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BULLETIN 98 • 2000

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Published by and available from

Wisconsin Geological and Natural History Survey
3817 Mineral Point Road • Madison, Wisconsin 53705-5100
☎ 608/263.7389 FAX 608/262.8086 http://www.uwex.edu/wgnhs/

James M. Robertson, *Director and State Geologist*

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ABSTRACT

We developed a three-dimensional groundwater flow model to simulate and assess the effects of current and potential groundwater withdrawals. The model was constructed as part of the Dane County hydrologic study, initiated in 1992 and conducted cooperatively by the Wisconsin Geological and Natural History Survey, the Dane County Regional Planning Commission, and the U.S. Geological Survey.

Three aquifer units underlie Dane County: a shallow, unlithified sand and gravel aquifer, an upper bedrock aquifer, composed of Cambrian and Ordovician sandstone and dolomite underlying the unlithified deposits, and a lower bedrock aquifer of Cambrian sandstone of the Eau Claire and the Mount Simon Formations. A shale layer that is part of the Eau Claire Formation serves as a confining unit separating the upper and lower bedrock aquifers. This confining unit is largely absent in the preglacially eroded valleys of the Yahara Lakes area and the northeastern part of Dane County. Precambrian crystalline basement rock forms the impermeable base of the groundwater flow system.

We used the U.S. Geological Survey groundwater flow model code, MODFLOW, to construct the Dane County groundwater flow model. Boundary conditions for the MODFLOW model were determined by using a screening model. Model input was obtained from published and unpublished geologic and hydrologic data and from recent estimates of aquifer hydraulic conductivities and groundwater recharge rates made earlier in the Dane County hydrologic study. We also simulated pumpages from a total of 93 high-capacity wells; these wells withdrew 48.5 million gallons per day in 1992.

Model calibration included a comparison of modeled and field-measured water levels and field-measured stream flows to simulated stream gains and losses. Water levels calculated by the calibrated model compared favorably to most measured water levels. Simulated stream gains and losses are below the 80 to 50 percent flow duration at most of the 15 sites where flow duration was estimated.

On the basis of our calibrated model, 89 percent of flow into the aquifer system resulted from recharge and 11 percent from lake and stream seepage; 88 percent of the flow out of the aquifer system was to rivers and streams, and 12 percent was captured by pumping wells.

We compared a simulation of conditions prior to urban development to the calibrated 1992 model simulation. The maximum water-level decline was 60 ft in the vicinity of Madison, which compares favorably to measured water-level decline; stream losses from predevelopment to 1992 were similar to the amount of groundwater pumped by wells in 1992. This indicates that groundwater withdrawn by Dane County wells is groundwater that would have discharged to streams and lakes under predevelopment conditions.

INTRODUCTION

Growing concern in Dane County, Wisconsin (fig. 1), over the effects of rapid urban growth and development on groundwater and surface-water resources requires an improved understanding of the effects of urbanization and associated increased groundwater withdrawals on local water resources. Groundwater is the sole drinking-water supply for county residents, and it sustains area lakes, streams, and wetlands. High-capacity wells located throughout the county supplied nearly 50 million gallons per day in 1992 (fig. 1). Urban and county planners are faced with making decisions that balance the need for increased groundwater withdrawals with maintaining the quantity and quality of groundwater-fed surface-water resources.

Large groundwater withdrawals from aquifers underlying the urban area in central Dane County have lowered water levels and induced cones of depression in the deep bedrock aquifers. Declining groundwater levels have decreased base flow to streams and lakes, dewatered wetlands, and increased the vulnerability of municipal wells to contamination. For example, the flow in the Yahara River near McFarland has been reduced by 50 cubic feet per second (ft^3/sec), or by about one-third of the previous total flow, as a result of pumping and subsequent wastewater diversion (fig. 2). Also, it appears that pumping from city of Madison wells and high-capacity private wells has diminished flow to the West Branch of Starkweather Creek below the Dane County Regional Airport and to the main stem of the creek (Dane County Regional Planning Commission, 1983).

There is evidence that the large groundwater withdrawals concentrated in central Dane County have an effect on regional and local groundwater flow. For example, the expanding cone of depression appears to have shifted the regional groundwater divide on the west side of the Madison area farther to the southwest, causing groundwater that previously discharged to the Sugar River to be diverted to the Yahara River basin. Diversion of groundwater may be occurring in other adjacent river basins as well. In the Madison area, the original direction of groundwater flow (toward the lakes and the Yahara River) has been reversed in the areas of heaviest groundwater use (Cline, 1965, p. 41). This heavy municipal pumping also has lowered water levels in deeper aquifers, creating downward leakage of shallow groundwater and surface water into deeper bedrock aquifers, which may be inducing flow of associated contaminants to some municipal wells. Analyses of water from city of Madison wells have indicated that sodium and chloride concentrations have increased over the past 30 to 40 years. The highest concentrations of these constituents have been found in three downtown wells that are no longer used. Sodium concentrations in these wells exceed the federal advisory level of 20 mg/L (U.S. Environmental Protection Agency, 1996). In addition, volatile organic chemicals have been detected in some private wells and in some deep municipal wells (Dane County Regional Planning Commission, 1999).

McLeod (1975a, 1975b) used a simple finite-difference model and superposition techniques to simulate the groundwater system in Dane County. He calibrated the flow model to steady-state 1970 drawdowns. In his report, McLeod predicted drawdowns from municipal well pumping in central Dane County on the basis of projections of future groundwater withdrawals and wastewater diversions.

McLeod's groundwater flow model, although adequate for its day, needs to be updated for several reasons. Hydrologic data collected since McLeod's groundwater flow

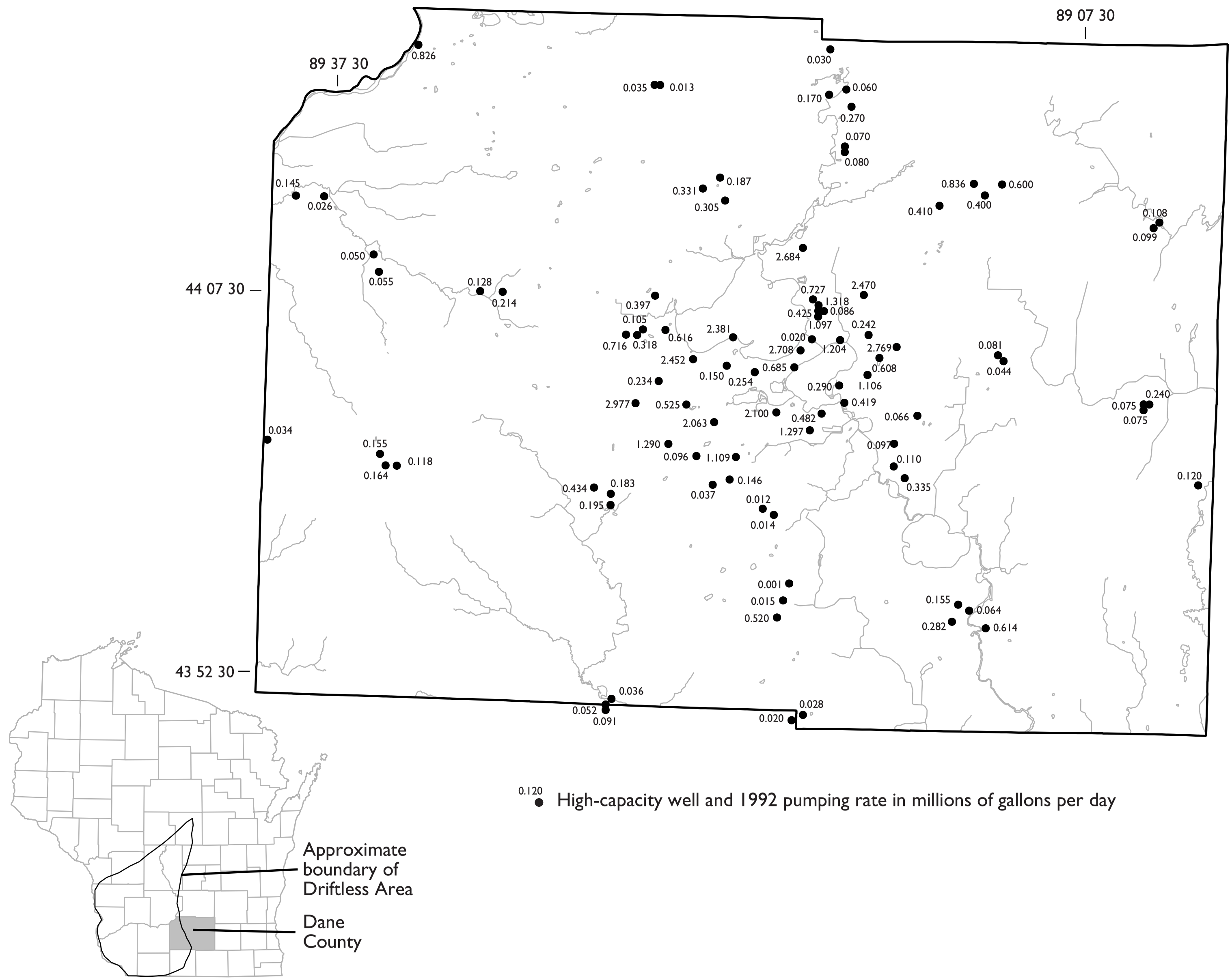
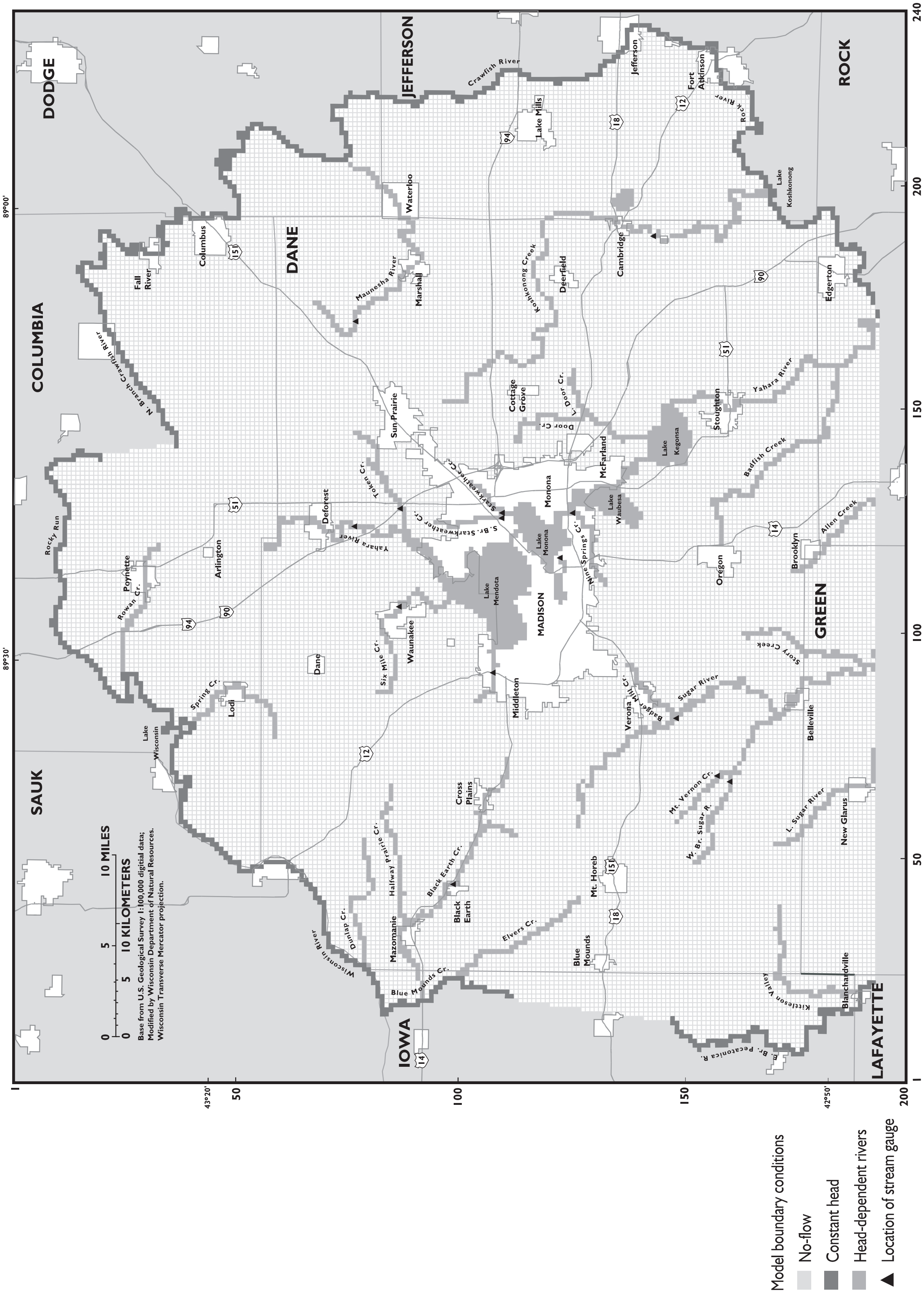


Figure 1. Location of Dane County, approximate boundary of Driftless Area, and high-capacity wells with 1992 pumping rates.



