JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
FEBRUARY AMERICAN WATER RESOURCES ASSOCIATION 2003

POTENTIAL EFFECTS OF CLIMATE CHANGE ON GROUND WATER IN LANSING, MICHIGAN[1]

Thomas E. Croley II and Carol L. Luukkonen[2]

ABSTRACT: Computer simulations involving general circulation models, a hydrologic modeling system, and a ground water flow model indicate potential impacts of selected climate change projections on ground water levels in the Lansing, Michigan, area. General circulation models developed by the Canadian Climate Centre and the Hadley Centre generated meteorology estimates for 1961 through 1990 (as a reference condition) and for the 20 years centered on 2030 (as a changed climate condition). Using these meteorology estimates, the Great Lakes Environmental Research Laboratory's hydrologic modeling system produced corresponding period streamflow simulations. Ground water recharge was estimated from the streamflow simulations and from variables derived from the general circulation models. The U.S. Geological Survey developed a numerical ground water flow model of the Saginaw and glacial aquifers in the Tri-County region surrounding Lansing, Michigan. Model simulations, using the ground water recharge estimates, indicate changes in ground water levels. Within the Lansing area, simulated ground water levels in the Saginaw aquifer declined under the Canadian predictions and increased under the Hadley.
(KEY TERMS: climate change; ground water hydrology; Lansing, Michigan; surface water hydrology; water policy; water resources planning.)

Croley II, Thomas E. and Carol L. Luukkonen, 2003. Potential Effects of Climate Change on Ground Water in Lansing, Michigan. J. of the American Water Resources Association (JAWRA) 39(1):149-163.

INTRODUCTION

Great Lakes Climate Change Studies

Considerations of potential future climate situations can help to identify possible effects of changing carbon dioxide levels and can bound estimates of future changed climate conditions. Preliminary estimates of impacts in the Great Lakes considered simple constant changes in air temperature or precipitation. Quinn and Croley (1983) estimated net basin supply to Lakes Superior and Erie. Cohen (1986) estimated net basin supply to all Great Lakes. Quinn (1988) estimated lower water levels due to decreases in net basin supplies on Lakes Michigan-Huron, St. Clair, and Erie.

Researchers have developed general circulation models (GCMs) of the Earth's atmosphere to simulate climates for current conditions and for a doubling of global carbon dioxide levels ($2xCO_2$). The U.S. Environmental Protection Agency (USEPA) used the hydrological components of general circulation models and assessed changes in water availability in several regions throughout North America (USEPA, 1984), but the regions were very large. Regional hydrological models can link to GCM outputs to assess changes associated with climate change scenarios. Allsopp and Cohen (1986) used Goddard Institute of Space Sciences (GISS) $2xCO_2$ climate scenarios with net basin supply estimates. The EPA also coordinated several regional studies of the potential effects of a $2xCO_2$ atmosphere (USEPA, 1989). They directed others to consider alternative climate scenarios by simulating GCM changes with historical meteorology. Changes were made to historical meteorology similar to the differences observed between GCM simulations of $2xCO_2$ and $1xCO_2$. Both the unchanged historical meteorology and the modified meteorology then were used with models to simulate the resultant hydrology. The hydrological differences were interpreted as climate change impacts. Cohen (1990, 1991) discusses other studies that use this type of linkage methodology and

[1]Paper No. 01051 of the *Journal of the American Water Resources Association*. **Discussions are open until August 1, 2003.**

[2]Respectively, Research Hydrologist, NOAA Great lakes Environmental Research Laboratory, 2205 Commonwealth Blvd., Ann Arbor, Michigan 48105-2945; and Hydrologist, U.S. Geological Survey, Water Resources Division, 6520 Mercantile Way, Suite 5, Lansing, Michigan 48911 (E-Mail/Croley: croley@glerl.noaa.gov).

also presents his concerns for comparability between studies using different types of linkages.

As part of the latter USEPA study, the Great Lakes Environmental Research Laboratory (GLERL) assessed steady state and transient changes in Great Lakes hydrology consequent with simulated $2xCO_2$ atmospheric scenarios from three GCMs (USEPA, 1989; Croley, 1990; Hartmann, 1990), representing both "present" and $2xCO_2$ steady state conditions. The USEPA studies, in part, and the high water levels of the mid-1980s prompted the International Joint Commission (IJC) to reassess climate change impacts on Great Lakes hydrology and lake thermal structure. GLERL adapted the USEPA study methodology for the IJC studies (Croley, 1992) to consider $2xCO_2$ GCM scenarios supplied by the Canadian Climate Centre (CCC). These previous studies assessed mean climate changes but not changes in climate variability. Croley *et al.* (1998) then used transpositions of actual climates from the southeastern and southwestern continental United States (U.S.) because they incorporate natural changes in variability within existing climates, as well as mean changes. Similar studies were made to transpose the climate occurring during the 1993 Mississippi flood to assess climate change impacts on hydrology in the Great Lakes (Quinn *et al.*, 1997). Most recently (Lofgren *at al.*, 2000), GLERL again applied its hydrologic models over the Great Lakes to daily outputs from two GCMs: the newer Canadian Centre for Climate Modeling and Analysis global coupled model (CCCMA GCM) and the United Kingdom Hadley Centre for Climate Prediction and Research second coupled ocean atmosphere GCM (Hadley GCM). Results of this recent study are used herein.

Global climate models indicate that changes in daily air temperatures and precipitation are possible with changes in atmospheric carbon dioxide and suspended aerosols. Because ground water resources are naturally replenished by infiltration of precipitation and subsequent percolation of water through geologic materials, a decline in precipitation or an increase in evapotranspiration would result in a decline in recharge, possibly resulting in a decline in ground water levels. In all of the climate studies mentioned here, estimates of water availability were made for ground water in the various riverine watersheds throughout the Great Lakes. The estimates were of various lumped areal ground water indices, however, and thus are considered too broad for specific sites. They have not been refined for individual sites within the Great Lakes basin. Loaiciga *et al.* (2000) used hydrologic models, historical data, and GCM results to investigate $2xCO_2$ climate scenarios impacts on ground water resources in Texas.

Effects on Ground Water in Lansing, Michigan

Ground water from the Saginaw aquifer is the primary source of water for residents and businesses in the Tri-County region (the study area) shown as the bottom inset in Figure 1. Figure 1 depicts the study area and its relationship to both the encompassing Great Lakes basin and the grids of the two GCMs used in this study. In 1992, more than 89 percent of the ground water withdrawn by public systems was withdrawn from the Saginaw aquifer (Luukkonen, 1995). Following a drought in 1988, which resulted in water rationing in the Tri-County region, local communities began to assess the adequacy of water resources for future needs. A regional water feasibility study was done to evaluate the development of a regional water supply system, to assess the total sustainable yield of the aquifer system, and to identify areas for future development (Tri-County Regional Planning Commission, 1992). To assist with the evaluation of the regional water supply system, the U.S. Geological Survey (USGS) developed a steady state ground water flow model to simulate ground water flow in the Tri-County region (Holtschlag *et al.*, 1996). Simulations with the Tri-County model using increased pumping rates, depicted lower ground water levels both in the glacial deposits and in the Saginaw aquifer. These simulations assumed that other parameters, such as hydraulic conductivity and recharge, remained the same.

The USGS and the National Oceanic and Atmospheric Administration (NOAA) assessed the potential impacts of climate change projections on a municipality that relies on ground water supplies. Simulations were done to investigate the effects of changes in recharge and ground water withdrawal rates on ground water levels and flow to rivers around Lansing, Michigan. Streamflow was calculated with GLERL's hydrologic modeling system by using the CCCMA and the Hadley GCM meteorology estimates for a 1961 through 1990 reference period and for 20 years centered on 2030 under a changed climate. These changed climate scenarios extend present trends in accumulation of carbon dioxide and aerosols. Base flow (ground water contribution to streamflow) was estimated for each of the streamflow simulations and ground water recharge rates in the Tri-County regional ground water flow model were adjusted based on the predicted changes in base flow. The adjusted ground water recharge estimates were used as input for the numerical ground water flow model (Holtschlag *et al.*, 1996) of the Saginaw and glacial aquifers in the Tri-County region surrounding Lansing, Michigan, under 1995 and increased pumping scenarios.

