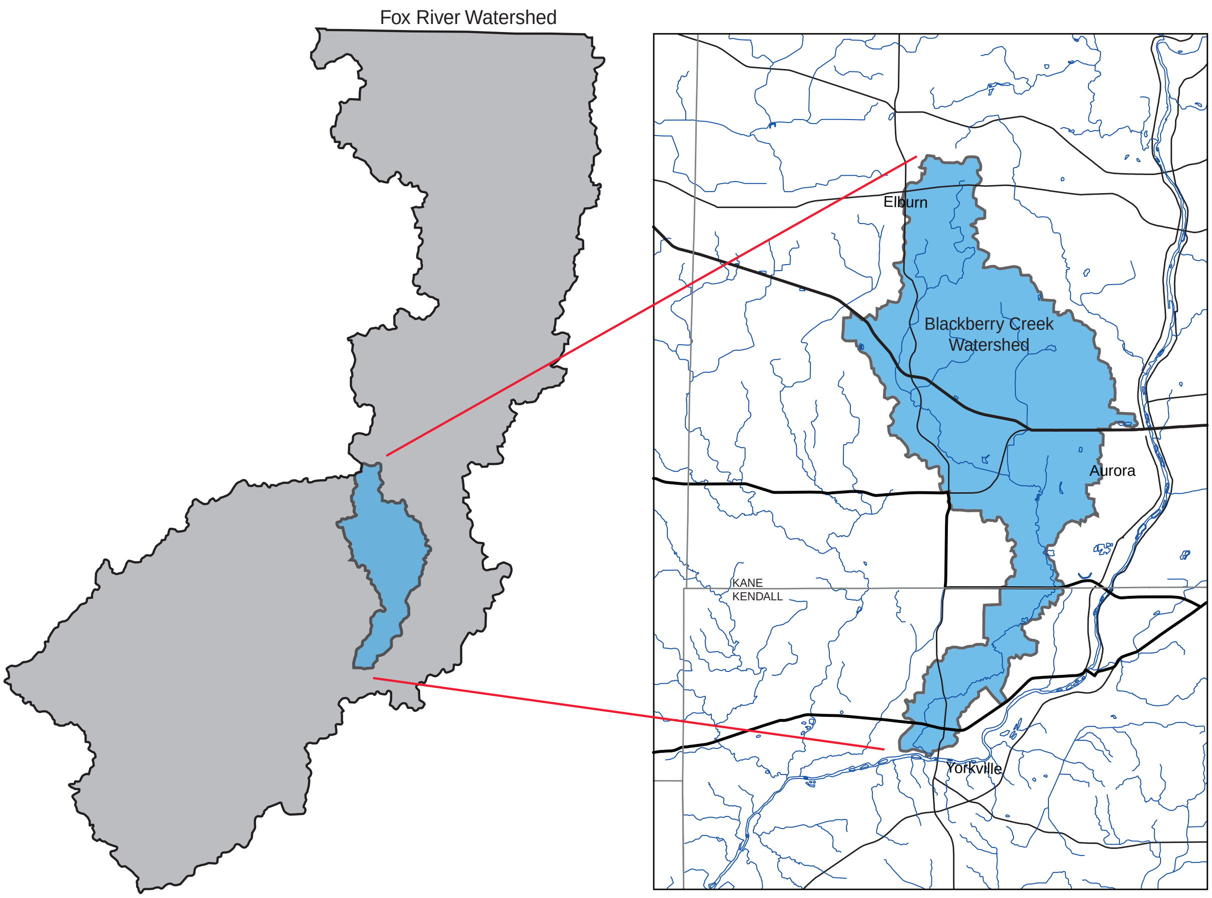
Groundwater Flow Modeling as a Tool to Understand Watershed Geology: Blackberry Creek Watershed, Kane and Kendall Counties, Illinois

Edward Mehnert



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Front Cover: *Map of the Blackberry Creek watershed in Kane and Kendall Counties, Illinois, and the Fox River watershed in northeastern Illinois (modified from Bartosova et al. 2007).*

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Institute of Natural Resource Sustainability
William W. Shilts, Executive Director
ILLINOIS STATE GEOLOGICAL SURVEY
E. Donald McKay III, Director
615 East Peabody Drive
Champaign, Illinois 61820-6964
217-333-4747
www.isgs.illinois.edu

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Abstract

Three-dimensional geologic modeling is a powerful tool for understanding the spatial relationships of subsurface geologic materials. The modeling process involves interpolating the tops of the geologic materials for the areas between known data points (e.g., core from drill holes; outcrop observations). Unfortunately, the interpolated surfaces may not accurately depict the true geology. For example, the interpolated surface may show that an aquitard extends across the watershed, but the aquitard actually may be absent locally, allowing groundwater to flow between aquifers. Water flow through a watershed is a continuous process; thus, an accurate water flow model may help evaluate the accuracy of different conceptual geologic models during their development. Understanding the watershed hydrology and hydrogeology provides another line of evidence to help identify potential hydraulic connections and possibly reveal important hydrogeologic properties of the watershed. This additional evidence can improve our understanding of watershed geology. An analytic element (AE) model was developed to analyze steady state, shallow groundwater flow, and streamflow for a watershed. AE models can be developed in a sequential or stepwise fashion, increasing in complexity when justified by the geologic or hydrologic observations. The purpose of this project was twofold: (1) to develop a model of shallow groundwater and surface water flow for a watershed; and (2) to demonstrate the utility of AE modeling to test conceptual models developed from geologic modeling.

The Blackberry Creek watershed was selected for study because of its location in Kane County, its low stream order, the availability of streamflow data (U.S. Geological Survey stream gages at Montgomery and Yorkville), and interest by local groups such as the Fox River Study Group. The Blackberry Creek watershed covers more than 70 mi^2 in southern Kane County and northern Kendall County and has more than 400 ft of topographic relief. The watershed is covered with less than 25 ft to more than 200 ft of Wisconsin and Illinois Episode materials over Paleozoic bedrock.

Increasingly complex groundwater flow models were developed to explain the available geologic and hydrologic data. First, a simple model based on uniform parameters was developed to fit streamflow at the Yorkville gage and surrogate groundwater levels. Next, the simple model was modified to include an area with different hydrogeologic properties. Numerous solutions were possible by varying the rate of recharge and groundwater discharge from this area to Blackberry Creek. Detailed streamflow data were collected from nine stations in June 2007, allowing us to develop a better solution. The AE flow modeling allowed the testing of more complex conceptual models of watershed geology, which were identified and interpreted from the geologic modeling and hydrologic data. The AE models are an efficient tool that can be developed with much less effort than the more common groundwater flow model based on the finite difference method. Overall, the AE modeling process provided insight into the hydrogeology of the watershed and ultimately into the geologic model for the watershed.

Introduction

Geologic modeling is a powerful tool for understanding the spatial relationships of the subsurface geologic materials in an area. The geologic modeling process involves compiling discrete data points, such as data from detailed boring logs, and using those data points to develop a set of surfaces depicting the tops of various geologic units. The modeling process also involves interpolation of the areas between the known data points. Unfortunately, the interpolated surfaces may not accurately depict the true geology. For example, the interpolated surface may show that an aquitard extends across the watershed, but in reality the aquitard may be absent in places, allowing groundwater to flow between aquifers. Because water flow through a watershed is a continuous process, developing an accurate model of water flow through a watershed should help improve the geologic model by identifying significant geologic features that might otherwise be missed using geologic data only. Understanding the watershed hydrogeology provides another line of evidence to help identify potential hydraulic connections and possibly reveal important hydrogeologic properties of the watershed. This additional evidence can thus improve our understanding of the geology of the watershed and perhaps indicate where additional geologic investigation may be needed. Scanlon et al. (2002) noted that the geologic framework controls recharge in humid areas with low relief such as the Blackberry Creek watershed. Thus, recharge estimates may reveal details about the watershed's geologic framework.

Analytic element (AE) models allow scientists and engineers to model the steady state groundwater and surface water flow in a watershed with limited input data. As described by Haitjema (1995) and Hunt (2006), AE models can be developed in a sequential or stepwise fashion, increasing in complexity as justified by the observed streamflow or other data. Increasing complexity might be needed, for instance, to show where a deep aquifer and a shallow aquifer connect or where an aquifer discharges to a stream. AE models are ideally suited for simulating combined groundwater and surface water flow based on limited hydrogeologic input data. In addition, unique estimates of recharge and hydraulic conductivity, specifically the ratio of recharge to hydraulic conductivity, are possible if surface water flow data are available for model calibration (Sanford 2002).

The purpose of this project was twofold: (1) to develop a model of shallow groundwater and surface water flow for the Blackberry Creek watershed, and (2) to demonstrate the utility of AE modeling to test conceptual models developed from geologic modeling. The AE modeling should enable better description of watershed hydrogeology and ultimately the watershed geology. AE modeling will allow us to identify areas with distinct hydrogeology within the watershed.

Watershed Geology, Hydrogeology, and Hydrology

The Blackberry Creek watershed is located in southern Kane County and northern Kendall County (Figure 1). The watershed covers 74.6 square miles (Bartosova et al. 2007) and has more than 400 ft of topographic relief. Topographic maps show that Blackberry Creek is a first-order to third-order stream that drains into the Fox River. First-order streams have no tributaries; second-order streams are the junction of two first-order streams (Strahler 1981). Strahler (1981) noted that third-order streams are the junction of two second-order streams.

Blackberry Creek was selected for study because of its location in Kane County, its low stream order, the availability of streamflow data, and existing interest by local groups such as the Fox River Study Group. The mission of the Fox River Study Group (http://foxriverstudygroup.org) is to bring together a diverse coalition of stakeholders to work together to preserve and enhance water quality in the Fox River watershed. Results from this study should benefit the Fox River Study Group because a requisite step to understanding water quality is generally an understanding of water flow.

U.S. Geological Survey (USGS) scientists have studied flooding in the Fox River watershed and have developed surface water flow models to predict flood elevations and flows (Soong et al. 2005, Murphy et al. 2007). In their modeling effort, the USGS scientists divided land cover into general categories, such as agriculture (cropland and grassland), urban (medium density, high density, and open space), wetlands, and other (surface water, barren and exposed land). Murphy et al. (2007) used data from the Illinois land cover database (Luman et al. 1996) and more recent data for urban areas (2003 data for Kendall County and 2004 data for Kane County) to compile a land cover map for the watershed (Figure 2). Land cover is predominantly agricultural (cropland and grassland) with urban areas near Yorkville (south), near Aurora (east), and along Illinois Route 47. Land cover is important for modeling surface and groundwater flows because it affects the amount of precipitation that may run off (to become surface water) or infiltrate (to become groundwater).