Model boundary conditions
No-flow
Constant head
Head-dependent rivers
Location of stream gauge
Base from U.S. Geological Survey 1:100,000 digital data; Modified by Wisconsin Department of Natural Resources. Wisconsin Transverse Mercator projection.
0 5 10 MILES
0 5 10 KILOMETERS
DODGE
COLUMBIA
SAUK
JEFFERSON
DANE
ROCK
GREEN
IOWA
LAFAYETTE
MADISON
Lake Mendota
Lake Monona
Lake Waubesa
Lake Kegonsa
Lake Koshkonong
Lake Wisconsin
Wisconsin River
Yahara River
Sugar River
Crawfish River
Rock River
Maunesha River
Koshkonong Creek
Badfish Creek
Token Cr.
Six Mile Cr.
Black Earth Cr.
Mt. Vernon Cr.
W. Br. Sugar R.
L. Sugar River
Allen Creek
Story Creek
Elvers Cr.
Blue Mounds Cr.
Halfway Prairie Cr.
Dunlap Cr.
E. Br. Pecatonica R.
Kittleson Valley
Badger Mill Cr.
Verona Cr.
Nine Springs Cr.
Starkweather Cr.
S. Br. Starkweather Cr.
Door Cr.
L. Door Cr.
Rowan Cr.
Spring Cr.
Rocky Run
N. Branch Crawfish River
Columbus
Fall River
Waterloo
Marshall
Lake Mills
Jefferson
Fort Atkinson
Cambridge
Deerfield
Cottage Grove
Sun Prairie
Deforest
Poynette
Arlington
Lodi
Dane
Waunakee
Middleton
Monona
McFarland
Stoughton
Edgerton
Oregon
Brooklyn
Belleville
Verona
Cross Plains
Black Earth
Mazomanie
Mt. Horeb
Blue Mounds
New Glarus
Blanchardville
89°00'
89°30'
43°20'
42°50'

model was developed have improved the conceptualization of the groundwater flow system in Dane County. Recent modifications and additions to groundwater flow model codes allow for a more complete simulation of groundwater systems and associated hydrologic features. Computer technology now allows high-resolution models to be developed. These large models and the software needed to pre- and post-process the data sets run rapidly on today's computers.

PURPOSE AND SCOPE

Planners and regulators need a flexible and sophisticated model that can help identify major areas of groundwater recharge and discharge, estimate the amount of groundwater discharging to surface-water bodies, and predict groundwater flow rates. This model would be an important tool for assessing effects of existing and potential groundwater withdrawals as well as the effects of proposed water-management programs.

The purposes of the Dane County regional hydrologic study, which began in 1992, were to improve the understanding of the groundwater system and its relation to surface water, update the last comprehensive groundwater-resource assessment (Cline, 1965), and to develop a groundwater flow model for use in future water-resource-management decision making on an ongoing basis. The study, conducted cooperatively by the Wisconsin Geological and Natural History Survey (WGNHS), the Dane County Regional Planning Commission (DCRPC), and the U.S. Geological Survey (USGS), is divided into three phases: 1) refining the conceptual understanding of the groundwater system and establishing a hydrogeologic database; 2) developing and calibrating a three-dimensional groundwater flow model; and 3) determining how proposed land-use and management strategies might affect water resources. This report represents phase 2 of the study and in it, we describe the conceptual hydrogeologic model, the methods used in simulating flow, and the calibrated model and sensitivity analyses of the flow simulations.

The model area comprises Dane County and parts of eight adjacent counties in south-central Wisconsin (fig. 2). The area includes parts of other counties because the hydrologic boundaries needed to accurately simulate the groundwater system within Dane County are located outside of the county. Aquifer and confining-unit thicknesses and hydraulic properties were estimated only for Dane County. Average hydraulic conductivities and recharge rates based on Dane County data were used for the model area outside of Dane County. Throughout the model area, aquifer and confining-unit geometry was determined from published and unpublished information. Published maps were included in the following reports: Cline (1965), Borman (1976), Borman and Trotta (1975), Duvaul and others (1983), and Harr and Trotta (1978). In addition, unpublished data on file at the WGNHS from recent geologic logs and Wisconsin Department of Natural Resources well constructor's reports were used to revise existing maps covering the area within Dane County.

← **Figure 2.** Groundwater flow model finite-difference grid, showing model boundary conditions and locations of stream gauges, Dane County, Wisconsin.

ACKNOWLEDGMENTS

The authors thank Dane County municipalities and the Wisconsin Department of Natural Resources and other state agencies for their interest in the Dane County hydrologic study. Special appreciation is given to the Madison Metropolitan Sewerage District, Dane County Public Works, Madison Water Utility, and the city of Middleton for their support and interest.

STUDY METHODS

Prior to constructing the three-dimensional groundwater flow model, we developed a conceptual model of the system on the basis of previously collected data and the interpretation of data collected during phase 1 of the study. An analytic-element groundwater model (Strack, 1989) was used as a screening model to test hydrologic boundaries of the conceptual model. This method mathematically represents hydrologic features on the basis of their geometry and physical properties and then superimposes their cumulative effects. These features include rivers, streams, lakes, and pumping wells. Analytic-element methods were chosen over finite-difference methods for this screening model because the time-intensive discretization of a grid over the domain is avoided, and features can be easily added to or removed from the model. This process facilitates the assessment of system boundaries and relative importance of individual features.

MODFLOW, a block-centered finite-difference code that can simulate many aquifer types, was used to simulate the Dane County groundwater flow system in three dimensions. MODFLOW requires input arrays that describe hydraulic parameters such as hydraulic conductivity and recharge, top and bottom elevation of aquifers, and boundary conditions. Detailed discussion of MODFLOW and finite-difference methods is beyond the scope of this report; MODFLOW input requirements and theory are described in McDonald and Harbaugh (1988) and Anderson and Woessner (1992).

Creating the input arrays required by MODFLOW was a two-step process. First, maps such as those depicting aquifer top and bottom elevations were digitized. Second, these digitized maps were intersected with the model grid using ArcInfo®, a geographic information system, to format the model input arrays.

Because most high-capacity wells in Dane County are open to more than one aquifer, a multi-aquifer well function is required to estimate the amount of water contributed to the well from each aquifer. Briefly, simulation of the effects of multi-aquifer wells requires model input data consisting of pumping rates, the model layers to which a well is open, and the ratio of r_a/r_w, where r_w is the radius of the well and r_a is an effective radius defined as the radius of a circle around a well along which the head in the node open to the well is assumed to prevail. The amount of water flowing to a well tapping more than one aquifer and the composite head in the well are based on the transmissivities of the aquifers open to the well.

The MODFLOW package used to simulate the multi-aquifer well effects was developed by Michael McDonald (U.S. Geological Survey, written communication, 1983) and is based on a simplification of multi-aquifer formulations described by Bennett and others (1982) and Mandle and Kontis (1992). The MODFLOW multi-aquifer package was tested (A.L. Kontis, U.S. Geological Survey, written communication, 1996) by comparing results of a hypothetical aquifer simulation with results from the multi-aquifer well code described by Kontis and Mandle (1988).

CONCEPTUALIZATION OF THE GROUNDWATER SYSTEM

Before simulating the groundwater system, a conceptualization of the system is essential because it forms the basis for model development. The conceptualization is a necessary simplification of the natural system because inclusion of all the complexities of the natural system into a computer model is not feasible. Steps in the development of the conceptual model include 1) definition of aquifers and confining units, 2) identification of sources and sinks, and 3) identification and delineation of hydrologic boundaries encompassing the area of interest. The first two steps were accomplished by reviewing and interpreting existing and new geologic and hydrogeologic data. The third step was accomplished by using a screening model.

AQUIFERS AND CONFINING UNITS

Bradbury and others (1999) have defined three aquifers and one confining unit in the Dane County area. Their concept of the groundwater flow system is shown in figure 3. A shallow sand and gravel aquifer is made up of unlithified glacial and alluvial materials overlying the bedrock. Except in narrow alluvial valleys, the sand and gravel aquifer is thin or absent in the Driftless Area (figs. 1 and 3). The upper bedrock aquifer underlies the unlithified deposits and overlies the Eau Claire Formation. The upper bedrock aquifer includes, where present, the Sinnipee, Ancell, Prairie du Chien, and Tunnel City Groups and the Wonewoc Formation. A shale that is part of the Eau Claire Formation forms a confining unit. This confining unit is largely absent in preglacially eroded valleys of the Yahara Lakes area (Lakes Mendota, Monona, Waubesa, Wingra, and Kegonsa) and the northeastern part of Dane County. The Mount Simon Formation and sandstone of the lower part of the Eau Claire Formation form the lower bedrock aquifer that overlies Precambrian crystalline basement rock. The Precambrian rock is assumed to be impermeable and forms the lower boundary of the groundwater flow system.

Water enters the groundwater flow system as recharge to the water table. Recharge takes place primarily in upland areas, although rates of recharge vary across the landscape. As shown in figure 3, groundwater flow paths may be local or regional. Local flow systems, which have short flow paths, are common in the sand and gravel and upper bedrock aquifers; regional flow, which has longer flow paths, takes place in the lower bedrock aquifer. Some recharging water may move downward to the sand and gravel or upper bedrock aquifer, travel a short horizontal distance, and then move upward, discharging to a stream, lake, or wetland (see Elvers Creek area in fig. 3). A relatively small part of this recharge moves downward through the confining unit and into the lower bedrock aquifer. Because of the conductive nature of the lower bedrock aquifer and the presence of the nearly impermeable Precambrian rock that forms the lower boundary of the system, flow paths in the lower bedrock aquifer are primarily horizontal. Pumping wells capture part of the groundwater that under predevelopment conditions would have discharged to area lakes, streams, and wetlands. In places where large amounts of groundwater are withdrawn, streams and lakes may recharge the groundwater system.

DEFINITION OF HYDROGEOLOGIC BOUNDARIES

Proper definition of hydrologic boundaries is essential for a successful groundwater flow model. Such boundaries include perimeter boundaries (major rivers or divides) and internal boundaries (streams and lakes).

