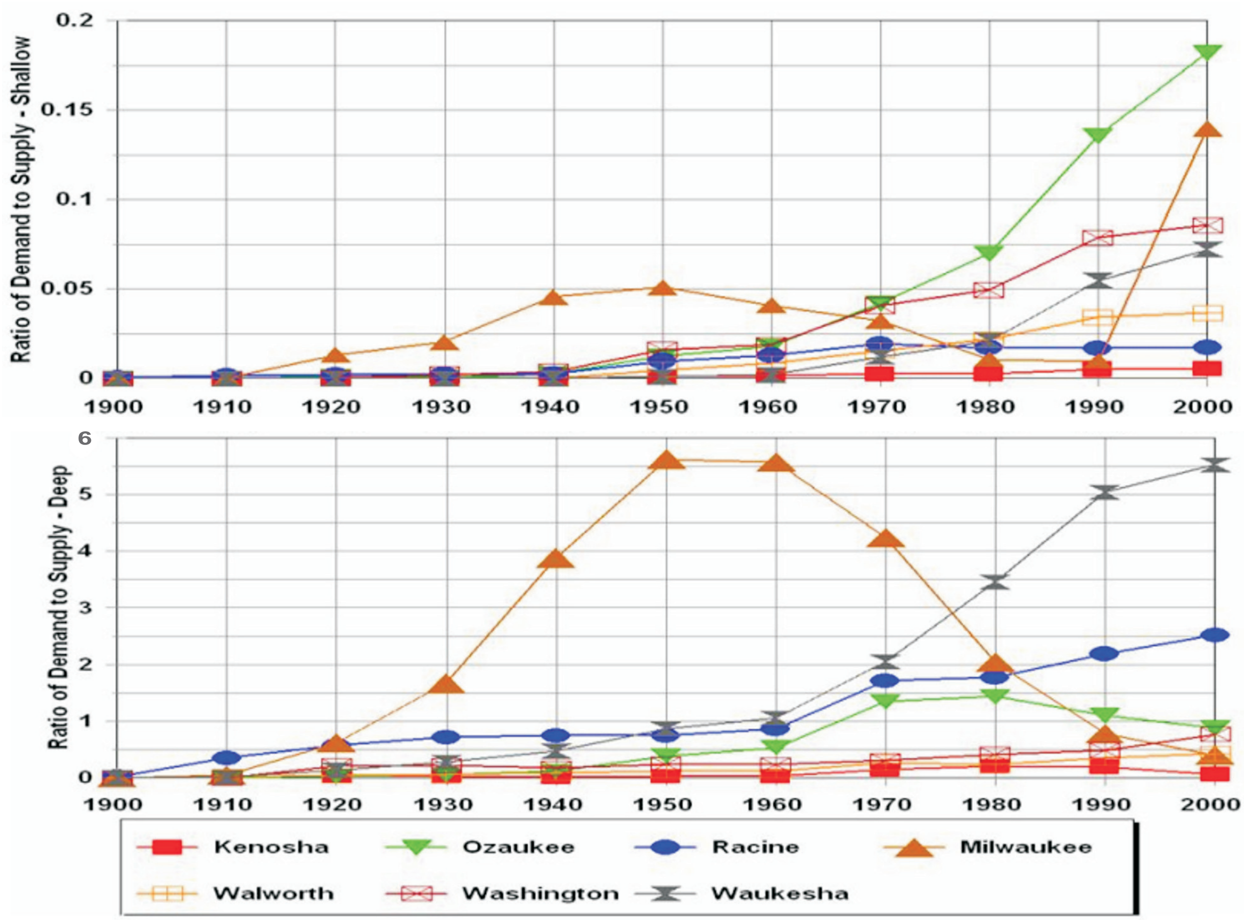
In the shallow aquifer (Figures 1B and 4), there is very little correlation between drawdown and the distribution of DSR. As indicated above, drawdown is not a good indicator of ground-water problems in an unconfined aquifer. The DSR is somewhat better, but still limited in what it shows.

The historical model also allows presentation of the change in indicator ratios through time. The historical progression is presented for the counties (Figure 5). These plots do not include domestic pumping, because a good estimate of it is not available for years prior to 2000.

There is a progressive increase in the DSR for the shallow aquifer in all counties except Milwaukee (Figure 5). Because the supply (denominator) is held constant in the ratio, the rise in DSR results from increased pumping. As noted above, these ratio values only incorporate high capacity wells for all known uses, including municipal and self-supplied systems for uses such as industrial, commercial, agricultural, and other irrigation. This allows comparison from year to year, but does underestimate the actual ratio at any given time, because the effects of domestic pumping are not included.

Milwaukee County's value rose in the 1940s and 1950s and then dropped as most communities switched to lake water. This pattern shows up in both aquifers (Figure 5). In the shallow aquifer, the value increased again after the deep tunnels were constructed in the mid 1990s. The deep tunnels drain ground water when they are empty, so they have been included as human extraction. They have no influence on the deep aquifer. Ozaukee County's communities and industries have been switching their pumping from the deep to the shallow aquifer, resulting in the very rapid rise in the county's ratio in the shallow aquifer over the most recent decades. During that same period, the county's ratio in the deep aquifer declined. Racine, Walworth and Washington Counties all have ratios which are rising slowly in both aquifers as they increase pumping. The only problem area is in the deep aquifer in Racine County, where the ratio shows a water budget deficit. In Racine County, the DSR is especially sensitive to small changes in pumpage because the magnitude of the replenishment is quite small. Waukesha County's ratio in the deep aquifer is rising rapidly and is well into the deficit budget range. In contrast, Waukesha County's ratio in the shallow aquifer (Figure 5) is also rising, but is unremarkable.

Figure 5 Historical change of county demand/supply ratios in the shallow aquifer (top panel) and the deep aquifer (bottom panel).
Values shown do not include the effects of domestic wells.



Human Influence Ratio (HIR)

This index is intended to quantify what portion of the ground water budget is controlled by human activity and whether that influence is predominantly on the inflow or outflow components. It is calculated as:

$$HIR = (\text{Human Inflows}/\text{Total Inflows}) - (\text{Human Outflows}/\text{Total Outflows}). \quad (2)$$

The first term on the right side of the equation defines the human returns to the ground water system as a percentage of the total inflows for the same period of time. The second term characterizes human outflows (usually pumping) as a percentage of the total outflows. Both terms can range between 0 (no human influence) and 1 (where all the water moving in or out is doing so under the influence of human activity). The total index can therefore range from -1 to +1. A value of 0 indicates that there is either no human influence or that its effects on inflows and outflows are balanced. As human influence increases, the HIR value moves toward ± 1, with negatives indicating that the influence is greater on the outflow components of the budget.

For the study area, the equations for the two aquifers are:

$$\text{HIR deep} = (0) - \{\text{Well dp}/(\text{D out} + \text{L up} + \text{Well dp})\}. \qquad (3)$$

$$\text{HIR sh} = \{H_{Sh}\ \text{in}/(\text{R} + \text{Sh in} + \text{L up} + \text{SW in} + H_{Sh}\ \text{in})\} - \{\text{Well sh}/(\text{Well sh} + \text{Sh out} + \text{SW out} + \text{L down})\} \qquad (4)$$

Because there is no human return to the deep aquifer in the region, the first term on the right side of the deep aquifer equation is 0. The individual terms are portrayed in Figure 2 and defined in Table 1.

The HIR index will respond to changes in ground water conditions outside the area of interest, particularly in the deep aquifer. Regional changes in water levels in the deep aquifer, for example, can alter the magnitude of leakages, lateral ground water fluxes or storage changes in a local area of interest. Therefore, HIR can change locally even if pumping does not, although such changes are commonly small.

Figures 6 and 7 show the spatial distribution of the HIR in 2005 in the deep and shallow aquifers, respectively. All colored areas on the maps indicate an HIR below -0.20, where human impacts on withdrawals exceed those on inputs. The white areas indicate either that there is no human use of ground water in an aquifer or that the human withdrawals and returns are both balanced and relatively small. There are many communities that do not use the deep aquifer, so that is the primary cause of white areas in Figure 6. In the shallow aquifer, the white areas are the result of both causes, with communities using both domestic wells and septic systems being the most frequent. The City of Lake Geneva, with its return to the shallow aquifer of treated wastewater, has an HIR of -0.22 on Figure 7, considerably better than the -0.55 it would be without the return.

The spatial distribution of the HIR (Figure 6 and 7) shows notable similarity to the DSR maps (Figures 3 and 4). In the deep aquifer, the zones of most negative HIR in eastern Waukesha County, the City of Oconomowoc, and the City of Cedarburg (Figure 6) are directly analogous to parallel zones on Figure 3. In addition, problem areas in the vicinity of the Village of Union Grove, and the City of Burlington appear for the deep aquifer (Figure 6). Areas which have a high demand to supply ratio also have strongly negative human impacts. Because there is no return of water by humans to the deep aquifer in the region, the values shown on Figure 6 also show the portion of the aquifer's outflow that is controlled by wells. For example, an HIR value of -0.50 means that flow to wells comprises 50 percent of the aquifer's discharge.

Figure 6 Human Influence Ratio in Deep Aquifer in 2005

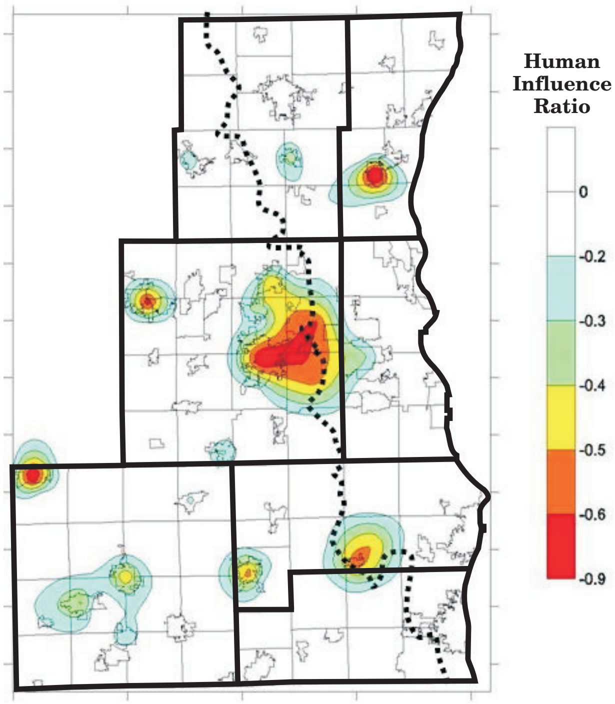
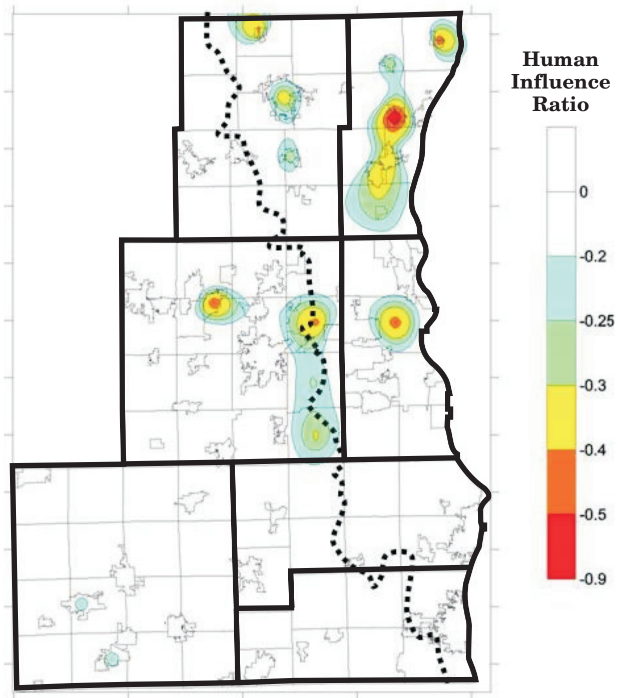


Figure 7 Human Influence Ratio in Shallow Aquifer in 2005

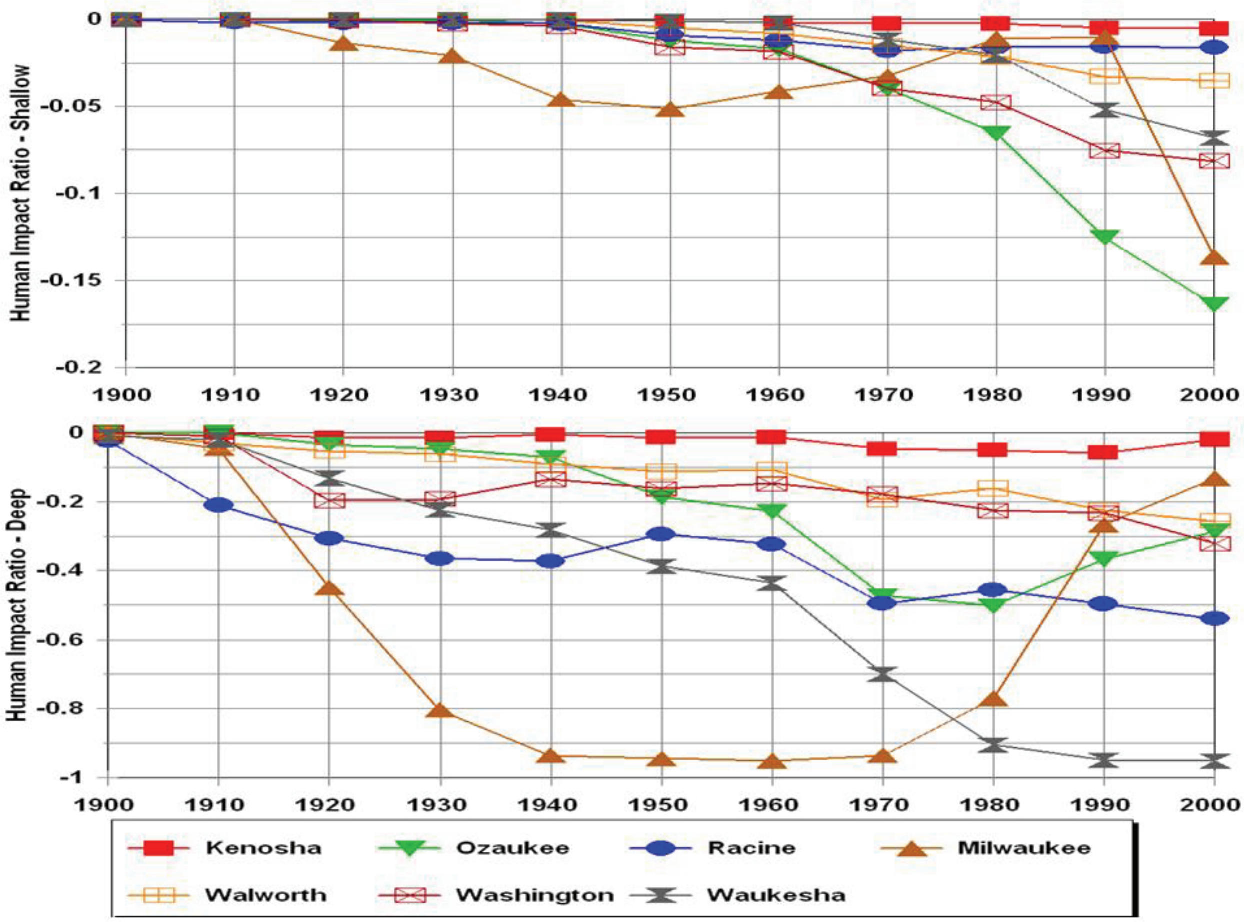


In the shallow aquifer, the Villages of Saukville, Belgium, Hartland and Kewaskum and the City of Brookfield show both high DSRs (Figure 4) and HIRs (Figure 7). As with the DSR, the central Milwaukee County HIR is the result of the MMSD tunnels.

HIR is a better indicator than drawdown of where ground-water impacts are occurring in the shallow aquifer. Figure 7 shows considerably more spatial detail than Figure 1B. HIR will also be a valuable indicator of the effects of any artificial recharge to be incorporated into simulations of other alternatives. With artificial recharge, the HIR will become less negative and may even go positive.

Historically, the variation of human impact ratios through time in each county (Figure 8) is essentially a mirror image of the demand supply ratio (Figure 5). The two measures track each other very closely, although the HIR appears to be somewhat more sensitive to the onset of human effects. Milwaukee County's HIR in the deep aquifer drops earlier than its DSR, for example.

Figure 8 Historical change of county human impact ratios in the shallow and deep aquifers
Values shown do not include the effects of domestic wells.



Baseflow Reduction Index (BRI)

Pumping in the shallow aquifer intercepts ground water that would have discharged to surface water bodies as baseflow. This ground water discharge is the inflow that keeps surface waters flowing during dry periods, when there is no surface runoff. As pumping increases, the baseflow in streams, wetlands and lakes decreases. The baseflow reduction index (BRI) has been developed to quantify that loss. It is the ratio of the change in ground water discharge between a base time period and the time of interest divided by the base period discharge. In the historical analysis of this report, it is expressed as the change between the predevelopment time of 1900 and 2005:

$$BRI = [(\text{Net Baseflow}_{2005} - \text{Net Baseflow}_{1900})/\text{Net Baseflow}_{1900}] * 100, \quad (5)$$

where Net Baseflow is SW out – SW in (Figure 2).

In the analysis of proposed management alternatives, it will be expressed as the change in baseflow between 2005 and 2035.

Baseflow changes only occur in the shallow aquifer, and the values, expressed as percents, are contoured in Figure 9. As with the other contour maps, Figure 9 shows the distribution of the BRI for each individual community. Net baseflow in a community can be influenced by ground water changes outside that area. For example, the baseflow in one community can be reduced by increased pumping of the shallow aquifer in a nearby community.

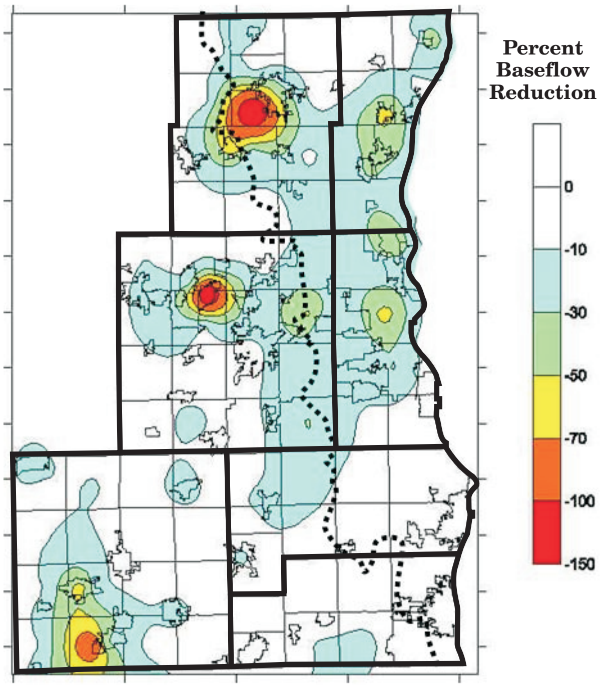


Figure 9 Baseflow Reduction Index in Shallow Aquifer between 1900 and 2005

Values below -100 percent indicate that the exchange between the aquifer and surface waters has reversed. In 1900 at these locations, ground water was discharging as baseflow. At present the surface water bodies are losing water to the aquifer

There has been a baseflow reduction of over 10 percent in the 20th century throughout most of the region (colored areas on Figure 9). Green, yellow, orange and red zones show progressively higher reductions by community and also a strong parallel to Figures 4 and 7. The areas where the shallow aquifer is most stressed by human activity (Figures 4 and 7) have experienced the greatest baseflow reduction. Once again, these areas do not appear clearly on the drawdown map for the shallow aquifer (Figure 1B).

Figure 9 is showing the effect of pumping on baseflows within individual communities. It is not showing the reduction of total flow in a river, just the ground water component of that total flow. In dry periods, virtually all of the flow in a river is ground water discharge (baseflow), so the effects will be most apparent in the summer, fall and early winter. In wet periods, flow in surface water bodies is dominated by surface runoff of rain or snowmelt. During these times, the effects of the ground water pumping would be indiscernible.

The baseflow reductions shown in Figure 9 have not been cumulated downstream; the map is showing just the magnitude of changes where they occur. The baseflow reductions due to pumping will be greatest on a percentage basis on smaller water bodies, such as springs, headwater streams and those small lakes, wetlands and ponds which are simulated in the model.

In addition, no allowance has been made to incorporate the amount of wastewater effluent in those rivers which receive it. That effluent is not direct ground-water discharge and is both thermally and chemically different.

Historically, baseflow has been progressively decreased through time in each county (more negative BRI on Figure 10). Ozaukee County's switch from the deep to the shallow aquifer has resulted in a reduction of nearly 11 percent due to high capacity wells alone. Waukesha County's reduction is over 9 percent and Milwaukee County's increased from 4 to 10 percent when the deep tunnels were completed (Figure 10). Because estimates of the distribution of domestic pumping are not available before 2000, Figure 10 is showing only the historical baseflow reductions due to municipal, industrial and other high capacity wells.