For this study of the Blackberry Creek watershed, shallow groundwater flow is defined as flow through the upper 50 ft of geologic materials. Deep groundwater flow refers to flows within or below this 50-ft layer. To construct an AE groundwater flow model, information is needed about the watershed geology, hydrogeology, and hydrology. Aquifer thickness, hydraulic conductivity, and recharge are the required hydrogeologic data. Surface water heads are also needed. The accuracy of the AE model can be improved by using streamflow data, streambed data, and groundwater heads in the calibration process.

Watershed Geology and Hydrogeology

A complete description of Kane County geology was recently completed by Dey et al. (2007a, 2007b, 2007c, 2007d, 2007e) and Abert et al. (2007). The brief geologic description in this present publication focuses on the Quaternary materials. Drift thickness is the thickness of the Quaternary materials above the bedrock. The drift thickness across the watershed varies considerably but generally thins to less than 25 ft near the Fox River (Figure 3). Within the Blackberry Creek watershed, which is primarily located in the four townships in the southeastern corner of Kane County, maximum drift thickness is more than 200 ft.

In Kane County, Quaternary materials from the Wisconsin and the Illinois Episodes overlie Paleozoic bedrock. As shown in Figure 4, sand and gravel (Henry Formation) may be interbedded with the glacial diamictons (Lemont and Tiskilwa Formations of the Wedron Group). Surficial deposits of peat (Grayslake Peat) and floodplain alluvium (Cahokia Formation) can be found in Kane County. In Kane and Kendall Counties, Quaternary materials overlie either Silurian limestone and dolomite or Ordovician Maquoketa Group rocks, which are predominantly shale. The Maquoketa is the uppermost bedrock where the Silurian rocks have been eroded.

In Kane and Kendall Counties, a number of moraines have been mapped (Figure 5). The locations of St. Charles and Minooka Moraines are significant landmarks and are referenced later in this report. The presence of the Yorkville Member of the Lemont Formation (Figures 4 and 6) is important to the discussions later in this report.

Curry and Seaber (1990) also mapped the groundwater resources in Kane County and compiled estimates of hydraulic conductivity for the sand and gravel aquifers there. In southern Kane County, the Kaneville aquifer member of the Elburn Aquiformation overlies the St. Charles aquifer. The Kaneville and St. Charles are separated by the Marengo aquitard. Hydraulic conductivity (K) values for the Kaneville aquifer member of the Elburn Aquiformation were published by Curry and Seaber (1990) and Visocky (1990) (Table 1). These values were determined mainly by specific capacity and time-drawdown analysis. The median hydraulic conductivity value was 140 ft/day or 5.0×10^{-2} cm/sec. These data provide some information on the hydraulic properties of the geologic materials to a depth of 135 ft.

Curry et al. (2001a) recently studied the geology and hydrology of Nelson Lake Marsh, which is located in the northeastern portion of the Blackberry Creek watershed. Four wells completed in the Kaneville aquifer member of the Elburn Aquiformation had hydraulic conductivity values of 16, 17, 130, and 400 ft/day or 5.8×10^{-3}, 6.1×10^{-3}, 4.6×10^{-2}, and 1.4×10^{-1} cm/sec, as determined by slug testing (Curry et al. 2001a). Slug testing is a technique for estimating hydraulic conductivity that involves adding or removing a known volume of water ("slug") from the well and monitoring the water level in the well over time. Gamma logs and slug testing indicated that the aquifer becomes more permeable as it thickens west of Nelson Lake. At baseflow conditions, very little water flows (<1 cubic feet per second [cfs]) out of Nelson Lake via Lake Run (Curry et al. 2001a).

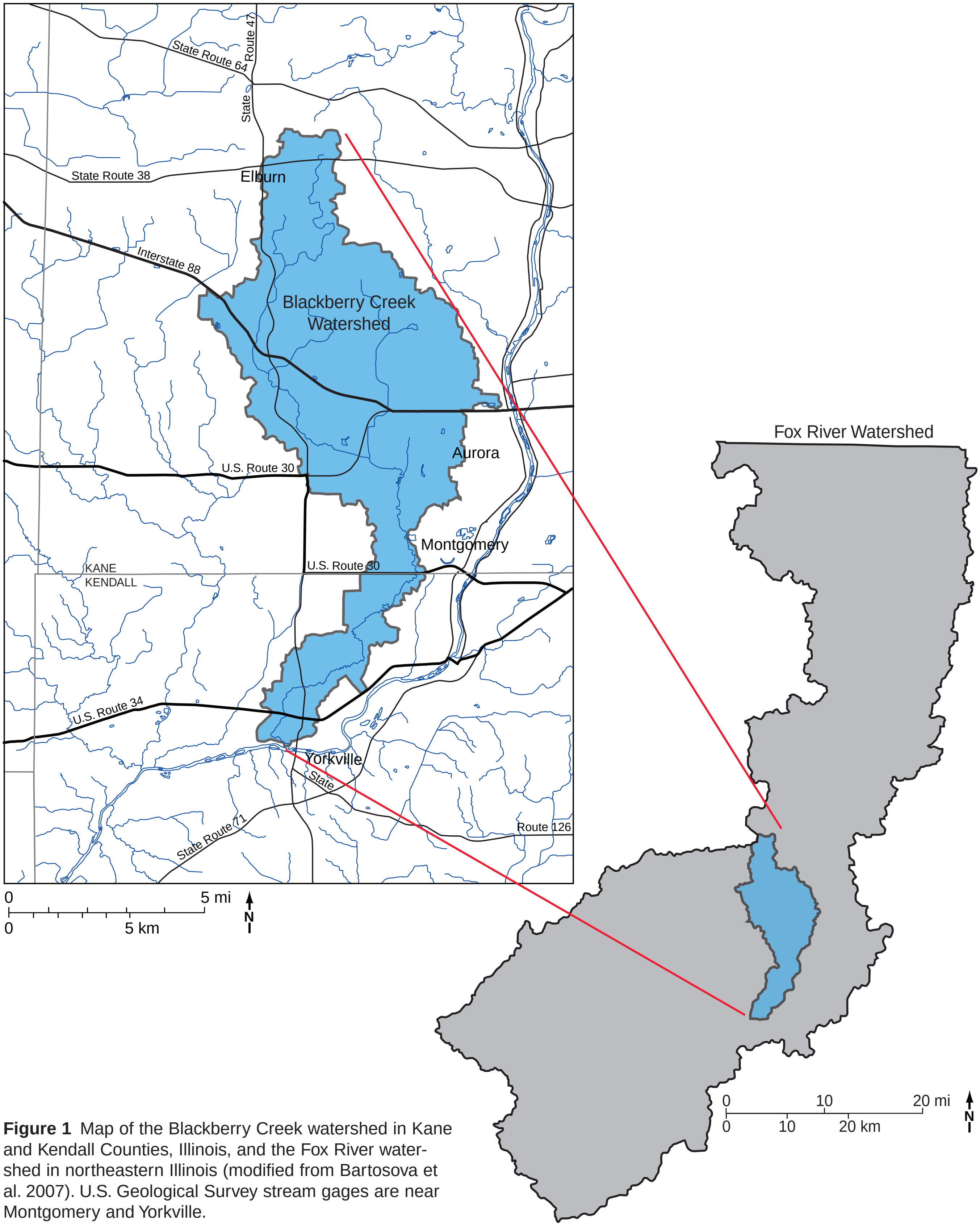

Figure 1 Map of the Blackberry Creek watershed in Kane and Kendall Counties, Illinois, and the Fox River watershed in northeastern Illinois (modified from Bartosova et al. 2007). U.S. Geological Survey stream gages are near Montgomery and Yorkville.