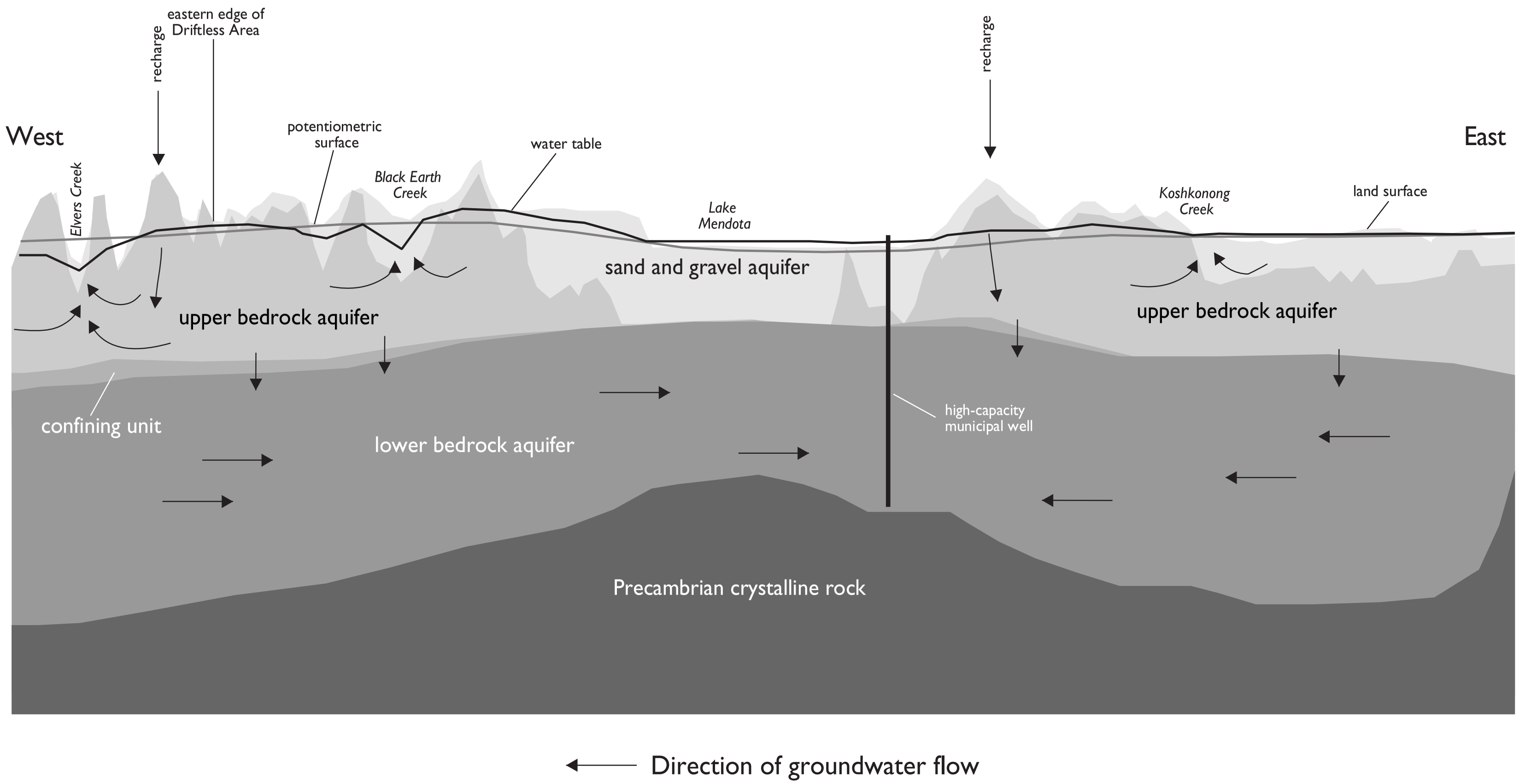


Figure 3. Conceptualized groundwater flow system (from Bradbury and others, 1999).

We developed an analytic-element model (Strack, 1989) to identify the boundary conditions needed to represent the regional system in Dane County. The analytic-element method is useful for this purpose because it allows rapid modifications to model boundaries.

Assumptions needed to develop the screening model, a simplified representation of the natural system, are that 1) the flow system is two-dimensional (vertical components of flow and the three-dimensional nature of the geologic deposits are ignored); 2) the recharge rate is uniform; 3) the aquifer system has uniform hydraulic conductivity; and 4) the system is at steady-state, that is, water levels are not changing over time. In addition, the screening model includes only a very coarse representation of surface-water features. Although the advantage of such simplification is that the model can be constructed with minimal time and data, the screening model is not generally suitable for extensive land-use planning or other future applications because of the limitations associated with these assumptions. This simplified model is able to serve, however, as a foundation upon which to build the more complex, realistic three-dimensional model.

The screening model was developed by digitizing surface-water features and assigning representative hydrologic properties. The model simulated the composite of the sand and gravel and bedrock aquifers as a single layer. Global uniform recharge was varied to obtain a reasonable fit for groundwater elevations and stream base flow measured in the area. Hydrologic parameters used in the screening model were 1) horizontal hydraulic conductivity of 9.8 feet per day (ft/d); 2) a lake-bed leakance of 0.007 foot per day per foot (ft/d/ft); 3) a stream-bed leakance of 0.02 ft/d/ft; and 4) a calibrated recharge rate of 5 inches per year (in/yr). Additional hydrologic features, such as streams north of Dane County, were added until the screening model acceptably reproduced regional potentiometric data (Bradbury and others, 1999), including hydraulic heads and the locations of potentiometric divides.

HYDRAULIC PROPERTIES OF THE GROUNDWATER FLOW SYSTEM

Initial estimates of hydraulic conductivity, recharge, and stream-bed leakance for the three-dimensional groundwater flow model were based on existing and recently collected geologic and hydrologic data. Bradbury and others (1999), Fritz (1996), and Swanson (1996) presented complete discussions of the collection and interpretation of these data.

HYDRAULIC CONDUCTIVITY

Swanson (1996) estimated the saturated horizontal and vertical hydraulic conductivities of the unlithified deposits in Dane County. Unlithified deposits were grouped into three distinct hydrogeologic units: sand and gravel deposits, sandy diamicton, and silt and clay deposits. Percentages of these hydrogeologic units were then assigned to specific geomorphic settings as delineated on Mickelson and McCartney's (1979) glacial landscapes map of Dane County. The six geomorphic settings are pitted outwash plains and valleys, alluvial valleys, landforms associated with ice-contact stratified deposits, ground and end moraines, outwash plains and valleys, and lake plains. Estimated hydraulic conductivities assigned to these settings were based on the percentage of each of the three hydrogeologic units in each geomorphic setting. The estimated hydraulic conductivities associated with the geomorphic settings are shown in table 1. The hydraulic conductivity of the lacustrine deposits varies depending on the bedrock elevation underlying the mapped lake plain.

Horizontal hydraulic conductivity of sandstone of the Eau Claire and Mount Simon Formations and the bedrock above these units was estimated from specific capacity or aquifer tests. The geometric mean of estimated horizontal hydraulic conductivity from 1,554 specific capacity or aquifer tests of the bedrock above the Eau Claire Formation is 4.2 ft/d and the range is 0.09 to 540 ft/d. The geometric mean of estimated horizontal hydraulic conductivity of 57 tests of the Eau Claire and Mount Simon Formations is 10 ft/d and the range is 7.5 to 22 ft/d (table 1). No measurements of the vertical hydraulic conductivity of these rock units have been made in the Dane County area to date.

RECHARGE

The estimated recharge distribution is based on a mass-balance model (Stoertz and Bradbury, 1989) and a modification of Thornthwaite and Mather's water-balance method (1957). Swanson (1996) gave a complete description of the methods and results.

The locations of recharge areas were determined by Swanson (1996) by developing a mass-balance model for the Dane County area using a three-layer numerical groundwater flow model and setting the uppermost model layer (layer 1) to a constant head boundary equivalent to the elevation of the measured water table. The first model layer was assigned the hydraulic properties of the unlithified materials, and the second and third model layers were assigned the hydraulic properties of the bedrock above the shaly facies of the Eau Claire Formation. The hydraulic conductivities of the second and third layers were adjusted until a reasonable mass balance was computed. Areas where the model predicted downward flow from the water table were then assumed to represent recharge areas; areas where the model predicted upward flow toward the water table were assumed to represent discharge areas.

Swanson (1996) also used a modified Thornthwaite and Mather water-balance method to estimate theoretical recharge rates. This method incorporates many parameters, such as soil percolation rate, soil moisture storage, temperature, precipitation, and evapotranspiration rates. The mass-balance and water-balance models were coupled to combine rates and areas to estimate the recharge distribution. Results of this method indicated that all recharge within Dane County occurs on hilltops (areas of high elevation) and discharge occurs on slopes and areas of low elevation. The recharge rate ranged between 0.3 to 6.7 in/yr and had an average value of 2.6 in/yr.

STREAM-BED LEAKANCE

Estimates of stream- and lake-bed leakance were needed to quantify the interaction between surface water and groundwater. For this study an estimate of stream-bed leakance (the vertical hydraulic conductivity of a stream or lake bed divided by its thickness) was calculated with Darcy's Law, using measurements of gradient between the surface-water and groundwater systems and measurements of the change in discharge over a known stream area (Bradbury and others, 1999). Leakance was estimated at 12 sites in the Upper Yahara and Sugar Rivers, Koshkonong, Sixmile, Black Earth, and Garfoot Creeks, and Pheasant Branch. Stream-bed leakance varied from 1.6 ft/d/ft for the Upper Yahara River to 37 ft/d/ft for Pheasant Branch; mean stream-bed leakance was 8.1 ft/d/ft.

Table 1. Estimated and simulated hydraulic conductivity, in feet per day.

	Initial estimated hydraulic conductivity		Final simulated hydraulic conductivity	
	horizontal	vertical	horizontal	vertical
Model layer 1: Sand and gravel aquifer				
Pitted outwash plains and valleys	1.0[1]	0.8	5.0	5.0
Alluvial valleys	0.3	0.02	1.5	0.15
Landforms associated with ice-contact stratified deposits	1.0	0.8	5.0	5.0
Ground and end moraines	0.6	0.6	3.0	3.0
Outwash plains and valleys	1.4	1.4	7.0	7.0
Lacustrine plains	0.10–1.4	0.01–1.4	0.50–7.0	0.05–0.7
Model layer 2: Upper bedrock aquifer				
Bedrock above Eau Claire Formation	4.2[2]	—[3]	5.0	0.5
Model layer 3: Lower bedrock aquifer				
Eau Claire and Mount Simon Formations	10.0[2]	—	10.0	1.0

[1] Initial estimated values for geomorphic settings are from Swanson (1996).
[2] Geometric mean of all values calculated from specific capacity and aquifer tests from Bradbury and others (1999).
[3] No data.

GROUNDWATER WITHDRAWALS

Municipal supply accounts for about 85 percent of groundwater use in Dane County. The city of Madison, the largest single consumer, withdraws more than 30 million gallons per day (Mgd) and accounts for more than half the total use in the county. Generally, municipal and industrial groundwater withdrawals in Dane County have increased steadily since the early 1900s; the greatest rate of increase occurred during the 1970s. The total withdrawal declined slightly, however, during the early to mid-1980s, mainly because of a reduction in self-supplied industrial use and water conservation efforts (DCRPC, 1987).

The lower bedrock aquifer (primarily the Mount Simon Formation) is used for municipal water supplies; the shallower unlithified materials and rock units above the Mount Simon Formation are used for rural domestic supplies. Large diameter wells open to the entire thickness of the Mount Simon sandstone generally yield 1,000 to 2,000 gallons per minute (gal/min); large diameter wells completed above the Mount Simon sandstone may yield as much as 600 gal/min.