When domestic pumping for 2000 is added to the models, the BRI values become more negative (Figure 11). However, even though domestic use accounts for 37 percent of the gross pumping in the region (and over 55 percent in the shallow aquifer), it adds relatively little to the baseflow reduction in 2000. The reason is that the bulk of the domestic pumped water is returned to the shallow aquifer via onsite wastewater treatment. It then continues to discharge to surface water bodies as baseflow.

Figure 10 Historical change in BRI by county in the shallow aquifer

The historical simulations include only the effects of pumping high capacity wells, because estimates of domestic pumping are only available for 2000.

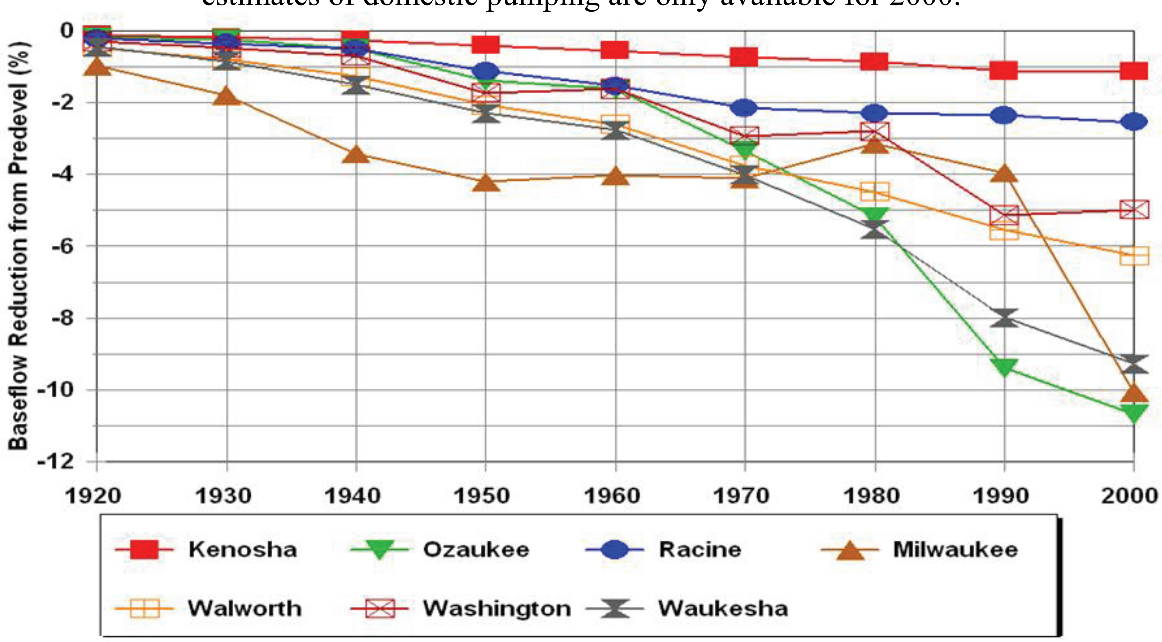
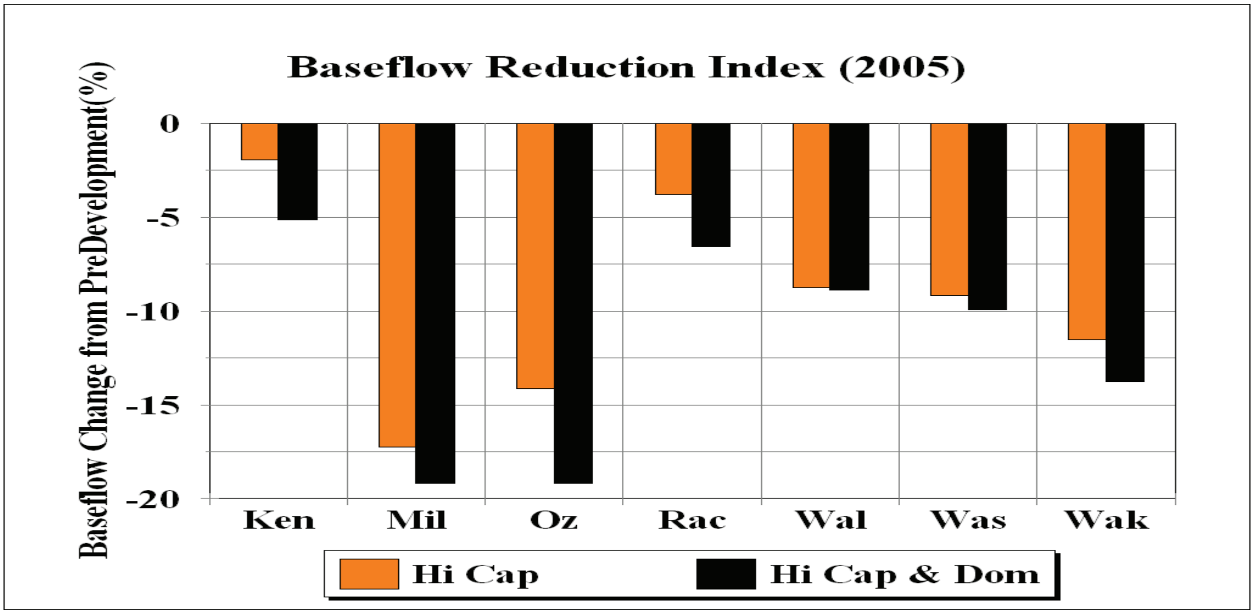


Figure 11 Comparison of the relative effects of high capacity and domestic pumping on baseflow reduction.

The orange bars show the BRI in each county due to high capacity wells only. The black bars are the effects of all pumping, so the difference between the bars is the effect of domestic wells



On a regional basis, high capacity wells caused baseflow in 2005 to decline 8.9 percent below that in 1900. When net domestic pumping is added, the reduction increases to 10.7 percent. The biggest decreases have occurred in Ozaukee County (where ground water communities are located along the Milwaukee River), in Waukesha County (where the greatest pumping from the shallow aquifer occurs), and in Milwaukee County (where the deep tunnels are constructed beneath the Milwaukee, Menomonee and Kinnickinnic Rivers).

Using performance indicators for management guidance

To date, there has been no significant regional management of the groundwater supplies of southeastern Wisconsin. Individual communities and developers have generally utilized the aquifers without regional coordination, but generally have considered the impacts of individual proposed wells on the existing wells of adjacent utilities. The communities have also provided system interconnections for emergency purposes. In addition, the WDNR regulates high-capacity well siting, and requires consideration of the impact of potential new wells on certain specified surface waters, as well as on other municipal wells. The result of this lack of regional management has produced some developing problems, including areas of groundwater budget deficit in the deep aquifer and attendant significant water level reductions, and locations where surface waterbodies have been impacted by heavy groundwater use in the shallow aquifer. The former has led to the Region being declared a groundwater management area by the WDNR, a designation that requires development of a regional plan to mitigate the problems.

SEWRPC has undertaken the development of a water plan intended to find solutions to the supply problems. As part of that process, it will investigate how different management alternatives will impact the ground water system. The indices presented above should serve as one mechanism to quantify the relative effectiveness of each of the alternatives.

In the deep aquifer, the focus should be on alternatives which stop or reverse water level declines by eliminating water budget deficits. In the confined portions of the deep aquifer, the goals should then be reducing the DSR regionwide toward 1.0 and ultimately below it, because values greater than 1.0 indicate budget deficits in closed (confined) systems. Simultaneously the HIR should probably be kept in the range between -0.30 and +0.30. In the historical results, where all human activity is extraction, the HIR typically has a value near -0.3 when the system approaches a ground-water deficit (DSR = 1.0), so that value has been taken as the limit of acceptability. Both goals will require reducing pumping of this aquifer in eastern Waukesha County and the other areas of budget deficit (Figure 3). Table 2 provides the 2005 indices for each county, and clearly points out that the primary budget deficits are in Waukesha and Racine Counties. In 2005, Waukesha County was the largest user of the deep aquifer, pumping over 20 mgd from it. Of the four lakeshore counties, where the deep aquifer is fully confined and gets very little replenishment, Racine County is the largest deep aquifer user. Its 2005 pumping was 3.3 mgd.

Pairing the DSR and HIR indicators also provides insight into the direction that an area is moving relative to budget deficit. Walworth County has been moving toward a budget deficit in the deep aquifer, with DSR values rising (Figure 5). The DSR is still below 1, but the HIR already exceeds -0.30 (Table 2). In contrast, Ozaukee County has had a budget deficit for years, but has taken steps to reduce it. Although its DSR is still above 1.0, the HIR has dropped below that of Walworth, indicating the downward trend in impact. The HIR index functions as a precursor to changes in the DSR.

Table 2 Performance Indicators by County – 2005

County	Shallow Aquifer			Deep Aquifer	
	DSR	HIR	BRI_{1900}(%)	DSR	HIR
Kenosha	0.047	-0.047	-5.1	0.101	-0.041
Milwaukee	0.159	-0.150	-19.2	0.567	-0.197
Ozaukee	0.199	-0.188	-19.2	1.040	-0.317
Racine	0.061	-0.060	-6.6	1.963	-0.500
Walworth	0.045	-0.044	-8.9	0.745	-0.326
Washington	0.083	-0.081	-9.9	0.453	-0.191
Waukesha	0.089	-0.086	-13.8	5.773	-0.881
Regional Composite	0.081	-0.079	-10.7	2.379	-0.706

In the shallow aquifer, drawdown simply is not a good indicator of ground-water impact. The most useful index will be that for baseflow reduction (BRI). Budget deficits in this aquifer are unusual, but impacts of pumping on surface water baseflows are widespread (Figure 9) and largely unrecognized. A suggested management goal would be to keep BRI less than -10 percent. All counties except Kenosha and Racine already exceeded this level in 2005 (Table 2) on a countywide basis. The problem will increase in most of the region as more development supplied by ground water occurs.

In Milwaukee County, the impact is largely the result of the MMSD deep tunnels. The ground water draining to the tunnels is pumped back into Lake Michigan, the ultimate natural sink for the baseflow in the lower Milwaukee, Menomonee and Kinnickinnic Rivers. The tunnels are included with wells in the BRI analysis because they are net extractors of ground water. In both models, the tunnels have been simulated as draining a time-invariant (steady) flow from the shallow aquifer.

The DSR and HIR indices are less directly useful in the shallow aquifer, but they can help identify the areas where baseflow problems exist. Generally the undesired baseflow reductions (reductions greater than 10 percent on Figure 9) are centered around areas where the DSR is greater than about 0.20 (Figure 4) or the HIR is more negative than -0.20 (Figure 7). For example, at the county scale the high baseflow reductions in Milwaukee, Ozaukee and Waukesha Counties are all associated with DSRs in excess of 0.13 and HIRs which are more negative than -0.127 (Table 2).

Historical Summary

The water budget analysis demonstrates that both aquifers in southeastern Wisconsin are showing signs of stress, but their responses are different. On a regional scale, the deep aquifer is heavily overexploited, with nearly twice as much water being pumped from it as was replenished under natural conditions. Because of its confined condition in most of the Region, the opportunity for replenishment is limited. The result of the imbalance is that water levels are dropping, and a huge cone of depression has formed.

The cone induces water to flow toward its center, drawing water from beneath neighboring areas to the north, south, and to a lesser extent to the east, and diverting baseflow from surface water bodies to the west. This situation could be sustained if the demand for water remains constant or is diminished, meaning other competing users do not develop. Chances of this happening are unlikely. SEWRPC is projecting continued increase in employment, population, urbanization, and water demand into the future throughout the Region. One of the most rapidly growing areas is Waukesha County It is also the center of the budget deficit, where the DSR approached 6.0 in 2005 and where human activity controls over 88 percent of the water movement in the deep aquifer.

In contrast, the shallow aquifer presently is producing twice as much water as the deep aquifer within the Region. Because it is unconfined, it receives considerable replenishment from recharge, and DSRs are much lower than in the deep. However, under natural conditions, most of that recharge flowed through the aquifer and discharged as baseflow to surface water bodies. As humans extract water from the aquifer, they are having two primary effects: 1. diverting baseflow from some receiving bodies, and 2. transferring that water (as treated wastewater) into a select few rivers. The result is that most surface waters are stressed at low flows, because the ground water discharge to them has been reduced almost 15 percent throughout the Region. On the other hand, those rivers into which wastewater flows actually have more flow throughout the year than occurred naturally. This additional water is thermally and chemically different from natural ground-water discharge, however.

Impacts of Future Water Supply Alternatives

Introduction

Initially four management alternative plans were described and evaluated under the regional water supply plan. These alternative plans have been simulated with the future model. Forecasts of water use were made to serve the employment, population, and land use forecasts developed under the 2035 regional land use plan (SEWRPC, 2008, Chapter IV). The total estimated increase in demand for the communities using ground water in 2005 is 28 mgd. Each of the four alternatives provides that increased demand from different sources.

Alternative 1 is considered the base case to which other water use alternatives are compared. The sources of supply under this alternative are based upon existing trends and committed actions. Almost all groundwater using communities are assumed to continue to apply groundwater management measures similar to current measures. These include limited coordination with respect to aquifer utilization by neighboring utilities, and the WDNR oversight of high-capacity well development considering impacts on municipal wells and selected surface water. The projected future demands require increased pumping of about 19.2 mgd from the shallow aquifer, and about 8.8 mgd from the deep aquifer.

Alternatives 2 through 4 examine different regionally managed approaches. Each is designed to decrease stress on the deep aquifer while testing one combination of alternative sources to replace part of the Alternative 1 extraction from the deep aquifer. Alternative 2 provides Lake Michigan water to several major ground-water users east of the sub-continental divide, while relying primarily on the shallow aquifer to supply new demands to the west. This plan results in a reduction of pumping of 16.7 mgd from the deep aquifer. It is replaced with 11.9 mgd of lake water and 4.8 mgd of additional extraction from the shallow aquifer. This plan produces a net reduction of 11.9 mgd of ground-water pumping in the region.

Alternative 3 keeps the extractive pumping of ground water identical to that in Alternative 2, but augments the aquifers with artificial recharge. A total of 9 mgd is simulated being injected into the deep aquifer, while another 13.8 is allowed to infiltrate into the shallow aquifer. The latter comes from both collection and infiltration of rainwater and from treatment and infiltration of wastewater effluent. This plan has a net reduction from Alternative 2 of 22.8 mgd of pumping, and a net reduction from Alternative 1 of 34.7 mgd (9 mgd reduction in the shallow aquifer and 25.7 mgd in the deep aquifer).

Alternative 4 is another modification of Alternative 2. In it, an additional 28 mgd of Lake Michigan service is advanced to select communities in straddling counties, but to the west of the sub-continental divide (Pewaukee, Sussex, Union Grove and Waukesha), and to the western parts of Brookfield and Menomonee Falls (straddling communities). The result is a reduction of net demand relative to Alternative 2 of 22 mgd in the shallow aquifer and of 6 mgd in the deep aquifer.

The effects of the altered pumping stresses on ground water budgets are reported below. In a confined aquifer, changes in pumping are mainly manifested in responding changes in head in the aquifer. As extraction increases, the cone of depression must expand to draw in more water from lateral inflow. In southeastern Wisconsin, the cone has already expanded beyond the edge of the Maquoketa Shale to the west, so water is also being indirectly induced to flow in from the shallow aquifer and surface water bodies it contains. To the south, the cone has merged with another generated by pumping in northeastern Illinois. Because the latter cone is larger, there is little possibility for inducing additional water to flow from the south. If projections decrease future extraction from the confined aquifer, then the cone of depression will shrink and heads will rise, causing drawup.

The effect of these changes in the deep aquifer can be shown using potentiometric surface and/or drawdown/drawup maps. But a drawback to these maps is that they contain historic artifacts of pumping in Milwaukee County and the effects of northeastern Illinois. In contrast, the DSR, mapped by community (as above) shows the active pumping centers which are driving the changes in head, a better depiction for resource planning than the drawdown maps. With the exception of Alternative 3, there are no additions of water to the deep aquifer via human actions. Therefore, the HIR distribution has a very similar pattern to DSR and will not be discussed herein.

In an unconfined aquifer, the response to changes in pumping is very different from that in a confined system. Cones of depression are very local in scale because replacement water comes both from interception of local recharge that would otherwise flow to surface water bodies and from inducement of water to flow out of those water bodies. The result is that impacts in an unconfined system are predominantly manifested in alterations of the exchange of water between aquifers and surface water baseflows.

This effect is presented for each alternative using maps showing the distribution of the BRI calculated for communities in the region. Maps of drawdown in unconfined aquifers at the regional scale are misleading. Drawdowns can be substantial near wells, but these effects commonly extend over only a few model cells. Consequently, they are localized and often don't show up on a regional map (such as Figure 1B). Drawdown maps in the shallow aquifer are better indicators of where the aquifer is partially confined by glacial till, in the eastern part of the region. As a result, drawdown maps are not presented in this report for the shallow aquifer; they do not show meaningful effects of pumping.

For each alternative, two sets of index maps are presented. The first set shows the distribution of the simulated values for 2035 of the DSR in the deep aquifer and the BRI in the shallow aquifer. These can be compared visually to the 2005 distributions (Figures 3 and 9, respectively). The second set plots the simulated changes in each respective index between 2005 and 2035. The color scale will contrast areas which change for the worse (reds) with those that change for the better (greens).

Cautions about interpreting index maps

In examining the maps which follow, it is important to remember four things. First, all the new water used in the proposed alternatives has to come from somewhere and then go somewhere after use. The regional flow model is designed to look at ground-water systems, along with ground water interactions with surface baseflows. As presently configured, the model does not deal directly with the movement of Lake Michigan water through the region. New lake water delivery is simulated only as a reduction of pumping of ground water. The model also does not simulate the effects of the return of treated wastewater to surface water bodies in the region. Thus there are locations today, such as the Fox River, where baseflow reductions due to ground water pumping are mitigated by wastewater return. There may also be increases of baseflow and total flow in receiving streams if diverted lake water is returned to tributaries to Lake Michigan. The modeled results presented below cannot account for these effects, so they must be considered separately when the viability of the alternatives is examined.

Second, baseflow reduction is also affected by the proximity of wells to surface water bodies. In general, the farther new wells are located from surface waters, the smaller the reduction of baseflow. Because of the size of the nodes in the ground water models, the effects of well placement can't be examined with high resolution. But there will appear to be some anomalous situations in which communities with relatively small pumping demands will have larger baseflow reductions than larger users, solely because of the closeness of a well field to a lake or stream.

Third, the new wells frequently could not be located within the boundaries of the municipality using them. This has resulted in the impact of some new municipal wells occurring in adjacent towns. It has the effect of spreading the impacts out over broader areas on the index maps.

Finally, changes in the DSR index will directly parallel change in pumping in a given community. BRI is also dominantly influenced by changes in pumping in a given community, but it is also sensitive to changes in nearby communities. BRI values can also go lower than -100 percent. In this case, ground water flow has changed from discharge to the surface water to having surface water induced to flow into the aquifer.

Alternative 1

In Alternative 1, the additional supplies of water needed for 2035 in ground-water using communities were simulated as coming from expanded ground-water extraction. If current or committed wells could not meet the projected demands of 2035, additional wells were inserted into the model to meet these supply shortfalls. In the process, most new wells were placed in the shallow aquifer. In addition, the boundaries of municipal utilities were expanded to include heavily populated surrounding areas presently served by private wells. This had the effect of transferring pumping in the model from domestic wells to municipal supply systems. It has also provided for municipal water supplies by 2035 to all areas in the Region which, in 2005, were served by private wells and municipal sewers in 2000.

Net pumping of the shallow aquifer increases 40 percent from 2005 to 2035 (48.5 mgd to 67.7 mgd) under this alternative. In the deep aquifer, the increase is 29 percent (30.2 mgd to 39.0 mgd). The increases in the shallow aquifer are distributed widely across the region, while the deep aquifer increases are concentrated in Brookfield, Elm Grove, Germantown, Mukwonago and Oconomowoc, and to a lesser extent in Burlington and along the north shore of Lake Geneva.