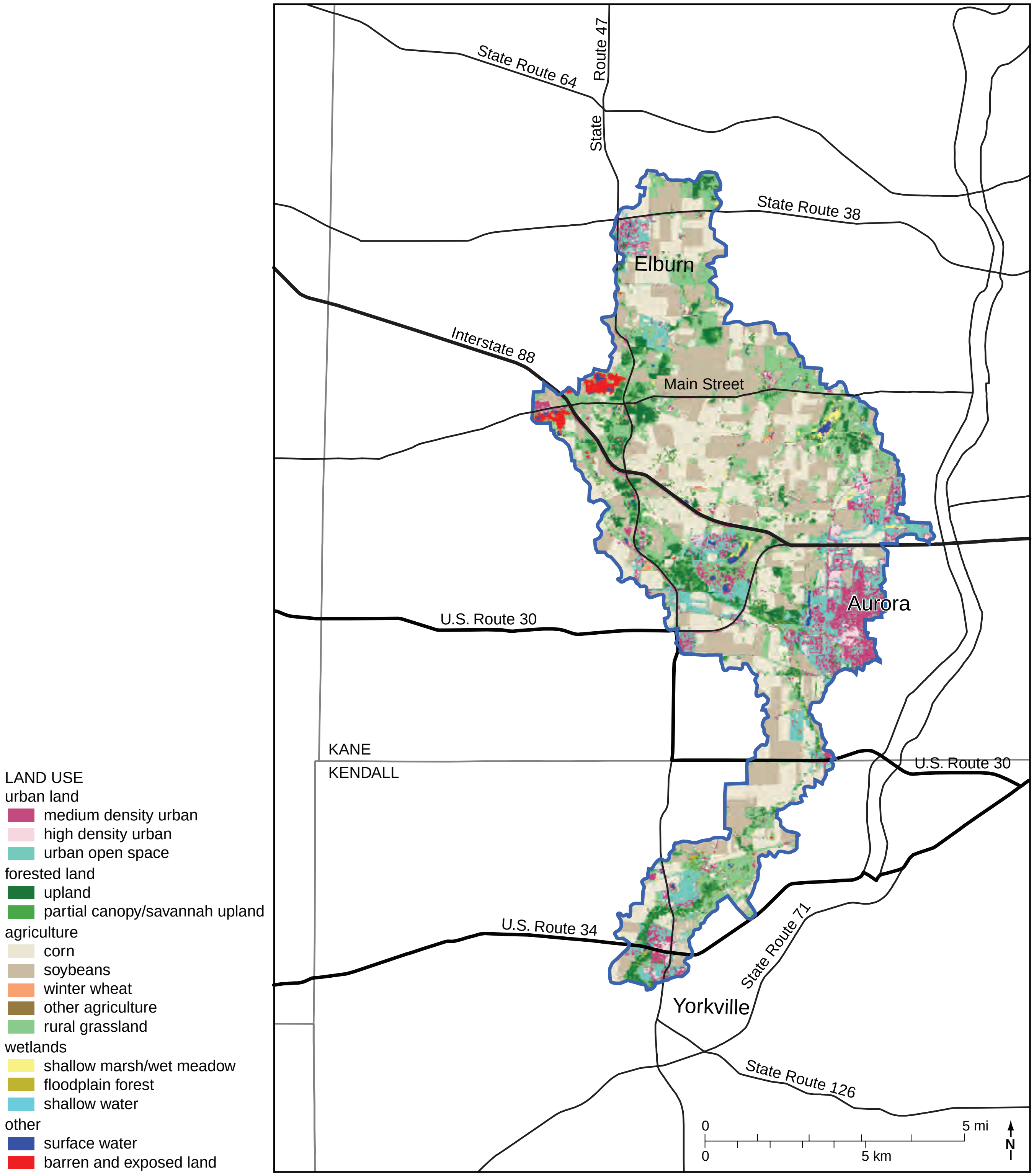

Figure 2 Land cover in the Blackberry Creek watershed (Murphy et al. 2007).

For the year 2000, the total precipitation at Nelson Lake was 37.2 inches, and recharge was estimated to be 1.4 inches/yr based on mass balance (Curry et al. 2001a). Nelson Lake water level varied from 693.0 ft to 693.5 ft for most of the year. Additionally, a calibrated, AE groundwater flow model was developed to define the capture zone of the lake, based on 3 inches of recharge per year and hydraulic conductivity of 60 to 200 ft/day or 2.1×10^{-2} to 7.0×10^{-2} cm/sec (Curry et al. 2001a).

Using subsoil hydraulic conductivity values ranging from 1.96 to 3.22 ft/day or 6.9×10^{-4} to 2.3×10^{-3} cm/sec in their Illinois Streamflow Assessment Model (ILSAM) model, Knapp and Myers (1999) estimated streamflow in Blackberry Creek. In their model, hydraulic conductivity generally increased from upstream to downstream areas of the watershed (Table 2). The average subsoil hydraulic conductivity for the Lake Run watershed (a subwatershed in the Blackberry Creek watershed) was 1.96 ft/day or 6.9×10^{-4} cm/sec. Knapp et al. (2007) revised the values of subsoil hydraulic conductivity used in their Kane County Surface Water Accounting Model (KC-SWAM) (Knapp and Myers 1999) (Table 2).

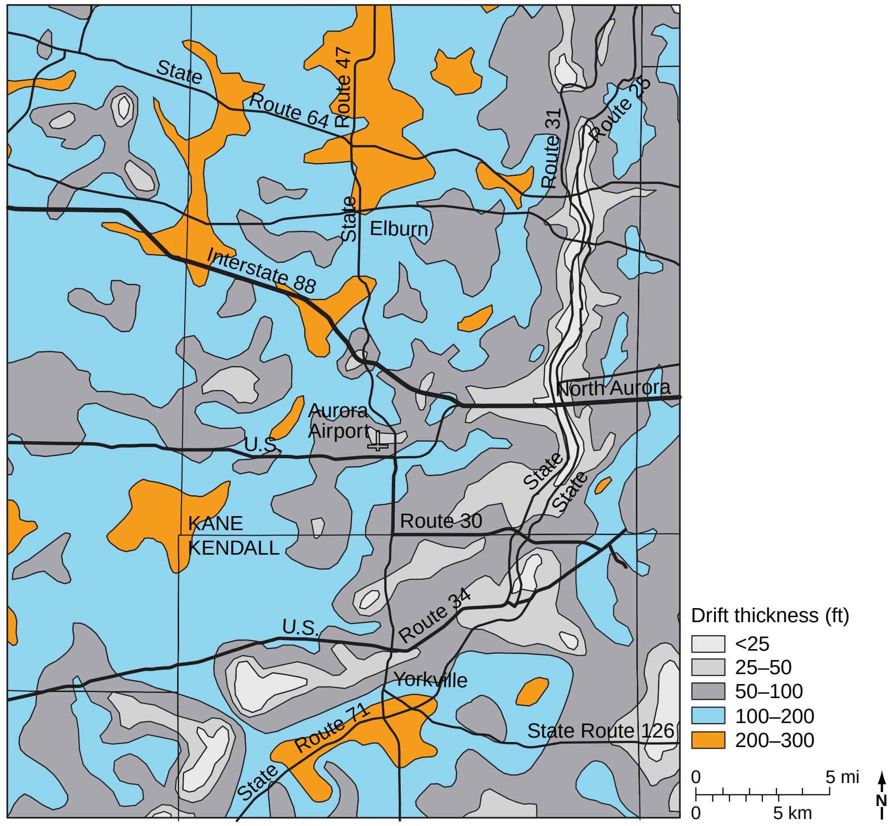

Figure 3 Drift thickness map for Kane, Kendall, and surrounding counties (from ISGS GIS database, *Glacial Drift in Illinois: Thickness and Character,* 1994). The contour interval is irregular.

Watershed Hydrology

Blackberry Creek is a headwaters stream and becomes a third-order stream before it discharges to the Fox River. The USGS maintains two stream gaging stations on Blackberry Creek (Figure 1) and provides data on its Web site (http://waterdata.usgs.gov/il/nwis/rt). Station 05551675 is located west of Montgomery and has an upstream drainage area of 55.0 mi^2. Station 05551700 is located north of Yorkville, just upstream from the confluence with the Fox River, and has an upstream drainage area of 70.2 mi^2. Station 05551700 became operational in October 1960, and Station 05551675 became operational in June 1998. The ratio of the Montgomery station streamflow to the Yorkville station streamflow ($Q_{05551675}/Q_{05551700}$) varied from 0.148 to 4.93 over the period analyzed (June 1998 through September 2003). Variations in this ratio may reflect the timing of flow down Blackberry Creek. For the period analyzed, the median value of $Q_{05551675}/Q_{05551700}$ was determined to be 0.864; that is, 86.4% of the flow passing the Yorkville gage also flows past the Montgomery gage. The median value (86.4%) is greater than the 78.3% estimated value based on the watershed area of both gaging stations.

Knapp and Myers (1999) updated the ILSAM that describes the streamflow in the Fox River watershed. The ILSAM describes streamflow at various locations for a range of flow conditions, including flood and drought. ILSAMs provide information about present and virgin (unaltered) flow conditions. Present flow describes flow from all sources. Virgin flow does not include flow alterations due to human activity, such as water supply withdrawals or wastewater discharge. Knapp and Myers (1999) noted that virgin flow should not be considered as “pristine” or predevelopment flow. The difference between virgin and present flow in Blackberry Creek is relatively small, 1 cfs or less (Table 3). Table 3 shows the mean virgin flow equals 49.6 cfs. The Q_{10} equals 112 cfs; Q_{10} is the daily flow rate that is exceeded 10% of the time. The median virgin flow (Q_{50}) equals 28.0 cfs. $Q_{7,10}$ is a common measure of low flow and indicates mild drought conditions. $Q_{7,10}$ is the the lowest average flow that would be experienced during a consecutive 7-day period with an average recurrence interval of 10 yrs. The $Q_{7,10}$ for virgin flow in Blackberry Creek is 3.9 cfs. The values listed in Table 3 were estimated using the subsoil hydraulic conductivity values listed in Table 2 and an annual net precipitation (precipitation minus evapotranspiration) value of 10.1 inches/yr.

Knapp et al. (2007) updated this analysis. The present flow for the most recent analysis was lower at the upper and lower flows (Table 3), but slightly higher in the middle flow conditions.