During 1992, a total of 93 high-capacity wells withdrew a reported 48.5 Mgal/d (Paul Gempler, DCRPC, written communication, 1994) (table 2). Pumpage from these wells was sufficiently large to include in the groundwater flow model. Pumpage from individual private wells in the county is not included in the model because the discharge of these wells is relatively small, widely distributed, and does not have a significant effect on the county's overall water balance.

Table 2. Dane County groundwater withdrawals in 1992, by model layer, row, and column designation and well owner; rate is in millions of gallons per day.

Layer	Row	Col.	Name	Rate (1992)	Layer	Row	Col.	Name	Rate (1992)
2	176	88	Anderson	0.036	3	114	120	Madison #24	2.708
2	177	87	Belleville #1	0.052	3	113	137	Madison #25	2.769
2	178	87	Belleville #2	0.091	2,3	125	91	Madison #26	2.977
3	99	44	Black Earth #1	0.050	2,3	118	112	Madison #27	0.254
2,3	102	45	Black Earth #2	0.055	2	91	184	Marshall #1	0.108
2	125	141	Blmg. Grove SD #8	0.066	2,3	91	182	Marshall #2	0.099
2,3	132	26	Blue Mounds #1	0.034	2,3	89	35	Mazomanie #2	0.026
2,3	179	120	Brooklyn #1	0.020	1	89	33	Mazomanie #3	0.145
3	178	122	Brooklyn #2	0.028	2,3	134	137	McFarland #1	0.110
2,3	136	191	Cambridge #2	0.120	2,3	130	137	McFarland #3	0.097
2	115	156	Cottage Grove #1	0.044	2,3	136	139	McFarland #4	0.335
2	114	155	Cottage Grove #2	0.081	2	111	91	Middleton #2	0.105
2	105	63	Cross Plains #1	0.128	2,3	112	91	Middleton #3	0.318
1	105	67	Cross Plains #2	0.214	2,3	105	94	Middleton #4	0.397
2	68	94	Dane #1	0.013	2,3	111	96	Middleton #5	0.616
2,3	68	93	Dane #2	0.035	2,3	112	88	Middleton #6	0.716
2,3	68	127	De Forest #2	0.060	2,3	120	127	Monona #1	0.290
2,3	69	124	De Forest #3	0.170	2,3	123	128	Monona #2	0.419
2,3	71	129	De Forest #4	0.270	3	125	124	Monona #3	0.482
2,3	123	181	Deerfield #1	0.075	2,3	62	124	Morrisonville SD #1	0.030
2,3	122	181	Deerfield #2	0.075	2,3	134	46	Mt. Horeb #3	0.155
3	137	108	Fitchburg #2	0.146	2,3	136	47	Mt. Horeb #4	0.164
3	133	109	Fitchburg #4	1.109	2,3	136	49	Mt. Horeb #5	0.118
3	133	102	Fitchburg #5	0.096	2,3	158	118	Oregon #2	0.015
2,3	142	114	Fitchburg #7	0.012	2,3	155	119	Oregon #3	0.001
2,3	143	116	Fitchburg #8	0.014	2,3	162	118	Oregon #4	0.520
3	137	105	Fitchburg #9	0.037	3	106	123	Oscar Mayer	1.318
2	122	182	Interplane	0.240	3	107	123	Oscar Mayer	0.425
2	111	90	Lycon	0.826	3	107	124	Oscar Mayer	0.086
2,3	112	122	Madison #3	0.020	3	108	123	Oscar Mayer	1.097
3	128	123	Madison #5	1.297	2,3	159	151	Stoughton #3	0.064
3	117	107	Madison #6	0.150	2,3	158	149	Stoughton #4	0.155
3	105	122	Madison #7	0.727	3	161	148	Stoughton #5	0.282
3	112	127	Madison #8	1.204	3	162	154	Stoughton #6	0.614
2,3	117	132	Madison #9	1.106	2,3	86	153	Sun Prairie #3	0.400
2,3	127	105	Madison #10	2.063	2,3	84	150	Sun Prairie #4	0.836
2,3	111	132	Madison #11	0.242	2,3	88	144	Sun Prairie #5	0.410
2,3	124	100	Madison #12	0.525	2,3	84	155	Sun Prairie #6	0.600
2,3	96	120	Madison #13	2.684	2,3	140	87	Verona #1	0.183
2,3	116	101	Madison #14	2.452	2,3	142	87	Verona #2	0.195
2,3	104	131	Madison #15	2.470	2,3	139	84	Verona #3	0.434
2,3	120	95	Madison #16	0.234	2,3	84	105	Waunakee #1	0.187
2,3	117	119	Madison #17	0.685	2,3	86	102	Waunakee #2	0.331
3	125	116	Madison #18	2.100	2,3	88	105	Waunakee #3	0.305
3	112	108	Madison #19	2.381	2,3	78	127	Windsor SD1 #1	0.070
3	131	97	Madison #20	1.290	2,3	79	127	Windsor SD1 #2	0.080
2,3	115	134	Madison #23	0.608	**County sum**				**48.488**

THREE-DIMENSIONAL SIMULATION OF THE GROUNDWATER SYSTEM

The three-dimensional model of Dane County's groundwater system is a mathematical representation of groundwater flow and uses the U.S. Geological Survey MODFLOW code (McDonald and Harbaugh, 1988). The steps involved in developing the three-dimensional model were

1. constructing a finite-difference grid;
2. inputting the boundary conditions identified by the screening model and selecting appropriate aquifers and confining units as identified in the conceptual model;
3. assembling hydrologic data (for example, aquifer and confining-unit geometry and hydraulic conductivities, recharge rate, and leakance of stream and lake beds);
4. inputting pumping rates and locations of simulated wells;
5. calibrating the model by adjusting parameters over realistic ranges until a reasonable match was made between measured and simulated groundwater levels and measured and simulated surface-water flows; and
6. ensuring that the model is in mass balance (that is, the volume of water entering the model approximates the volume of water being withdrawn or leaving the model).

MODEL ASSUMPTIONS AND CONSTRUCTION

As currently implemented, the model assumes that the groundwater system is at steady state—that groundwater levels are not changing with time. The steady-state assumption is appropriate because of the good hydraulic connection between aquifers and between aquifers and surface water, which mitigates the effects of pumping. The results of simulations made with the screening model, also a steady-state model, compared favorably to the measured groundwater system. Water levels during the 1992 steady-state calibration were within one standard deviation of the 20-year mean.

The model is constructed so that simulated saturated aquifer thickness can change if water levels decline below the top of an aquifer. Saturated aquifer thickness does change because of the large amount of groundwater withdrawn in the Madison area and because the water table in most of the western part of the model area (the Driftless Area) is in the upper bedrock aquifer; in the eastern part of the model area, it is in unlithified materials.

As specified in the conceptual model, the sand and gravel aquifer is the uppermost aquifer and is model layer 1 (fig. 4). The upper bedrock aquifer is model layer 2 and represents the rock units above the shaly part of the Eau Claire Formation. The upper bedrock aquifer is absent in some areas, such as beneath the Yahara Lakes (fig. 4). Where it is absent, the upper bedrock aquifer (model layer 2) is assigned a thickness of 1 ft and given the hydraulic properties of the lower bedrock aquifer (model layer 3) so that, as required by MODFLOW, a continuous layer is maintained. The shaly part of the Eau Claire Formation forms a confining unit. Sandstone of the lower part of the Eau Claire and Mount Simon Formations forms the lower bedrock aquifer (model layer 3), which underlies the upper bedrock aquifer and overlies Precambrian crystalline rock. Figure 4 shows these model layers in section. Model layers are mathematically connected by a leakance term that takes into account the vertical hydraulic conductivities and thickness of the adjacent aquifers and confining unit (McDonald and Harbaugh, 1988, p. 5B13, eq. 51).

The sand and gravel aquifer (layer 1) uses the boundary conditions determined by the screening model. The boundary type

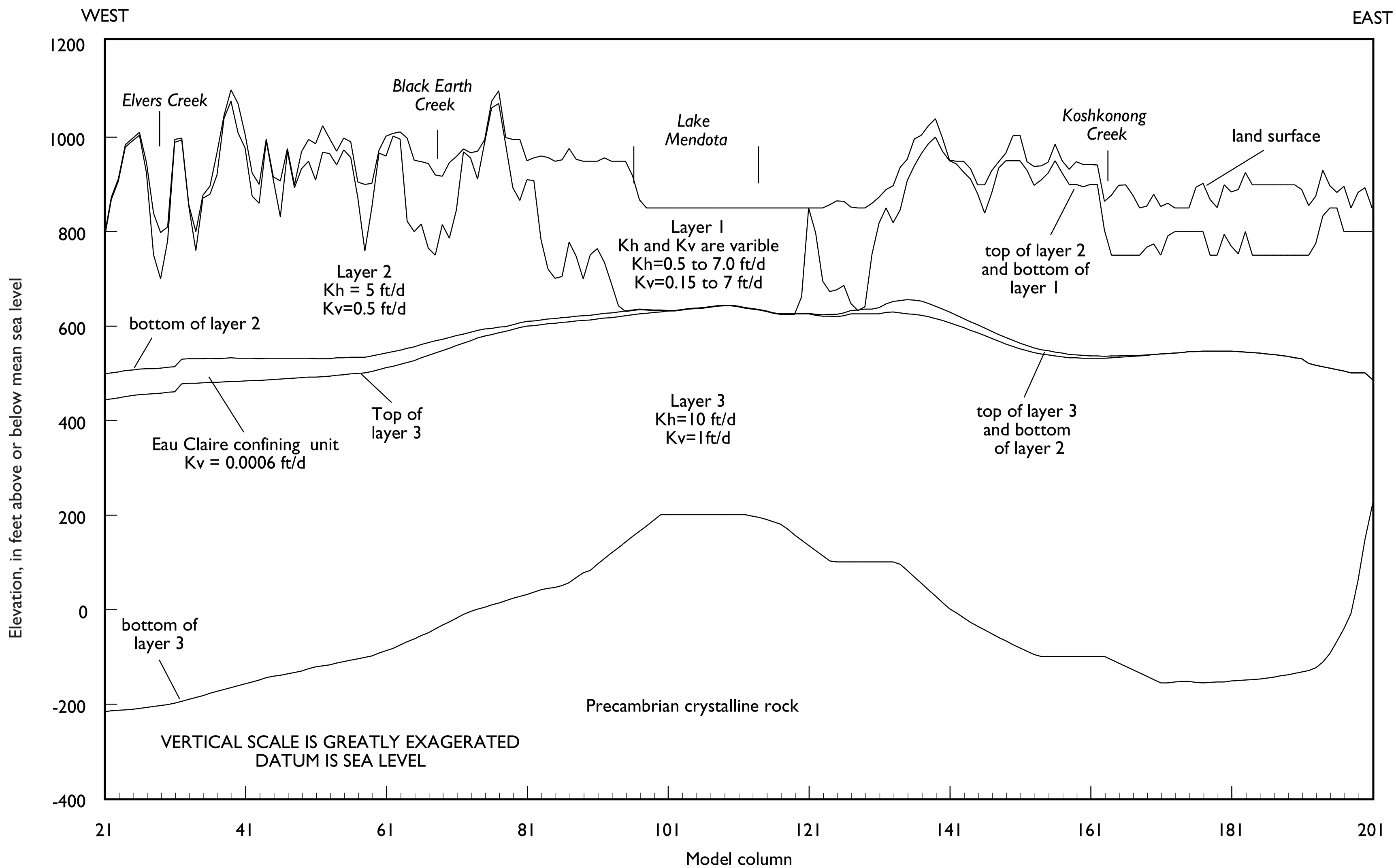


Figure 4. Model layers and confining unit and hydraulic parameters used for final calibrated model row 110 (Kh: horizontal hydraulic conductivity; kv: vertical hydraulic conductivity).

assigned is based on either the presence of streams and lakes, which are assumed to completely penetrate the flow system and thus are treated as constant heads, or the presence of surface-water divides, which are assumed to be groundwater divides and are treated as no-flow boundaries. Constant heads (equivalent to the lake or stream elevation) are assigned to the finite-difference-grid blocks that intersect the Wisconsin River and Lake Wisconsin, most of the Crawfish River, Lake Koshkonong, the Rock River, and the East Branch of the Pecatonica River (fig. 2). Lateral boundaries for the remaining part of the sand and gravel aquifer are no flow. The boundary conditions for the upper and lower bedrock aquifers (layers 2 and 3) are different from those of the sand and gravel aquifer; all their lateral boundaries are no flow.