Under this scenario, numerous communities in the region continue to have DSRs in the deep aquifer in excess of 1.0, indicating budget deficit, and baseflow reductions in the shallow system exceeding 10 percent since 2005 (Figures 12 and 13). In fact, the DSR of the deep aquifer has increased dramatically since 2005 (Figure 14), with the change focused in those

Figure 12 Demand to Supply Ratio in Deep Aquifer in 2035: Alternative 1

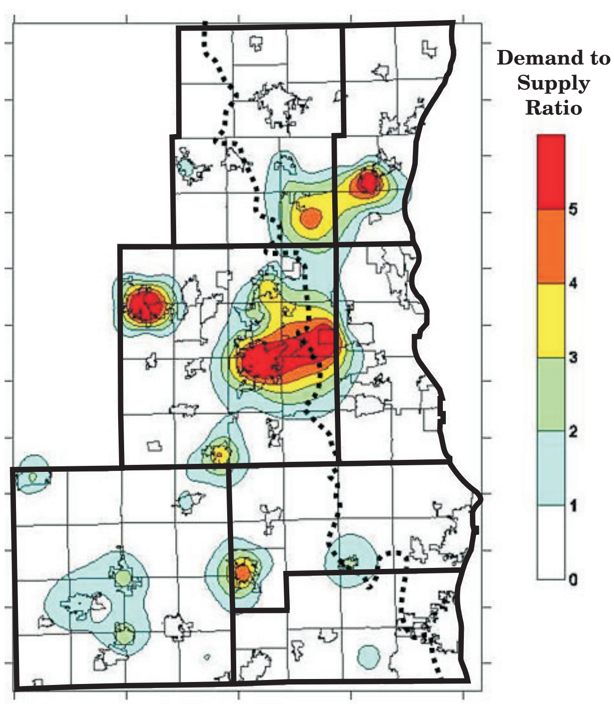


Figure 13 Baseflow Reduction Index in Shallow Aquifer in 2035: Alternative 1 (from 2005)

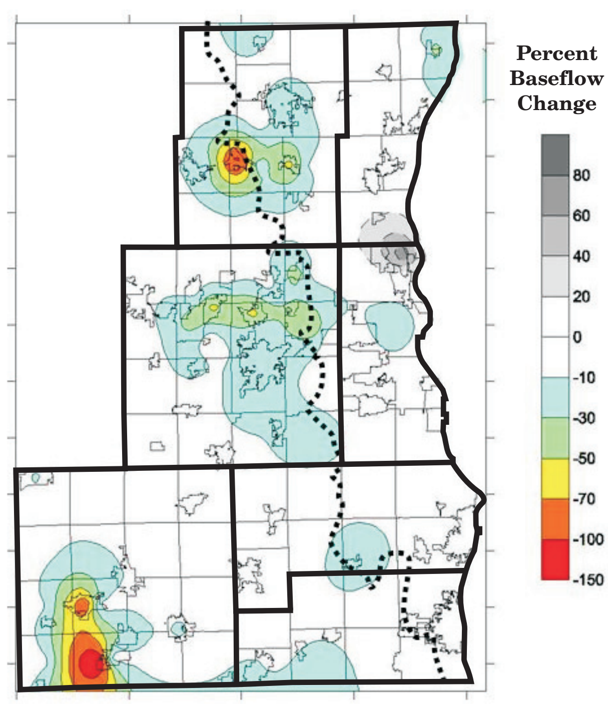


Figure 14 Change in Demand to Supply Ratio in Deep Aquifer between 2005 and 2035: Alternative 1

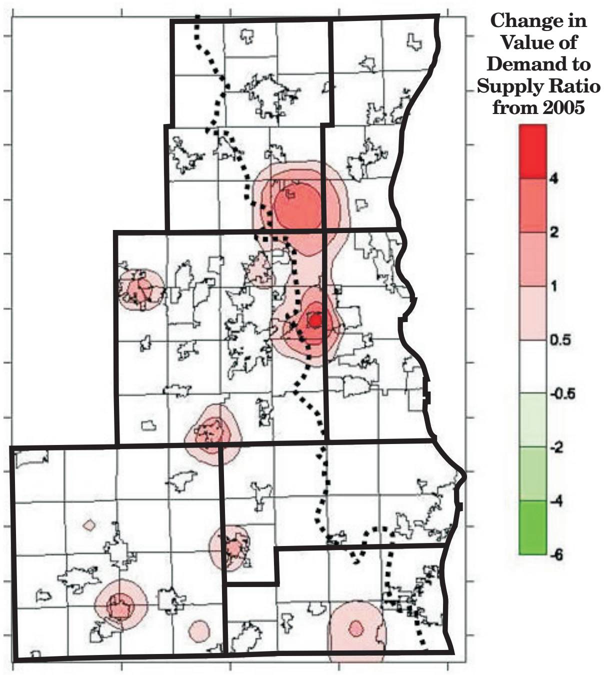
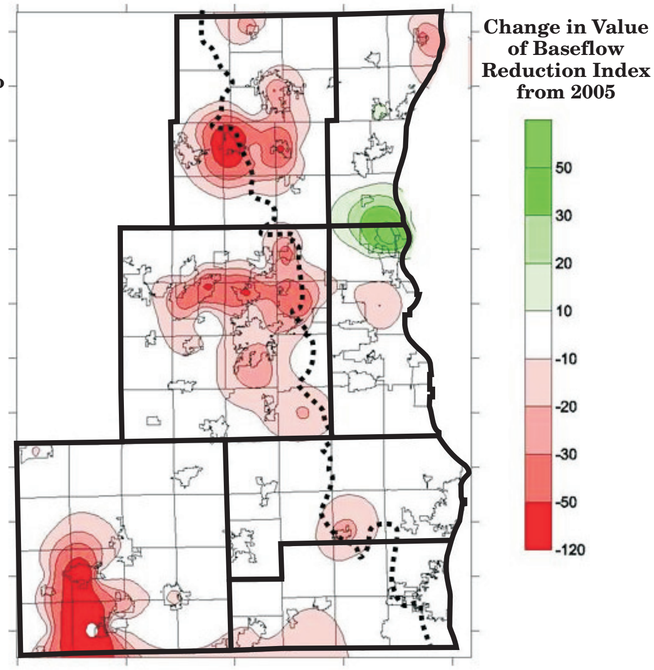


Figure 15 Change in Baseflow Reduction Index in Shallow Aquifer between 2005 and 2035: Alternative 1



communities with greater deep aquifer pumping. The net result is that water levels in the deep aquifer continue to be drawn down under Alternative 1 (Figure 16), and the cone of depression grows deeper and westward (Figure 17). Baseflow reductions also increase throughout the region (Figure 15), except in northeastern Milwaukee and southeastern Ozaukee Counties, where pumping has been reduced with the delivery of lake water to additional parts of Mequon, Thiensville and Bayside. Here baseflow actually increases between 2005 and 2035 (gray areas on Figure 13).

Figure 16 Simulated drawdown in upper sandstone (deep) aquifer between 2005 and 2035: Alternative 1

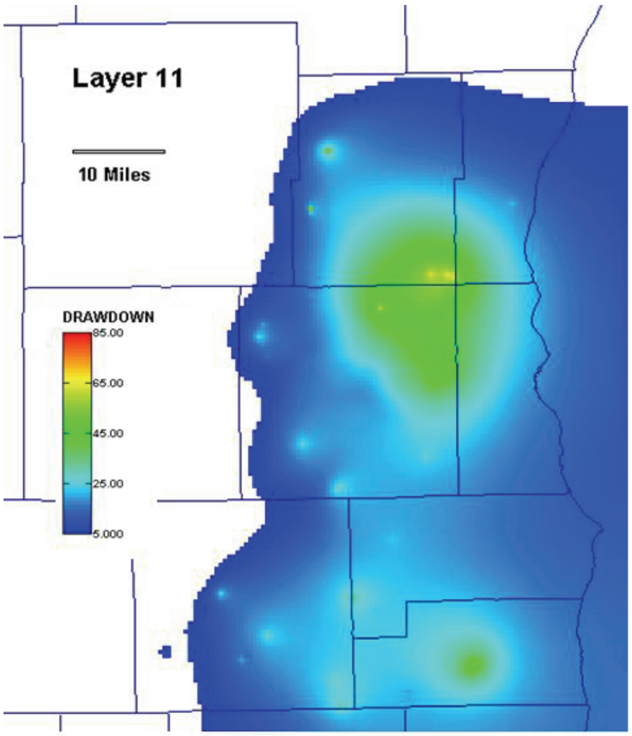
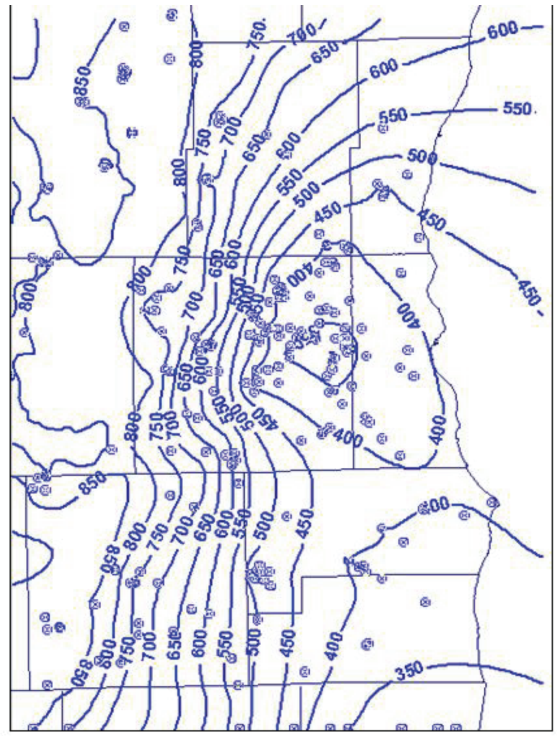


Figure 17 Simulated 2035 potentiometric surface (NGVD29) in the upper sandstone (deep) aquifer: Alternative 1



Both figures from Feinstein (2008)

At the county and regional scales, the projected water budget indices have been determined for both 2005 and 2035 and are presented in Tables 3 and 4. In the deep aquifer, increased regional pumping causes the regional DSR to rise 29 percent and the HIR to become 15 percent more negative. Five counties (all except Kenosha and Milwaukee) have their DSRs rise essentially to 1.0 or above and their HIRs drop to less than -0.30 by 2035. The additional pumping projected in the deep aquifer for Alternative 1 causes greater net human impacts which, in turn, causes the aquifer to go farther out of budget balance.

Walworth, Washington and Waukesha Counties account for most of the increased pumping and also show the largest changes in both DSR and HIR (Table 3). Kenosha County is projected to have a fivefold increase in deep aquifer pumping by 2035, also resulting in large index changes.

Table 3 Projected Future Values for Pumping, DSR and HIR in Deep Aquifer – Alternative 1								
County	Net Pumping (mgd)			Demand to Supply Ratio			Human Impact Ratio	
	2005	2035		2005	2035		2005	2035
Kenosha	0.17	0.90		0.101	0.539		-0.041	-0.204
Milwaukee	0.89	0.89		0.567	0.567		-0.197	-0.176
Ozaukee	0.86	0.88		1.040	1.075		-0.317	-0.302
Racine	3.30	3.86		1.963	2.293		-0.500	-0.555
Walworth	5.57	7.74		0.745	1.034		-0.326	-0.409
Washington	0.81	2.44		0.453	1.369		-0.191	-0.483
Waukesha	18.63	22.27		5.773	6.906		-0.881	-0.949
Region	30.22	38.98		2.379	3.069		-0.706	-0.810

In the shallow aquifer, DSRs rise and HIRs become more negative in the counties with increased pumping (Table 4). The largest increases are in Walworth, Washington, Waukesha and Kenosha Counties. Milwaukee and Ozaukee Counties are both projected to decrease their

Table 4 Projected Future Values for Pumping, DSR, HIR and BRI in Shallow Aquifer – Alternative 1											
County	Net Pumping (mgd)			Demand to Supply Ratio			Human Impact Ratio			Baseflow Reduction (percent)	
	2005	2035		2005	2035		2005	2035		Total from 1900 *	Future after 2005 #
Kenosha	3.06	5.79		0.047	0.089		-0.047	-0.087		-9.90	-5.03
Milwaukee	4.09	3.38		0.159	0.131		-0.150	-0.127		-18.99	+0.23
Ozaukee	7.60	7.16		0.199	0.188		-0.188	-0.183		-17.90	+1.58
Racine	4.54	5.47		0.061	0.073		-0.060	-0.072		-8.06	-1.59
Walworth	6.62	11.25		0.045	0.077		-0.044	-0.075		-13.63	-5.21
Washington	8.25	11.78		0.083	0.118		-0.081	-0.115		-14.05	-4.59
Waukesha	14.30	22.83		0.089	0.141		-0.086	-0.137		-20.36	-7.64
Region	48.45	67.67		0.081	0.113		-0.079	-0.109		-14.87	-4.66

* The first BRI (BRI_{1900}) is the change from 1900 to 2035; negative values indicate baseflow reduction.

\# The second BRI (BRI_{2005}) is the change from 2005 to 2035, with same sign convention as for above.

pumping from the shallow aquifer. The values of these indices remain low, however, in comparison to those in the deep aquifer because of the greater exchanges with both the atmosphere (recharge) and surface water bodies.

As anticipated, the largest impacts from the use of the shallow aquifer are on baseflow discharges to surface waters. Two sets of BRIs have been calculated and are presented in Table 4. The baseflow reduction after 2005 will be the basis for comparison among all SEWRPC's alternative plans. Without proper context, however, this projected future BRI_{2005} can be misleading because it doesn't show all human impacts, only those in the future. Table 4 also contains the cumulative baseflow reductions since 1900, essentially before there was any significant pumping of ground water in the region.

The future regional reduction of baseflow (BRI_{2005}) is 4.7 percent, with Waukesha, Kenosha, Washington and Walworth Counties having the largest decreases, the same counties with the largest increases in shallow aquifer pumping. In the 30 year planning period, these four counties show a drop of 4 percent or higher.

Of the countywide BRI_{2005} values, none are more negative than the unacceptability criterion of -10 percent. However, if demand for ground water were to continue to increase beyond 2035 at the same rate as between 2005 and 2035, Waukesha County's BRI would exceed -10 percent in 2043. These countywide indices don't present a complete picture of impact on baseflows. There is a wide spatial variability of baseflow reductions within each county (Figure 13). Impacts tend to be greater on headwater reaches, or adjacent to a stress on the shallow aquifer. Figure 13 demonstrates that there are many communities in the region within which the net baseflow will be reduced much more than 10 percent between 2005 and 2035 under Alternative 1.

In addition, many surface waterways were already strongly impacted by historic pumping prior to 2005 (BRI from 1900 in Table 4). In 2005, baseflow in the region had already been reduced 10.7 percent from 1900, and the total reductions increased to 14.9 percent in 2035 (a 39 percent net reduction of baseflow). By 2035, the projected cumulative baseflow reductions (from 1900) will exceed 10 percent in all counties except Kenosha and Racine, and will exceed 17 percent in Milwaukee, Ozaukee and Waukesha Counties (Table 4). As alternative plans are compared and assessed, it must be understood that the future baseflow reductions are being added onto past baseflow reductions that had already stressed some waterways.

It is also important to note that Milwaukee and Ozaukee Counties are projected to show increases in ground water baseflows (less negative BRIs) between 2005 and 2035 (Table 4). These are the counties in which shallow aquifer pumping decreases. This demonstrates that baseflow reduction can be mitigated by reducing pumping in the shallow aquifer. BRIs can also be reduced by augmenting recharge to the shallow aquifer, a situation not simulated in the base alternative but planned for others.

Comments on system limits suggested by simulation of Alternative 1

The insertion of new shallow aquifer wells in the future model caused some problems in the model. Many more model cells went dry in 2035 (Alternative 1) than had done so under earlier conditions. This means that the simulated water level in a cell dropped below the bottom of the cell during the iterative solution process. At that point, the cell was dewatered (drained). For the purpose of stability, the models are designed to permanently shut off a cell that goes dry.

There are some cells in the models that are naturally dry; locations where the water table elevation is below the base of the surficial glacial deposits. However, the appearance of new dry cells demonstrates that new stresses are lowering water levels. In the future model's simulation of Alternative 1, 13 new dry cells developed in the first stress period (2005 to 2010). This was followed by 19 new ones in the second stress period (2010 to 2020) and 58 in the third (2020 to 2035). The acceleration of the number of dry cells through time indicates that in some areas the simulated ground-water system is not able to deliver the increasing amounts of water supply sought. This should be viewed as a warning that the demands of Alternative 1 are approaching the supply limits of the ground-water system in some areas.

Two situations merit specific mention. In the shallow aquifer, some of the new wells inserted to supply future needs went dry. There was also a significant increase in the portion of the topmost layer of the deep aquifer (Layer 9; top of the Sinnippee Formation) which went dry in Waukesha County. The former situation indicates that the shallow aquifer is not as prolific as hoped; it often cannot supply the desired pumpage to a single well. It was overcome by splitting the proposed well into two or four wells placed two nodes apart (Feinstein, 2008). The latter phenomenon will probably not affect ground-water quantity in a noticeable way, but it may have effects on ground-water quality. Under Alternative 1 conditions, air is now being introduced to geologic formations that have been fully saturated with water. In other parts of Wisconsin (notably Outagamie County), dewatering of the deep aquifer has resulted in increased solution of arsenic from the rock and increased arsenic concentrations in the water.

Alternative 2

Under this alternative, net pumping in the deep aquifer is reduced 26.3 percent (from 30.2 to 22.3 mgd), while that in the shallow aquifer is increased 49.3 percent (from 48.5 to 72.4 mgd). Lake water is provided to replace extraction from the deep aquifer east of the sub-continental divide in Brookfield, Cedarburg, Germantown, Menomonee Falls, and New Berlin, among others. The communities of Cedarburg, Delavan, Elkhorn, Hartford, Pewaukee and Waukesha are simulated as switching a large part of their deep aquifer pumping to the shallow aquifer, putting greater stress on that aquifer than under Alternative 1. As in Alternative 1, there were many cases where the new shallow wells could not be placed in the municipality using them and instead were placed in surrounding towns. The same changes in domestic pumping simulated in Alternative 1 are included here.

Figure 18 Demand to Supply Ratio in Deep Aquifer in 2035: Alternative 2

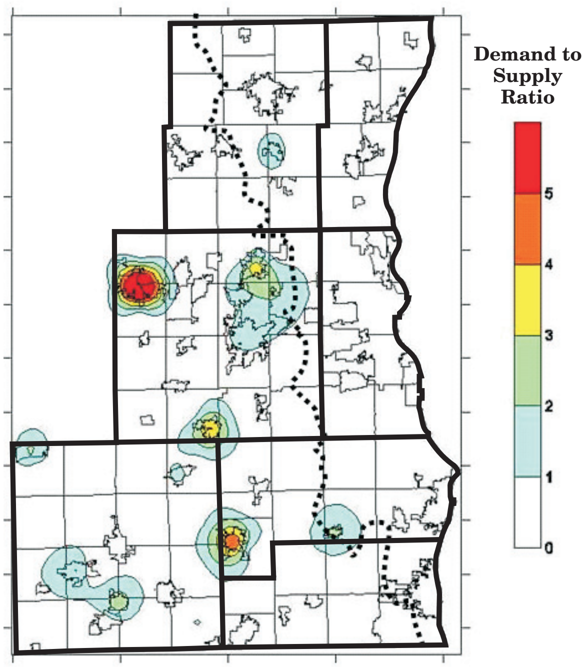


Figure 19 Baseflow Reduction Index in Shallow Aquifer in 2035: Alternative 2 (from 2005)

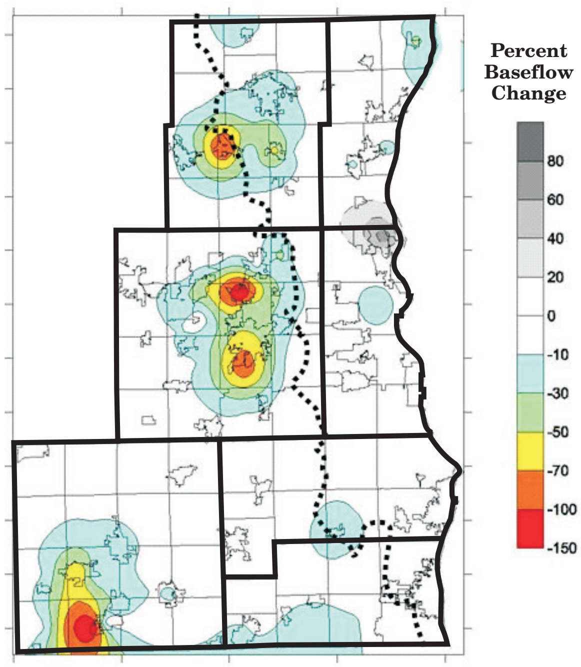


Figure 20 Change in Demand to Supply Ratio in Deep Aquifer between 2005 and 2035: Alternative 2

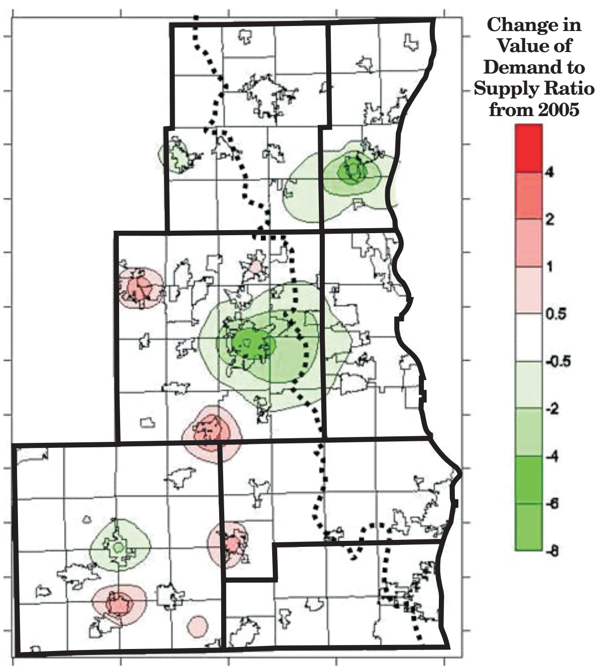
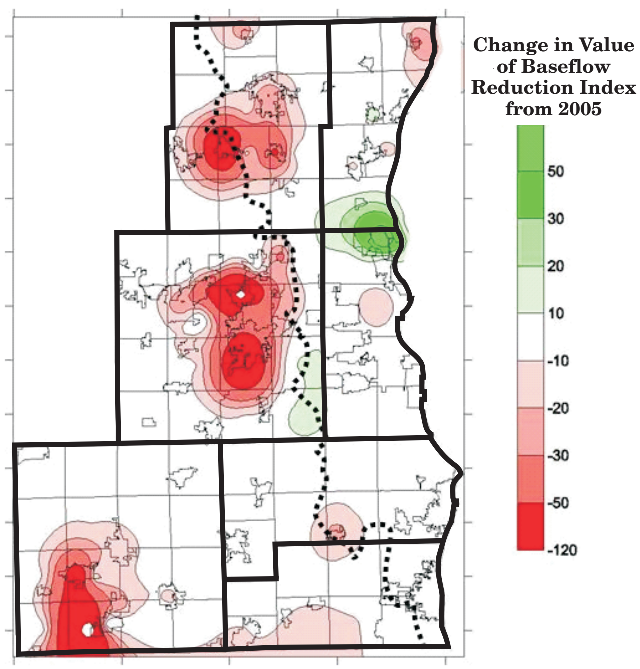


Figure 21 Change in Baseflow Reduction Index in Shallow Aquifer between 2005 and 2035: Alternative 2



The DSR of the deep aquifer is reduced markedly from Alternative 1, as the red and orange areas in Figure 12 (DSR greater than 4) from Waukesha through Germantown to Cedarburg disappear (Figure 18). The reduced pumping greatly improves the deep aquifer's water balance. In contrast, this alternative moves a considerable amount of pumping into the shallow aquifer. Comparison of Figures 13 and 19 shows much larger baseflow reductions in Alternative 2 around Pewaukee and Waukesha, and smaller ones at Delavan and Cedarburg.