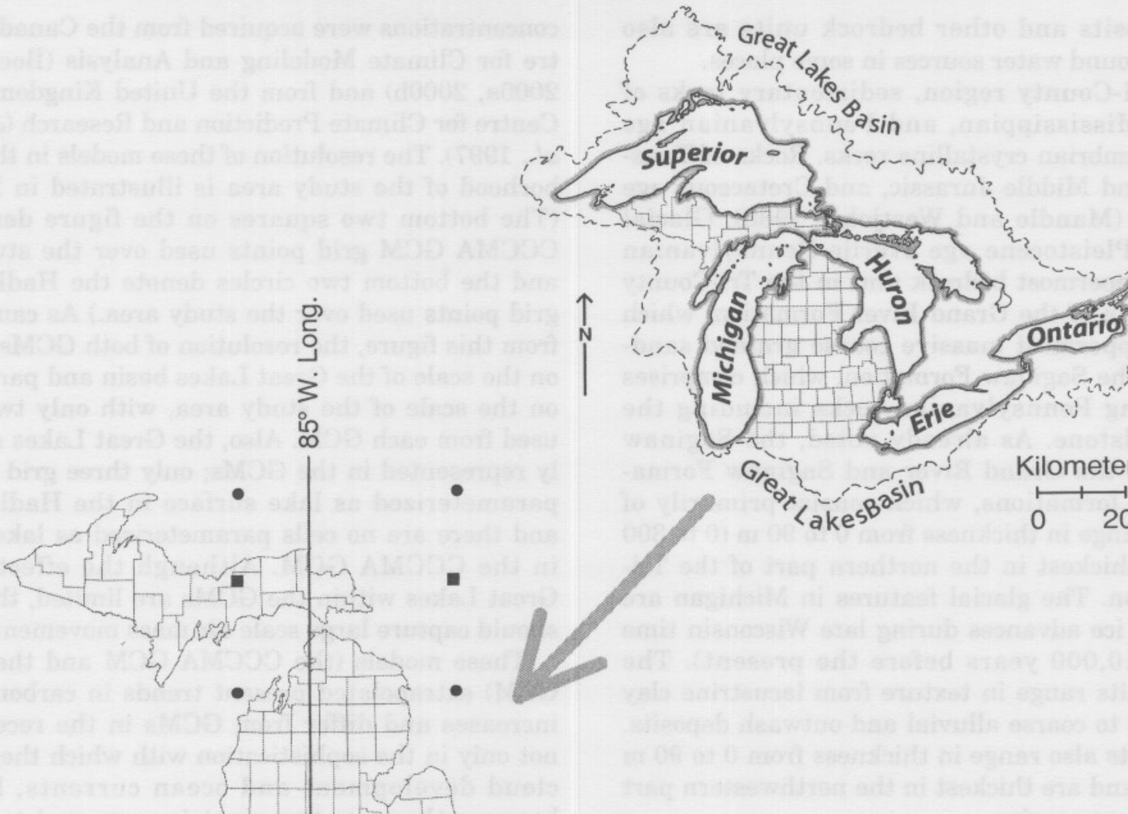

Figure 1. Active Model Area in the Tri-County Region in the Lower Peninsula of Michigan.

DESCRIPTION OF STUDY AREA

The Tri-County region, which consists of Clinton, Eaton, and Ingham Counties, covers about 4,395 km^2 (1,697 mi^2) in the south central part of the Lower Peninsula of Michigan (Figure 1). In 1997, the 432,700 people (U.S. Department of Commerce, 1991) who lived in this region relied on ground water withdrawals of about 1.86 m^3/s [42.4 million gallons per day (Mgal/d)]. The primary source of ground water in the Tri-County region is the Saginaw aquifer, which is located within the Grand River and Saginaw Formations of Pennsylvanian age. Aquifers in the glacial deposits and other bedrock units are also important ground water sources in some places.

In the Tri-County region, sedimentary rocks of Devonian, Mississippian, and Pennsylvanian age overlie Precambrian crystalline rocks. Rocks of Triassic, Lower and Middle Jurassic, and Cretaceous age are missing (Mandle and Westjohn, 1988). Glacial deposits of Pleistocene age overlie Pennsylvanian rocks. The uppermost bedrock unit in the Tri-County region consists of the Grand River Formation, which comprises uppermost massive coarse grained sandstones, and the Saginaw Formation, which comprises all remaining Pennsylvanian rocks including the Parma Sandstone. As already noted, the Saginaw aquifer is in the Grand River and Saginaw Formations. These formations, which consist primarily of sandstone, range in thickness from 0 to 90 m (0 to 300 ft) and are thickest in the northern part of the Tri-County region. The glacial features in Michigan are the result of ice advances during late Wisconsin time (35,000 to 10,000 years before the present). The glacial deposits range in texture from lacustrine clay or glacial till to coarse alluvial and outwash deposits. These deposits also range in thickness from 0 to 90 m (0 to 300 ft) and are thickest in the northwestern part of the Tri-County region.

Ground water flow in the glacial deposits and in the Saginaw aquifer is primarily from south to north. Flow from east or west of the Tri-County area, where the sandstone of the Saginaw Formation is very thin or absent, is minimal. The Saginaw aquifer is recharged principally by leakage from the glacial deposits. The bottom of the Saginaw aquifer is assumed to be impermeable.

Ground water withdrawals within the Tri-County region equaled 1.82 m^3/s (41.6 Mgal/d) in 1995. Ground water withdrawals increased from 1.75 m^3/s (39.9 Mgal/d) in 1992 to 1.86 m^3/s (42.4 Mgal/d) in 1997, an increase of 6.3 percent or about 1.3 percent per year. Tri-County ground water withdrawals of 2.79 m^3/s (63.7 Mgal/d) are projected for 2020 (Jon Coleman, Tri-County Regional Planning Commission, personal communication, 1994), an increase of 2.1 percent per year. Following this same rate of increase, ground water withdrawals for 2030 are projected to be 3.16 m^3/s (72.2 Mgal/d). These projections are based on anticipated changes in population and do not include potential changes in recharge due to wetter or drier conditions.

GENERAL CIRCULATION MODELS

Monthly mean data from GCM runs with transient carbon dioxide content and sulfate aerosol concentrations were acquired from the Canadian Centre for Climate Modeling and Analysis (Boer *et al.*, 2000a, 2000b) and from the United Kingdom Hadley Centre for Climate Prediction and Research (Johns *et al.*, 1997). The resolution of these models in the neighborhood of the study area is illustrated in Figure 1 (The bottom two squares on the figure denote the CCCMA GCM grid points used over the study area and the bottom two circles denote the Hadley GCM grid points used over the study area.) As can be seen from this figure, the resolution of both GCMs is crude on the scale of the Great Lakes basin and particularly on the scale of the study area, with only two points used from each GCM. Also, the Great Lakes are poorly represented in the GCMs; only three grid cells are parameterized as lake surface in the Hadley GCM and there are no cells parameterized as lake surface in the CCCMA GCM. Although the effects of the Great Lakes within the GCMs are limited, the GCMs should capture large scale air mass movements.

These models (the CCCMA GCM and the Hadley GCM) extrapolated present trends in carbon dioxide increases and differ from GCMs in the recent past, not only in the sophistication with which they handle cloud development and ocean currents, but also because they are transient (as opposed to steady-state) and include the effects of sulfate aerosols (e.g., see Reader and Boer, 1998). These aerosols mask the warming effects of increasing carbon dioxide, an effect that is likely to be temporary. The steady state nature of previous models allowed only an evaluation of effects from a doubling of carbon dioxide at some time into the future when conditions were considered unchanging, rather than from a more realistic steady increase. The two models recreate the current conditions well (Sousounis and Albercook, 2000) but suggest slightly different climate scenarios for the Great Lakes region. As guided by the National Assessment of Climate Change, the model period 1961 through 1990 was considered as the reference period to be compared with the 20-year future model period centered on 2030 at which time carbon dioxide doubles in the GCMs. In general, the CCCMA GCM scenario is drier and warmer than the Hadley GCM scenario.

HYDROLOGIC SIMULATION SYSTEM

The GLERL developed, calibrated, and verified conceptual model based techniques for simulating hydrological processes in the Laurentian Great Lakes and integrated them into a hydrologic simulation system (Croley, 1990, 1993; Croley *et al.*, 1998). These include a model for rainfall/runoff, evapotranspiration, and moisture storage in the Grand River basin.

Croley *et al.* (1998) summarizes details of this and other models in the system. The runoff model subdivides precipitation into watershed intraflows based on a cascade among five reservoirs: the snow pack, upper soil zone, lower soil zone, ground water zone, and surface storage. These moisture storages are arranged as a serial and parallel cascade of tanks to coincide with the perceived basin storage structure. Precipitation is considered rainfall if the air temperature is above 0°C. Otherwise, it is considered snowfall and stored in the snow pack until it melts. Water enters the snow pack, which supplies the basin surface (degree day snowmelt). Infiltration is proportional to this supply and to nonsaturation of the upper soil zone (partial area infiltration). Excess supply is surface runoff. Flows from all tanks are proportional to their amounts (linear reservoir flows). Evapotranspiration is proportional to available water and to sensible heat (a complementary concept in that energy used for evapotranspiration is unavailable as sensible heat and vice versa). Mass conservation is applied to calculate snow pack and tank storages; energy conservation is applied to calculate evapotranspiration. Complete analytical solutions exist for the resulting system of conservation equations. The partitioning of rainfall or snowmelt between surface runoff and infiltration and the partitioning of infiltration into percolation, interflow, deep percolation, ground water flow, and evapotranspiration are calculated by using daily maximum and minimum air temperature and nine empirically calibrated parameters.