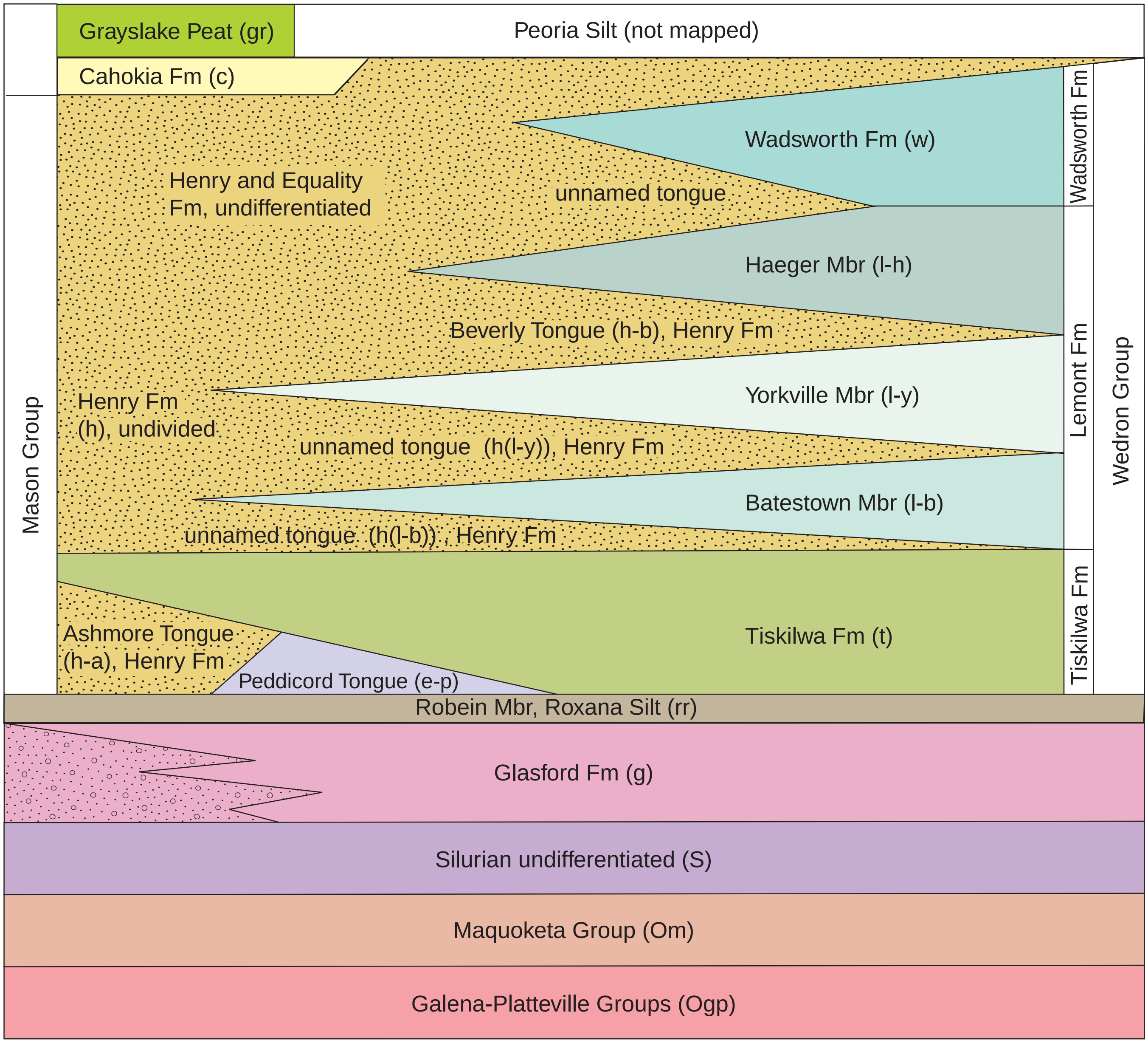

Figure 4 Diagram showing the stratigraphic relationships of the Quaternary materials and the upper bedrock (Dey et al. 2007e).

The revised flows were based on different values of subsoil hydraulic conductivity (Table 2).

During low flow conditions, specifically $Q_{7,10}$ conditions, flow in Blackberry Creek starts south of Elburn (Figure 7) near the intersection of Main Street and Illinois Route 47 (Figure 2). A number of small ponds and a wetland are mapped at this intersection (Figure 2).

Streamflow data were collected on June 11 and June 12, 2007, using a USGS pygmy meter (model 6205, Rickly Hydrological Co., Columbus, OH, www.rickly.com) with a horizontal axis rotor. The streamflow data were collected and analyzed according to Rantz (1982). Streamflow was measured at nine locations around the watershed (Figure 8). We measured streamflow at the USGS Montgomery gage at 25.0 cfs; the USGS-reported streamflow was 23.6 cfs, a difference of 6%, which is within the ±10% error range generally reported (Rantz 1982). The streamflow for the USGS Yorkville gage was obtained from the USGS Web site.

Streamflow was normalized by dividing the flow value at a given location by the flow value obtained at the Yorkville gage. Thus, the normalized flow equals 1.00 at the Yorkville gage and 0.00 at the headwaters (Figure 9). The field data were plotted with values from Knapp and Myers (1999) and Knapp et al.

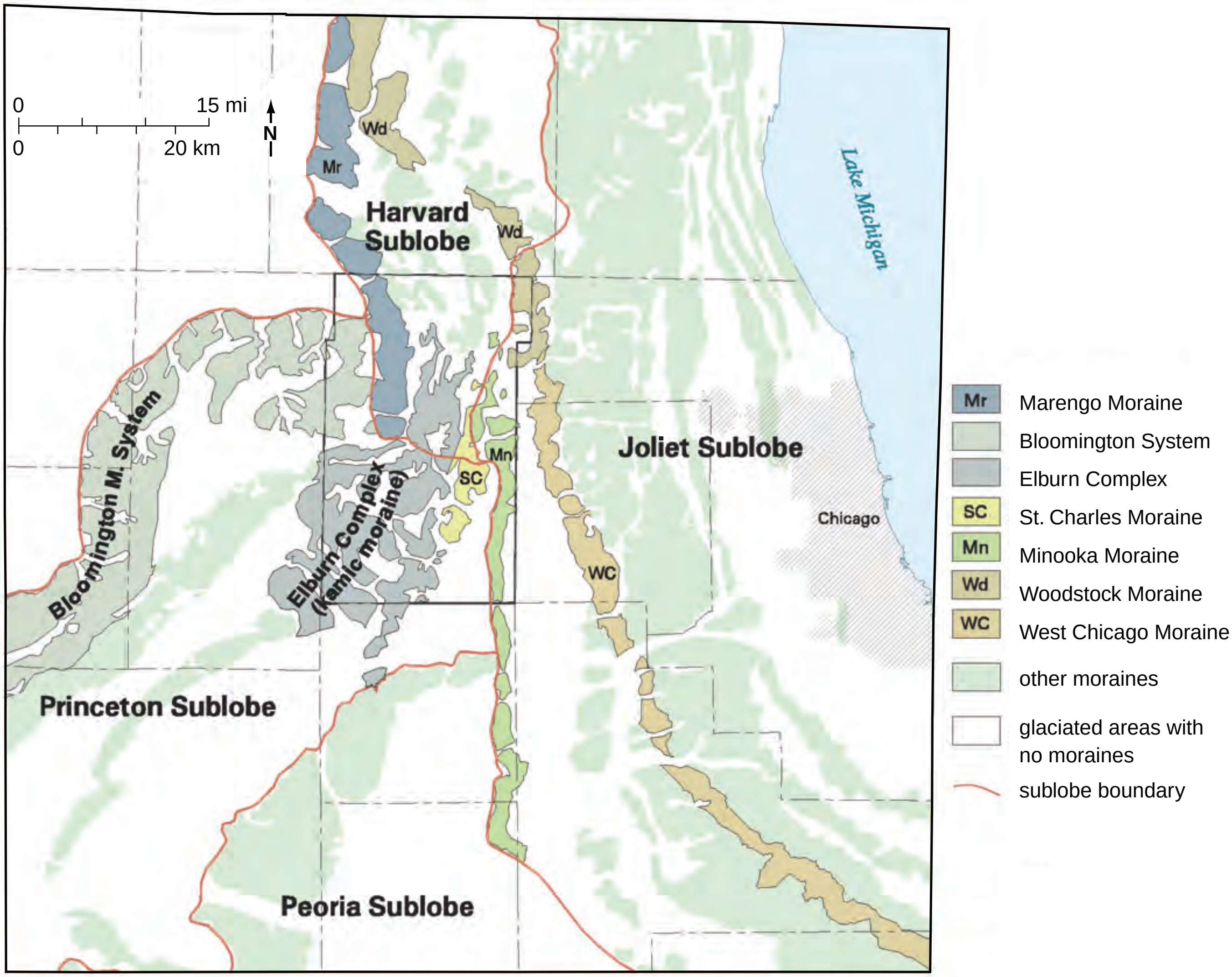

Figure 5 Wisconsin Episode moraines in northeastern Illinois (Dey et al. 2007e).

(2007). The Knapp et al. (2007) values matched the field data better than the Knapp and Myers (1999) values. Because Knapp and Myers (1999) and Knapp et al. (2007) modeled flow to the confluence with the Fox River (downstream from the Yorkville gage), their normalized flow values exceeded 1.00.

When the streamflow data were collected in June 2007, the limits of Blackberry Creek and the surrounding streams were mapped. A survey was conducted to determine the physical limits of each stream, primarily in the upper reaches to determine the origin of each stream. The mapping results were included in the modeling process.

Stepwise Development of an AE Model for the Blackberry Creek Watershed

Shallow groundwater flow in the Blackberry Creek watershed was modeled using the AE model, GFLOW (Haitjema Software, Bloomington, Indiana; http://www.haitjema.com). This software allows one to simultaneously model steady state, two-dimensional groundwater flow and surface water flow. The model requires limited input data: recharge, hydraulic conductivity, aquifer porosity, aquifer thickness, and surface water heads. Areas with different properties can also be input into the model. GFLOW simulates these areas as "inhomogeneities," referred to as "unique areas" in this report. Streams can be input as far-field or near-field features. Far-field streams are generally those that are in areas outside the modeler's direct interest but that still exert some influence on flow within the area of interest. Near-field streams are located in areas where detailed results are sought, such as the Blackberry Creek watershed. For near-field streams, GFLOW also requires input data for stream width, flow depth, and hydraulic resistance of the streambed. GFLOW produces solutions that can be used to map the hydraulic head in the aquifer and to estimate streamflow for near-field streams.

AE models can be developed in a sequential or stepwise fashion, as complexity of the models increases as a result of observations. Haitjema (1995) and Hunt (2006) advocate stepwise modeling as a way to understand the significant hydrologic features of the watershed. Increasing complexity might be needed to show where a deep aquifer and shallow aquifer connect or where an aquifer discharges to a stream.

Inputs for the surface water features were obtained from several sources. For far-field streams and lakes, surface water heads were determined from USGS 7.5-minute series topographic maps and stream mapping conducted in June 2007. When needed, more recent information about hydrologic features (such as boundaries of streams and ponds) was obtained from satellite images available on Google Map (www.google.com). Streamflow in Blackberry Creek at the Yorkville gage was used to calibrate the AE model. For the AE model, Q_{75} was selected as the calibration target for streamflow in Blackberry Creek. Q_{75} is the flow that is exceeded 75% of the time. At Q_{75}, stormwater runoff is zero, and groundwater discharge sustains streamflow. Q_{75} equals 14.0 cfs for virgin flow in Blackberry Creek (Figure 9 and Table 3) (Knapp and Myers 1999). Virgin flow was chosen for calibration because it does not include alterations to flow such as wastewater discharges in present flow.

The model was calibrated using groundwater heads at two locations, Aurora Municipal Airport (ground elevation: 700 ft) and southwestern Village of Elburn (ground elevation: 840 ft near the intersection of the Union Pacific railroad tracks and Illinois Route 47). The Aurora Airport is located in the center of the watershed, and Elburn is located at the northern end. Observation wells were not available at these locations, but groundwater heads should not have been above ground level during the low flow conditions considered. Groundwater heads tend to follow the surface topography, but would be several feet below ground during the low flow conditions considered. Because of their relative position within the landscape, the groundwater heads were assumed to be 10 to 20 ft below the ground surface at Elburn and 5 to 10 ft below the ground at the airport. Elburn is located halfway between the moraine top and bottomlands; the Aurora Airport is located in an area with less relief.