When the changes in DSR and BRI are considered (Figures 20 and 21), the same pattern emerges. The DSR of the deep aquifer is reduced (green color) in Cedarburg, Germantown, Brookfield, Elm Grove, Waukesha, New Berlin, Hartford and Elkhorn. This is a much improved distribution of change than in Alternative 1 (Figure 14). However, the additional extraction from the shallow aquifer produces much larger and more intense baseflow reductions (reds) in central Waukesha County, and mappable increases around Elkhorn (Figure 21). The changes in Alternative 2 improve impacts in the deep aquifer and worsen them in the shallow aquifer. Under this Alternative, water levels in the deep aquifer (Figure 22) rise (drawup) notably. The prominent cone of depression seen under Alternative 1 (Figure 17) has been reduced to the point where only a slight depression in the potentiometric surface remains in north-central Waukesha County (Figure 23).

Figure 22 Simulated drawup in upper sandstone (deep) aquifer between 2005 and 2035: Alternative 2

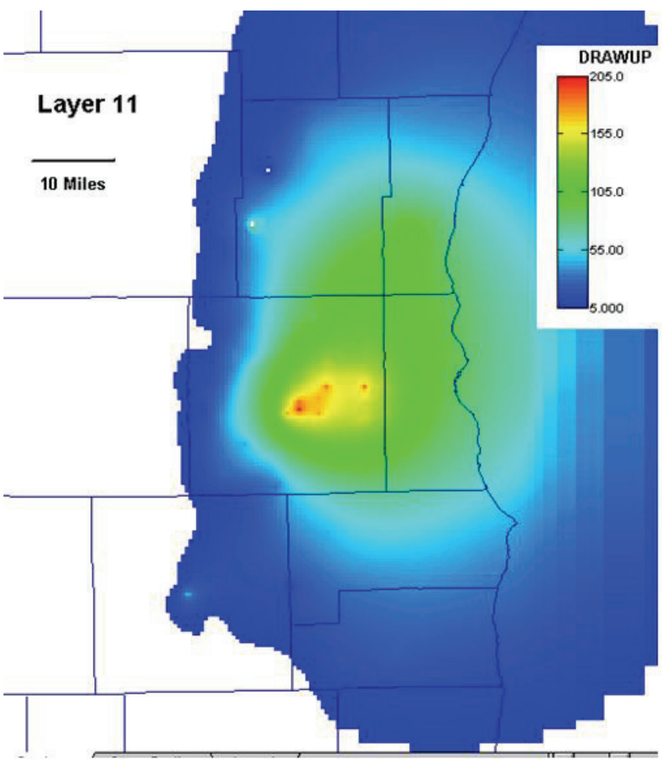
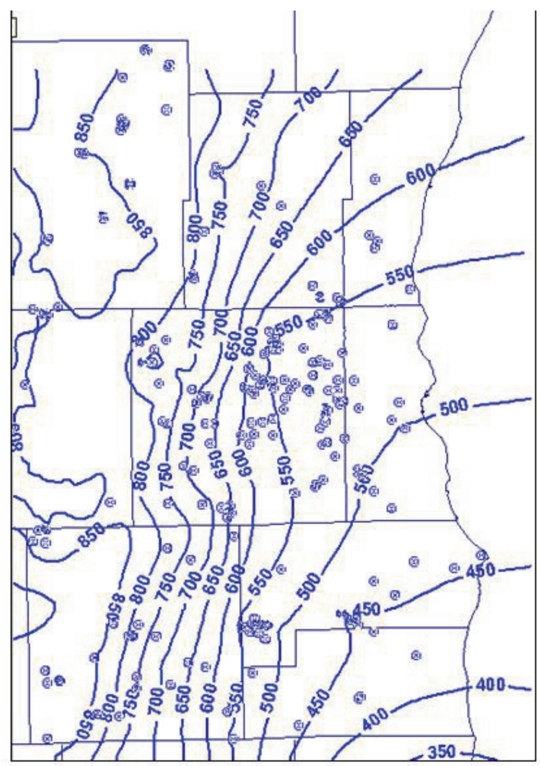


Figure 23 Simulated 2035 potentiometric surface (NGVD29) in the upper sandstone (deep) aquifer: Alternative 2



Both figures from Feinstein (2008)

At the county scale, in the deep aquifer, Ozaukee and Waukesha Counties show large drops in DSR, due to parallel drops in extraction (Table 5). Ozaukee drops well below the target value of 1.0, but no other county makes such a shift. Similarly, because of the elimination of the last remaining major user of the deep aquifer (Cedarburg), Ozaukee County moves inside the goal of -0.3 for HIR. Racine and Walworth Counties are simulated with increased pumping from the deep aquifer, so both show poorer DSR and HIR indices. Overall, the region's DSR in the deep aquifer drops 26 percent from 2005 (Table 5), paralleling the decline in pumping.

The 46.5 percent increase in net pumping from the shallow aquifer increases that aquifer's DSR 49 percent and makes the HIR 48 percent more negative (Table 6). More tellingly, however, the additional extraction reduces baseflow in Waukesha, Ozaukee and Kenosha Counties from Alternative 1 (compare Tables 4 and 6). Regionally, the reduction in these three counties is almost balanced by gains in Milwaukee and Racine Counties (Table 6). This is at least partly due to large pumping increases being in Kenosha and Ozaukee Counties, where clay-rich glacial tills constrain the ground-water effect on baseflows by partially confining the shallow aquifer.

Table 5 Projected Future Values for Pumping, DSR and HIR in Deep Aquifer – Alternative 2

County	Net Pumping (mgd)			Demand to Supply Ratio			Human Impact Ratio	
	2005	2035		2005	2035		2005	2035
Kenosha	0.17	0.09		0.101	0.057		-0.041	-0.020
Milwaukee	0.89	0.58		0.567	0.369		-0.197	-0.225
Ozaukee	0.86	0.01		1.040	0.017		-0.317	-0.008
Racine	3.30	3.86		1.963	2.293		-0.500	-0.563
Walworth	5.57	6.61		0.745	0.883		-0.326	-0.390
Washington	0.81	0.52		0.453	0.294		-0.191	-0.153
Waukesha	18.63	10.60		5.773	3.287		-0.881	-0.784
Region	30.22	22.28		2.379	1.754		-0.706	-0.644

Note that Waukesha County will exceed the baseflow reduction limit of 10 percent by 2041 if growth continues at the rate projected between 2005 and 2035. This is even sooner than under Alternative 1, because of the heavier demands on the shallow aquifer. In general, however, the introduction of lake water in this alternative does have positive ground-water effects in the deep aquifer. These are contrasted by only small increases in the regional scale baseflow reductions and in most counties.

Table 6 Projected Future Values for Pumping, DSR, HIR and BRI in Shallow Aquifer – Alternative 2												
County	Net Pumping (mgd)			Demand to Supply Ratio			Human Impact Ratio			Baseflow Reduction (percent)	
	2005	2035		2005	2035		2005	2035		Total from 1900 *	Future after 2005 #
Kenosha	3.06	6.10		0.047	0.094		-0.047	-0.091		-10.19	-5.35
Milwaukee	4.09	3.38		0.159	0.131		-0.150	-0.127		-17.26	+2.37
Ozaukee	7.60	8.03		0.199	0.210		-0.188	-0.204		-19.29	-0.14
Racine	4.54	5.14		0.061	0.069		-0.060	-0.068		-7.49	-0.98
Walworth	6.62	12.48		0.045	0.085		-0.044	-0.084		-13.48	-5.04
Washington	8.25	11.79		0.083	0.118		-0.081	-0.115		-13.99	-4.53
Waukesha	14.30	25.51		0.089	0.158		-0.086	-0.149		-20.95	-8.32
Region	48.45	72.43		0.081	0.121		-0.079	-0.116		-14.97	-4.76

* The first BRI (BRI_{1900}) is the change from 1900 to 2035; negative values indicate baseflow reduction.
# The second BRI (BRI_{2005}) is the change from 2005 to 2035, with same sign convention as for above.

Overall, Alternative 2 improves water levels and indicator indices in the deep aquifer relative to base conditions (Alternative 1), by replacing ground-water supplies with lake water for select communities east of the subcontinental divide. However, it produces much greater BRIs due to the simulated 7 percent increase in net pumping from the shallow aquifer. These changes don't appear at the county level (Table 6), except in Waukesha and Ozaukee Counties, because most counties contain both increases and decreases. As with Alternative 1, some new wells inserted to meet new demands could not produce the amount of water needed and had to be split. This is further evidence that the increased demands are approaching the ability of the shallow aquifer to supply them.

Alternative 3

As described above, Alternative 3 simulates the same extractive pumping distribution as Alternative 2 but adds artificial recharge in both aquifers. Consequently, it needs to be compared to both 2005 and Alternative 2 conditions. Under this alternative, the net discharge from the deep aquifer is reduced 56 percent from 2005 (30.2 to 13.3 mgd). This includes 9 mgd of artificial recharge, meaning that the net discharge is 9 mgd (40.4 percent) less than Alternative 2. The net extraction from the shallow aquifer is 20.6 percent greater than 2005 (an increase of 10 mgd, from 48.5 to 58.5 mgd). This change is a combination of 24.0 mgd additional extraction beyond 2005 (the same increase as in Alternative 2) minus 13.8 mgd of artificial recharge.

Artificial recharge is added three ways in the simulations. In the deep aquifer, 1 mgd is injected into each of nine wells (9 mgd total) located along the border between Milwaukee and Waukesha Counties. In the shallow aquifer, the bulk is added through infiltration fields near four sewage treatment plants (5 mgd at Waukesha, 4 mgd at West Bend, 1.6 mgd at Grafton, and 0.4 mgd at East Troy). These simulated infiltration areas are frequently outside the current municipality boundaries, so they may not appear on the index maps within the community for which they are named. In addition, another 2.8 mgd of artificial recharge is simulated from the collection of rainwater at 83 sites disseminated throughout the region, but generally located near headwater reaches of surface systems. The locations are shown on Map VIII-15 of the preliminary draft of the SEWRPC planning report (2009).

Figure 24 Demand to Supply Ratio in Deep Aquifer in 2035: Alternative 3

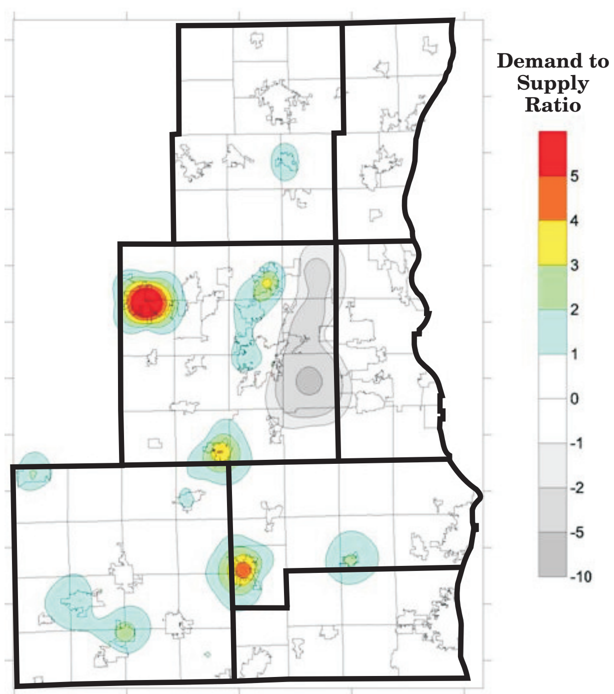
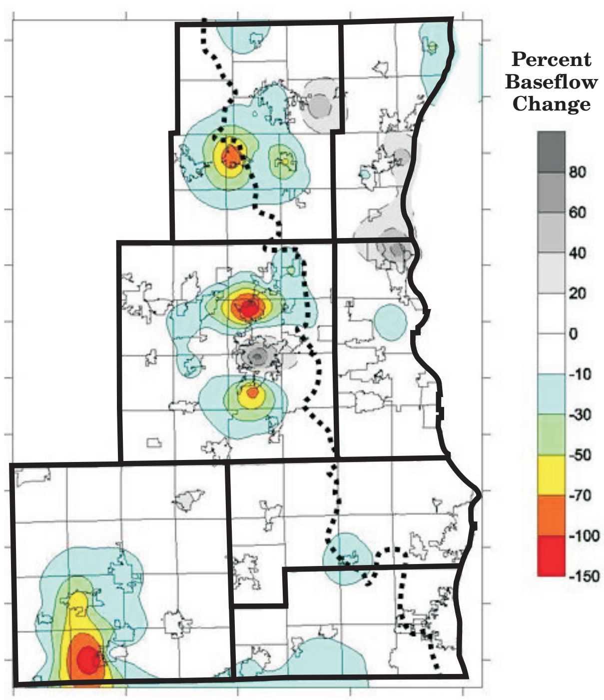


Figure 25 Baseflow Reduction Index in Shallow Aquifer in 2035: Alternative 3 (from 2005)



In the deep aquifer, the DSR is reduced markedly from both 2005 and Alternative 2. Comparison of Figures 24 and 18 shows the deep aquifer injection has reduced the area where DSR is greater than 1.0 (colors) in northeastern Waukesha County considerably from Alternative 2. The addition of injected water to the deep aquifer actually causes the DSR to go negative (gray areas on Figure 24). This indicates that the volume of injected water is larger than the amount pumped in three communities in northeastern Waukesha County. In the shallow aquifer, baseflow has actually increased from 2005 (gray color; positive BRI values) at the four effluent infiltration sites (Figure 25).

Figure 26 Change in Demand to Supply Ratio in Deep Aquifer between 2005 and 2035: Alternative 3

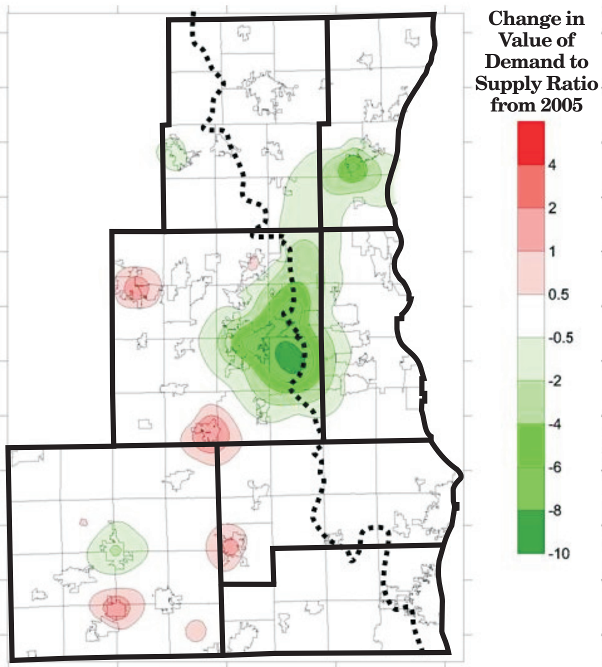
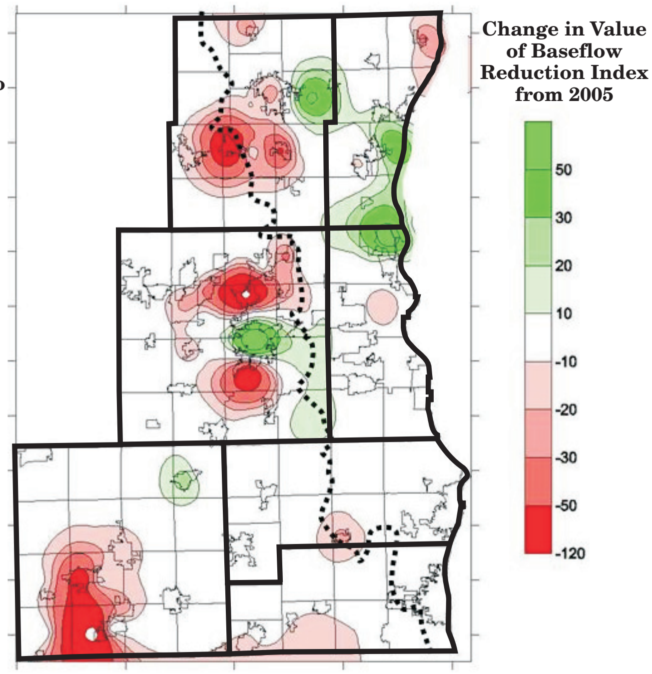


Figure 27 Change in Baseflow Reduction Index in Shallow Aquifer between 2005 and 2035: Alternative 3



The same patterns are apparent on Figures 26 and 27. In the deep aquifer, Alternative 3 has improved the ground-water budget balance (reduced, or green, DSR values) in all communities except Sussex, Oconomowoc, Mukwonago, Williams Bay, Burlington, and Genoa City/Bloomfield (Figure 26). Similarly noticeable increases in baseflow occur in Figure 27 when compared to Figure 21.

For more direct depiction of the effects of artificial recharge, Figures 28 and 29 are provided. Figure 28 shows the difference in BRI between Alternatives 2 and 3, in which case only the effects of artificial recharge are illustrated. At the contour scale used in Figure 28, all visible increases (greens) are due to the four effluent infiltration sites. When just the effects of the rainwater infiltration are plotted (Figure 29), the effects are much smaller locally than effluent infiltration (maximum gain in any community is less than 4 percent), but are widely dispersed across the region. This shows that artificial recharge from rain infiltration can increase both recharge and baseflow across wide areas. The total simulated infiltration of 2.8 mgd is an upper limit on the effect; if more were used for artificial recharge, the effect would be greater. Overcoming local effects of large pumping centers would require infiltration of a like amount of water in a relatively small nearby area.