Internal boundaries include streams and lakes. These boundaries are head dependent, that is, groundwater flow to or from these surface-water bodies depends on the difference in surface-water and groundwater elevations as well as stream- or lake-bed leakance and the length and width of the stream or lake. The streams simulated in this fashion are indicated in fig. 2. The average stream-bed leakance (8.1 ft/d/ft) calculated from stream-flow measurements of selected streams indicated an excellent hydraulic connection; that is, the hydraulic conductivity of the stream beds is similar to that of the underlying aquifer so that the streams have a substantial effect on the water table. We also assumed Lakes Mendota, Monona, Wingra, Waubesa, and Kegonsa to be head-dependent boundaries; however, no measurement of leakance for these lakes was made. The leakance of the lake beds was assumed to be much smaller than that of the stream beds because the lake beds are composed of lacustrine sediment rather than sand and gravel.

In addition to boundary conditions, initial input to the model included the top and bottom elevations of each aquifer (model layers 1, 2, and 3), hydraulic conductivities, recharge rates, and pumping rates and locations of wells. Initial model input represents a node average of the hydraulic conductivities of the sand and gravel aquifer and the recharge rate estimated by Swanson (1996).

MODEL GRID

The three-dimensional finite-difference groundwater flow model covers a 50- by 60-mile land area subdivided into 144,000 nodes (200 rows, 240 columns, and 3 layers). The row and column dimension of each node is uniform throughout the model area; each node measures 1,312.4 ft on a side and has an area of about 40 acres (fig. 2). This uniformly spaced grid was used to simulate all parts of the flow system equally. The model does not calculate a water level at each node because some of the nodes are inactive or are used as no-flow or constant head boundaries. For example, of the 48,000 nodes simulating the sand and gravel aquifer (layer 1), 31,318 nodes were active (that is, hydraulic head was calculated), 900 nodes were constant head, and 15,782 were inactive no-flow nodes. The number of active nodes in each aquifer layer varies slightly because the extent of each model layer is slightly different.

MODEL CALIBRATION

The model was calibrated by adjusting input parameters over reasonable ranges in a series of model runs. After each model run, simulated water levels and stream gains and losses were compared to measured water levels and base flow. The model was calibrated using 1992 pumpage rates; however, measured water levels used for calibration spanned many years. Therefore, contoured surfaces and point measurements were used during calibration. Stream-flow measurements generally made between 1989 and 1994 were used to estimate base flow. These base-flow estimates were compared to simulated stream gains and losses as part of the model calibration.

The first model run was made using the initial estimates of hydraulic conductivities, recharge distribution, and stream-leakance values presented in previous sections of this report. Subsequent model runs were made by varying hydraulic conductivities and recharge rates until simulated water levels and stream flow agreed reasonably well with measured water levels and stream flow.

Values for hydraulic conductivities used in the final calibrated model are shown in table 1 and figure 4. During calibration, the initial horizontal hydraulic conductivity values of the sand and gravel aquifer had to be increased by a factor of 5, which may reflect the scale dependence of these values (Bradbury and Muldoon, 1990). The horizontal hydraulic conductivity of the upper bedrock aquifer is 5 ft/d, a value similar to the initial estimate of 4.2 ft/d. The horizontal hydraulic conductivity of the lower bedrock aquifer is 10 ft/d, which is the same as the initial estimate. The ratio of horizontal to vertical hydraulic conductivity is 1:1 for the sand and gravel aquifer (layer 1), except for areas underlying alluvial valleys and former glacial lake plains (lacustrine deposits), where a ratio of 10:1 was used. The horizontal to vertical hydraulic conductivity ratio is 10:1 for each of the two bedrock aquifers (layers 2 and 3). The Eau Claire confining unit was assigned a vertical hydraulic conductivity of 0.0006 ft/d. The average recharge rate at calibration is 5 in/yr—1.9 times the initial estimate of 2.6 in/yr. Stream-bed leakance was uniformly set to 8 ft/d/ft for interior streams and represents the average of the measured values. Lake-bed leakance of perimeter nodes around lakes was set to 0.5 ft/d/ft and interior nodes for lakes were set to 0.01 ft/d/ft.

We compared two sets of field-measured groundwater levels to model-calculated groundwater levels at specific model nodes.

1. We compared water-level measurements from 3,426 well constructor's reports for the period of 1974 to 1994, which represent the water table in either the sand and gravel aquifer or the upper bedrock aquifer, to model-calculated water levels. When more than one water-table well occurred in a single node, the average of measured water levels from the wells in the node was compared to the model-calculated water level.
2. We compared water-level measurements from 16 municipal wells and one observation well measured in 1992, which represent the potentiometric surface of the lower bedrock aquifer or, in places, a combination of the upper and lower bedrock aquifers, to model-calculated water levels. The observation well is open to the lower bedrock aquifer. Three of the 16 municipal wells are open only to the lower bedrock aquifer; 13 are open to the upper and lower bedrock aquifers. For municipal wells open to both bedrock aquifers, a composite model-calculated water level using water levels from the upper and lower bedrock aquifers was compared to measured water levels.

Most model-calibrated water-table elevations compared favorably to measured water-table elevations and fall within the 95 percent confidence interval as indicated on figure 5 (Draper and Smith, 1966). However, figure 5 shows that the maximum simulated water table was about 975 ft above sea level and that for a few wells, the measured water level exceeded 1,200 ft above sea level. This is probably caused by the large number of head-dependent boundaries (interior streams) and the excellent hydraulic connection to surface-water features and the underlying aquifer. The highest stream-surface elevation assigned to the head-dependent boundaries is about 920 ft above sea level. The simulated groundwater flow system does not support a water table at an altitude much higher than this elevation because the horizontal and vertical hydraulic conductivities of the underlying aquifer are similar to those of the stream beds. Therefore, the effects of the stream-surface elevations are felt throughout the model domain.

A root mean square (RMS) difference between measured and simulated water levels was calculated to judge the goodness of fit for the water table and the potentiometric surface for each calibration run. At calibration, the RMS for the water table was 37.4 ft; for the potentiometric surface, 43.7 ft.

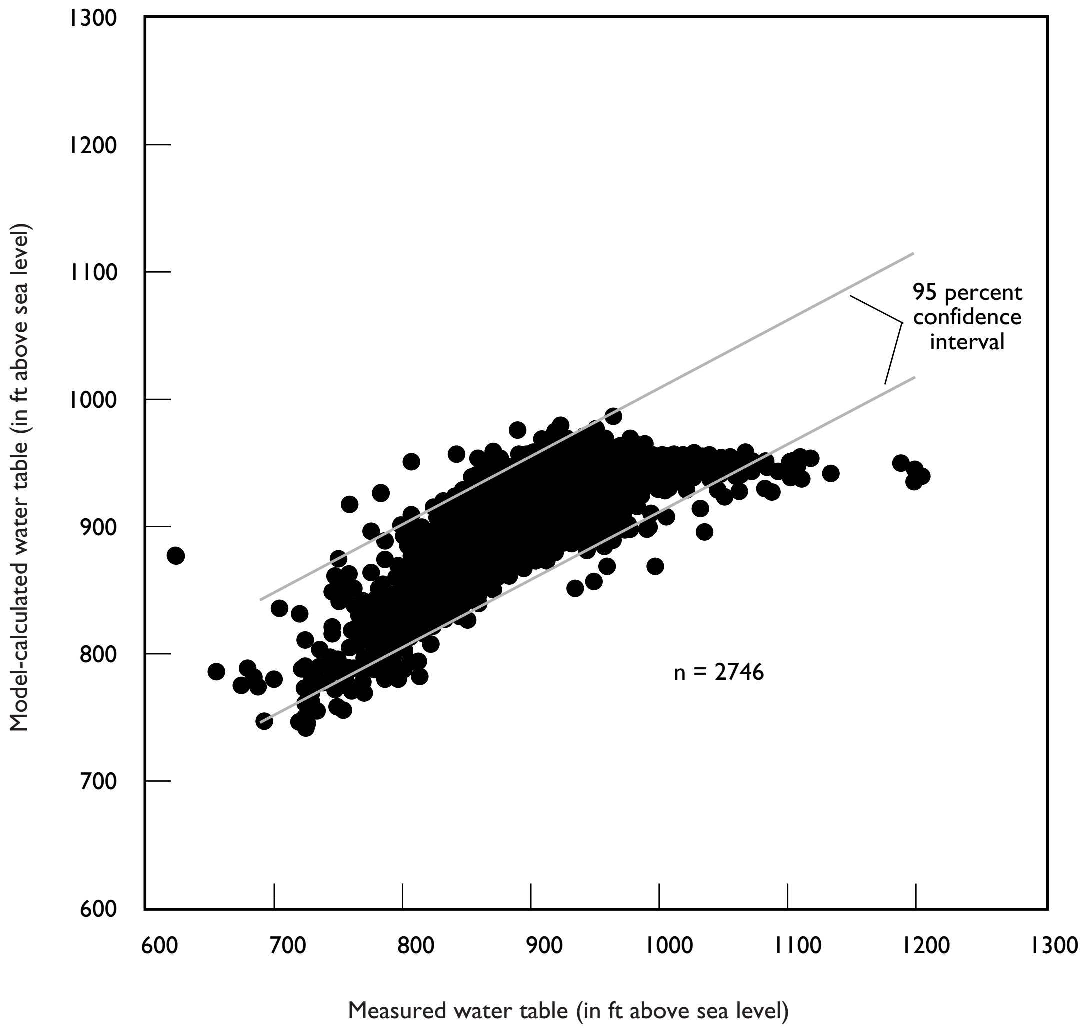
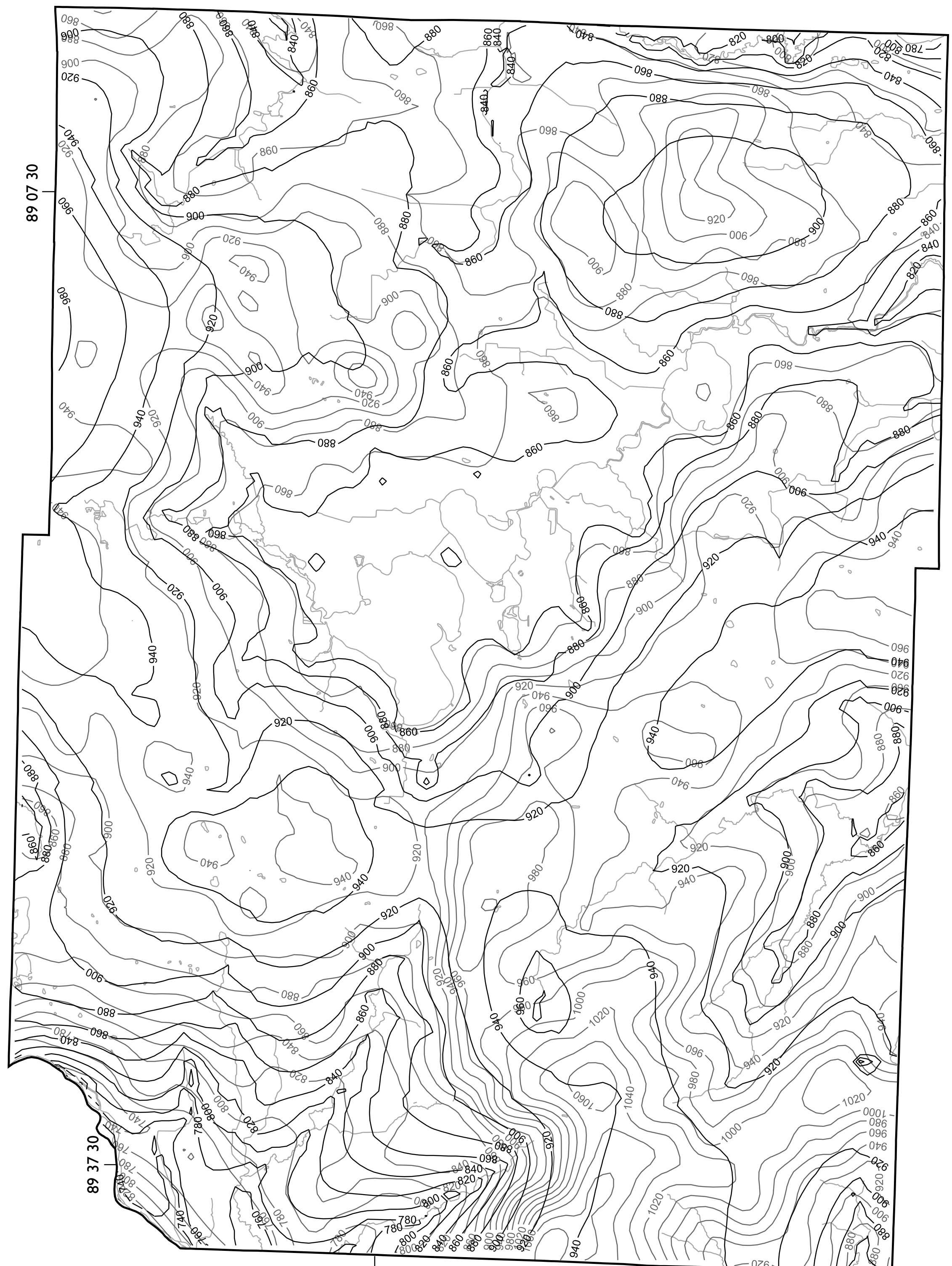