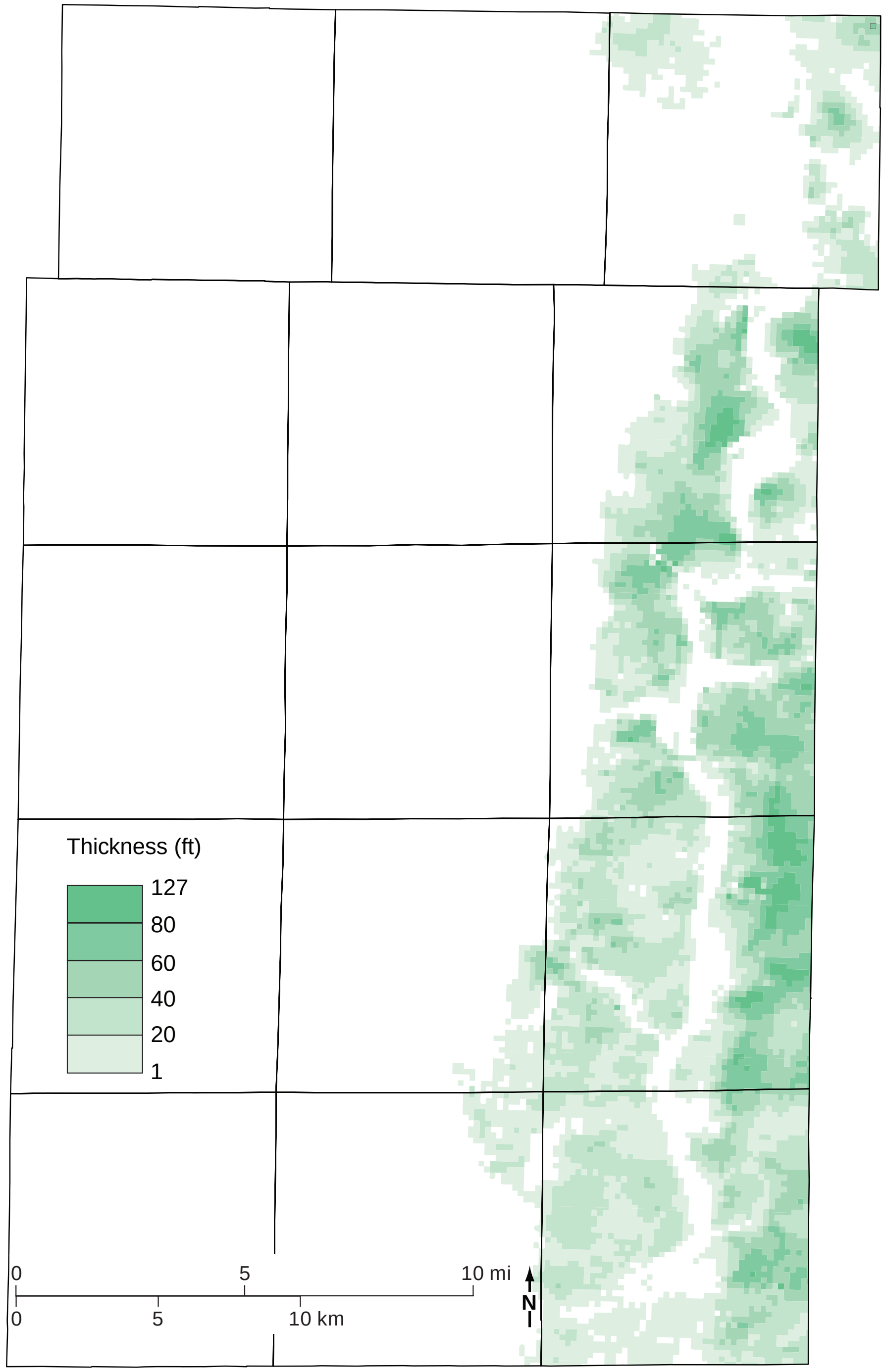

Figure 6 Thickness of the Yorkville Member of the Lemont Formation in Kane County (Dey et al. 2007e).

During calibration of the groundwater flow models, matching all calibration data is rarely possible. In this study, greater emphasis was placed on matching the streamflow data than the groundwater head data. Because the groundwater level data in this study were estimated, the streamflow data were carefully measured and thus deserve greater emphasis.

Table 1 Hydraulic conductivity (K) estimated from wells completed in the Kaneville aquifer member of the Elburn Aquiformation (Curry and Seaber 1990, Visocky 1990).

Well location	Well depth (ft)	K (ft/day)	K (cm/sec)	Analysis[1]	Aquifer type
T38N, R7E, Sec. 21	104	50	1.7×10^{-2}	SC	Unconfined
T38N, R7E, Sec. 21	107	210	7.4×10^{-2}	SC	Unconfined
T38N, R7E Sec. 21	110	130	4.6×10^{-2}	SC	Unconfined
T38N, R7E, Sec. 33	77	230	8.1×10^{-2}	TD	Confined
T39N, R6E, Sec. 25	125	630	2.2×10^{-1}	SC	Confined
T39N, R7E, Sec. 20	110	180	6.4×10^{-2}	TD	Confined
T40N, R8E, Sec. 11	131	140	5.0×10^{-2}	SC	Unconfined
T40N, R8E, Sec. 11	135	110	3.7×10^{-2}	SC	Unconfined
T42N, R8E, Sec. 28	34	82	2.9×10^{-2}	SC	Unconfined

[1]SC, specific capacity analysis; TD, time-drawdown analysis.

Establishing the Base Case Model

The first model considered is the base case, which includes uniform hydrogeologic features and parameters across the watershed and the entire model area. The surface water features are shown in Figure 10. Blackberry Creek is a near-field feature and is shown in orange. Streams surrounding Blackberry Creek, including the Fox River to the east and south of Blackberry Creek, are shown in green. These streams are considered far-field features. Each node is depicted with a diamond and represents a constant head node. Input data for these nodes were obtained from the ground elevations on USGS 7.5-minute series topographic maps. For near-field streams, the AE model determines the streamflow based on an iterative solution with groundwater heads. Input data for the near-field streams include stream width, flow depth, and hydraulic resistance of the streambed (Table 4). Higher hydraulic resistance might be appropriate for streambeds covered by fine-grained sediments, whereas lower hydraulic resistance might be appropriate for streambeds covered by coarse-grained sediments. Although sections of the Blackberry Creek streambed are known to be covered with fine-grained sediments and other sections with coarse-grained sediments, no maps of streambed sediments exist. Thus, hydraulic resistance was set at zero days for all streams.

Groundwater recharge is applied to the area inside the red rectangle. Input values for this base case and other cases are shown in Table 5. For all cases modeled, the aquifer was assumed to be 50 ft thick and represents the geologic materials to a depth of 50 ft. To facilitate modeling, these geologic materials were assumed to have uniform properties.

Table 2 Watershed characteristics for Blackberry Creek used in ILSAM (Knapp and Myers 1999) and KC-SWAM models (Knapp et al. 2007).[1]

Stream	River mileage	ILSAM drainage area upstream (mi^2)	ILSAM subsoil K (ft/day)	KC-SWAM subsoil K (ft/day)
Blackberry Creek	34.6	0.0	2.32	
	31.9	3.5	2.32	1.04
	27.9	6.0	2.32	1.96
	25.4	9.2	3.34	5.50
	22.6	18.7	4.28	5.50
	21.9	21.1	4.4	5.62
	19.8	25.2	4.08	5.52
	17.5	27.3	3.98	4.92
	17.0	30.7	3.78	NR[2]
Confluence with Lake Run	17.0	30.7	3.62	3.98
	15.5	45.4	4.30	3.78
	13.0	54.9	5.16	3.44
	11.3	60.2	5.34	3.44
	7.4	64.0	5.68	3.48
	3.3	70.2	6.22	3.54
	1.8	71.7	6.34	3.54
	0.0	72.9	6.44	3.56
Lake Run	7.3	0.0	1.96	NR
	6.0	2.1	1.96	2.92
	3.98	8.8	1.96	2.54
	3.3	11.0	1.96	2.16
	2.0	12.5	1.96	2.24
	0.0	13.6	1.96	2.58

[1]ILSAM, Illinois Streamflow Assesment Model; KC-SWAM, Kane County Surface Water Accounting Model.

[2]NR, No recorded value.

For this base case (the first case modeled), uniform hydrogeologic features and parameters were assumed for the watershed and the entire modeled area. The model was calibrated using hydraulic conductivity (K) of 37.5 ft/day, aquifer thickness of 50 ft, and recharge of 4.6×10^{-4} ft/day or 2.0 inches/yr. The modeled streamflow matched actual streamflow, and the predicted depth to water seems reasonable for both locations (Table 5).