Figure 28 Difference in Total 2035 Baseflow Reduction Index between Alternative 3 and Alternative 2

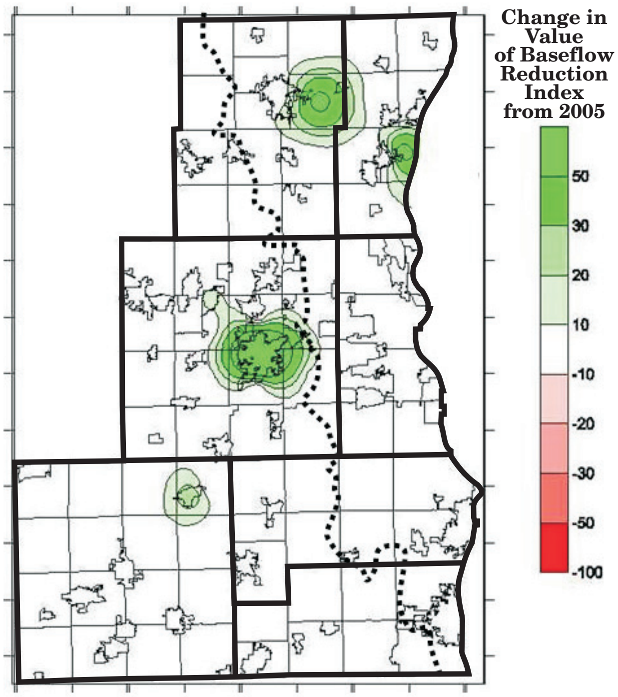
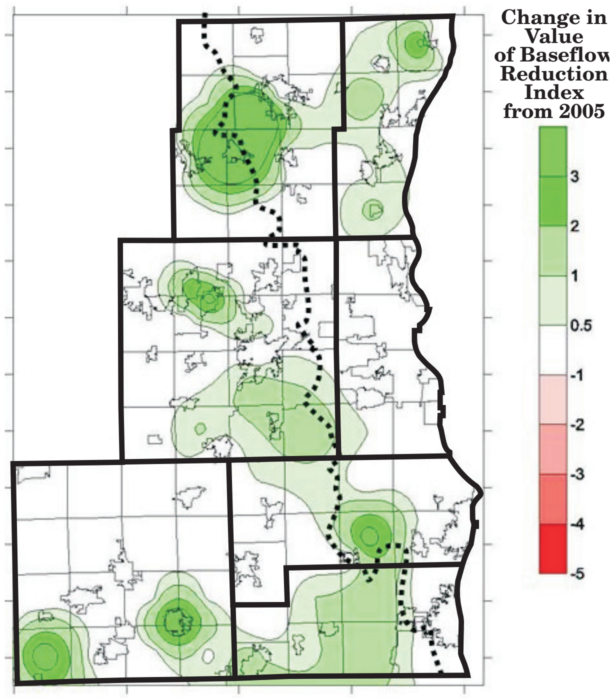


Figure 29 Change in Baseflow Reduction Index between Alternatives 3 and 2 Resulting from Rainwater Infiltration Alone



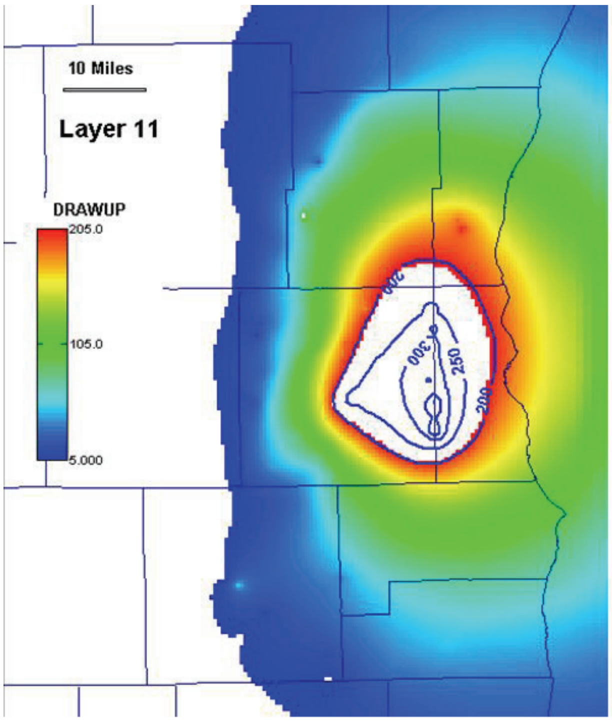
The effects of the injection wells on water levels in the deep aquifer are dramatic. Drawups exceed 350 feet in some locations (Figure 30). A tiny vestige of the cone of depression remains between Waukesha and Sussex, but largely because a ground-water ridge develops along the county line (Figure 31). The ridge has the intriguing side effect of diverting flow in the deep aquifer into a more southerly direction toward the Illinois cone of depression. Some portion of the simulated injected water would ultimately flow to Illinois.

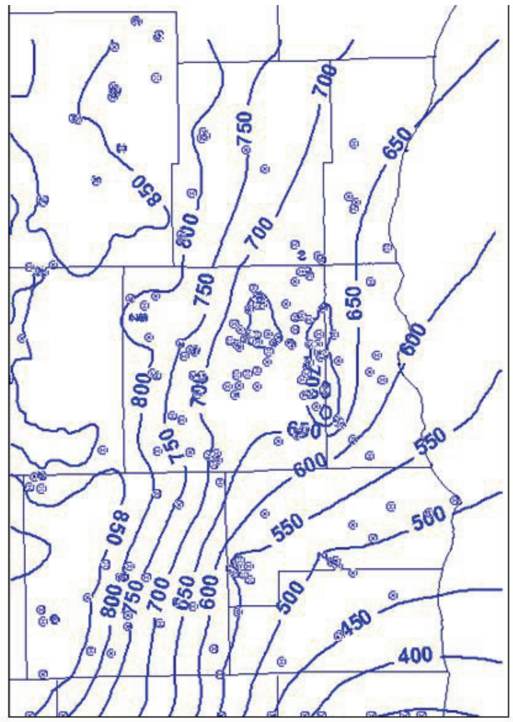
Regionally, the reduction of net pumping in the deep aquifer of 56 percent from 2005 (Table 7) causes that aquifer's DSR to drop 86 percent and HIR to become 40 percent less negative. The regional DSR has dropped to 0.344 , well below the target of 1.0, although Racine County remains well above 1.0. Racine has an HIR that remains below -0.3 (Table 7), indicating that supply sustainability issues remain.

Because of the injection wells, Waukesha County's DSR drops well below 1.0, meaning that the artificial recharge has pushed it into a sustainable situation. Although Walworth County has a DSR below 1.0, its HIR has dropped below -0.3 (Table 7). As discussed above, this is an indication that Walworth is moving toward a deep aquifer budget deficit.

Figure 30 Simulated drawup in upper sandstone (deep) aquifer between 2005 and 2035: Alternative 3

Figure 31 Simulated 2035 potentiometric surface (NGVD29) in the upper sandstone (deep) aquifer: Alternative 3





Both figures from Feinstein (2008)

Table 7 Projected Future Values for Pumping, DSR and HIR in Deep Aquifer – Alternative 3

County	Net Pumping (mgd)		Demand to Supply Ratio		Human Impact Ratio	
	2005	2035	2005	2035	2005	2035
Kenosha	0.17	0.09	0.101	0.057	-0.041	-0.016
Milwaukee	0.89	0.58	0.567	0.369	-0.197	-0.087
Ozaukee	0.86	0.01	1.040	0.017	-0.317	-0.010
Racine	3.30	3.86	1.963	2.293	-0.500	-0.437
Walworth	5.57	6.61	0.745	0.883	-0.326	-0.407
Washington	0.81	0.52	0.453	0.294	-0.191	-0.181
Waukesha	18.63	1.60	5.773	0.496	-0.881	-0.088
Region	30.22	13.29	2.379	0.337	-0.706	-0.341

When compared to Alternative 2, Alternative 3 has a net reduction of 40 percent in extraction from the deep aquifer. That causes 40 percent reduction of the DSR and HIR to become 38 percent less negative. The injection of 9 mgd into this aquifer has extremely positive effects on the quantity of water in the deep aquifer.

In the shallow aquifer, Alternative 3 simulates an increase in net pumping of 21 percent (10 mgd) from 2005 (Table 8). This causes a regional reduction in baseflow of 1.7 percent, although that decrease is not uniformly distributed. Ozaukee, Washington and Milwaukee Counties actually show an increase in baseflow from 2005, the first two resulting from the Grafton and West Bend effluent infiltration sites and the third from the conversion of parts of Franklin to lake water. Waukesha County's total baseflow reduction is also limited to only 3.0 percent by the Waukesha effluent site. There are other nearby areas (notable Pewaukee and the Town of Waukesha on Figure 27) that continue to have local baseflow reductions exceeding -50 percent.

Comparison of Tables 8 and 6 (Alternatives 3 and 2) confirms what can be seen in Figures 28 and 29. The artificial recharge in Alternative 3 mostly increases countywide baseflow in Waukesha, Washington and Ozaukee Counties (+5.3 percent, +5.7 percent and +6.9 percent, respectively), where the largest effluent infiltration sites are simulated. All other counties also have baseflow increases in response to the artificial recharge measures (Walworth, +1.0 percent; Kenosha, +0.7 percent; Milwaukee, +0.7 percent; and Racine, +0.5 percent).

Table 8 Projected Future Values for Pumping, DSR, HIR and BRI in Shallow Aquifer – Alternative 3

County	Net Pumping (mgd)		Demand to Supply Ratio		Human Impact Ratio		Baseflow Reduction (percent)	
	2005	2035	2005	2035	2005	2035	Total from 1900 *	Future after 2005 #
Kenosha	3.06	5.66	0.047	0.087	-0.047	-0.084	-9.51	-4.63
Milwaukee	4.09	3.38	0.159	0.131	-0.150	-0.127	-16.72	+3.04
Ozaukee	7.60	5.89	0.199	0.154	-0.188	-0.142	-13.68	+6.80
Racine	4.54	4.80	0.061	0.064	-0.060	-0.063	-7.03	-0.49
Walworth	6.62	11.58	0.045	0.079	-0.044	-0.077	-12.58	-4.05
Washington	8.25	7.25	0.083	0.073	-0.081	-0.068	-8.83	+1.21
Waukesha	14.30	19.94	0.089	0.123	-0.086	-0.114	-16.38	-3.02
Region	48.45	58.50	0.081	0.075	-0.079	-0.092	-12.20	-1.67

* The first BRI (BRI_{1900}) is the change from 1900 to 2035; negative values indicate baseflow reduction.
# The second BRI (BRI_{2005}) is the change from 2005 to 2035, with same sign convention as for above.

The increased net pumping in the shallow aquifer produces similar magnitudes of worsened DSR and HIR (21 percent and 18 percent, respectively) from 2005 (Table 8). The increase of net discharge from 2005 is largely due to changes already existent in Alternative 2, upon which Alternative 3 is built. When Alternatives 3 and 2 are compared directly, the net pumping in the shallow aquifer is reduced 19 percent by the artificial recharge. This causes the aquifer's DSR to be reduced by 19 percent and its HIR to get 21 percent better (less negative).

Alternative 3 demonstrates that artificial recharge can have major positive impacts on ground-water budgets. In the deep aquifer, injection of 9 mgd can largely eliminate the drawdowns resulting from historical overextraction from the aquifer. However, such injection is not currently allowed under Wisconsin regulations. Because of the current regulations, it is likely that significant pilot testing would be required prior to implementing a deep aquifer injection system. The water quality issues associated with Alternative 3 are described in greater detail in the regional water supply plan report now under preparation. In addition, a portion of the water, while injected at a location east of the subcontinental divide, would—at least for a time until the aquifer were fully recharged—travel westward beneath the subcontinental divide. This issue may have to be addressed in the context of the rules governing the Great Lakes Compact.

In the shallow aquifer, artificial recharge reduces net baseflow reduction and can even reverse historical losses of ground-water derived baseflow. All counties show an increase in baseflow relative to both Alternatives 1 and 2 (less negative, or more positive, values of both BRI_{1900} and BRI_{2005}). Only four counties have a cumulative baseflow reduction (BRI_{1900}) exceeding -10 percent (down from five and six for Alternatives 1 and 2, respectively). The infiltration of treated effluent has larger effects in Alternative 3 than those of rainwater, because larger amounts are simulated. The effects of both activities are also largely localized. Finally, Waukesha County would never reach the point where the post-2005 baseflow reductions exceeded -10 percent under this Alternative, because its baseflow actually increases from 2005.

Alternative 4

Like Alternative 3, this one builds on Alternative 2. In this scenario, however, 28 mgd of additional lake water is delivered to select straddling communities and some in Waukesha County that lie outside the Great Lakes watershed. Net pumping in the deep aquifer is reduced from 2005 by 46 percent (30.2 to 16.3 mgd), by providing sufficient lake water to supply all the projected needs of Brookfield, Menomonee Falls, Pewaukee, Sussex, Union Grove and Waukesha. Additional lake water will be delivered to replace the shallow aquifer use of Saukville, Cedarburg, Grafton, Fredonia, within the Great Lakes watershed; and Lisbon and Lannon, outside the watershed. Other users of the shallow aquifer, farther away from lake sources, will continue to have to increase their extraction from that source, in the same amounts as in Alternative 2. As a consequence, net extraction from the shallow aquifer is actually increased 4.1 percent from 2005 (48.5 to 50.4 mgd).

When compared to Alternative 2, Alternative 4 decreases stress on the deep aquifer by

26.8 percent (22.3 to 16.3 mgd) and on the shallow aquifer by 30.4 percent (72.4 to 50.4 mgd). So the bulk of the new lake water (22 mgd) is being used to reduce stress on the shallow aquifer relative to Alternative 2, while the remaining 6 mgd relieves the deep aquifer. In comparison to Alternative 3, Alternative 4 increases the net pumping from the deep aquifer 22.6 percent (13.3 to 16.3 mgd), while reducing that from the shallow aquifer by 13.8 percent (58.5 to 50.4 mgd).

Figure 32 Demand to Supply Ratio in Deep Aquifer in 2035: Alternative 4

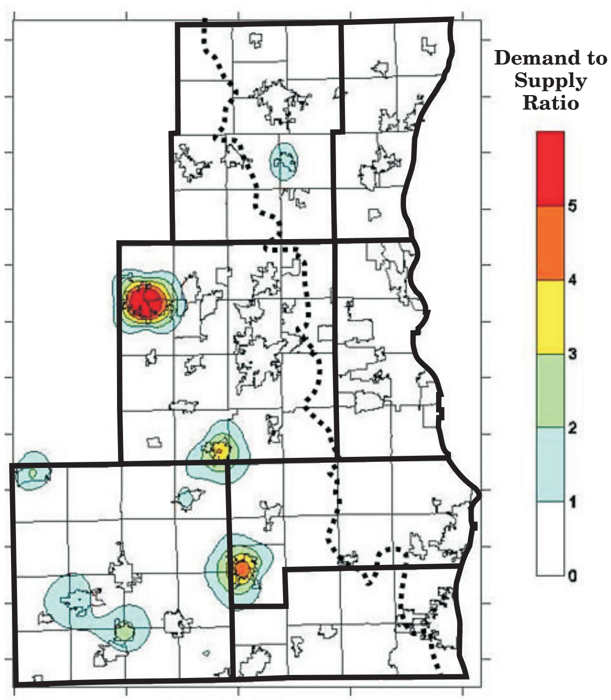


Figure 33 Baseflow Reduction Index in Shallow Aquifer in 2035: Alternative 4

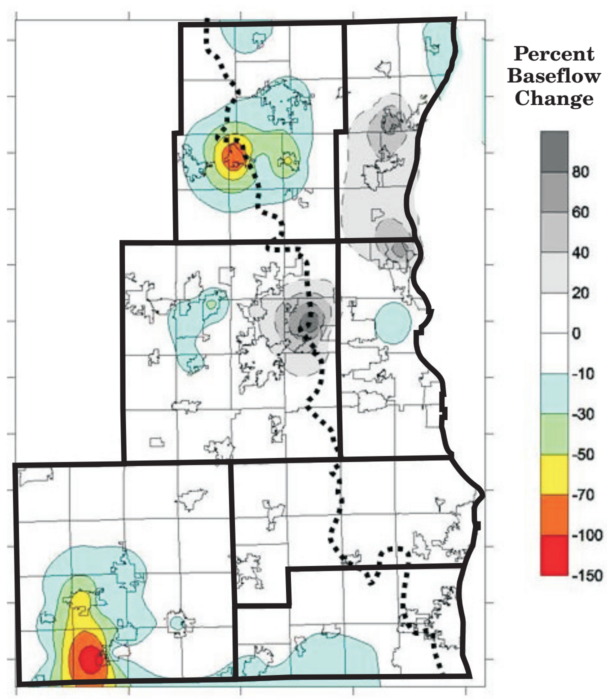


Figure 34 Change in Demand to Supply Ratio in Deep Aquifer between 2005 and 2035: Alternative 4

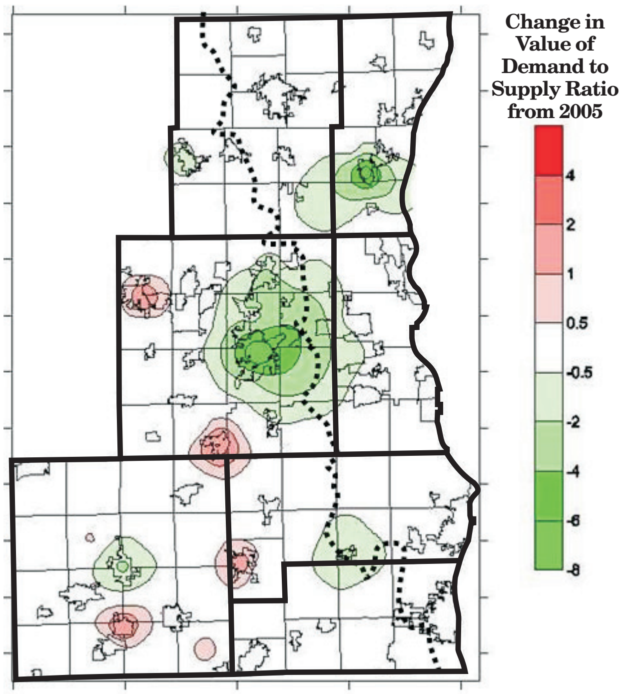
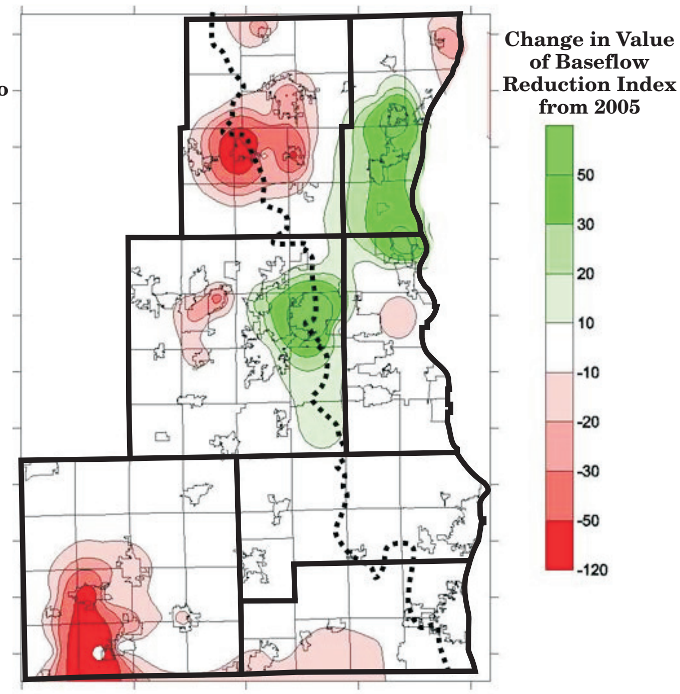


Figure 35 Change in Baseflow Reduction Index in Shallow Aquifer between 2005 and 2035: Alternative 4



As with Alternative 3, the effect of Alternative 4 is to greatly reduce the areas in the deep aquifer in budget deficit from both 2005 and Alternative 2 conditions. Only Oconomowoc, Mukwonago and Burlington continue to have DSRs greater than 4 (Figure 32). Within the shallow aquifer, baseflows (Figure 33) are greatly improved (BRIs become less negative) over 2005 (Figure 9) and Alternative 2 (Figure 19) in the parts of Racine, Ozaukee and Waukesha Counties getting lake water. In the latter two counties, baseflows actually increase from those in 2005 (gray zones in Figure 33).

Figure 34 shows primarily improvement (greens) in the DSR of the deep aquifer relative to 2005. Baseflows are increased where lake water is provided to shallow aquifer users in Ozaukee and Waukesha Counties (Figure 35). Outside the lake delivery area, in Walworth, Washington and western Waukesha counties, the changes in baseflow reductions (Figure 35) remain essentially the same as they are in Alternatives 2 and 3 (Figures 21 and 27, respectively).

Heads in the deep aquifer rise under Alternative 4 (Figure 36), but less so than in Alternative 3 (Figure 30), because of the absence of injection. The regional cone of depression has been eliminated (Figure 37). Without the injection wells of Alternative 3, the ground-water ridge along the Waukesha/Milwaukee county line (Figure 23) is absent, but water in this aquifer will still flow toward the Illinois cone of depression in 2035.