Figure 5. Relationship of measured and model-calculated water-table elevation and the 95 percent confidence interval for the linear regression (n=number of model cells that have water-table measurements).

These RMS values represent only about 10 percent of the total range of water-level elevation across the model area.

In addition to comparing measured and modeled water levels at specific nodes, we compared measured and modeled water-table and potentiometric surfaces. The potentiometric contours interpreted from measured water levels are based on less than 50 measurements in the entire county. Only model-calculated water levels for the lower bedrock aquifer were used to represent the potentiometric surface for this comparison. The differences between the measured and modeled water table and potentiometric surfaces are shown in figures 6 and 7, respectively. The "matches" between measured and model-calculated surfaces of the water table and the potentiometric surface were much better in the central part than in the western part of the model area; the hydrogeology of the western part of the county is not as well understood as it is in the central part of the modeled area. Perched water tables and local confining conditions are probably common in western Dane County. The hydraulic conductivity of the lower bedrock aquifer was derived from only 57 estimated values; few of them were from the Driftless Area.

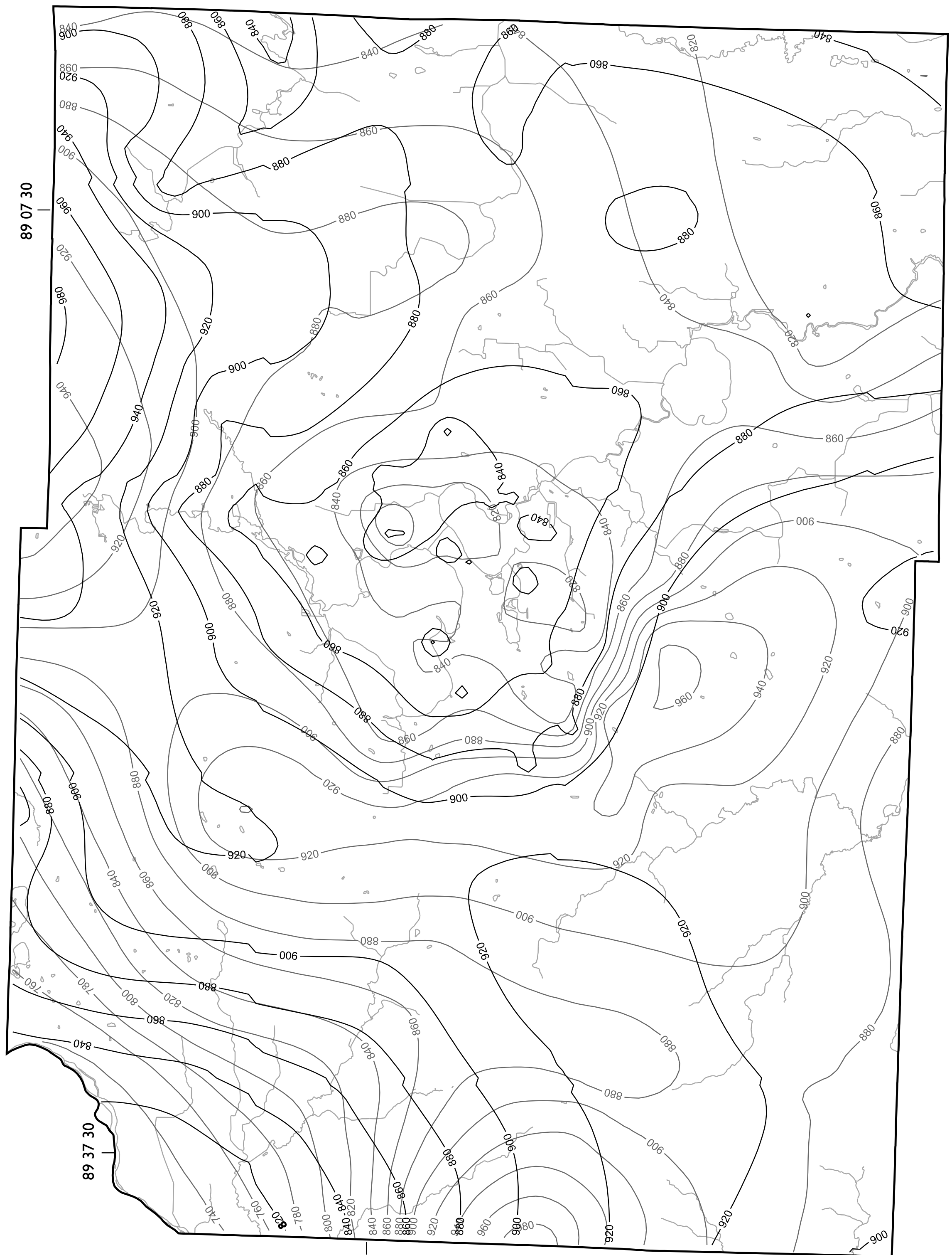
Measured stream flow was compared to



900 Simulated water-table contour. Contour interval 20 feet. Datum is sea level.

900 Measured water-table contour. Contour interval 20 feet. Datum is sea level.

Figure 6. Altitude of simulated and measured water table (model layers 1 and 2).



— 900 — Simulated water-table contour. Contour interval 20 feet. Datum is sea level.

— 900 — Measured water-table contour. Contour interval 20 feet. Datum is sea level.

Figure 7. Altitude of simulated and measured potentiometric surface (model layer 3).

simulated net stream gain and loss at 15 sites throughout Dane County (fig. 2). Measured stream flow was used to estimate 80 and 50 percent flow duration for each site. Because the model is a steady-state simulation, simulated net stream gains are considered to represent base-flow conditions, which fall within the 80 to 50 percent flow duration for a given stream. Table 3 lists the 80 and 50 percent flow duration and the simulated flow at calibration for the 15 sites. Not enough streamflow measurements were available from two of the sites to estimate the 50 percent flow duration. Of the 13 sites having estimates of the 80 and 50 percent flow duration, only simulated stream gains for Six Mile Creek at Mill Road near Waunakee fell within these flow durations. Of the remaining 12 sites, eight were below the estimated 80 to 50 percent flow duration and four were above.

The calibration procedure primarily matched measured to simulated water levels and secondarily matched measured stream base flow to simulated stream gains. The calibrated model indicated that simulated stream gains are generally lower than measured stream flow. To improve the match between simulated and measured stream flows, a higher recharge rate than that used in the calibrated model (5 in/yr) would be required. An increase in recharge rate would raise simulated groundwater levels unless offset with higher aquifer hydraulic conductivities. Simulated groundwater levels using a higher recharge rate would not match measured groundwater levels as well as the calibrated model would.

It is possible that measured groundwater levels used in the water-level calibration may not reflect the 1992 conditions used in the stream base-flow calibration. Most of the measured water levels used in the water-level calibration represent reported water levels from well constructor's reports for wells drilled between 1974 and 1994. Gebert and Krug (1996) reported that for the Driftless Area, stream base flows have steadily increased during the past 50 years. For example, the stream base flow of Black Earth Creek at Black Earth has increased about 0.24 ft^3/sec since 1950 (William R. Krug, U.S. Geological Survey, written communication, 1996). The measured stream base flows that were compared with simulated stream gains represented present conditions. However, to increase stream base flow, there must also be an increase in groundwater levels (gradients), and it is possible this increase in groundwater levels is not represented in the measured water-table levels used to calibrate the model.

MASS BALANCE

Calibrated model results indicated two major sources of inflow to the groundwater flow system. Recharge accounted for 89 percent, or 571 ft^3/sec, and seepage from internal rivers, streams, and lakes accounted for about 11 percent, or 72 ft^3/sec. A minor amount of flow was from boundary rivers (less than 1%, or 3 ft^3/sec). These sources were balanced by flow from the aquifers to internal rivers (66%, or 427 ft^3/sec), boundary rivers (22%, or 145 ft^3/sec), and pumping wells (12%, or 75 ft^3/sec). The mass balance indicated that groundwater withdrawn by Dane County wells is water recharged within the modeled area and, if it had not been withdrawn, it would have discharged to local streams and lakes.

Table 3. Comparison of measured 80 (Q_{80}) and 50 (Q_{50}) percent flow duration to simulated stream flow (gain and loss) in selected Dane County streams; all values in cubic feet per second. Locations of gauging stations are shown in figure 2.