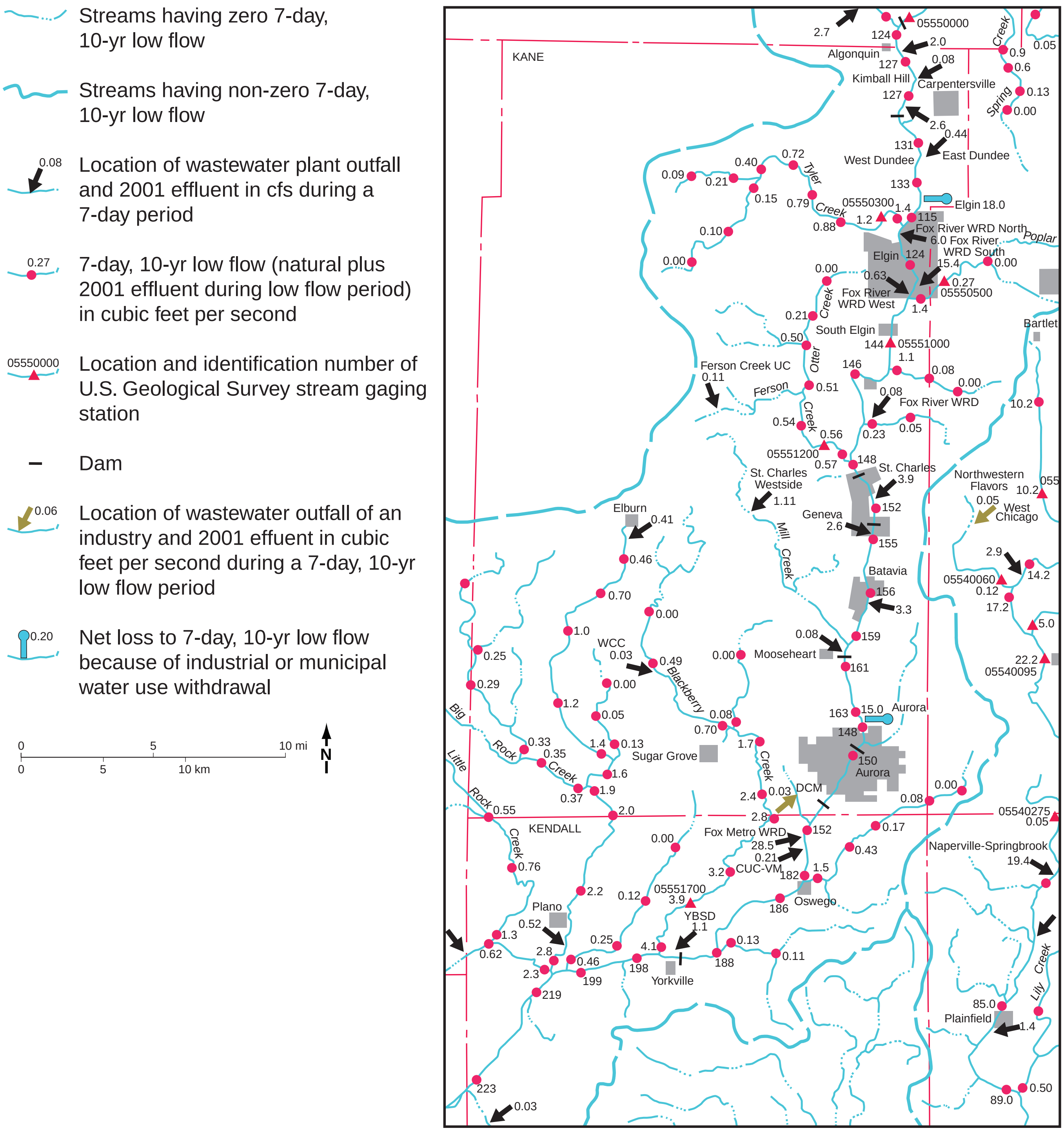

Figure 7 Seven-day, 10-yr low streamflow ($Q_{7,10}$) map of the Fox River watershed including Blackberry Creek (modified from Illinois State Water Survey Web site http://www.isws.illinois.edu/docs/maps/lowflow/maps.asp; select NE Illinois streams).

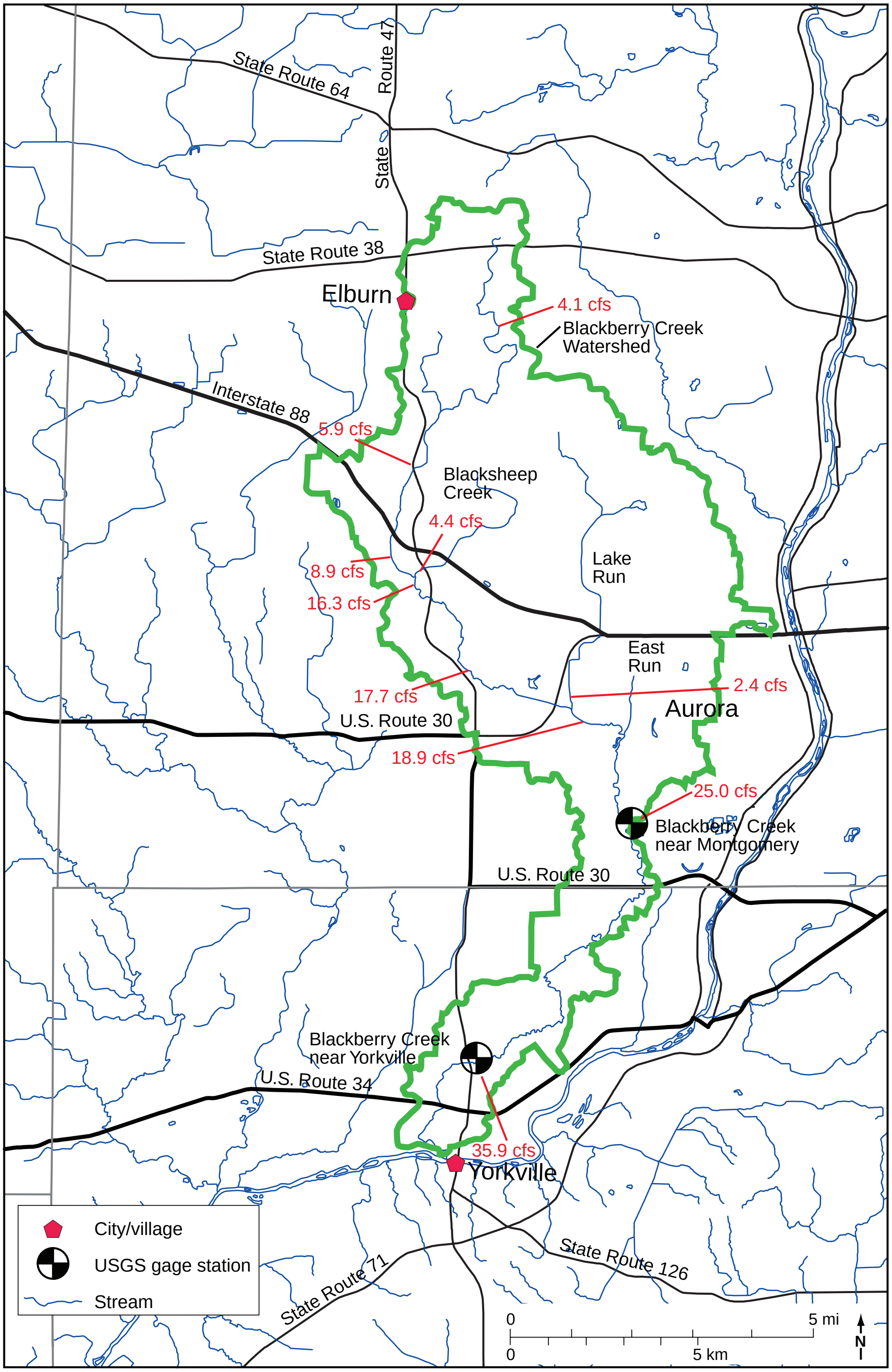

Figure 8 Streamflow measured in Blackberry Creek on June 11 and June 12, 2007 (modified from Bartosova et al. 2007).

The model results also illustrate the dominant effect of the Fox River on shallow groundwater (Figure 11). Additionally, close inspection of the modeled flow in the lower reaches of Blackberry Creek shows it to be a losing stream that recharges shallow groundwater in the southern end of the watershed (Figure 12).

The calibrated value of hydraulic conductivity for this model was 37.5 ft/day, which was higher than the subsoil values (1 to 6 ft/day) used by Knapp and Myers (1999) and Knapp et al. (2007) but is lower than the median hydraulic conductivity values of 140 ft/day reported by Curry and Seaber (1990) for the Kaneville aquifer member of the Elburn Aquiformation. Our hydraulic conductivity value (37.5 ft/day) matches that value for a calibrated AE model of an agricultural watershed in east-central Illinois (Mehnert et al. 2005, 2007).

For the 131 USGS eight-digit watersheds within the Upper Mississippi River watershed, Arnold et al. (2000) estimated baseflow and recharge based on daily streamflow records from 1960 through 1980. Baseflow was estimated using the SWAT (Soil and Water Assessment Tool) model (Arnold et al. 1998), a water balance model for daily water data. For steady state conditions, baseflow and recharge are considered equivalent. The Lower Fox River and Upper Fox River basins are both classified as USGS eight-digit watersheds. Arnold et al. (2000) estimated mean recharge for the Lower Fox River basin to be 6.0 inches/yr using the SWAT model. That estimate is considerably higher than the GFLOW estimate of 2.0 inches/yr (4.6×10^{-4} ft/day) for the Blackberry Creek watershed. For the Lower Fox River basin, Arnold et al. (2000) calibrated their SWAT model using a target streamflow of 1,630 cfs, which exceeds Q_{75} (732 cfs) but is between the Q_{50} (1,350 cfs) and Q_{40} (1,710 cfs) estimated by Knapp et al. (2007). Thus, the Arnold et al. (2000) recharge value apparently is higher because it is based on higher streamflow than the Q_{75} used to estimate recharge in this study.

Table 3 ILSAM- (Knapp and Myers, 1999) and KC-SWAM- (Knapp et al. 2007) predicted flow conditions for Blackberry Creek at the Yorkville gage.[1]

	ILSAM		KC-SWAM
Flow condition[2]	Virgin flow (cfs)	Present flow (cfs)	Present flow (cfs)
Q_{01}	389	390	371
Q_{10}	112	113	106
Q_{25}	57	58	56
Q_{50}	28.0	28.8	29.1
Q_{75}	14.0	14.7	14.4
Q_{90}	8.0	8.7	8.4
Q_{99}	3.9	4.4	2.9
Q_{mean}	49.6	50.4	50.0
$Q_{7,10}$	3.9	4.4	2.5

[1]ILSAM, Illinois Streamflow Assesment Model; KC-SWAM, Kane County Surface Water Accounting Model.

[2]Q, streamflow; subscript number following Q indicates percentage of time that daily streamflow rate was exceeded (e.g., Q_{10}, daily streamflow rate exceeded 10% of the time); Q_{50}, median virgin flow; Q_{mean}, mean daily streamflow rate; $Q_{7,10}$, the lowest average daily flow that will occur over 7 consecutive days and will occur on average once every 10 years; cfs, cubic feet per second.