Figure 36 Simulated drawup in upper sandstone (deep) aquifer between 2005 and 2035: Alternative 4

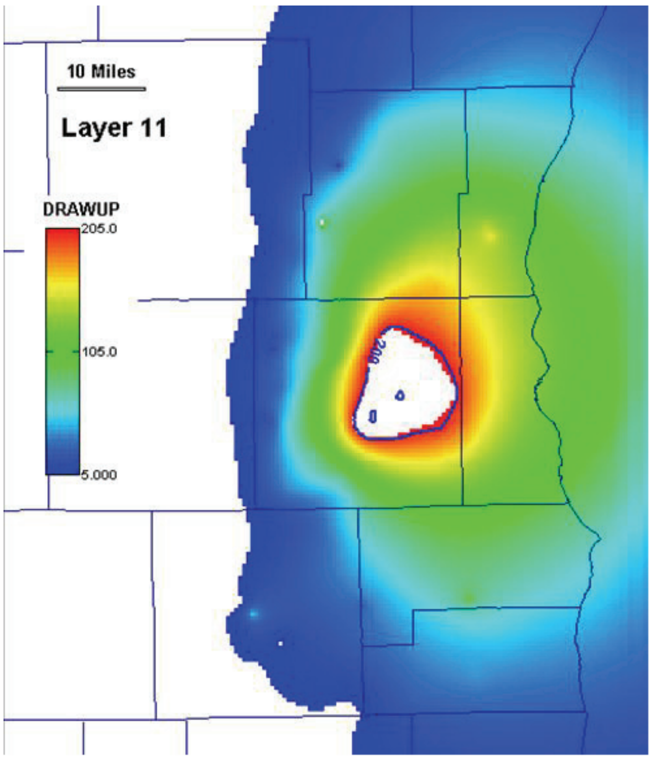
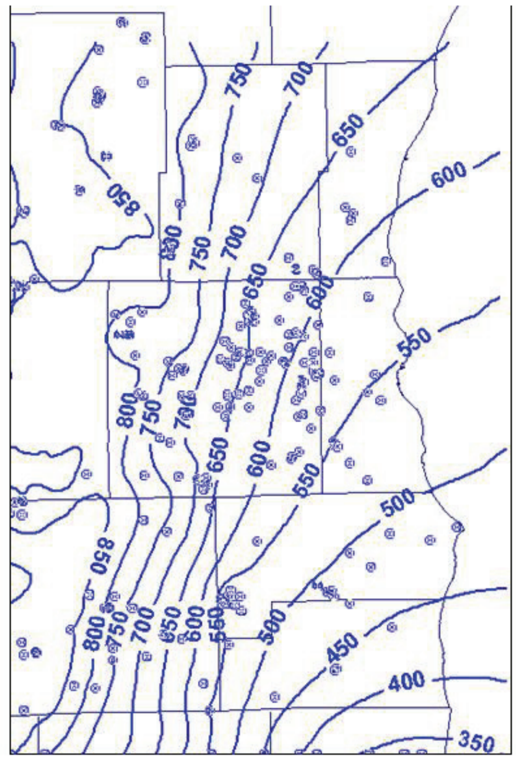


Figure 37 Simulated 2035 potentiometric surface (NGVD29) in the upper sandstone (deep) aquifer: Alternative 4



Both figures from Feinstein (2008)

At the county scale, DSRs in the deep aquifer drop dramatically from 2005 in Ozaukee and Waukesha Counties, the ones getting substantial lake water (Table 9). With no major users of the deep aquifer remaining in Ozaukee County, the DSR is nearly 0. Kenosha, Milwaukee and Washington Counties show modest DSR reductions as their pumping is decreased. Racine has almost no change, while DSR in Walworth County increases because net pumping does (Table 9). Parallel effects are apparent in HIR. If Alternative 4 were implemented, only Racine and Waukesha Counties would lie outside the management targets in both indices. Walworth would exceed that for HIR, but not DSR, indicating it is moving toward undesirable conditions.

Table 9 Projected Future Values for Pumping, DSR and HIR in Deep Aquifer – Alternative 4									
County	Net Pumping (mgd)			Demand to Supply Ratio			Human Impact Ratio	
	2005	2035		2005	2035		2005	2035
Kenosha	0.17	0.09		0.101	0.057		-0.041	-0.018
Milwaukee	0.89	0.58		0.567	0.369		-0.197	-0.142
Ozaukee	0.86	0.01		1.040	0.017		-0.317	-0.008
Racine	3.30	3.25		1.963	1.932		-0.500	-0.441
Walworth	5.57	6.61		0.745	0.883		-0.326	-0.400
Washington	0.81	0.52		0.453	0.294		-0.191	-0.174
Waukesha	18.63	5.24		5.773	1.626		-0.881	-0.494
Region	30.22	16.32		2.379	1.285		-0.706	-0.524

When compared to Alternative 2 in the deep aquifer, Alternative 4 has a regional reduction of 27 percent in net pumping. That causes reductions of 27 percent in the aquifer's DSR and an improvement (becoming less negative) of 13 percent in HIR. Relative to 2005, the 40 percent reduction of net extraction causes a 40 percent reduction of regional DSR and an HIR improvement of 17 percent (Table 9).

Table 10 Projected Future Values for Pumping, DSR, HIR and BRI in Shallow Aquifer – Alternative 4											
County	Net Pumping (mgd)			Demand to Supply Ratio			Human Impact Ratio			Baseflow Reduction (percent)	
	2005	2035		2005	2035		2005	2035		Total from 1900 *	Future after 2005 #
Kenosha	3.06	6.91		0.047	0.094		-0.047	-0.091		-10.16	-5.32
Milwaukee	4.09	3.38		0.159	0.131		-0.150	-0.127		-16.94	+2.76
Ozaukee	7.60	1.79		0.199	0.047		-0.188	-0.046		-6.53	+15.64
Racine	4.54	4.69		0.061	0.063		-0.060	-0.062		-7.05	-0.51
Walworth	6.62	12.48		0.045	0.085		-0.044	-0.084		-13.32	-4.87
Washington	8.25	11.79		0.083	0.118		-0.081	-0.115		-13.46	-3.94
Waukesha	14.30	10.20		0.089	0.063		-0.086	-0.063		-10.48	+3.82
Region	48.45	50.44		0.081	0.084		-0.079	-0.082		-11.16	-0.49

* The first BRI (BRI_{1900}) is the change from 1900 to 2035; negative values indicate baseflow reduction.
# The second BRI (BRI_{2005}) is the change from 2005 to 2035, with same sign convention as for above.

In the shallow aquifer, Alternative 4 simulates a 4 percent increase in net pumping (2 mgd) from 2005. Baseflow reductions between 2005 and 2035 for the region, however, are reduced to less than 0.5 percent (Table 10). This is because many of the big users receiving lake water previously caused major baseflow reductions, often because of high capacity wells located near surface water bodies. In Ozaukee and Waukesha Counties, for example, delivery of lake water causes baseflows to increase significantly compared to 2005 (positive values of BRI_{2005} in Table 10). Ozaukee County actually has its cumulative baseflow reduction (BRI_{1900}) drop below 10 percent, while Waukesha County closely approaches that goal. The entire region ends up with a BRI_{1900} of -11 percent.

On the regional scale, the 4 percent increase in net pumping from 2005 causes parallel changes in the regional DSR (+4 percent) and HIR (5 percent more negative) in the shallow aquifer (Table 10). When compared to Alternative 2, Alternative 4 has a reduction of 30 percent in net pumping and improvements of 31 and 29 percent in DSR and HIR, respectively (Tables 6 and 10).

This alternative demonstrates that replacing deep aquifer water with lake water for the largest users at or near the subcontinental divide can have positive effects on that aquifer, both locally and regionally. Heads increase and both the DSR and HIR show movement toward more balanced ground-water budgets. The effects are not quite as positive as those simulated under Alternative 3, however.

The effects of lake water delivery are also considerable in the shallow aquifer. Areas getting lake water show baseflow increases relative to both 2005 and Alternative 1. Cumulative baseflow reductions (BRI_{1900}) are reduced from Alternative 1 in all counties except Kenosha, and particularly in Ozaukee and Waukesha. Because many large users of the shallow aquifer were taken off ground water in this simulation, baseflows increase notably in Ozaukee and Waukesha Counties between 2005 and 2035 relative to Alternative 3.

It must be noted, however, that the diversion of lake water to communities west of the divide will require return of treated wastewater to the Great Lakes watershed. The impacts of that return will need to be identified and weighed. They have not been presented here because they are beyond the scope of this report.

Comparison of Alternative Plans

Alternative 1: This unmanaged approach would make conditions worse in both aquifers. Drawdowns increase in the deep aquifer, with parallel increases in DSR, which indicate that the system is moving farther out of balance (Table 11). Declining water levels will also increase pumping costs and increase the dewatering of the upper portions of the deep aquifer, increasing the potential for arsenic contamination.

In the shallow aquifer, Alternative 1 causes a decrease in baseflow beyond that already in existence in 2005. SEWRPC has identified 100 target sites at which to assess changes in baseflow for each alternative. The frequency distribution of the changes from 2005 is shown in Figure 38. For Alternative 1, the distribution is strongly skewed toward baseflow losses; 81 percent of the sites show decreases in baseflow since 2005.

Simulation of this alternative demonstrates quite clearly that continued unmanaged exploitation of the region's ground water will lead to undesirable results in the ground water system. The entire region has a cumulative baseflow reduction (since 1900) of 14.9 percent, and Waukesha County's baseflow reduction post 2005 will exceed 10 percent by 2043. In addition, many of the new wells added to the model to meet the increased demands for water in this aquifer couldn't produce sufficient water and had to be split into multiple sites. This indicates that the increased demands projected may be approaching the limits of aquifer productivity in some areas.

Table 11 Comparison of regional pumping and water budget indices among alternatives

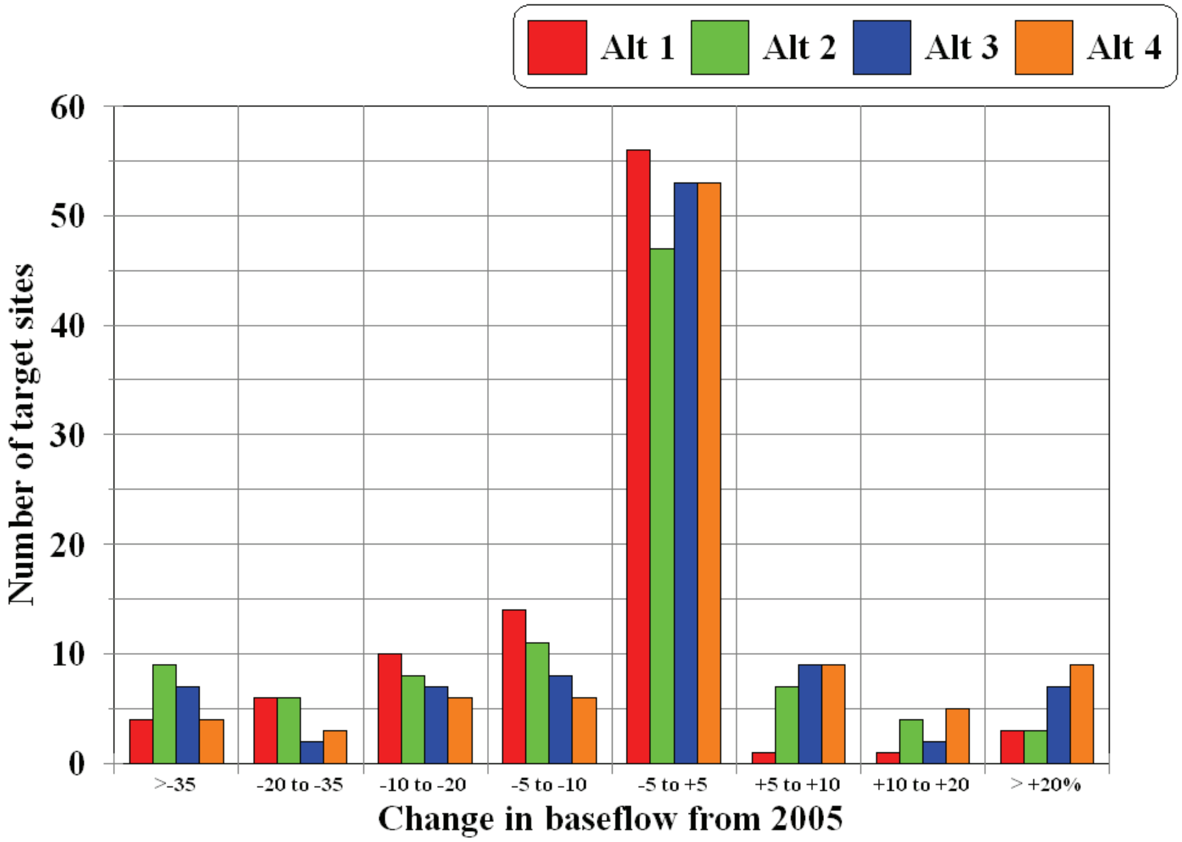
Deep Aquifer	Pumping (mgd)	DSR	HIR	BRI_{2005}	BRI_{1900}
2005	30.22	2.38	-0.706	na	na
Alternative 1	38.98	3.07	-0.810	na	na
Alternative 2	22.28	1.75	-0.644	na	na
Alternative 3	13.29	0.34	-0.341	na	na
Alternative 4	16.32	1.29	-0.524	na	na
Shallow Aquifer	Pumping (mgd)	DSR	HIR	BRI_{2005}	BRI_{1900}
2005	48.45	0.081	-0.079	0	-10.72
Alternative 1	67.67	0.113	-0.109	-4.66	-14.87
Alternative 2	72.43	0.121	-0.116	-4.67	-14.97
Alternative 3	58.50	0.075	-0.093	-1.67	-12.20
Alternative 4	50.44	0.084	-0.082	-0.49	-11.16

na indicates not applicable.

Alternative 2: This scenario examines the effects of relatively minimal management focused on reducing impacts in the deep aquifer. Lake water is delivered to some ground-water using communities east of the subcontinental divide and to some communities that straddle it, and there is an additional shift of some extraction from the deep to the shallow aquifer. Both moves improve the DSR and HIR of the deep and also allow its water levels to rise noticeably. However, the impacts on the shallow aquifer get worse than those in Alternative 1. On a regional scale (Table 11) the BRI_{2005} remains the same as for Alternative 1, but this is misleading. It occurs because baseflow gains in areas receiving lake water balance losses where the shallow aquifer is used more heavily (as can be seen in Figure 21, for example). Waukesha County will actually see BRI_{2005} drop below -10 percent sooner (2041) than under Alternative 1. Figure 38 shows there is a shift to more frequent large losses (below -35 percent) and low to intermediate gains (between 0 and +20 percent) relative to Alternative 1. In fact, six counties have cumulative baseflow reductions (BRI_{1900}) which are worse than -10 percent, as opposed to only five in Alternative 1.

Overall, however, the net impact of some management of ground water under Alternative 2 is not very different from the results of no management at all (Alternative 1). To decide whether this alternative has any real value, one would have to weigh the relative merits of

Figure 38 Frequency distribution of changes in baseflow from 2005 at selected target sites on streams
(modified from Feinstein, 2008)



increasing water levels in the deep aquifer against large local baseflow reductions in the shallow aquifer, especially around Pewaukee and Waukesha. These decreases will be felt mostly in springs, wetlands and small streams in the short term and via alteration of lake water budgets over longer times.

Alternative 3: This approach tests the effects of using artificial recharge to partly replenish both aquifers while they are simultaneously being pumped at the same rates as in Alternative 2. Injections of 9 mgd of treated Lake Michigan water into the deep aquifer has huge positive effects: water levels rise between 200 and 350 feet; the DSR drops 81 percent; and HIR shows an improvement of 38 percent. The aquifer ends up with no ground-water budget deficit (DSRgreater than 1.0 in Table 11), the only alternative to accomplish this. However, the injected water would require variances from current state policies to be allowed. In addition, some of the injected water would flow westward under the subcontinental divide (Figure 31, thereby becoming what could be interpreted as a diversion from the Great Lakes. Consequently, that amount of water would need to be quantified and then returned to Lake Michigan. This could lead to impacts associated with the return, which are not ground water impacts and therefore not assessed in this report.

Both rainwater (2.8 mgd) and treated wastewater effluent (11 mgd) are simulated as artificial recharge to the shallow aquifer, providing augmented inflow and notable reuse of water. The artificial recharge reduces the post-2005 baseflow reductions by 64 percent. Compared to Alternative 2, artificial recharge in the shallow aquifer decreases the number of target sites where baseflow is reduced and greatly increases the number where it rises (Figure 38). Alternative 2 has 34 targets with baseflow decreases greater than 5 percent and 14 with increases exceeding 5 percent, while Alternative 3 shows 24 and 18 with decreases and increases exceeding 5 percent, respectively. Alternative 3 includes just four effluent return sites, where there will be major, but local, baseflow increases. If effluent return were used at more sites, the positive impact on water quantity in the shallow aquifer would be greater.

Alternative 4: This alternative greatly improves conditions within the deep aquifer, although not as much as Alternative 3. Drawups from 2005 are up to 200 feet, and the reductions of DSR and HIR, relative to Alternative 2, are 27 percent and 13 percent, respectively, both smaller than those of Alternative 3.

In the shallow aquifer, net pumping is reduced more from 2005 than in Alternative 3, so baseflows are reduced less. The post 2000 baseflow reduction (BRI_{2005}) is only -0.5 percent, compared to -1.7 percent in Alternative 3 and -4.7 percent in Alternative 2 (Table 11). The change is largely the result of actions in Ozaukee and Waukesha Counties, where baseflows actually increase after 2005, while the other counties show a baseflow reduction relative to Alternative 3.

Alternative 4 also increases the number of target cells where post 2000 baseflow increases to 42 from 23 in Alternative 2 (Figure 38). The targets that continue to have baseflow reduction go down an equal amount, from 72 in Alternative 2 to 53 in Alternative 4. Both changes are greater than in Alternative 3 (Figure 38).

Alternative 4 uses a direct diversion of water from the Great Lakes to replace some of the stress on ground-water systems. Under the Great Lakes Compact, that diversion will require approval of the other Great Lakes states, as well as return of treated effluent to Lake Michigan. Under the preliminary recommended water supply plan, consideration is given to both direct return all the way to Lake Michigan and indirect return by discharge to tributaries to the Lake. The return flow and any impacts associated with it are surface water phenomena, which are not addressed in this report.

Composite Plan

Based on the results presented above, management Alternatives 2 through 4 all show improvements in the ground-water budgets in some areas, but not in others. Continued trends management, however (Alternative 1), has almost universally negative impacts on the region's ground-water resources.

A logical outgrowth of this analysis has been to develop a preferred, composite management plan, one that combines the strengths of individual alternatives to produce a better end result. The details of the plan developed by SEWRPC are presented in Chapter IX of SEWRPC (2008). It includes these primary components:

1. In ground-water using areas east of the subcontinental divide, extend Lake Michigan supply to the City of Cedarburg, the Villages of Elm Grove, Grafton and Saukville, as well as the parts of the straddling communities of the Cities of Brookfield and Muskego, the Village of Germantown and the Town of Yorkville that lie east of the divide.

2. Provide Lake Michigan water to the parts of the Cities of New Berlin and Muskego that are served by the Milwaukee Metropolitan Sewerage District, but which lie west of the subcontinental divide.

3. Water efficiency and conservation programs to include measures to be developed on a utility-specific basis.

4. Encourage new municipal supply wells in the shallow aquifer to be located so as to minimize baseflow reduction, with preference given to sites along the rivers that receive treated effluent, which will balance or overcome baseflow reduction.

5. Enhance recharge to the shallow aquifer by collecting rainwater and allowing it to infiltrate where practical and where it would mitigate baseflow reductions in nearby surface water bodies.

The composite plan also contains two options for the City of Waukesha: 1. continued reliance on ground water as its sole source, but with a shift of much of the pumping (2.6 mgd) to the shallow aquifer, or 2. provision of 9.8 mgd of lake water to completely replace ground water. Under the latter option, the return of the diverted water to the Great Lakes watershed is required. Two alternatives for the return have been proposed: 1. a direct pipeline from Waukesha to Lake Michigan, or 2. discharge of the return to tributary streams. Underwood Creek and the Root River have been proposed as possible receiving bodies.

The composite plan also proposes an analysis plan for the siting of high capacity wells in the shallow aquifer, which assesses impacts to surface waters and other wells. It further recommends development of a mitigation plan with enhanced recharge and modified pumping plans if the impacts are deemed undesirable. Because of the coarseness of the regional ground water model's grid, this proactive process cannot be fully incorporated into the simulations, however.

Option 1- Community Scale

Under this option, the City of Waukesha remains on ground water, but switches much of its pumping from the deep to the shallow aquifer. The simulated demand in 2035 is 5.4 mgd from the deep aquifer and 4.4 from the shallow (compared to 7.7 and 0.2 mgd from those respective aquifers in 2005).

In the deep aquifer, the DSR improves from 2005, notably in Ozaukee, Washington and Waukesha Counties (Figures 39 and 41), where pumping is reduced in the communities getting lake water (Cities of Brookfield, Cedarburg, and New Berlin, and Village of Germantown) and in communities switching pumping from the deep to the shallow aquifer (Cities of Waukesha and Hartford). There are, however, six areas where pumping, and thus DSR, increase in the deep aquifer (red areas on Figure 41). These include the Cities of Oconomowoc and Burlington, the Villages of Sussex, Mukwonago and Williams Bay, and the Town of Bloomfield and Village of Genoa City. [The latter two communities have been combined as a single entity for the development of ground water budgets and indices.]