The hydrologic simulation system used variables derived from the GCM runs: daily maximum, minimum, and average air temperature, precipitation, relative humidity, cloud fraction, and wind speed. The average monthly changes in these variables from the reference period (1961 through 1990) to those from the period centered on 2030 are expressed as differences or ratios of monthly means. Temperature changes were expressed as differences and other changes were expressed as ratios.

These differences and ratios were calculated at each GCM grid point for each variable and for each month of the year, based on the reference period (1961 through 1990) and on the average GCM mean values. The CCCMA model was run three times and the Hadley model four times for the entire length of the model run, using different initial conditions. The differences and ratios were then interpolated to the Grand River basin. Daily observations of the input variables over the period 1954 to 1995 (42 years) were also spatially interpolated to the Grand River basin. The differences and ratios associated with each GCM were then applied to these 42 years of daily Grand River meteorology to generate two 42-year scenarios of daily meteorology, one for each GCM. The scenarios are referred to by the GCM used to make the adjustments. Figure 2 depicts the average monthly variation in precipitation and air temperature, used in the Grand River Basin runoff model, which result from scaling of historical data by GCM generated adjustments. The hydrologic simulation system was run using the 42 years of observed meteorology as a reference or base case; it was also run for each scenario of 42 years of adjusted daily meteorology for each set of GCM generated adjustments.

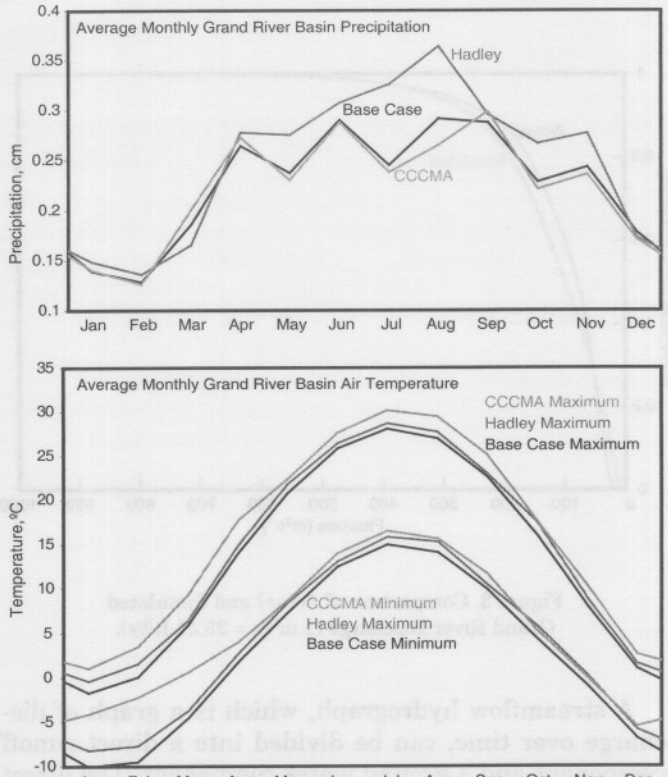

Figure 2. Average Monthly Meteorology Used for Grand River Basin Runoff Modeling.

DEVELOPMENT OF RECHARGE ESTIMATES

Base case values of streamflow at the mouth of the Grand River were compared to actual flows measured at the USGS gaging station for the Grand River at Grand Rapids, Michigan (Station No. 04119000). Flows at Grand Rapids are assumed to be similar to those at the mouth of the Grand River. Figure 3 illustrates the approximate agreement in the cumulative distribution functions of the base case flow rates (simulated) and of the measured (actual). Actual flow rates should be less than simulated, as shown in Figure 3 for flows greater than 50 m^3/s (1,800 ft^3/s), since the simulated flow site is slightly downstream from the measured flow site. For flow rates less than 50 m^3/s (1,800 ft^3/s), Figure 3 shows the two flow rates are close, but the simulated value is slightly less than the actual value. This could result because the simulated flows represent more natural streamflow conditions while the measured flows overestimate natural streamflow by including wastewater or other discharges. However, the agreement in Figure 3 is judged acceptable with possible underestimation of low flows.

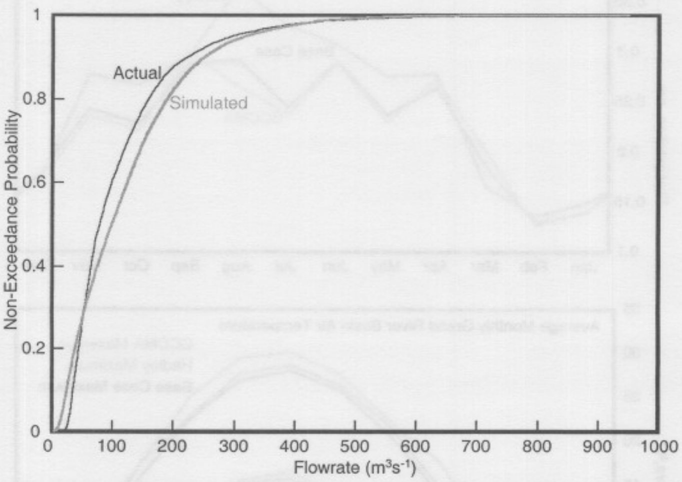

Figure 3. Comparison of Actual and Simulated Grand River Discharge (1 m^3/s = 35.31 ft^3/s).

A streamflow hydrograph, which is a graph of discharge over time, can be divided into a direct runoff component and a ground water component. The direct runoff component is associated with precipitation that enters the stream as overland runoff, and the ground water component, also called the base flow component, is associated with ground water flow into the stream. Rutledge (1998) developed programs that use streamflow partitioning to estimate a daily record of base flow under the streamflow record. The method designates base flow to be equal to streamflow on days that fit a requirement of antecedent recession, linearly interpolates base flow for other days, and is applied to a long period of record to obtain an estimate of the mean rate of ground water flow into the stream. Streamflow estimates generated using GLERL's hydrologic simulation system are averaged over the annual cycle for comparison purposes in Figure 4. All simulated streamflows are used with the method of Rutledge (1998) to compute simulated base flows for the base case meteorology and for the CCCMA and Hadley adjusted meteorologies.

Changes in base flow (not shown) reflect changes in the amount of water available for recharge to, or discharge from, the ground water system. The changed climate scenario estimates of base flow for the years 1954 to 1995 were compared to the reference condition to determine whether base flow increased or decreased due to the GCM meteorology estimates. The mean and standard deviation of the percent difference between the CCCMA GCM changed climate and reference estimates of base flow is -19.7 plus or minus 4.7 percent. The mean and standard deviation of the percent difference between the Hadley GCM changed climate and reference estimates of base flow is 4.1 plus or minus 3.3 percent. Thus the changed climate scenarios indicate a possible decrease or slight increase in ground water recharge.

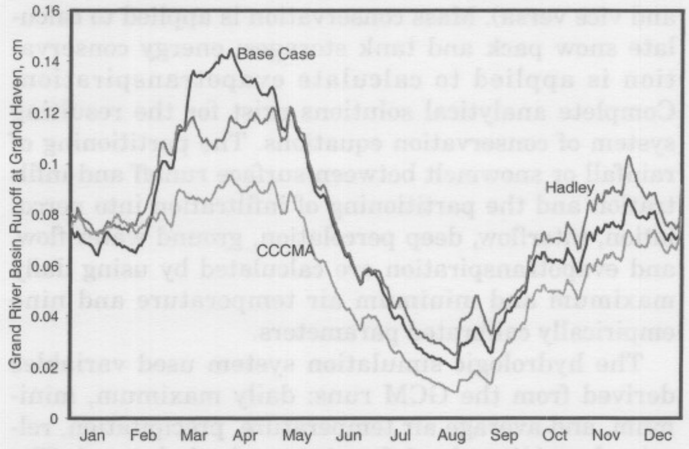

Figure 4. Average Daily Grand River Basin Runoff Estimated With the Runoff Model.

GROUND WATER FLOW MODEL

The ground water flow code, MODFLOW (McDonald and Harbaugh, 1988), was used to simulate the regional, steady state response of the Saginaw aquifer to major ground water withdrawals in the Tri-County region surrounding Lansing, Michigan. Details on model development, parameters, and calibration are described by Holtschlag *et al.* (1996). This model was later refined to better represent flow within the nine-township area (see Figure 1) surrounding Lansing, Michigan (Luukkonen *et al.*, 1997). Some details on model development and calibration are briefly described below.