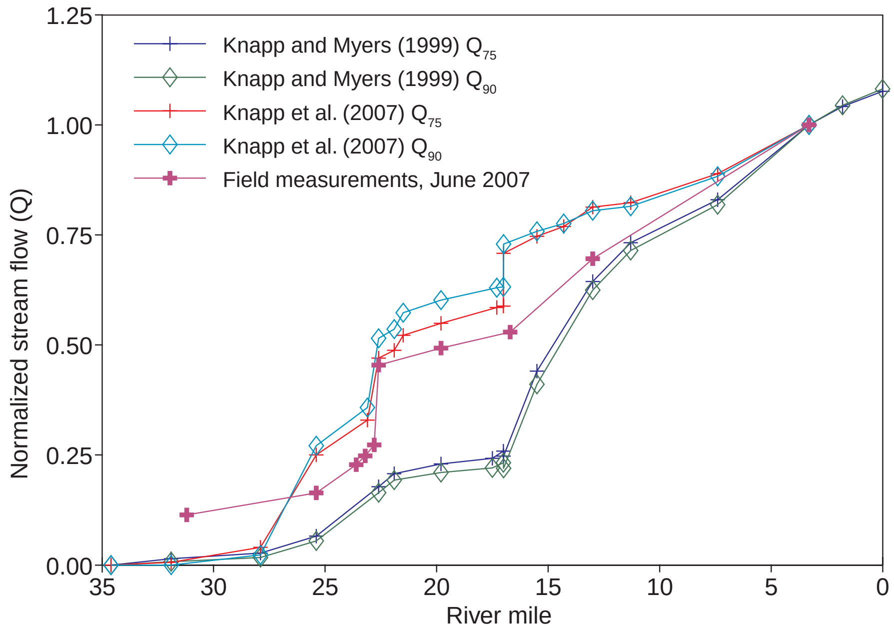

Figure 9 Normalized streamflow in Blackberry Creek showing field data and Illinois State Water Survey modeling results.

Demonstrating the Value of Streamflow Data

The second case modeled demonstrates the value of using streamflow data to understand the watershed hydrology. Sanford (2002) noted the utility of flux data such as streamflow to find a unique solution when modeling shallow groundwater flow. Using the flux data, the recharge and hydraulic conductivity input values were both decreased by an order of magnitude from those used in case 1 (Table 5). The modeled depth to water (DTW) remains the same as case 1, but

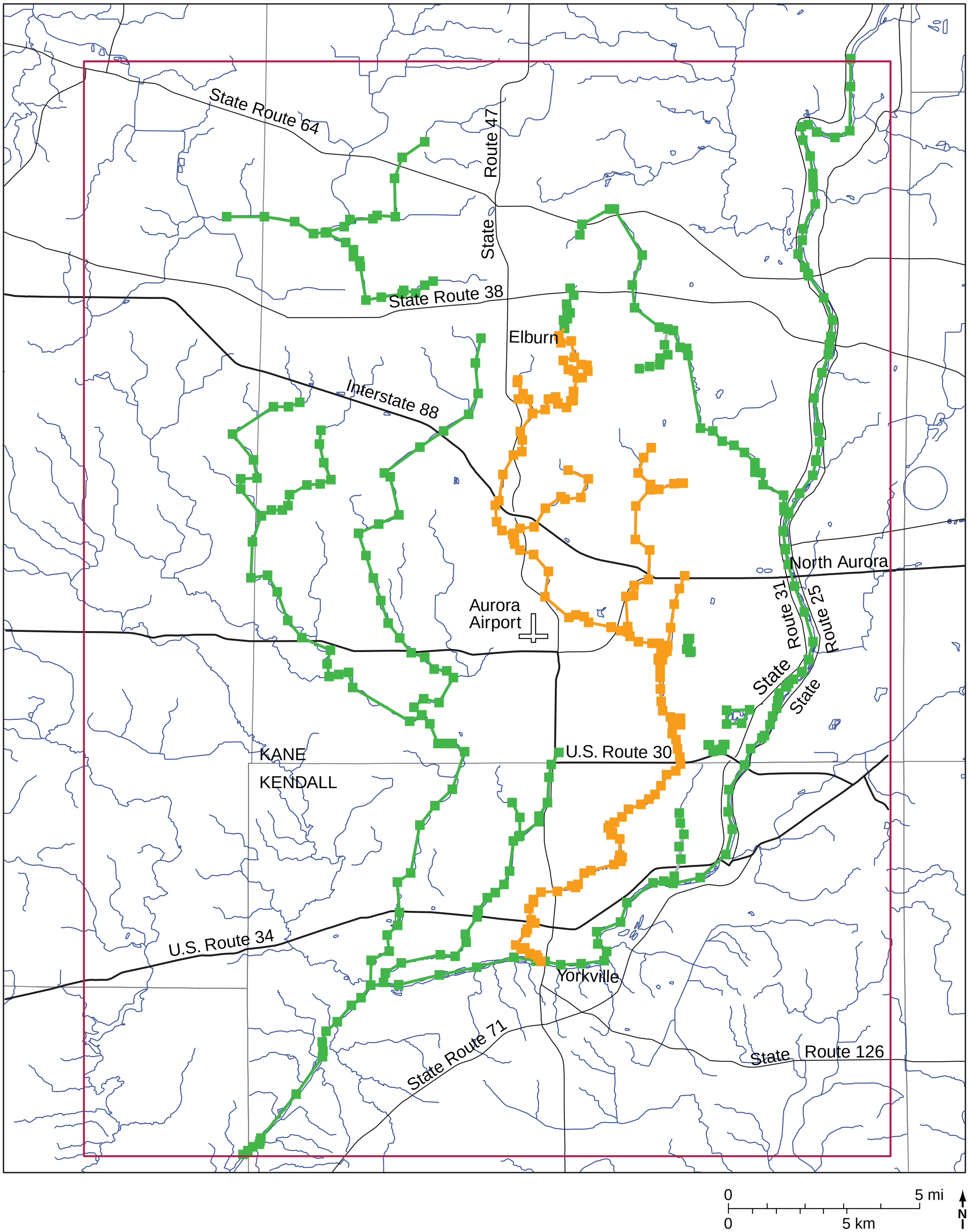

Figure 10 GFLOW model output showing the far-field (green) and near-field (orange) features used to model the watershed. Groundwater recharge exceeds zero inside the red rectangle and equals zero outside the red rectangle. The base map shows other cultural features, such as major roads (black) and surface water (blue) features.

Table 4 Input parameters for the near-field streams for Blackberry Creek and its tributaries when streambed hydraulic resistance is set to zero.

Stream	Stream width (ft)	Flow depth (ft)
Blackberry Creek Segment 1	8	2
Blackberry Creek Segment 2	10	2
Blackberry Creek Segment 3	12	3
Blackberry Creek Segment 4 (lowest elevation)	15	3
Tributary		
Unnamed	3	0
Lake Run segment 1	3	0
Lake Run segment 2	3	0
East Run	3	1

Table 5 Model input and results for the Blackberry Creek watershed. Italic type indicates changes in input data from the previous case.

Model	Input (overall area)			Input (unique area)			Results					
case number	K (ft/day)	r (ft/day)	b (ft)	K (ft/day)	r (ft/day)	Area (ft^2)	Q_{outlet} (cfs)	Q_{BS} (cfs)	Q_{LR} (cfs)	Q_{ER} (cfs)	DTW_{Elburn} (ft)	$DTW_{airport}$ (ft)
1	37.5	4.6×10^{-4}	50	NA	NA	NA	14.0	NA	NA	NA	18	5
2	*3.75*	*4.6×10^{-5}*	50	NA	NA	NA	1.4	NA	NA	NA	18	5
3	*37.5*	*3.0×10^{-4}*	50	*150*	*4.0×10^{-2}*	*6.8×10^{6}*	14.0	0.2	1.5	0.04	16	5
4	37.5	*2.5×10^{-4}*	50	150	*4.3×10^{-3}*	*8.2×10^{7}*	14.0	1.7	1.4	0.1	18	7
				150	4.3×10^{-3}	8.2×10^{7}						
5	37.5	*2.8×10^{-4}*	50				14.0	1.7	1.0	0.0	17	5
				37.5	*-2.5×10^{-4}*	*5.4×10^{8}*						
				150	4.3×10^{-3}	8.2×10^{7}	14.0	1.6	1.1	0.45	18	6
6	37.5	*2.45×10^{-4}*	50									
				37.5	*-2.45×10^{-4}*	5.4×10^{8}						
				150	4.3×10^{-3}	8.2×10^{7}						
7	37.5	2.45×10^{-4}	50	37.5	22.45×10^{-4}	5.4×10^{8}	14.0	1.6	1.1	0.45	17	5
				37.5	*2.0×10^{-4}*	*1.4×10^{8}*						
8	37.5	2.45×10^{-4}	50	150	4.3×10^{-3}	8.2×10^{7}						
				37.5	-2.45×10^{-4}	5.4×10^{8}	14.4	1.6	1.1	0.3	18	22
				150	0	*2.3×10^{9}*						
						Calibration target for results	14.0	1.7	0.9	<0.9	10–20	5–10

[1]K, hydraulic conductivity; r, recharge; b, aquifer thickness; cfs, cubic feet per second; Q_{outlet}, streamflow at the Yorkville gage; Q_{BS}, streamflow from Black-sheep Creek; Q_{LR}, streamflow from Lake Run; Q_{ER}, streamflow from East Run; DTW_{Elburn}, depth to water at Elburn; $DTW_{airport}$, depth to water at Aurora Airport; NA, not applicable.

the flow at the Yorkville gage (Q_{outlet}) drops by an order of magnitude (Table 5). Although the groundwater heads are equal, case 1 is considered a better model because it matches the known streamflow. Thus, case 2 demonstrates the utility of this modeling process to determine the watershed scale recharge for the desired flow condition (Q_{75}).

In case 3, the assumption of uniform geology was abandoned, and an area of unique hydrogeology was added. The unique area represents an area of significant groundwater discharge to Blackberry Creek (magenta polygon in Figure 13). Empirical data indicate that groundwater discharges in the area near the intersection of Illinois Route 47 and Main Street. At this location, several wetlands are present, and Fisherman's Inn uses the cool water to keep trout (a cool-water species) throughout the year. Cross section E–E′ from Dey et al. (2007e) indicates that the aquitards separating the Glasford sand from the shallower alluvial sands may be discontinuous, providing a hydraulic window for deeper groundwater to discharge to the stream. In cross section B–B′ of Curry et al. (2001b), a possible connection between the Glasford sand and the alluvial sands along Blackberry Creek was mapped. Although the hydraulic gradients between the deep and shallow aquifers are not known, this hypothetical modeling allows us to evaluate the potential impact of deep groundwater discharge directly to the stream or indirectly through the alluvial sands.