In the shallow aquifer, the most notable situation is the gain in baseflow in Ozaukee and northern Milwaukee Counties (gray areas on Figure 40). Providing lake water to the Cities of Cedarburg and Mequon, and the Villages of Bayside, Grafton, Saukville, and Thiensville results in increases of net baseflow of over 30 percent throughout much of that area from 2005 to 2035 (Figure 40). Throughout much of the rest of the region, however, baseflows will decline under Option 1 (Figures 40 and red zones on 42) wherever pumping in the shallow aquifer is projected to increase. The largest declines (darkest reds on Figure 42) occur in the Villages of Slinger, Jackson, Pewaukee and Walworth, and the Cities of Delavan and Waukesha.

In the City of Waukesha, pumping is simulated as increasing 3.7 mgd in the shallow aquifer, consisting of a switch of 2.6 mgd from the deep and an overall increase of demand of 1.1 mgd, all of which is supplied by the shallow. This causes the DSR of the deep aquifer to improve from 8.5 to 6.0 (a decrease of 29 percent), but net baseflow within the city to decrease by over 50 percent (BRI becomes 50 percent more negative).

Water levels in the upper part of the deep aquifer will rebound notably under Option 1, (Figure 44) due to a regional decrease in pumping from the aquifer of nearly 5 mgd. Heads will continue to decline in southeastern Walworth County (Figure 43). Overall, the regional cone of depression (Figure 45) remains, but water levels are projected to increase as much as 100 feet from current conditions.

The simulations of Option 1 have shown that the ground water system can provide both the region and the City of Waukesha with a sufficient quantity of water for 2035. There will be increasing impacts in the shallow aquifer, primarily at the City of Waukesha and other areas where pumping is projected to increase by 2035. The condition of the deep aquifer will improve substantially under this option, with an appreciable rise in water levels, although the cumulative drawdown since predevelopment will remain above 150 feet in much of the region. The transfer of pumping from the deep to the shallow aquifer west of the subcontinental divide will produce

Figure 39 Demand to Supply Ratio in Deep Aquifer in 2035: Composite Plan Option 1

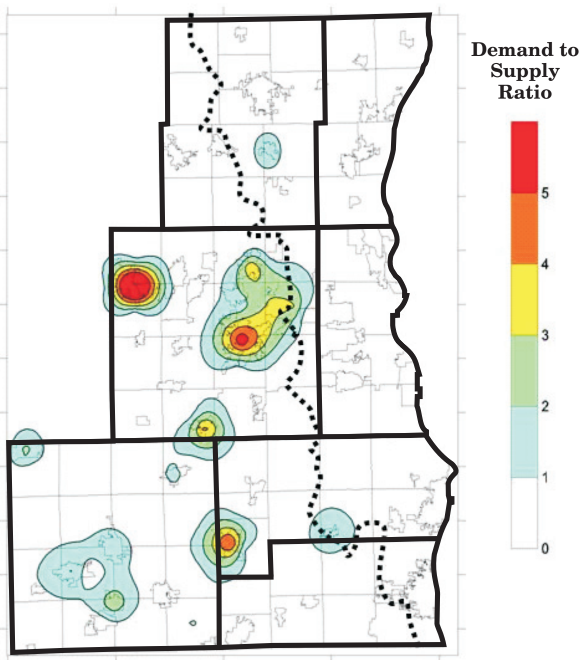


Figure 40 Baseflow Reduction Index in Shallow Aquifer in 2035: Composite Plan Option 1

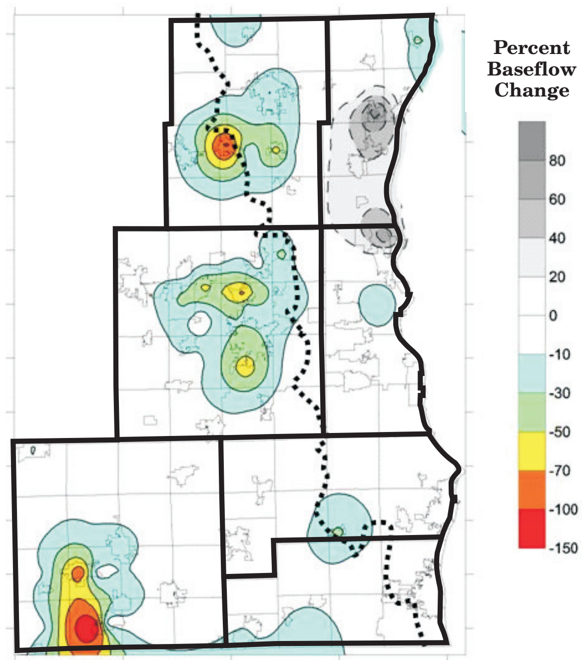


Figure 41 Change in Demand to Supply Ratio in Deep Aquifer from 2005 to 2035 Composite Plan Option 1

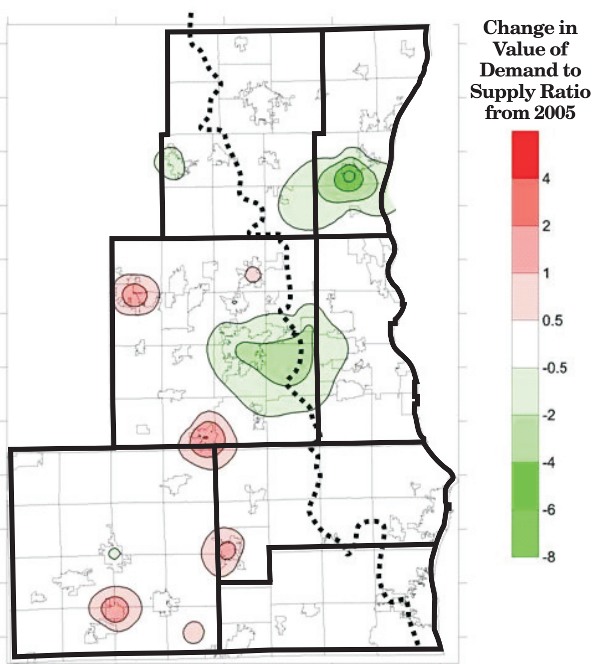


Figure 42 Change in Baseflow Reduction Index in Shallow Aquifer from 2005 to 2035 Composite Plan Option 1

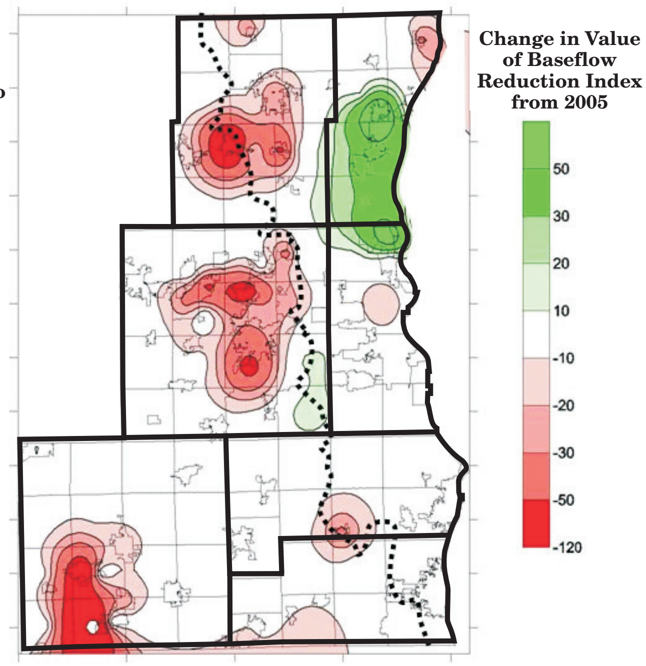


Figure 43 Simulated Drawdown in Upper Sandstone (deep) Aquifer from 2005 to 2035: Composite Plan Option 1

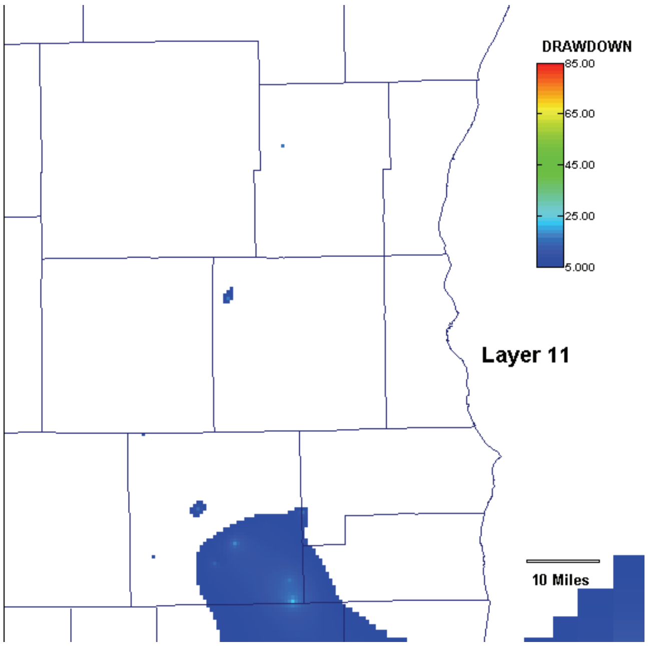
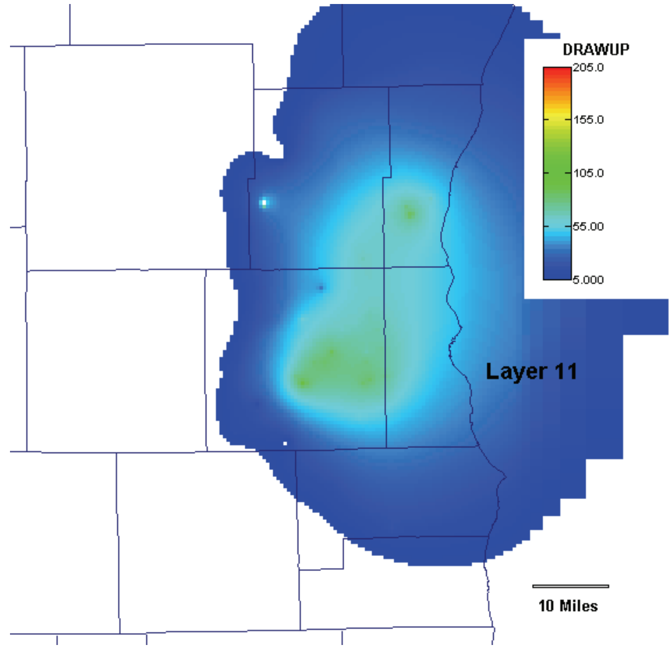


Figure 44 Simulated Drawup in Upper Sandstone (deep) Aquifer from 2005 to 2035: Composite Plan Option 1



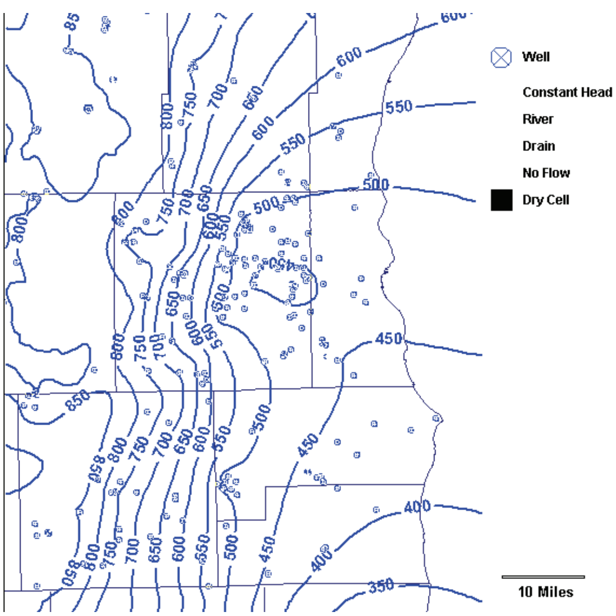


Figure 45 Simulated Potentiometric Surface (NGVD29) for the Upper (deep) Sandstone Aquifer in 2035: Composite Plan Option 1

All three figures are from Feinstein, 2008

some reductions in baseflow between 2005 and 2035 that exceed 10 percent (Figure 40), the stated target for the plan. Some of these reductions are volumetrically balanced by treated effluent (in the larger rivers), but those on lakes, wetlands and smaller streams are not. Because the shallow aquifer is unconfined, there will be no significant drawdown in the aquifer.

Option 2 - Community Scale

The only difference between this option and Option 1 is that all of the City of Waukesha's pumping (5.1 mgd from the deep and 3.9 mgd from the shallow aquifer) has been removed from the model to simulate its replacement with lake water. The effects can be seen by comparing Figures 46 to 49 (Option 2) to Figures 39 to 42 (from Option 1), respectively.

In the deep aquifer, the DSR at the City of Waukesha is reduced from essentially 6 to 0 (Figures 39 and 46), with a resultant increase in the green area (improved conditions) in Figure 48 (compared to Figure 41). The DSR values in all the other areas remain identical between the two options.

In the shallow aquifer, the effects of the City of Waukesha on baseflows are removed. The negative BRIs at Waukesha under Option 1 (Figure 40) are entirely absent under Option 2 (Figure 47). The parallel increase in BRI (Figure 49) is less than 20 percent, because there was only minimal pumping (0.2 mgd) from the domestic wells in the shallow aquifer in 2005.

Removal of Waukesha's pumping produces considerable change in the water levels in the deep aquifer. In almost the entire region, water levels would be drawn up (compare Figures 51 and 44) with only slight drawdowns in Walworth County (Figure 50). The cone of depression is considerably reduced (Figure 52), although the composite drawdown from predevelopment to 2035 would remain greater than 150 feet in much of Waukesha County and some surrounding areas.

The simulations show that the ground water impacts of Option 2 are less than those of Option 1 in both aquifers in the area around the City of Waukesha. However, Option 2 could produce impacts on the surface water bodies receiving Waukesha's treated effluent as well as on the lowest flows in the Fox River. These surface impacts need to be fully examined to determine if they are an acceptable alternative to the ground water impacts of Option 1. The ground water indices presented in this report are insensitive to such surface impacts and cannot provide that comparison.

Both options of the Composite Plan provide only limited management of ground-water resources outside the areas targeted to receive lake water (eastern Waukesha and southern Ozaukee Counties). Primarily, the Composite Plan encourages those communities to rely more heavily on the shallow aquifer in the future, effectively transferring impacts from drawdowns in the deep aquifer to much more diffuse reductions of low flow in surface waters. Both options show baseflow reductions exceeding 10 percent in Walworth County (Figures 40 and 47). Both also create a situation in which further growth in water demand will result in further baseflow reductions. This cycle cannot be maintained indefinitely.

Figure 46 Demand to Supply Ratio in Deep Aquifer in 2035: Composite Plan Option 2

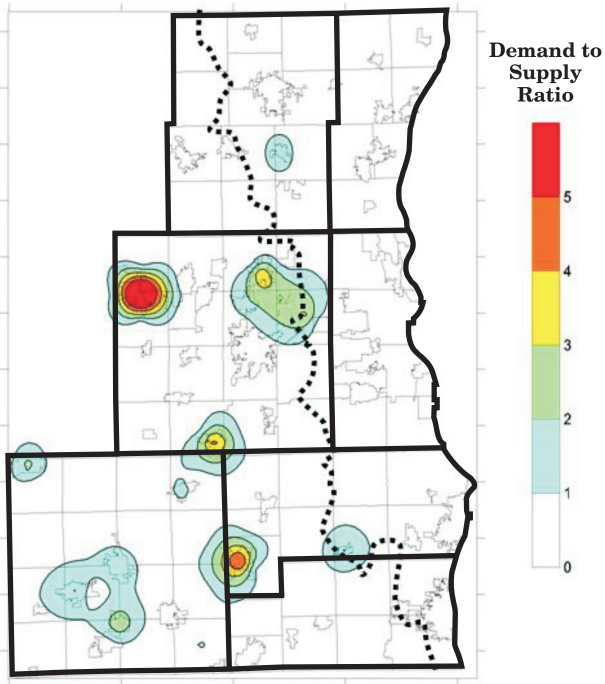


Figure 47 Baseflow Reduction Index in Shallow Aquifer in 2035: Composite Plan Option 2

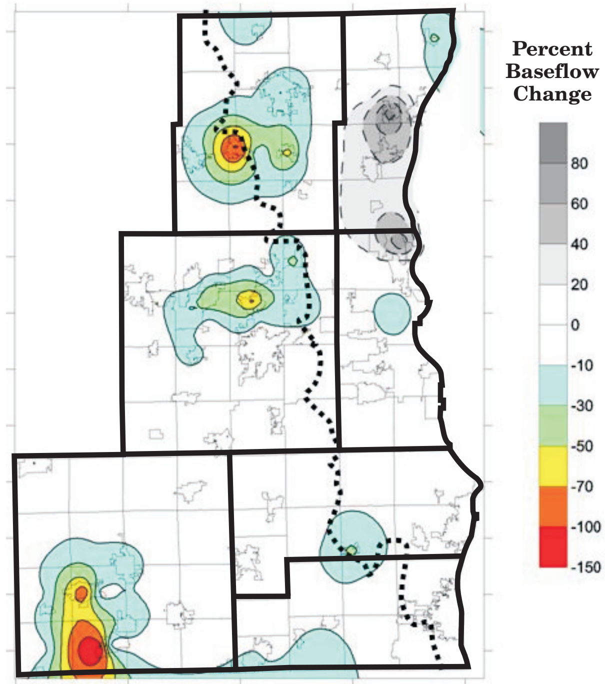


Figure 48 Change in Demand to Supply Ratio in Deep Aquifer from 2005 to 2035 Composite Plan Option 2

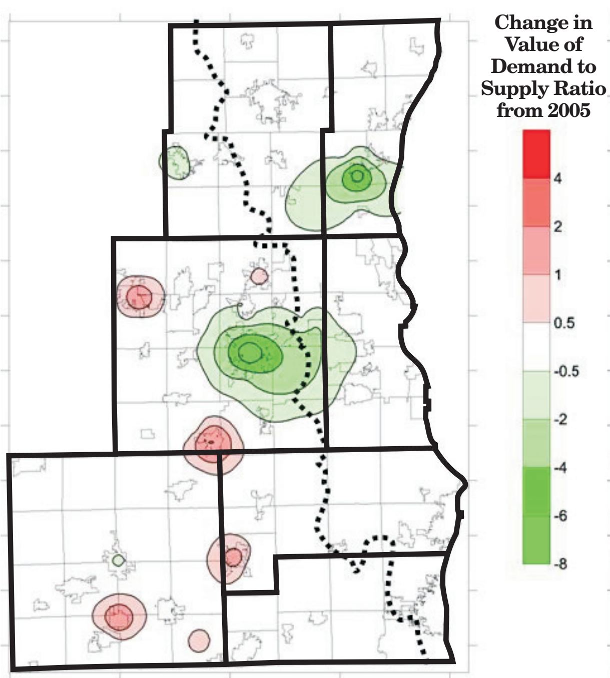


Figure 49 Change in Baseflow Reduction Index in Shallow Aquifer from 2005 to 2035 Composite Plan Option 2

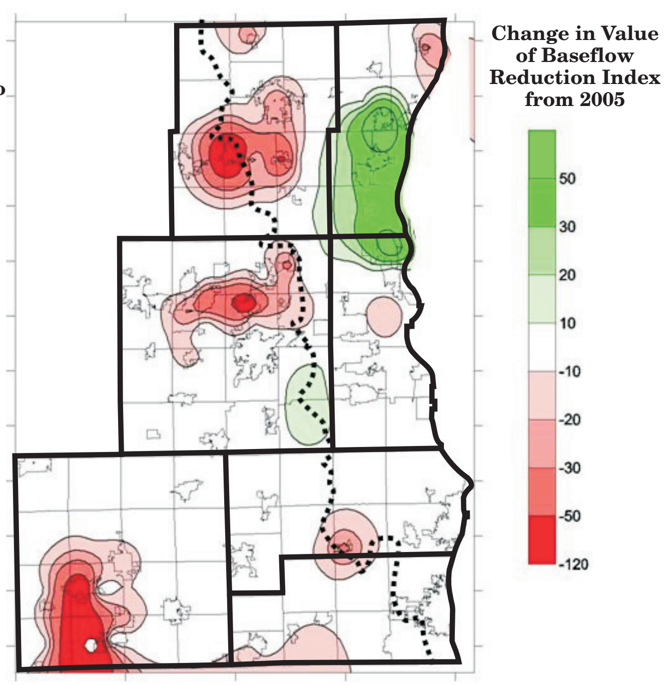


Figure 50 Simulated Drawdown in Upper Sandstone Aquifer from 2005 to 2035: Composite Plan Option 2