The Tri-County regional model simulates ground water flow by dividing the Tri-County region into a variably spaced grid of cells in two layers. Within the nine-township area, cells are 200 m (660 ft) per side. Outside of this area, cells increase in height and width from 200 to 270 to 340 m (660 to 880 to 1,100 ft) and then to a constant 402 m (1,320 ft). The upper layer of the model represents the glacial deposits, and the lower layer represents the Saginaw aquifer. Water enters the glacial deposits as recharge from precipitation and moves to streams or to the Saginaw aquifer in response to hydraulic gradients. Ground water exits the model at streams or wells. No-flow boundaries are located at drainage and ground water divides; constant-head cells are located along the Grand River on the south and Maple River on the north (Figure 5). Simulated well pumpages are assumed to come from the centers of the grid cells. Small pumpages from domestic wells were not included. Of the ground water withdrawals in 1995, 10 percent was withdrawn from aquifers in the glacial deposits and 90 percent was withdrawn from the Saginaw aquifer. Of the withdrawals from the Saginaw aquifer, 91 percent were from wells in the nine-township area (Figure 1).

Within the Tri-County model, the spatial variation of average ground water recharge rates for 1951 through 1980 was determined from an analysis relating base flow characteristics of streams to land use and basin characteristics in the Lower Peninsula of Michigan (Holtschlag, 1994). Recharge to the glacial deposits shown in Figure 5 averaged 17 cm/y (6.7 in/y) and ranged spatially from 11 to 42 cm/y (4.4 to16.5 in/y).

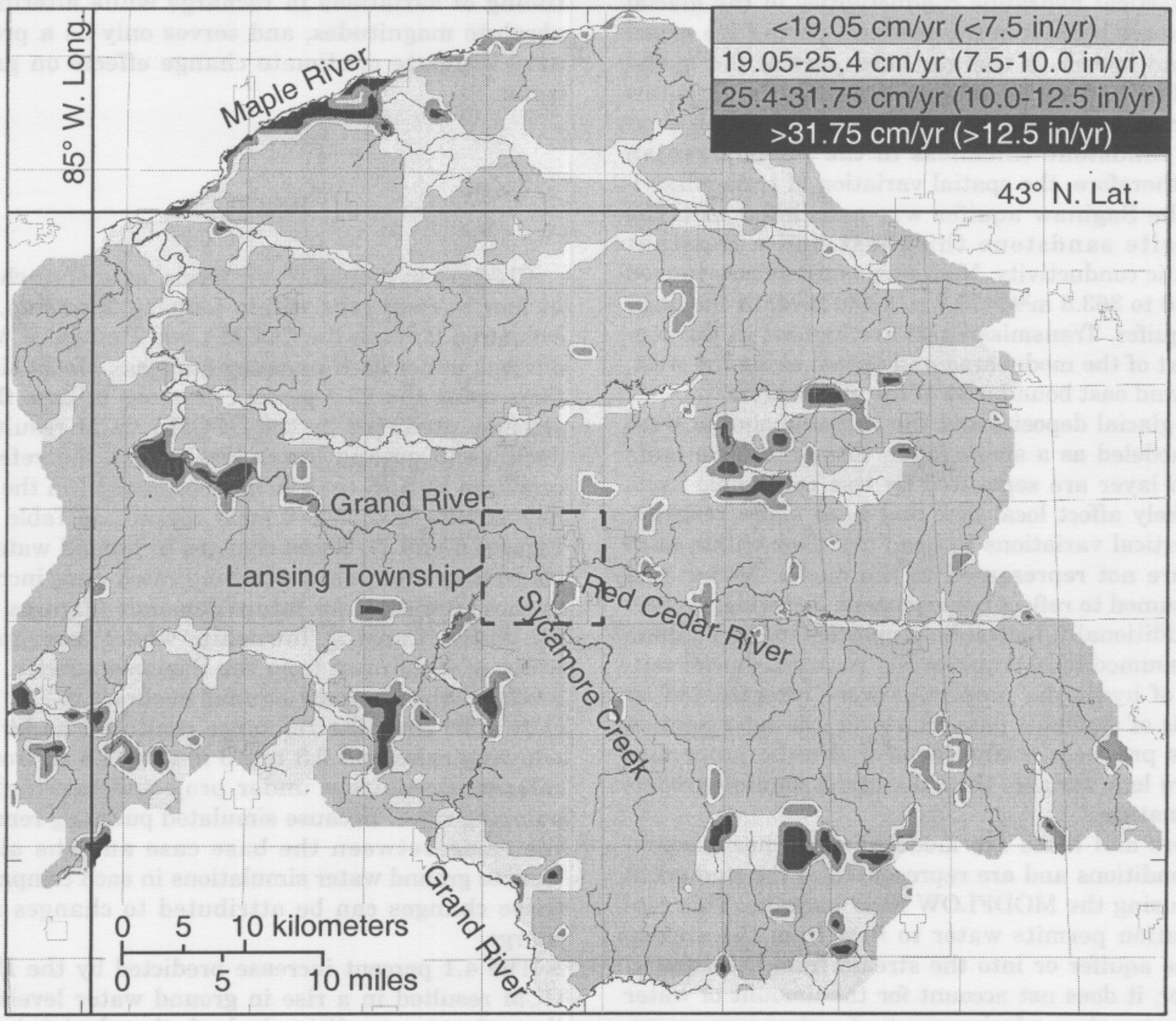

Figure 5. Spatial Variation of Average Ground Water Recharge in the Tri-County Model Area (modified from Holtschlag, 1994). (Base maps from Michigan Resource Information System, Michigan Department of Environmental Quality, Land and Water Management Division.)

The horizontal flow of water in the glacial deposits is controlled by the hydraulic conductivity of the unconsolidated materials. The vertical flow of water between the glacial deposits and the Saginaw aquifer was assumed to be controlled by the vertical hydraulic conductivity in the glacial deposits. Because of the local variability and nonhomogeneity of the glacial deposits, estimates of the spatial variation in the horizontal and vertical hydraulic conductivities in the glacial deposits were determined on the basis of a geostatistical analysis of available lithologic logs. The horizontal hydraulic conductivity of the glacial aquifer ranged from 6.8 to 26.7 m/d (22.3 to 87.5 ft/d), while the vertical hydraulic conductivities ranged from 1.6×10^{-4} to 1.2×10^{-2} m/d (4.7×10^{-4} to 4.0×10^{-2} ft/d). The horizontal hydraulic conductivities are highest in the west central part of the model area and lowest in the north and south parts of the model area. Vertical hydraulic conductivities of the glacial deposits are highest in the southern part of the model area and lowest in the northern part of the model area. The horizontal flow of water in the Saginaw aquifer was assumed to be proportional to the composite sandstone thickness in the Pennsylvanian rocks; therefore, the spatial variation of transmissivity in the Saginaw aquifer was associated with the composite sandstone thickness and a constant hydraulic conductivity. Model transmissivities ranged from 7.0 to 363.8 m^2/d (75.7 to 3,430 ft^2/d) in the Saginaw aquifer. Transmissivities are highest in the central part of the model area and lowest along the west, south, and east boundaries of the model area.

The glacial deposits and the Saginaw aquifer were each modeled as a single layer. The permeable units in each layer are separated by less permeable units that likely affect local flow and head characteristics. Any vertical variations in head and flow within each layer are not represented in the model. Model cells are assumed to reflect homogeneous hydraulic properties. Additionally, hydraulic properties in the aquifers were assumed to be transversely isotropic. Initial estimates of hydraulic properties were interpolated by analysis of available data. However, the interpolation process produces estimates of hydraulic properties that are less variable than the corresponding properties in nature.

Rivers and lakes are modeled using head dependent conditions and are represented in the numerical model using the MODFLOW river package. This representation permits water to flow from the stream into the aquifer or into the stream from the aquifer; however, it does not account for the amount of water in the river, thus a losing reach of a stream may produce more water than is physically possible.

Estimates of recharge in the Tri-County regional ground water flow model were adjusted on the basis of the -19.7 percent (CCCMA GCM adjustments) and 4.1 percent (Hadley GCM adjustments) differences in base flow and the model was then used with wells pumping at 1995 and 2030 rates, as estimated in the section, Description of Study Area. This is an idealized approach that does not capture transient changes in ground water conditions at seasonal, monthly, or daily time scales, which may be more pronounced than changes averaged annually using a steady state model. Water use and withdrawal tend to be reasonably uniform and therefore a steady state approximation is appropriate in determining the impacts of withdrawals on ground water conditions. For ground water recharge, however, changes at seasonal and monthly scales are expected with altered climates due to shifting patterns of snow accumulations and melting. Thus, this approach to modifying steady state recharge in the Tri-County model preserves present timing of variations in recharge while altering the absolute magnitudes, and serves only as a preliminary estimate of climate change effects on ground water.