			Pre-development		Calibration		Increase recharge 25 percent		Decrease recharge 25 percent	
Station name: Location	Q_{80}	Q_{50}	**Gain**	**Loss**	**Gain**	**Loss**	**Gain**	**Loss**	**Gain**	**Loss**
Black Earth Creek: East of Black Earth	19.5	26.5	14.5	0.0	13.1	0.0	16.5	0.0	9.7	0.0
Badger Mill Creek: Highway 69 south of Verona	2.1	13.2	2.0	0.0	0.6	0.1	2.2	0.0	0.3	1.6
East Branch Starkweather Creek: Milwaukee Street	0.3	0.6	2.2	0.0	0.9	0.0	1.3	0.0	0.5	0.1
Koshkonong Creek: Bailey Road near Sun Prairie	0.6	1.1	0.6	0.0	0.1	0.1	0.7	0.0	0.0	0.7
Koshkonong Creek: Hoopen Road near Rockdale	13.0	26.0	36.4	0.0	33.8	0.1	44.1	0.0	24.4	1.2
Maunesha River: South of U.S. Highway 151	1.9	4.4	12.3	0.0	11.9	0.0	15.3	0.0	8.4	0.0
Mt. Vernon Creek: Highway 92	11.0	—[1]	2.4	0.0	2.1	0.0	3.0	0.0	1.2	0.0
Murphy (Wingra) Creek: Beld Street	2.3	—	3.4	0.0	1.3	0.0	2.0	0.0	0.6	0.0
Nine Springs: Highway 14	5.6	10.8	4.9	0.0	2.2	0.1	3.2	0.0	1.4	0.2
Pheasant Branch Creek: U.S. Highway 12, Middleton	0.8	1.7	2.7	0.0	1.2	0.0	2.7	0.0	0.7	0.1
Six Mile Creek: Mill Road near Waunakee	2.9	14.0	5.0	0.0	4.3	0.0	6.6	0.0	2.1	0.0
Token Creek: U.S. Highway 51	15.0	19.0	13.0	0.0	10.6	0.0	14.2	0.0	7.2	0.3
West Branch Starkweather Creek: Milwaukee Street	0.6	1.1	2.8	0.0	0.0	2.3	0.0	1.5	0.0	3.1
West Branch Sugar River: Highway 92 near Mt. Vernon	11.0	20.0	5.6	0.0	5.3	0.0	6.8	0.0	3.9	0.0
Yahara River: Golf course near Windsor	9.3	13.0	8.8	0.2	8.0	0.3	12.6	0.1	4.6	2.7

[1] No data.

SENSITIVITY ANALYSIS

There is always some uncertainty about the accuracy of a model. The importance of calibration error associated with each input parameter and its effect on the simulation results can be evaluated through sensitivity tests, in which the value of a hydraulic parameter, such as hydraulic conductivity, is adjusted above or below the calibrated value. Sensitivity analysis of the Dane County model was limited to variations of hydraulic conductivity, recharge, and stream- and lake-bed leakance. Differences between results with calibrated input parameters and those with adjusted input parameters are shown in figure 8.

The hydraulic conductivities of the sand and gravel and the upper bedrock aquifers (layers 1 and 2, respectively) were varied simultaneously because these aquifers are in good hydraulic connection and because the water table can be in either aquifer, depending upon local hydrogeologic conditions. The ratio of horizontal to vertical hydraulic conductivity of the aquifers was held constant, and vertical leakance between model layers was recalculated with each change in horizontal hydraulic conductivity.

Increasing the recharge rate, hydraulic conductivity of layers 1 and 2 or layer 3, or vertical conductivity of the confining unit resulted in an RMS greater than the RMS calculated at calibration for the potentiometric surface (fig. 8B). Except for increasing the recharge rate, the water-table levels were insensitive to increases in other model parameters (fig. 8A). The water table is less sensitive to these increases because, as previously discussed, the large number of head-dependent boundaries tends to dampen the effects on the water-table elevation. That is, increasing the hydraulic conductivity of layers 1 and 2 increases flow to and from nearby constant head and head-dependent boundaries, but causes little change in the water-table elevation and configuration. The same small increase in the RMS of the water table occurs when the hydraulic conductivity of layer 3 is increased (fig. 8A), but is largely due to increases only in flow to and from constant-head boundaries. Finally, increasing the vertical hydraulic conductivity of the confining unit causes only small changes in flow to the constant head and head-dependent boundaries and therefore does not cause the water table to change.

A decrease of 25 to 75 percent in the recharge rate or the horizontal hydraulic conductivity of the aquifers resulted in an RMS greater than that calculated at calibration for the water table and potentiometric surface. Decreasing the vertical conductivity of the confining unit resulted in an RMS greater than the RMS calculated for calibration of the water table, but not for the potentiometric surface.

Increasing or decreasing the recharge rate by 25 percent resulted in proportional increases and decreases in stream flow (table 3). Increasing or decreasing other hydraulic parameters, including stream-bed leakance, had little effect on stream gains.

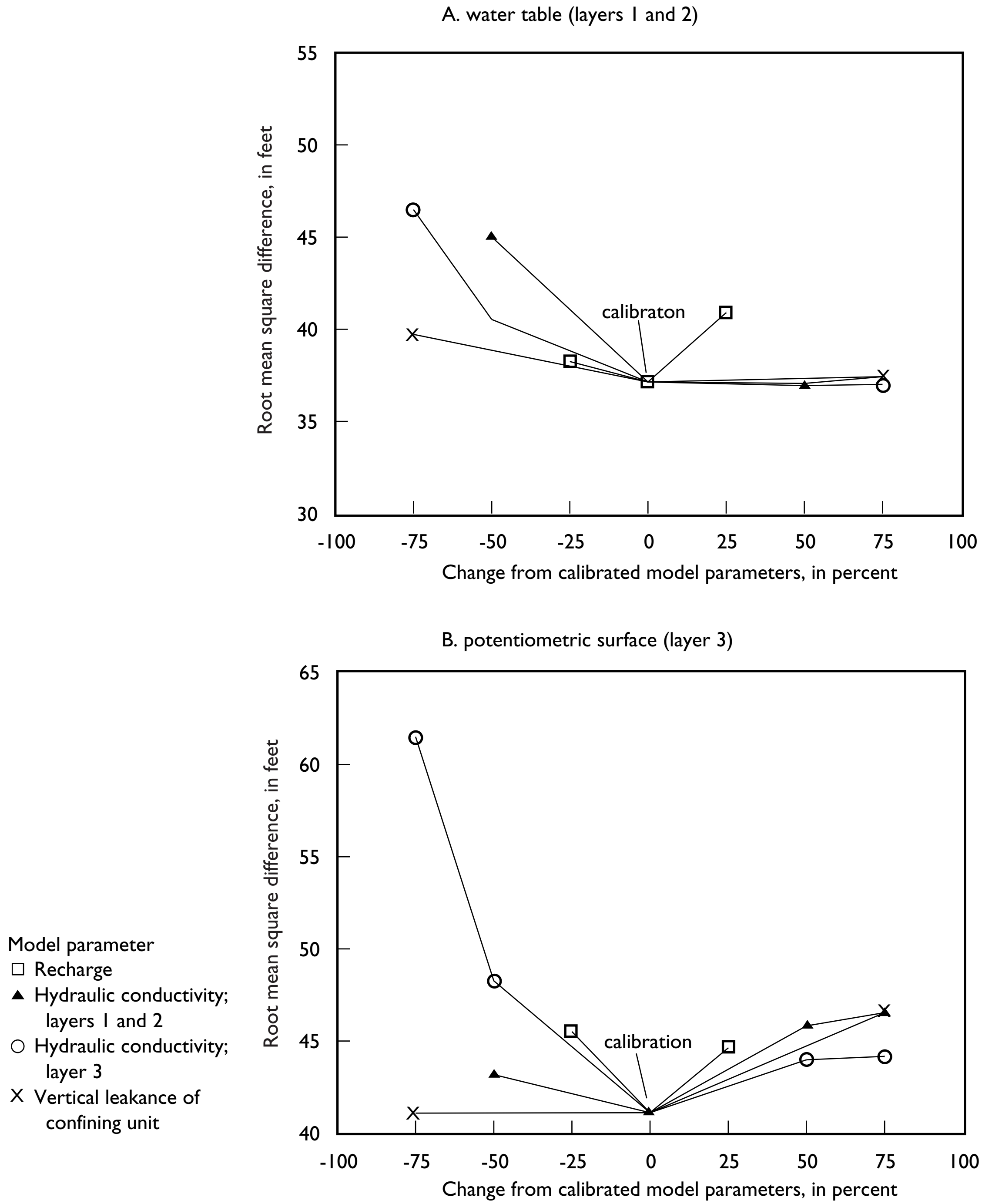


Figure 8. Relationship between root mean square of the differences between measured and modeled groundwater levels from water table (model layers 1 and 2) and potentiometric surface (model layer 3) and model parameters.

PREDEVELOPMENT CONDITIONS COMPARED TO 1992 CONDITIONS

The reasonableness of the simulation results can be tested by using the calibrated model input, excluding pumping wells, to simulate predevelopment conditions.

The greatest effect of pumping on water levels is in the Madison metropolitan area. By 1992 the water table and potentiometric surface in the vicinity of Madison had each declined more than 60 ft from simulated predevelopment levels (figs. 9 and 10). The largest declines are at the centers of two cones of depression that developed in the water table and potentiometric surface. One cone is on the southwest side and the other is on the northeast side of Lakes Mendota and Monona. Inspection of figures 9 and 10 shows there is no drawdown in the water table and only about 10 ft of drawdown in the potentiometric surface directly adjacent to and beneath these two lakes. The minimal drawdowns in the potentiometric surface and the presence of two distinct cones of depression indicate that these lakes are significant water sources that contribute water to the pumping wells. The aquifers are in good hydraulic connection with these lakes because the upper bedrock aquifer is thin and the confining unit is absent or very thin in this area.

The lakes and wetlands within the Madison area were primarily groundwater discharge areas under predevelopment conditions, but are primarily groundwater recharge areas under 1992 conditions. Because of pumping, they receive less groundwater inflow under 1992 conditions than under predevelopment conditions. By comparing simulated predevelopment flows to simulated 1992 flows at gauging stations, it is apparent that pumping has also reduced base flow in Madison area streams (table 3). That is, groundwater that would have contributed flow to these streams under predevelopment conditions is now captured by pumping wells under 1992 conditions.

The amount of drawdown and the reduction of base flow indicated by the predevelopment model simulation results seem reasonable. McLeod (1975, p. 16) reported a maximum of 60 ft of measured drawdown in what he called the sandstone aquifer (essentially equivalent to the lower bedrock aquifer) in 1970 in the vicinity of Madison. Although total withdrawals in the Madison metropolitan area have increased by about 5 Mgd between 1970 and 1992, most of this increase is from new wells located west and east of central Madison and therefore has less effect on drawdown in the aquifers near the lakes. Reduction in base flow to the West Branch of Starkweather Creek (fig. 2) has also been documented by the Dane County Regional Planning Commission (1983).