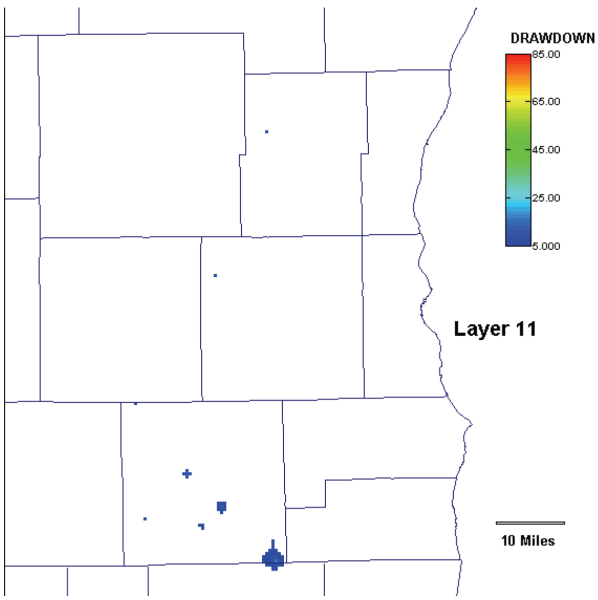
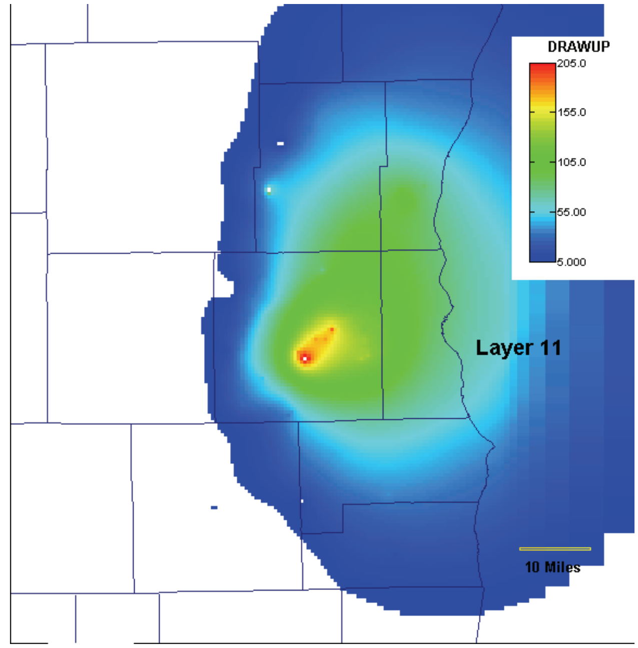


Figure 51 Simulated Drawup in Upper Sandstone Aquifer from 2005 to 2035: Composite Plan Option 2



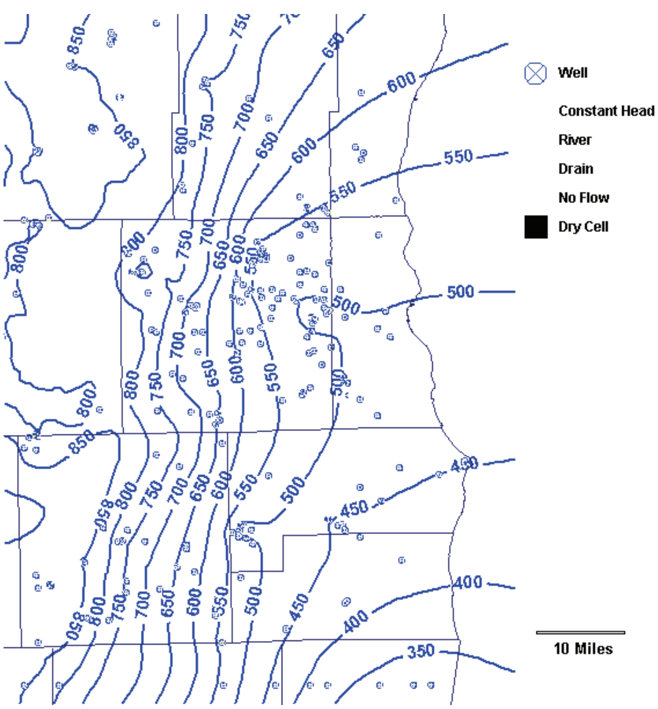


Figure 52 Simulated Potentiometric Surface (NGVD29) for the Upper Sandstone (deep) Aquifer in 2035: Composite Plan Option 2

All three figures are from Feinstein, 2008.

Composite Plan Options at County Scale

At the county scale, both options produce similar to identical effects except in Waukesha County. In the deep aquifer, net pumping is projected to drop between 2005 and 2035 in Milwaukee, Ozaukee, Washington and Waukesha Counties, remain about the same in Kenosha County, and increase in the other counties (Table 12). The DSR values follow the net pumping changes directly, getting larger with pumping increases and smaller with decreases. In Waukesha County, Option 1 is simulated as reducing both pumping and DSR in the deep aquifer 18 percent from 2005 (Table 12), while under Option 2, the reductions are larger (45 percent).

Despite the improvements, both Waukesha and Racine County would remain well above the target DSR of 1.0 under either option of the composite plan (Table 12). Walworth County will nearly have reached that level by 2035. This indicates that in 2035 these three counties will be pumping the deep aquifer at a rate that cannot be sustained unless they can continue to draw water from beneath their neighbors. In the cases of Waukesha and Walworth Counties, one needs to be cautious in making an interpretation, because pumping in areas outside the region (Rock, Jefferson and Dodge Counties in Wisconsin, as well as in northern Illinois) has been simulated as remaining constant at the 2005 rate. In reality, those areas are likely to change their use of the deep aquifer in the future. If those areas increase their use of the deep aquifer, it may be more difficult for Waukesha and Walworth Counties to induce the same amount of water to flow from the surrounding areas.

Table 12 Projected Future Values for Pumping, DSR and HIR in Deep Aquifer – Composite Plan

County	Net Pumping (mgd)		Demand to Supply Ratio		Human Impact Ratio	
	2005	2035	2005	2035	2005	2035
Kenosha	0.17	0.23	0.101	0.137	-0.041	-0.053
Milwaukee	0.89	0.58	0.567	0.369	-0.197	-0.238
Ozaukee	0.86	0.01	1.040	0.017	-0.317	-0.008
Racine	3.30	3.78	1.963	2.242	-0.500	-0.607
Walworth	5.57	7.38	0.745	0.986	-0.326	-0.411
Washington	0.81	0.52	0.453	0.294	-0.191	-0.143
Waukesha 1	18.63	15.22	5.773	4.718	-0.881	-0.905
Waukesha 2		10.31		3.197		-0.769
Region 1	30.22	27.72	2.379	2.182	-0.706	-0.723
Region 2		22.81		1.796		-0.654

In Table 12, Waukesha 1 and 2, and Region 1 and 2, in 2035 are the values for Options 1 and 2 of the Composite Plan. All other values are from Option 1 only.

For the region as a whole, the DSR of the deep aquifer under Option 1 remains above 2 (Table 12). Again, this means that water will have to be drawn from beneath neighboring areas to sustain the projected pumping rates.

The Human Impact Ratio shows parallel patterns to DSR except for Milwaukee and Waukesha Counties, where HIR becomes more negative even as pumping is reduced in the future (Table 12). This is because lateral ground water outflows from these counties have been decreased (more than the amount of pumping decrease) by changes in the deep aquifer's potentiometric surface. As a result, pumping's portion of total outflows actually increases in both counties, causing the HIR to become more negative. In Milwaukee County, outflow to Waukesha County decreases because the hydraulic gradient toward the west decreases as water levels rebound. The change in Waukesha County is more subtle. The rising water level in the deep aquifer is a reversal from 2005. It results in a gain in ground water storage, treated as an inflow to the aquifer, compared to a storage loss (outflow) in 2005. The result is that the total outflows in 2005 were larger than those under Option 1 in 2035, making the outflow term of the HIR equation more negative in 2035.

In Option 2, the reduced pumping in Waukesha County has two effects. First, it reduces the DSR and makes the HIR less negative in Waukesha County as expected. Both indicate improvement in the ground water budget. Secondly, the HIR values become slightly less negative in Kenosha, Milwaukee and Racine Counties, and slightly more negative in Walworth and Washington Counties. In the first three, the changes are the result of an increase in the lateral outflows (primarily to the east) in counties along Lake Michigan (as hydraulic gradients become weaker toward the cone of depression). In Walworth and Washington Counties, lateral outflows toward Waukesha County decrease as the cone of depression and its induced hydraulic gradients weaken.

In the shallow aquifer, the reduction of Waukesha's pumping by 4.9 mgd causes a substantial improvement in the county's baseflow, with reduction diminishing from 6 percent under Option 1 to less than 2 percent under Option 2 (Table 13). For Option 2, the BRIs in counties other than Waukesha improve slightly (an average of 0.2 percent less negative). The reduction of pumping in the deep aquifer in Option 2 causes water levels to rise in that aquifer reducing leakage from the shallow to the deep aquifer. Instead of leaking to the deep aquifer, this water discharges from the shallow aquifer to surface water bodies.

The reduced pumping also causes improvements in both the DSR and HIR of the shallow aquifer in Waukesha County. Parallel improvements also occur for the composite measures for the whole region (Table 13).

Table 13 Projected Future Values for Pumping, DSR, HIR and BRI in Shallow Aquifer – Composite Plan								
County	Net Pumping (mgd)		Demand to Supply Ratio		Human Impact Ratio		Baseflow Reduction (percent)	
	2005	2035	2005	2035	2005	2035	Total from 1900 *	Future after 2005 #
Kenosha	3.06	5.96	0.047	0.087	-0.047	-0.085	-9.61	-4.74
Milwaukee	4.09	3.38	0.159	0.131	-0.150	-0.127	-17.41	+2.18
Ozaukee	7.60	2.18	0.199	0.054	-0.188	-0.054	-6.45	+15.75
Racine	4.54	5.22	0.061	0.069	-0.060	-0.069	-7.70	-1.20
Walworth	6.62	11.68	0.045	0.077	-0.044	-0.075	-13.15	-4.68
Washington	8.25	11.79	0.083	0.116	-0.081	-0.113	-13.54	-4.03
Waukesha 1	14.30	21.71	0.089	0.133	-0.086	-0.127	-19.19	-6.28
Waukesha 2		16.82		0.104		-0.102	-15.30	-1.76
Region 1	48.45	61.93	0.081	0.098	-0.079	-0.097	-13.51	-3.13
Region 2		57.04		0.091		-0.065	-12.34	-1.82

* The first BRI (BRI_{1900}) is the change from 1900 to 2035; negative values indicate baseflow reduction.
# The second BRI (BRI_{2005}) is the change from 2005 to 2035, with same sign convention as for above.

In Table 13, Waukesha 1 and 2, and Region 1 and 2, in 2035 are the values for Options 1 and 2 of the Composite Plan. For all other counties, only the values for Option 1 are shown.

Assessment of the Composite Plan

Regionally, either option of the composite plan will reduce total impacts to the ground water system below what would occur if current trends in groundwater use continued (Alternative 1). However, this plan contains significant spatial differences, which can be summarized as follows:

- It has a strong positive impact on ground water quantity in areas east of the subcontinental divide and beneath those straddling communities projected to receive lake water.

- It causes increased baseflow ground water impacts west of the divide and in the northern parts of the region.

- It demonstrates that the Region will have an adequate quantity of water through 2035 under either option. The groundwater impacts under both options and related surface water baseflow impacts are reviewed herein. In selected areas of the Region, there is a need to revisit the management recommendation in the future as new development and water use data become available.

These points bear closer examination. The composite plan will greatly reduce demand for ground water in eastern Waukesha County and southern Ozaukee County by utilizing Lake Michigan as an alternative supply. For most other areas currently served by groundwater supplies, the preliminary regional water supply plan recommends continued use of groundwater as the source of supply with supplementation, in some cases, by treatment and changes in the sources from the deep to the shallow aquifer. The analyses conducted indicate that this course of action will provide for an adequate source of supply through the year 2035. On a countywide average basis the baseflow reduction index in the shallow aquifer is generally maintained at -5 percent or less from 2005 to 2035 (Table 12). However, in the deep aquifer, Waukesha County's DSR remains well above 1.0, even when the City of Waukesha is simulated as no longer using ground water (Option 2; DSR = 3.197). This means that water must be induced to flow toward Waukesha County from surrounding areas to balance the remaining overdraft from this aquifer. The imbalance indicated by the high DSR is verified by the continued existence of a reduced cone of depression (Figures 45 and 52; Options 1 and 2, respectively). However, the deep aquifer recovery illustrated in Figures 44 and 51 indicates that the deep aquifer quantity issues are substantially improved through the year 2035 under both options, but particularly under Option 2. It must be remembered, however, that the return of treated wastewater to the Lake Michigan watershed will also have impacts on surface water quantity that have not been addressed and are beyond the scope of this report.

This situation will remain stable until 2035 as long as the water demands remain within the range projected in the Water Supply Plan (SEWRPC, 2009). If, or when, water demands in western Waukesha County and surrounding areas grow beyond those simulated in the regional model, the indices indicate a need for further periodic evaluation in selected areas as future land use and water demand projections beyond 2035 become available.

One step that the Composite Plan projects for the outlying areas is an increase in the shift from the deep to the shallow aquifer. As a consequence, the water levels in the deep aquifer will rise, but the baseflow reductions in these areas will be larger than under either Alternative 3 or 4. The effect is particularly apparent in Walworth County. At the same time, the DSR in the deep aquifer in Walworth County is approaching the undesirable level of 1.0 by 2035 and will presumably exceed it shortly after the end of the planning period without a change to management of the resource. The ground water indices indicate that there could be some problem areas that will develop in the western part of the planning area, and these should be revisited in the future.

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Appendix A: Procedures for generating ground-water budget indices

Preparation of the ground-water flow model

The process utilized to develop groundwater indices described in this report requires having a well-designed, calibrated, three-dimensional ground-water flow model. It needs to extend well beyond the area of interest in order to avoid the influence of lateral boundary effects. It should also have sufficient resolution that the main aquifers of interest are treated as separate entities, and it must include a reasonable representation of stresses to the ground-water system, including recharge, wells, rivers, streams, lakes and wetlands. The model can be designed as either steady state or transient. In this case, the southeast Wisconsin regional model (Feinstein, et al, 2005) provided the necessary platform.

Within the model, the areas for which ground-water budgets and indices are sought need to be specified. The work for this report used the Groundwater Vistas computer program (Rumbaugh and Rumbaugh, 2005) as the pre- and post-processor for Modflow. The Vistas computer program allows designation of polygons (called HSUs in the program) to be used for water budget accounting. During a model run, Vistas tabulates all the ground-water fluxes through the sides, top and bottom of each HSU, as well as any exchanges between an HSU and all the designated stresses that lie within it.

The HSUs can range in size from a single model cell up to the entire area of the model. For this report, two separate sets (county and community scales) were used. At each scale, one set of HSUs was generated for the shallow aquifer (layers 1 through 6), and another for the deep aquifer (layers 7 through 18). The regional aquitard which separates the two aquifers (the Maquoketa shale, layers 7 and 8) was incorporated into the deep aquifer under the assumption that whatever fluxes enter it from above or below will be transmitted into or out the top of the deep aquifer. For consistency of accounting, the separation of the two aquifers was continued into the western part of the model's nearfield, where the Maquoketa shale is absent.

The HSU array at the community scale is presented in Figure A-1. Different colors represent different HSUs. The large rectangular areas are generally towns, while the smaller, less regularly shaped areas are cities and villages. Communities smaller than eight to 10 model cells (roughly 2 to 2.5 square miles) were combined with adjacent entities, both to simplify the accounting and because they are probably at or near the model's budgeting resolution. At this scale, a total of 121 HSUs (117 for community areas and four for the surrounding farfield) were defined for each aquifer. At the county scale, 11 were needed (seven counties and four lateral boundaries in the farfield).

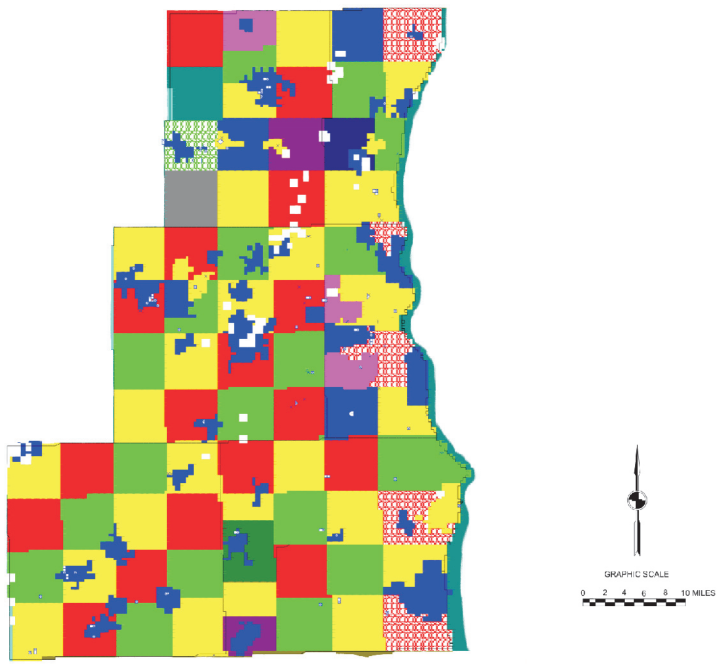

Figure A-1 Community areas (HSUs) used for ground water budget accounting. A parallel set was used for each aquifer.

Extraction of fluxes from the model.

Once the HSU array has been defined, the model is run to generate a full ground-water budget for each area. The Groundwater Vistas computer program provides an "HSU report" which specifies:

Inflows to an HSU from:

- Above or below (recharge or leakage)
- Sides (lateral inflows)
- Surface water bodies (Modflow head dependent flux boundaries)
- Artificial recharge (infiltration basins, recharge wells)

Outflows from an HSU to:

- Above or below (leakage)
- Sides (lateral outflows)
- Surface water bodies (Modflow head dependent flux boundaries)
- Wells

The fluxes for each HSU can then be exported to a csv (comma separated values) file for direct importation into a spreadsheet. The report can be generated for any stress period and time step combination within a simulation.

Conversion from ground-water budget to indices.

A spreadsheet template was programmed to translate the csv output into a set of inflows and outflows for each HSU consistent with the designations shown in Table 1 of this report. The primary complexity encountered in this step is that each HSU will adjoin a unique set and number of other HSUs. As a result, the csv file contains a different number of lines for each HSU, which must be recognized in the handling of lateral inflows and outflows.

The template spreadsheet takes the csv output for a given stress period and time step and converts it into a single row of inflows and outflows for each HSU. This is then exported to a second spreadsheet which calculates the indices for each HSU. For a given HSU set, this second spreadsheet can be used to store and compare the results for multiple stress periods or simulations.

Both the DSR and BRI indices refer to a base condition in which human influence is negligible. The southeastern Wisconsin regional model is transient with recharge held constant through time, so the appropriate base is an early stress period before there is significant pumping. For a steady state model, or for one in which recharge is varied with time, an appropriate base condition can be obtained by running a simulation for the period of influence with all wells (and other human influences, such as artificial recharge) deactivated (Feinstein, 2009).

Mapping results.

The index maps shown in this report were then generated using the contouring computer program Surfer (Golden Software, 1999). The value of an index for each community HSU was identified as occurring at the centroid of that HSU. The GIS coordinates for the centroid and the appropriate index value were entered into Surfer, gridded and then contoured. This process treats the values as a continuum, which is not truly the case, but it allows a simple visual display (as presented in the report).

Effects of the scale of analysis

As indicated above, an index can be calculated for a variety of scales, ranging from individual model cells to the full model grid. In this study, the largest scale (county) was helpful in that it allowed development of simple summary tables containing relatively few entries. These tables are quick to read but can be misleading, because the index values are averaged over a broad area. Waukesha County, for example, has major ground-water impacts in the eastern half of its 576-square-mile area and relatively minor impacts to the west. The countywide values of the DSR for the deep aquifer (5.77 in 2005) and of BRI for the shallow (-13.8 in 2005) are therefore understatements of the higher human impacts within the county.

The smaller, community scale used in the report works considerably better for getting a sense of the distribution of human effects, but has cumbersome data handling requirements. Communities were used as HSUs because they are the political entities that currently govern human stresses on ground-water systems (through water supply systems and land use zoning). Their variable sizes and shapes, however, cause the resolution of the indices and contour maps to vary across the study area.

For the scales reported on, there is also a problem of lack of coincidence between political boundaries and the model grid. Each model cell was assigned to the HSU which occupied the greatest portion (usually greater than 50 percent) of the cell. This sometimes led to a major stress in a given community being inadvertently assigned to an adjoining HSU. Care had to be taken to reassign such cells to the correct political HSU to avoid confusion in interpretation. An alternative approach would be to separate the index calculation from political boundaries. One could assign HSUs which are of uniform shape and size (16 or 25 model nodes, for example). However, this approach was not taken in this report.

Finally, it is possible to calculate index values for each individual model cell. However, this approach would create visual chaos in any graphic presentation of DSR or HIR, for example. Cells with wells or other stresses would have large index values, while adjoining areas without wells or stresses would have smaller values. For BRI, however, there is value in calculating values for just the cells in which surface water bodies occur. This has, in fact, been accomplished as part of SEWRPC's regional water supply plan (SEWRPC, 2009).