RESULTS

Changes in ground water levels, as well as changes in flow to river cells within Lansing Township, were compared for both the CCCMA and Hadley GCM predictions under each pumping scenario. Model simulations using the 19.7 percent decrease in base flow to streams predicted by the CCCMA GCM resulted in declines in ground water levels from the reference condition in both the glacial deposits and in the Saginaw aquifer in the Tri-County region (see Table 1 and Figures 6 and 7). These changes in ground water levels were greater when pumping rates were increased to those projected for future demands (Figures 8 and 9). Within Lansing Township, where most ground water is withdrawn from the Saginaw aquifer, water levels in the Saginaw aquifer declined 0.3 to 1.2 m (1 to 4 ft) from the reference condition under 1995 pumping rates and 0.3 to 2.3 m (1 to 7.6 ft) from the reference condition under projected future (2030) pumping rates. Because simulated pumping remained the same between the base case and the altered climate ground water simulations in each comparison, these changes can be attributed to changes in recharge.

The 4.1 percent increase predicted by the Hadley GCM resulted in a rise in ground water levels from the reference condition in both the glacial deposits and the Saginaw aquifer. Under 1995 pumping conditions, water levels were higher under the Hadley GCM conditions than under the reference condition as

TABLE 1. Changes* in Ground Water Levels in the Glacial and Saginaw Aquifers.

Climate Scenarios	Changes in Ground Water Levels			
	1995 Pumping Rates		Future Pumping Rates	
CCCMA Predictions – Layer 1	0.0 to 2.7 m 0.0 to 8.9 ft	(64 cm) (2.1 ft)	0.0 to 3.5 m 0.0 to 11.5 ft	(64 cm) (2.1 ft)
CCCMA Predictions – Layer 2	0.0 to 2.6 m 0.0 to 8.5 ft	(61 cm) (2.0 ft)	0.0 to 2.6 m 0.0 to 8.5 ft	(64 cm) (2.1 ft)
Hadley Predictions – Layer 1	-55 to 0.0 cm -1.8 to 0.0 ft	(-12 cm) (-0.4 ft)	-82 to 0.0 cm -2.7 to 0.0 ft	(-12 cm) (-0.4 ft)
Hadley Predictions – Layer 2	-52 to 0.0 cm -1.7 to 0.0 ft	(-12 cm) (-0.4 ft)	-52 to 0.0 cm -1.7 to 0.0 ft	(-12 cm) (-0.4 ft)

*Positive changes indicate *decreases* in ground water levels, negative changes indicate *increases* in ground water levels; average values are enclosed in parentheses.

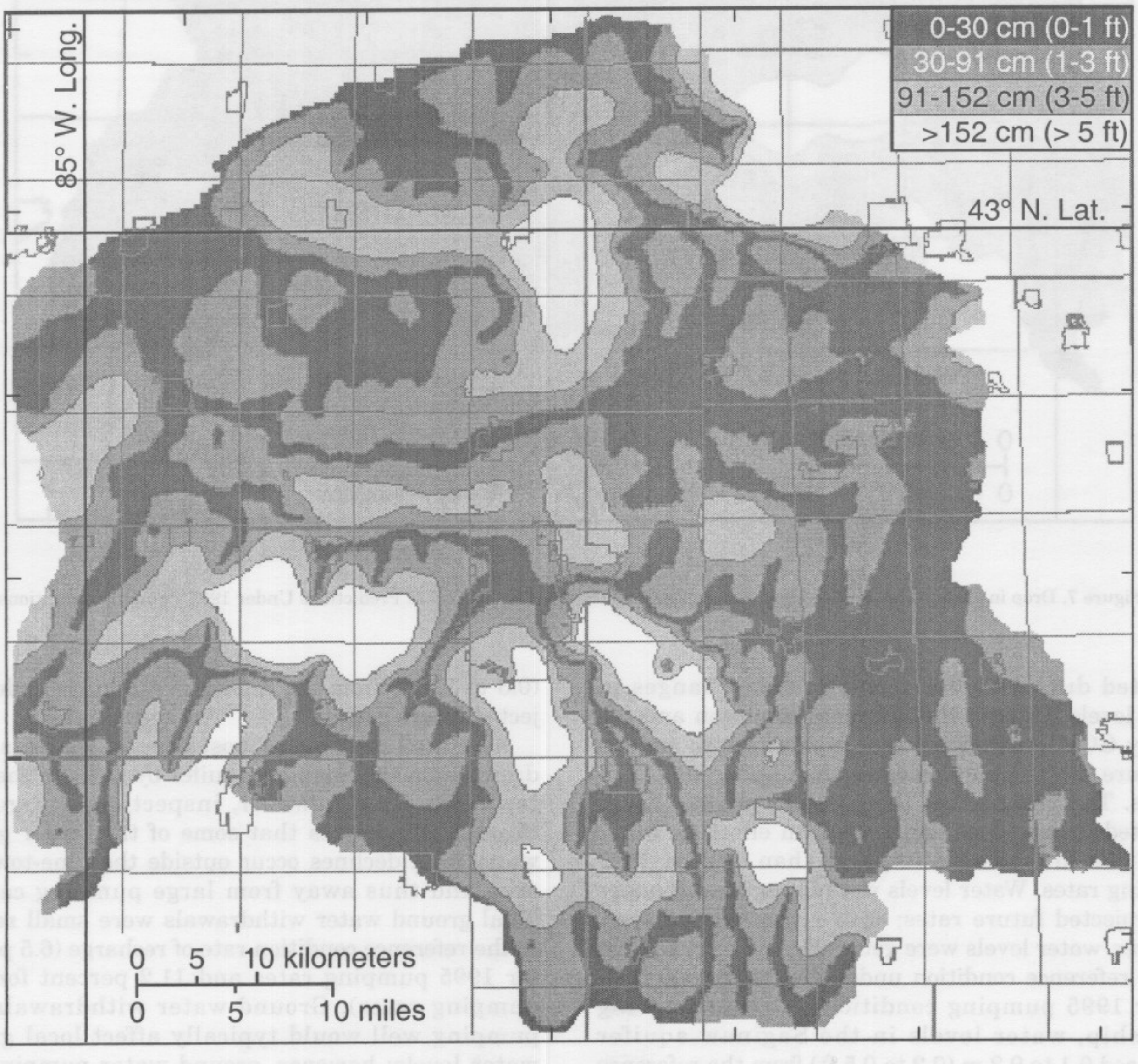

Figure 6. Drop in Head in Layer One From Reference Conditions to CCCMA GCM Predictions Under 1995 Pumping Conditions.