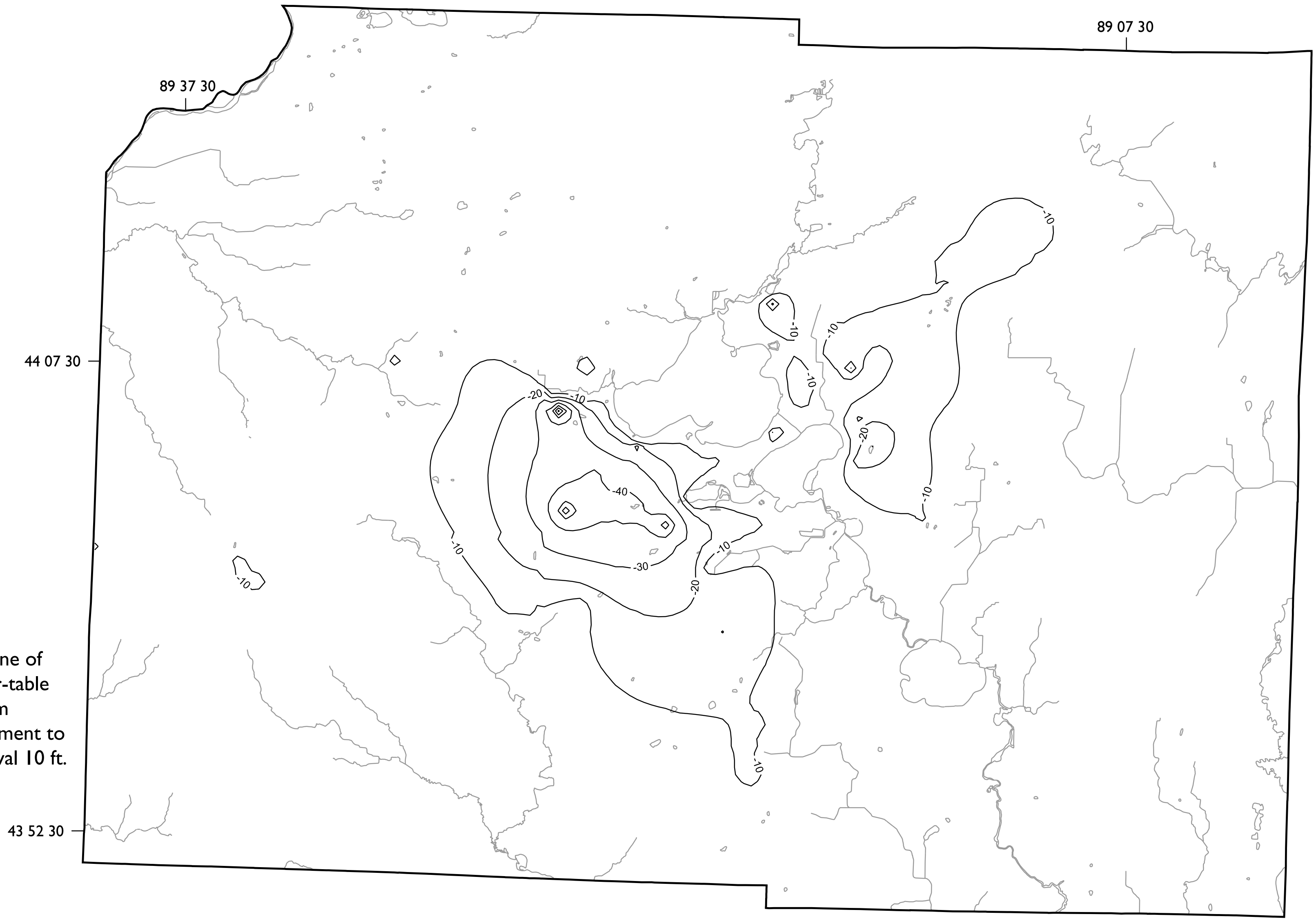
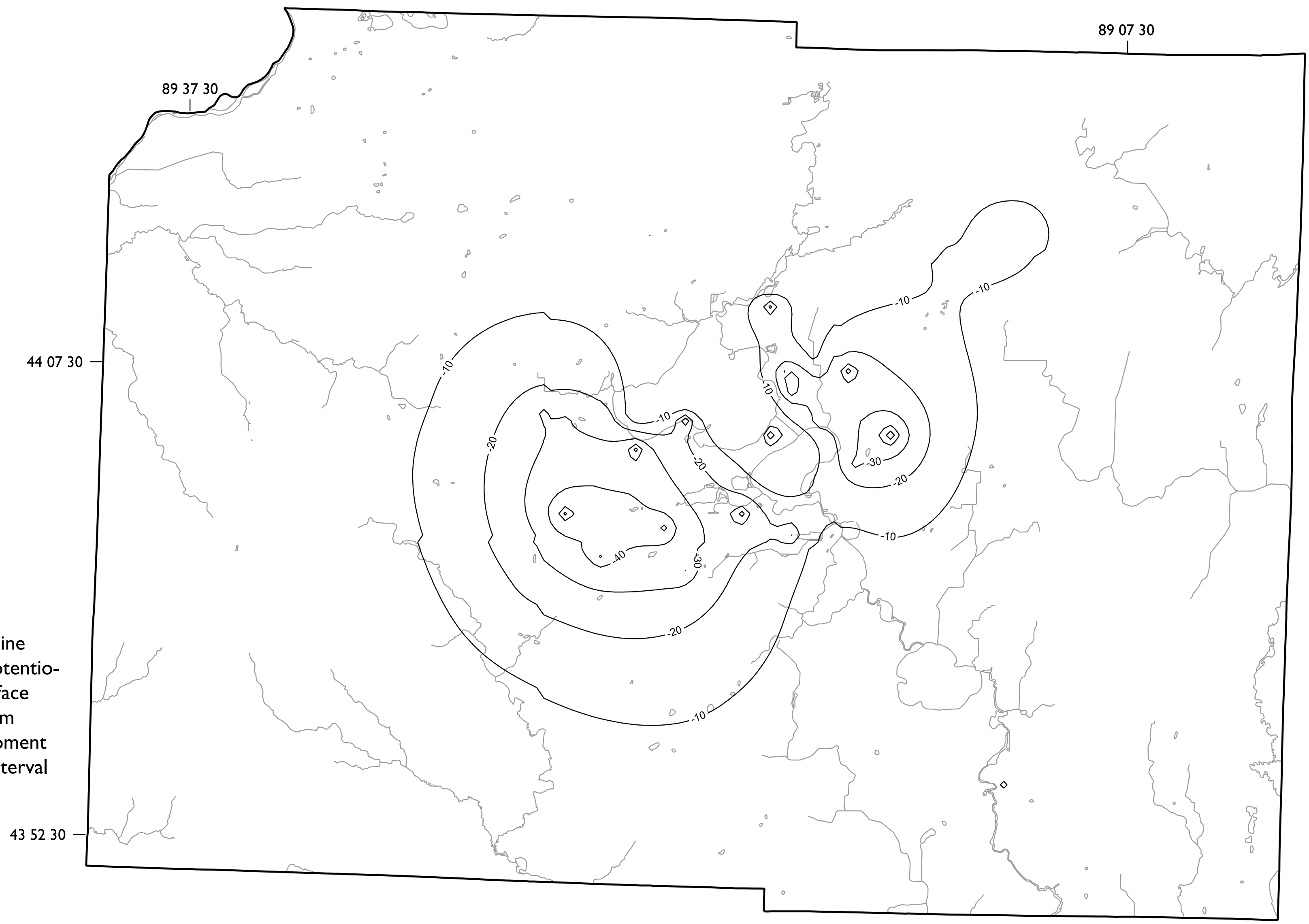


Figure 9. Water-table decline from predevelopment to 1992.



—— 40 —— Simulated line of equal potentiometric surface decline from predevelopment to 1992. Interval 10 ft.

Figure 10. Potentiometric surface decline from predevelopment to 1992.

MODEL LIMITATIONS

Like any groundwater model, the Dane County model is a simplification of the real world groundwater system, with corresponding limitations in model precision and how the model can be used. Each model node represents a surface area of approximately 40 acres and the thickness of model layers ranges from 50 to 500 ft. Hydrologic parameters and aquifer and confining unit geometry in much of the model area are not clearly defined or well known at a 40-acre resolution; for example, aquifer thickness and hydraulic conductivity can change vertically at intervals smaller than the current model resolution. Therefore, although the resolution of the model grid is relatively high, the model is not suitable for analysis of site-specific problems or issues.

There are more and better-quality hydrologic and geologic data for the central part of the model area than for other model areas, so an excellent match of measured and simulated water levels can be obtained for central Dane County. The match is not as good elsewhere, particularly in the western part of the model area. The bedrock geology and the hydrogeology of the Driftless Area are complex. Perched water tables and local confining conditions are common there, and reported water levels may not always represent the water levels of the modeled aquifers. Because of the inherent simplifying assumptions, the groundwater flow model cannot simulate all the complexities of the groundwater flow system. The model can be used, however, to predict water-level changes or trends and changes in stream gains and losses that result from changes in land and water use. The model has accurately simulated declines in water levels and stream losses from predevelopment to 1992.

SUGGESTED ADDITIONAL RESEARCH NEEDS IN DANE COUNTY

The Dane County groundwater flow model could be improved with additional hydrologic and geologic research, data collection and interpretation, and the use of additional MODFLOW options and packages. As new data become available, the model could be updated and recalibrated. The following is a list of research, data-collection needs, and MODFLOW options that would enable refinements, and in turn increase the utility of the Dane County groundwater flow model:

1. Within Dane County no observation wells (non-pumping wells) open to the lower bedrock aquifer are being monitored continuously. Only two known observation wells open to the lower bedrock aquifer exist in Dane County, one at Springfield Corners (not shown in figures in this report) about 5 mi northwest of Middleton and one at Refuse Hideaway (not shown), a monitored landfill located along Highway 14 just west of Madison. A minimum of three observation wells, one within the cone of depression, one on the western divide, and one on the far west side of the county, are needed. Continuous water-level measurements of these wells would provide calibration points.

2. The hydraulic relationship between the Yahara Lakes and the groundwater system is not understood completely. For example, mass balances for the Yahara Lakes cannot be estimated because of insufficient flow data. The amount of stream flow entering and leaving these lakes is historically poorly known. Such data would allow a better calibration in an area critical to the accuracy of the Dane County groundwater flow model. (This lack of data is true for all of Dane County's wetlands.)
3. The groundwater flow system is probably more complex in the western part of the county than indicated by the conceptual model used in the Dane County hydrologic study. Even after the model was calibrated, in many places the water levels for the simulated lower bedrock aquifer differed by more than 40 ft from the potentiometric surface on the basis of measured water levels. Hydrogeologic data, including measured water levels, are sparse in this area, making model interpretations difficult. A reinterpretation of the groundwater flow system in western Dane County will be needed as new data become available.
4. Several springs exist in the Madison metropolitan area. The relationship of the springs to the groundwater flow system is not completely understood. If springs are to be preserved, an understanding of how to sustain their flow is required.
5. More detailed study of the relationship between selected streams and the groundwater system is required if the Dane County groundwater flow model is to approximate stream gains and losses accurately. Such study would provide better estimates of hydraulic parameters of stream beds and additional data on stream flow and water-level measurements of the sand and gravel and upper bedrock aquifers.
6. Without an understanding of recharge distribution, it is impossible to judge the effectiveness of mitigation practices, such as detention basins or the importance of protecting recharge areas.
7. To increase the utility of the Dane County groundwater flow model, several features need to be added to the model. Climatic variations such as drought and significant recharge events can be simulated if the model is run in transient mode. The addition of MODFLOW packages, such as the Stream Routing Package and Lake Stage Package, would improve the calibration procedure and explicitly couple the groundwater to the surface-water systems.
8. An optimization code, which helps select the optimum, or "best," pumping schemes for a given objective, such as maintaining surface-water flow, coupled to the groundwater flow model would greatly enhance the model as a tool to guide location of future wells and developments. An optimization model could be used to choose well locations so that future pumping would have a minimal adverse effect on stream flow and wetlands, but still meet the increased water needs associated with population growth in Dane County.

SUMMARY

The Dane County hydrologic study was initiated because of concern that large withdrawals of groundwater by high-capacity municipal wells are having an adverse effect on groundwater and surface-water resources. In addition, the last comprehensive groundwater-resource assessment for Dane County was made more than 30 years ago, and new data available since that assessment had not been interpreted and incorporated into a regional hydrologic framework.

The groundwater flow model described in this report successfully simulated the major hydrogeologic features of Dane County, including bedrock and surficial aquifers, groundwater–surface-water interactions, and groundwater withdrawal from high-capacity wells. Simulations made with the model reproduced groundwater levels and stream base flows representative of 1992 conditions and also reproduced groundwater flow patterns and directions delineated on field-based water-table and potentiometric maps. In particular, the model accurately simulated measured drawdown caused by the pumping of municipal wells in the Madison metropolitan area. As currently calibrated, the model is suitable for use as a predictive tool for regional water management. Because of its regional focus, the model cannot be used for site-specific predictions. It does, however, provide a valuable framework (regional flow patterns, boundary conditions, aquifer parameters) within which site-specific studies can be carried out.

For most efficient use, the model will need to be continually updated and improved with field data that can be used to improve characterization of the aquifers, lakes, springs, wetlands, and recharge distribution and magnitude. The addition of modeling modules, such as Stream Routing and Lake Stage, to the MODFLOW code will improve the calibration and explicitly couple the groundwater to the surface-water system.

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Bulletin 98

Numerical Simulation of Groundwater Flow in Dane County, Wisconsin

2000

ISSN: 0375-8265