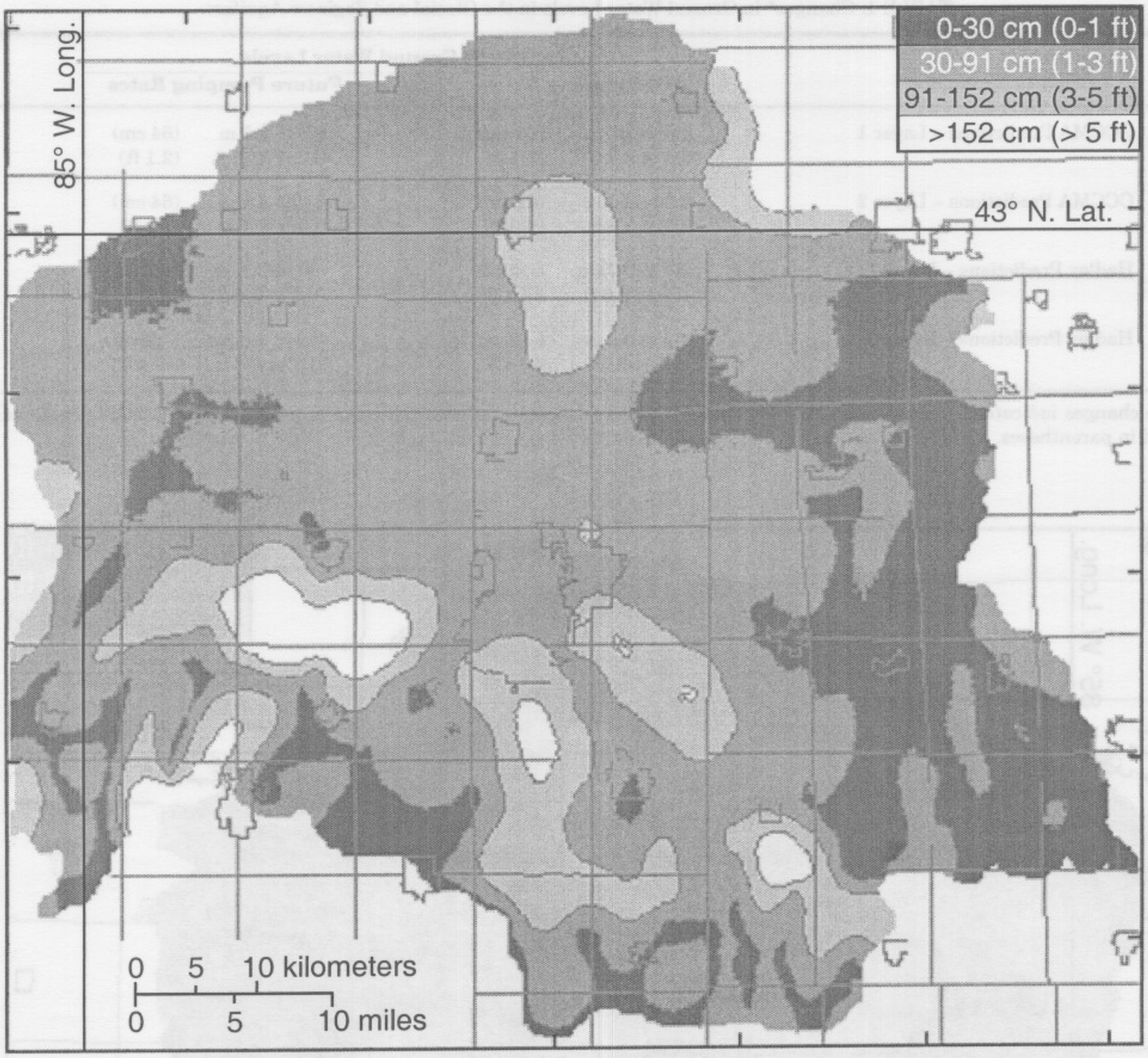

Figure 7. Drop in Head in Layer Two From Reference Conditions to CCCMA GCM Predictions Under 1995 Pumping Conditions.

expected due to higher recharge. The changes in water levels between the reference condition and the Hadley GCM predictions were greater under projected future (2030) pumping rates than under 1995 conditions. This means that the greater pumping under projected future rates had less of an effect on water levels due to increased recharge than did the 1995 pumping rates. Water levels were lower overall under the projected future rates; with increased recharge, however, water levels were generally higher compared to the reference condition under the 2030 rates than under 1995 pumping conditions. Within Lansing Township, water levels in the Saginaw aquifer increased 0.1 to 0.2 m (0.2 to 0.5 ft) from the reference condition under 1995 pumping rates and 0.1 to 0.3 m (0.3 to 1.0 ft) from the reference condition under projected future rates.

As stated previously most ground water is withdrawn from the Saginaw aquifer by wells in the nine-township area; however, inspection of Figures 6 through 9 indicates that some of the larger ground water level declines occur outside the nine-township area and thus away from large pumping centers. Total ground water withdrawals were small relative to the reference condition rate of recharge (6.5 percent for 1995 pumping rates and 11.2 percent for 2030 pumping rates). Ground water withdrawals by a pumping well would typically affect local ground water levels; however, ground water pumping also causes a diversion to the well of water that was

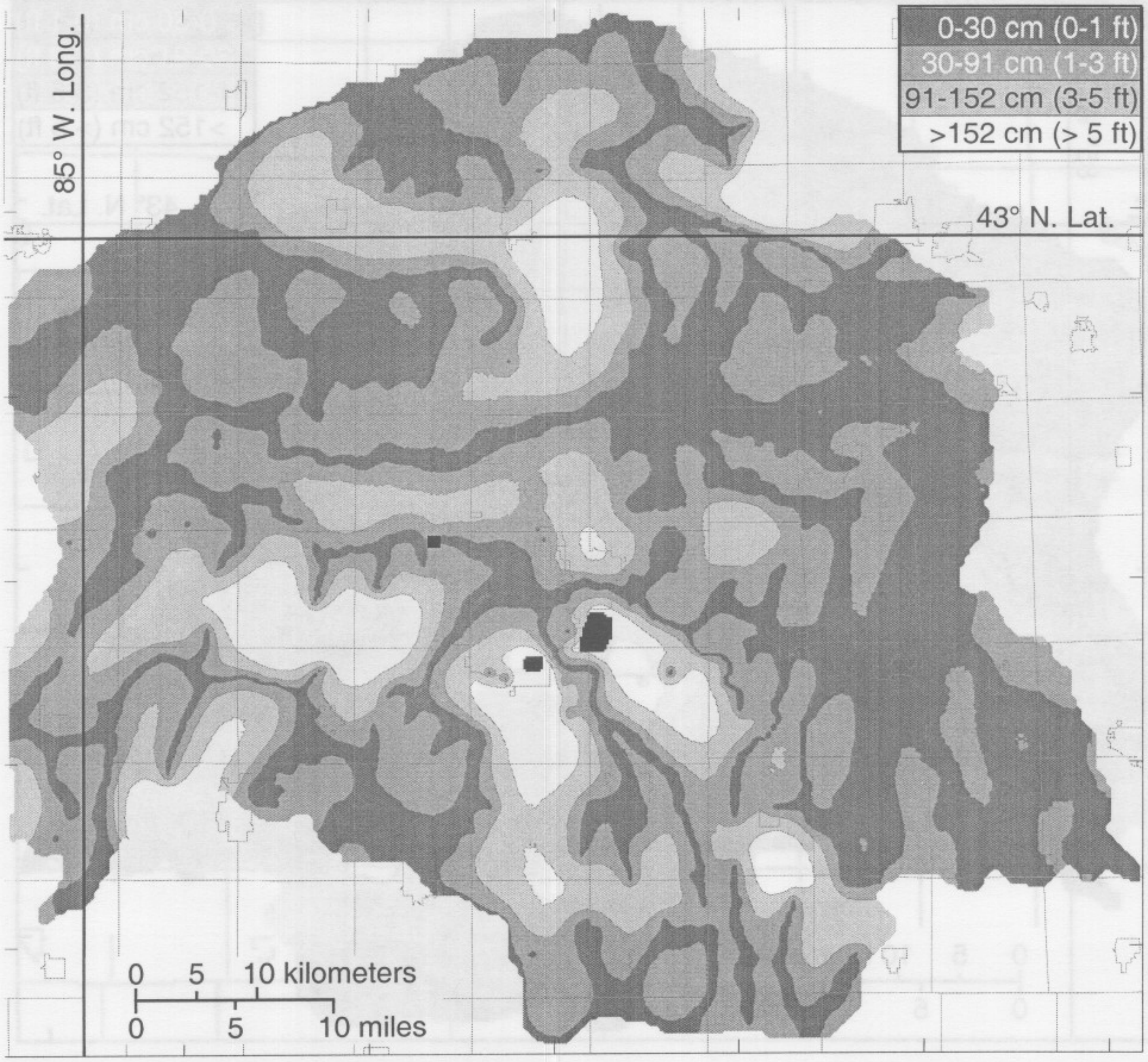

Figure 8. Drop in Head in Layer One From Reference Conditions to CCCMA GCM Predictions Under Projected 2030 Pumping Conditions (black areas depict dry cells).

moving to its natural, and possibly distant, area of discharge. Ground water levels are a function not only of the discharge rate of the well, but also the transmitting properties of the aquifers and confining units, distance to ground water system boundaries, and the spatial distribution of recharge (Alley *et al.,* 1999). Thus pumping of many wells can have regionally significant effects on ground water levels. Stresses on the aquifer by changes in recharge rates and increases in pumping can have unexpectedly nonuniform effects. For example, reduced recharge from precipitation has caused more water to be induced from streams, thus creating the bull's eye patterns from pumping in Figures 6 through9. These effects will be most pronounced where areal recharge rates are low and the hydraulic properties of the aquifers and confining units are low.

Changes in recharge rates combined with increased pumping rates projected for future demands led to dewatering of some areas within the glacial deposits. For the reference condition, areas of about 1 km^2 (0.4 mi^2) south and west of Lansing were dewatered during model simulations. An area of about 0.5 km^2 (0.2 mi^2) was dewatered in the same general location in the simulation of the Hadley predictions despite an increase in recharge. For the simulation of the CCCMA predictions, areas of about 4.4 km^2 (1.7 mi^2) to the south, west, and southeast of Lansing were dewatered during model simulations.

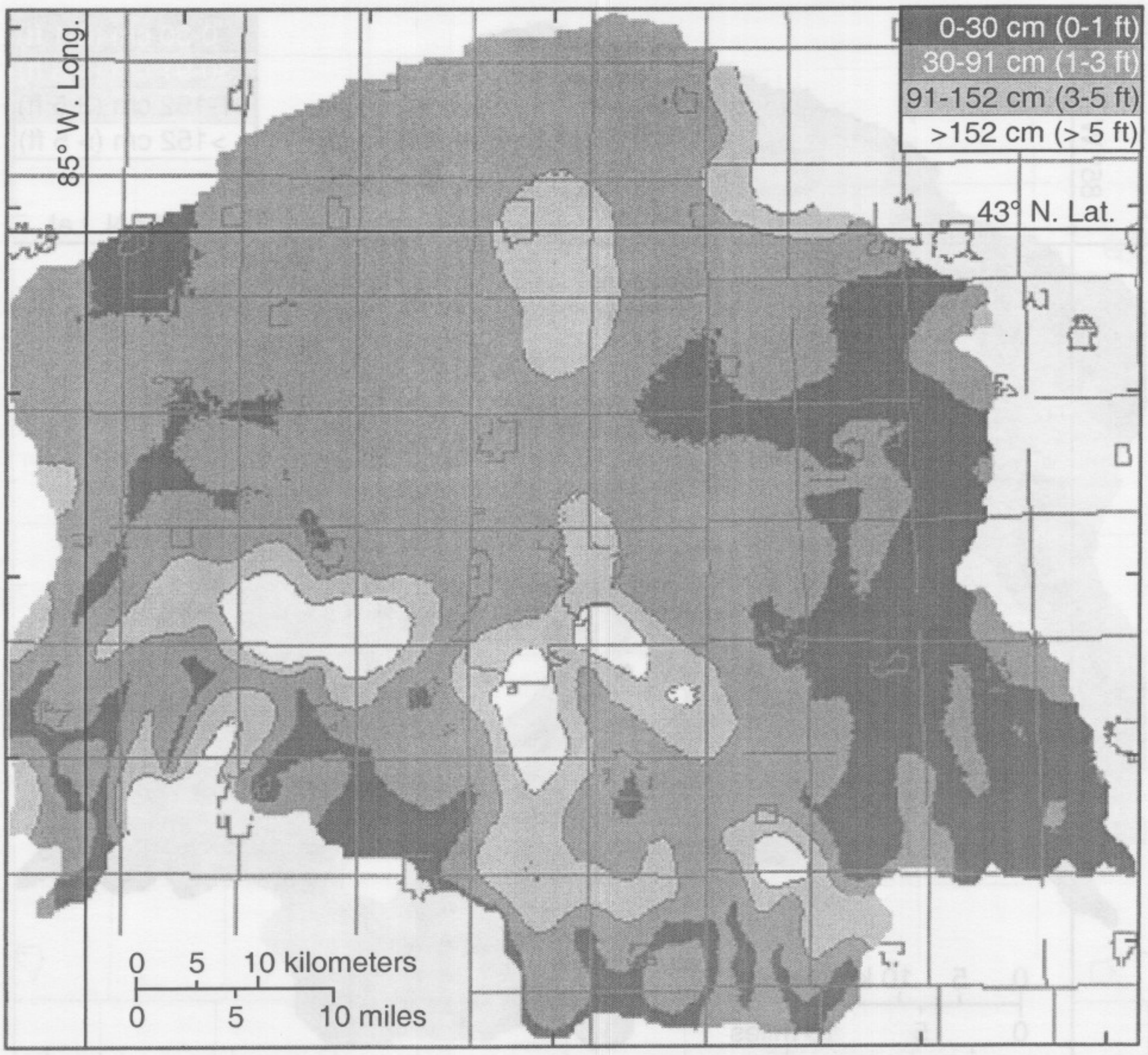

Figure 9. Drop in Head in Layer Two From Reference Conditions to CCCMA GCM Predictions Under Projected 2030 Pumping Conditions.

Flow through river cells was investigated to determine the possible impacts of changes in pumping under the same recharge conditions and changes in recharge under the same pumping conditions (Table 2). Changes in flow to river cells due to an increase in pumping from 1995 to 2030 rates were determined for the reference, CCCMA, and Hadley scenarios. Changes in flow to river cells due to changed recharge were determined from the reference to the CCCMA scenario and from the reference to the Hadley scenario. Percent differences for river flow in the model area were determined by using model budget summaries and in Lansing Township by using flow through the faces of 117 cells comprising portions of the Grand River, Red Cedar River, and Sycamore Creek (see Figure 5). With increased pumping, flow to river cells in the model area and in Lansing Township decreased under each climate scenario. With a decrease in recharge, flow to river cells in the model area and in Lansing Township decreased under both 1995 and projected future rates. With an increase in recharge, flow to river cells in the model area and in Lansing Township increased under 1995 and projected future rates. Because net flows through cells were used, decreases greater than 100 percent indicate a situation in which a river cell changed from gaining to losing. However, because actual streamflows were not considered further, work is needed to determine

TABLE 2. Percent Changes* in Flow to River Cells.

	Increase in Pumping From 1995 to Future Pumping Rates			Decrease in Recharge From Reference Conditions to CCCMA GCM Conditions		Increase in Recharge From Reference Conditions to Hadley GCM Conditions	
River Cells	**Reference Condition**	**CCCMA GCM**	**Hadley GCM**	**1995 Pumping Rates**	**Future Pumping Rates**	**1995 Pumping Rates**	**Future Pumping Rates**
Tri-County Model Area	-5.5	-7.1	-5.3	-22.1	-23.4	4.6	4.9
Lansing Township	-71.0	-104.6	-66.6	-32.2	-110.8	6.3	22.5

*Positive changes indicate *increased* flow to river cells, negative changes indicate *decreased* flow to river cells.

whether this change in flows is realistic because a losing reach could lose more water than is being carried in the stream.

The accuracy of the model is limited by the data available to estimate the transmissivity of the Saginaw aquifer, the horizontal hydraulic conductivity of the glacial deposits, and the vertical hydraulic conductivity between the Saginaw aquifer and the glacial deposits. The Tri-County model simulates the regional response of the Saginaw aquifer to changes in withdrawals and recharge. Ground water flow in the glacial deposits was modeled to support analysis of flow in the Saginaw aquifer. Local flows over distances smaller than the dimensions of the grid cell cannot be represented accurately. Additional geologic and hydrologic data, as well as finer discretization of the model, would be needed to simulate local flow systems.

The response of the ground water system depicted in these simulations depends on the particular stress pattern described (different ground water withdrawal amounts or locations would result in a different distribution of ground water levels) and represents steady-state conditions. Under steady state conditions, stresses such as ground water pumping and recharge are constant; in reality, however, ground water withdrawals and recharge can vary temporally, both seasonally and annually, and spatially. Local variations in recharge rates, for example those associated with impermeable surfaces, are not accounted for in the model. One potential climate change effect, the changes in ground water recharge, was investigated in this study in order to illustrate potential effects on ground water levels and flow, to demonstrate that development of ground water resources affects surface water resources, and to show that the potential effects of future climate changes differ. Other effects of climate change that were not modeled in this study include more severe or longer lasting droughts, changes in vegetation resulting in changes in evapotranspiration, and possible increased demands for ground water or surface water as a backup source of water supply (Alley *et al.*, 1999).

Based on available climate change estimates, this preliminary analysis suggests that ground water should be managed from the perspective of an anticipated broad range of climate possibilities that may result from global warming. It would be insufficient to merely plan for drier conditions. With changes in ground water levels, ground water managers may need to consider well reconstruction, alternative sources of supply, or changes in water quality resulting from different ground water source areas. With changes in base flow to streams, other factors may need to be considered. These include the effects of reduced or increased flows on aquatic habitat, the effects of reduced or increased water quality on aquatic habitat, and the effects of flows on lakes (such as lake level and shoreline changes). Earlier studies of this type in the Great Lakes (with other GCM simulations of global warming) all indicate decreases in streamflow. The estimates of future climates differ in their forecasts of the direction, magnitude, and timing of changes. Coupled with the assumptions used in the approach taken here (which preserve current timing of changes while allowing variations in magnitude), the evaluation of impacts associated with global warming, estimated from available GCMs, should be viewed as preliminary only.

SUMMARY

The potential impacts of selected climate change projections on streamflow and ground water levels in the Lansing, Michigan, area were assessed by the USGS and NOAA by using a sequence of computer simulations. Monthly mean data from GCM runs (with increasing carbon dioxide content and sulfate aerosol concentrations) were acquired from the Canadian Centre for Climate Modeling and Analysis

(CCCMA) and from the Hadley Centre for Climate Prediction and Research. Variables derived from the GCM runs were used in GLERL's hydrologic modeling system to generate streamflow estimates for the Grand River. The base flow portion of total streamflow was determined from simulations with historical data from 1954 through 1995 modified with GCM generated adjustments for the 1961 through 1990 reference period and for the 20 years centered on 2030 for the changed climate condition. Ground water recharge estimates used in the Tri-County model, developed to simulate the regional steady state response of the Saginaw aquifer, were adjusted by the percent difference in base flows between the reference condition and each of the GCM changed climate predictions. This resulted in a 19.7 percent decrease in recharge using the CCCMA GCM predictions and a 4.1 percent increase using the Hadley GCM predictions. Changes in ground water levels and flows through river cells were compared for each GCM prediction using 1995 and projected 2030 pumping rates in the ground water model of aquifers near Lansing, Michigan.

Ground water levels in both the glacial and Saginaw aquifers declined from reference conditions levels under both pumping conditions when recharge rates were decreased by the 19.7 percent predicted by the CCCMA GCM. Some areas within the glacial deposits were dewatered under the increased pumping conditions. Water levels in both the glacial and Saginaw aquifers increased slightly over reference condition levels under both pumping conditions when recharge rates were increased by the 4.1 percent predicted by the Hadley GCM. Some areas within the glacial deposits were dewatered under the increased pumping conditions. Flow through river cells decreased as recharge was decreased for the CCCMA GCM predictions and increased slightly as recharge was increased for the Hadley GCM predictions.

ACKNOWLEDGMENTS

This is GLERL Contribution No. 1198. The Tri-County regional ground water flow model was developed in cooperation with the Tri-County Regional Planning Commission and a coalition of 22 communities in the Tri-County region. The GCM results and their transference to hydrological impacts for change climates with GLERL's hydrology models were part of the work undertaken by the Great Lakes Regional Assessment Team regarding the potential impacts of future climate change and variability in the Great Lakes region. It complements work being prepared by the National Assessment Synthesis Team as part of the National Assessment of Climate Change conducted by the U.S. Global Change Research Program.

LITERATURE CITED

Alley, W. M., T. E. Reilly, and O. L. Franke, 1999. Sustainability of Ground-Water Resources. U.S. Geological Survey Circular 1186, 79 pp.

Allsopp, T. R. and S. J. Cohen, 1986. CO_2-Induced Climate Change and Its Potential Impact on the Province of Ontario. *In:* Preprint Volume, Conference on Climate and Water Management – A Critical Era. American Meteorological Society, Boston, Massachusetts, pp. 285-290.

Boer, G. J., G. M. Flato, M. C. Reader, and D. Ramsden, 2000a. A Transient Climate Change Simulation with Greenhouse Gas and Aerosol Forcing: Experimental Design and Comparison With the Instrumental Record for the 20th Century. Climate Dynamics 16(6):405-425.

Boer, G. J., G. M. Flato, and D. Ramsden, 2000b. A Transient Climate Change Simulation With Greenhouse Gas and Aerosol Forcing: Projected Climate for the 21st Century. Climate Dynamics16(6):427-450.

Cohen, S. J., 1986. Impacts of CO_2-Induced Climatic Change on Water Resources in the Great Lakes Basin. Climatic Change 8:135-153.

Cohen, S. J., 1990. Methodological Issues in Regional Impacts Research. *In:* Proceedings of an International Symposium/Workshop on Climate Change, Implications for Water and Eco-logical Resources, G. Wall and M. Sanderson (Editors). Department of Geography Publication Series, Occasional Paper No. 11, University of Waterloo, Waterloo, Ontario, pp. 31-43.

Cohen, S. J., 1991. Caveats in Applying GCM Output to Regional Impact Assessments. Proceedings of A Symposium on Climate Scenarios, The Water Network, University of Waterloo, Waterloo, pp. 16-32.

Croley II, T. E., 1990. Laurentian Great Lakes Double-CO2 Climate Change Hydrological Impacts. Climatic Change 17:27-47.

Croley II, T. E., 1992. Climate Change Impacts on Great Lakes Water Supplies. Proceedings of the Symposium on Managing Water Resources During Global Change, 28th American Water Resources Association Conference, pp. 241-250.

Croley II, T. E., 1993. Probabilistic Great Lakes Hydrology Outlooks. Water Resources Bulletin 29(5):741-753.

Croley II, T. E., F. H. Quinn, K. E. Kunkel, and S. A. Changnon, 1998. Great Lakes Hydrology Under Transposed Climates. Climatic Change 38:405-433.

Hartmann, H. C., 1990. Climate Change Impacts on Laurentian Great Lakes Levels. Climatic Change 17:49-67.

Holtschlag, D. J., 1994. A Generalized Estimate of Ground-Water Recharge Rates in the Lower Peninsula of Michigan. U.S. Geological Survey Water-Supply Paper 2437, 81 pp.

Holtschlag, D. J, C.L. Luukkonen, and J. R. Nicholas, 1996. Simulation of Ground-Water Flow in the Saginaw Aquifer, Clinton, Eaton, and Ingham Counties, Michigan. U.S. Geological Survey Water-Supply Paper 2480, 49 pp.

Johns, T. C., R. E. Carnell, J. F. Crossley, J. M. Gregory, J. F. B. Mitchell, C. A. Senior, S. F. B. Tett, and R. A. Wood, 1997. The Second Hadley Centre Coupled Ocean-Atmosphere GCM: Model Description, Spinup and Validation. Climate Dynamics 13:103-134.

Lofgren, B. M., F. H. Quinn, A. H. Clites, R. A. Assel, and A. J. Eberhardt, 2000. Water Resources. *In:* Preparing for a Changing Climate: the Potential Consequences of Climate Variability and Change, Peter J. Sousounis and Jeanne M. Bisanz (Editors). University of Michigan, Ann Arbor, Michigan, pp. 29-37.

Loaiciga, H. A., D. R. Maidment, and J.B. Valdes, 2000. Climate-Change Impacts in a Regional Karst Aquifer, Texas, USA. Journal of Hydrology 227:173-194.

Luukkonen, C. L., 1995. Ground-Water Withdrawals in Clinton, Eaton, and Ingham Counties, Michigan. U.S. Geological Survey Fact Sheet 226-295.

Luukkonen, C. L., N. G. Grannemann, and D. J., Holtschlag, 1997. Ground-Water Flow in the Saginaw Aquifer in the Vicinity of the North Lansing Well Field, Lansing, Michigan – Part 2: Simulations With a Regional Model Using a Reduced Cell Size. U.S. Geological Survey Open-File Report 97-570, 25 pp.

Mandle, R. J. and D. B. Westjohn, 1988. Geohydrologic Framework and Ground-Water Flow in the Michigan Basin. *In:* Regional Aquifer Systems for the United States, Aquifers of the Midwestern Area, L. A. Swain and A. L. Johnson (Editors). AWRA Monograph Series 13, American Water Resources Association, Middleburg, Virginia, pp. 83-109.

McDonald, M. G. and A. W. Harbaugh, 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. U.S. Geological Survey Techniques of Water Resources Investigations, Book 6, Chapter A1, 576 pp.

Quinn, F. H., 1988. Likely Effects of Climate Changes on Water Levels in the Great Lakes. *In:* Proceedings, First North American Conference on Preparing for Climate Change, Climate Change Institute, Washington, D.C., pp. 481-487.

Quinn, F. H. and T. E. Croley II, 1983. Climatic Water Balance Models for Great Lakes Forecasting and Simulation. *In:* Preprint Volume: Fifth Conference on Hydrometeorology, American Meteorological Society, Boston, Massachusetts, pp. 218-223.

Quinn, F. H., T. E. Croley II, K. E. Kunkel, and S. J. Changnon, 1997. Laurentian Great Lakes Hydrology and Lake Levels Under the Transposed 1993 Mississippi River Flood Climate, Journal of Great Lakes Research 23(3):317-327.

Reader, M. C. and G. J. Boer, 1998. The Modification of Greenhouse Gas Warming by the Direct Effect of Sulphate Aerosols. Climate Dynamics 14:593-607.

Rutledge, A. T., 1998. Computer Programs for Describing the Recession of Ground-Water Dis-charge and for Estimating Mean Ground-Water Recharge and Discharge from Streamflow Records – Update. U.S. Geological Survey Water Resources Investigations Report 98-4148, 43 pp.

Sousounis, P. J. and G. M. Albercook, 2000. Potential Futures. *In:* Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change, Peter J. Sousounis and Jeanne M. Bisanz (Editors). University of Michigan, Ann Arbor, Michigan, pp. 19-24.

Tri-County Regional Planning Commission, 1992. Tri-County Regional Water Feasibility Study. Burns and McDonnell, Snell Environmental Group, and Dickinson, Wright, Moon, Van Buren, and Freeman Report 90-338-4-005.

U.S. Department of Commerce, 1991. 1990 Census of Population and Housing: Summary Population and Housing Characteristics for Michigan. Bureau of the Census, Economics and Statistics Administration Report 1990 CPH-1-24.

USEPA (U.S. Environmental Protection Agency), 1984. Potential Climatic Impacts of Increasing Atmospheric CO_2 With Emphasis on Water Availability and Hydrology in the United States. U.S. EPA Office of Policy, Planning, and Evaluation, Washington, D.C.

USEPA (U.S. Environmental Protection Agency), 1989. The Potential Effects of Global Climate Change on the United States. Report to Congress. J. B. Smith and D. A. Tirpak (Editors). Report EPA-230-05-89-050, EPA Office of Policy, Planning, and Evaluation, Washington, D.C.