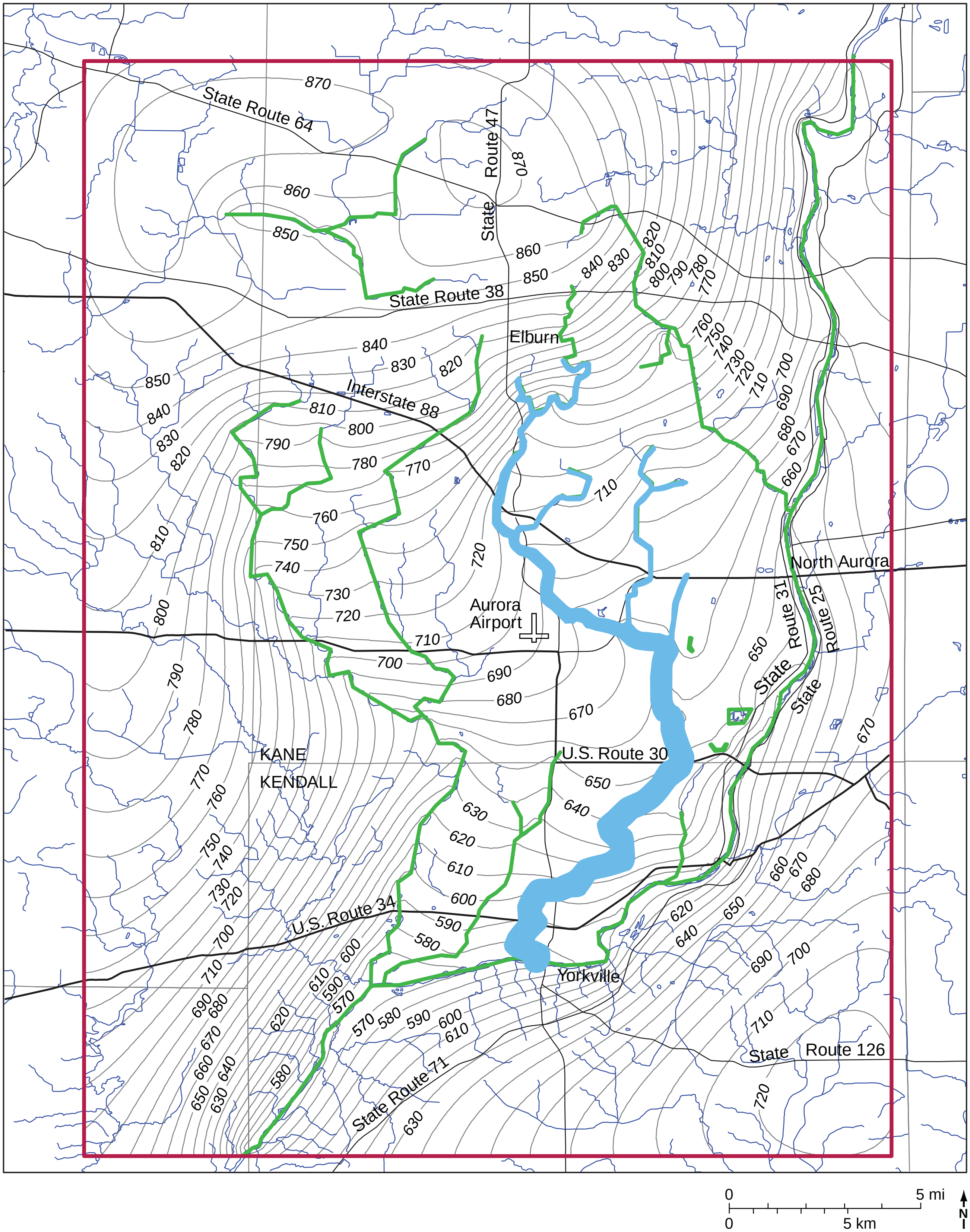

Figure 11 GFLOW model results for the base case (case 1) showing groundwater heads (contour lines) and estimated streamflow for Blackberry Creek (width of blue line increases as flow increases). The contour interval is 10 ft.

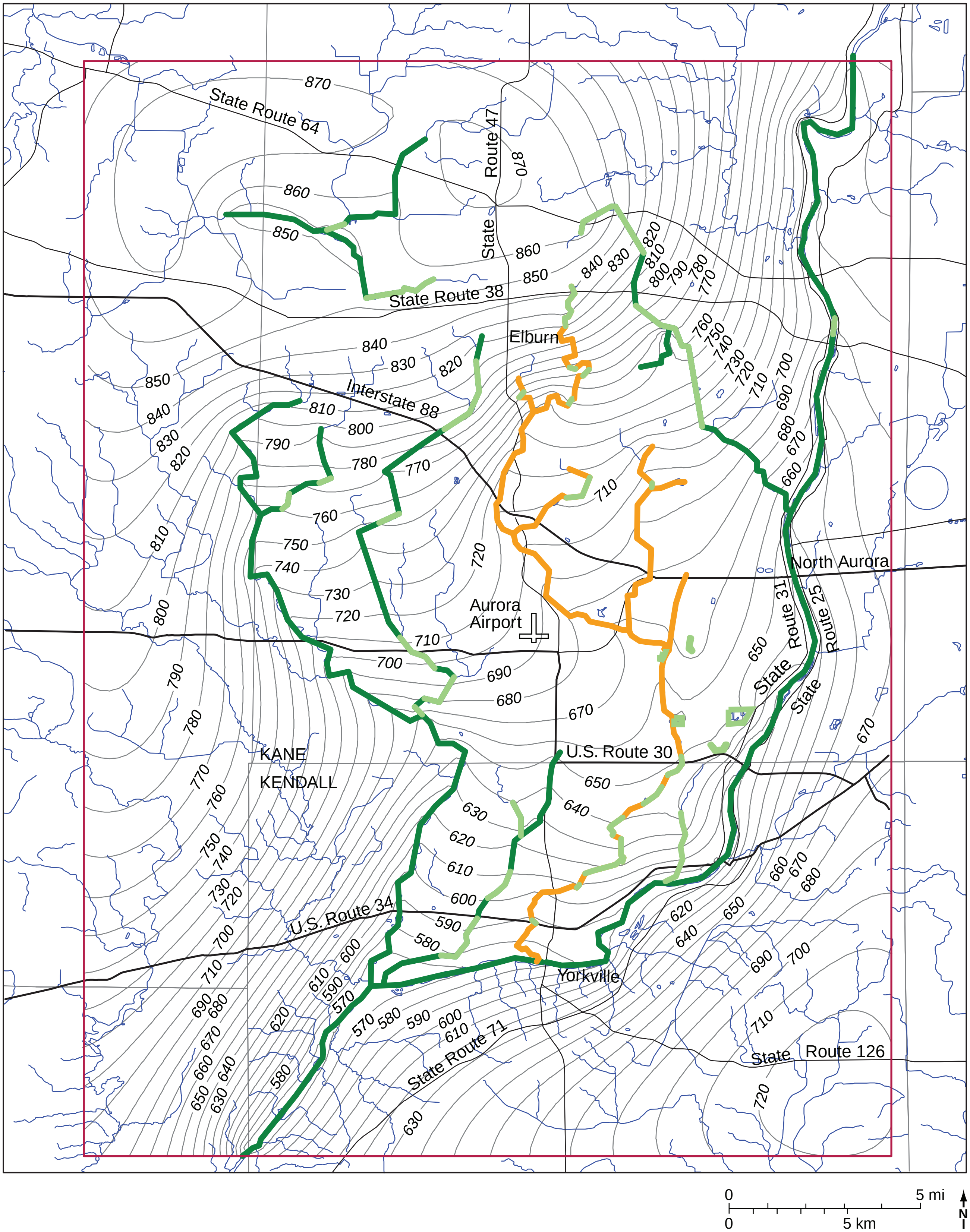

Figure 12 GFLOW model results for the base case (case 1) showing where Blackberry Creek and other streams recharge groundwater (light green stream segments). The contour interval is 10 ft.

In this case, the overall recharge (red rectangle) was decreased to 3.0×10^{-4} ft/day (1.3 inches/yr). The area (magenta polygon) was assigned a discharge of 4.0×10^{-2} ft/day and hydraulic conductivity of 150 ft/day (Table 5). The results for this case show that the streamflow (Q_{outlet}) matches that of case 1, but the depth to water is 2 ft less at Elburn (Table 5). Although the overall recharge was reduced to 3.0×10^{-4} ft/day (1.3 inches/yr), no changes in groundwater heads were observed at the Aurora Airport. The discharge from the magenta area may have sustained groundwater heads near the Aurora Airport and near the magenta polygon.

In case 3, streamflow was supplemented by the deep groundwater discharge to Blackberry Creek from the magenta area. It was also possible to calibrate the GFLOW model (Q_{outlet} = 14.0 cfs) when the discharge from the area represented by the magenta polygon was doubled and the overall recharge was reduced. Thus, an infinite number of solutions are possible by varying the proportion of streamflow originating from the overall recharge and the groundwater discharging from the magenta polygon. Additional data were needed to determine which model is a more realistic representation of the watershed hydrology. In June 2007, streamflow data were collected at numerous locations along Blackberry Creek to help evaluate the fit of the various GFLOW models.

The normalized flow (Figure 14) for the field measurements and several model estimates (both GFLOW models and Illinois State Water Survey [ISWS] surface water modeling) were plotted in relation to river mile. The gage at Yorkville is located at river mile 3.3, and the stream originates at approximately river mile 35. The measured flow (purple line) is higher than the model estimates above river mile 25, is close to the model estimates from river mile 25 to 15, and is lower than the model estimates below river mile 15. The magenta polygon runs from river mile 25.2 to 23.7. The confluences of three tributaries (Blacksheep Creek, Lake Run, and East Run) are located at river mile 22.6, 17.0, and 15.5, respectively.

The normalized flow for the watershed was plotted from the field data. The field data also were used to calibrate the model at locations other than the outlet. Assuming the proportion of flow remains constant for the field data and modeled scenario (Q_{75}), we can calibrate the model using flow from the tributaries. Flow was measured from Blacksheep Creek as 4.4 cfs, from Lake Run as 2.4 cfs, and from East Run as much less than 2.4 cfs. For the Q_{75} modeled scenario, these flows equate to 1.7 cfs, 0.9 cfs, and <0.9 cfs, respectively (calibration targets in Table 5). (Please note that “Blacksheep Creek” is a name assigned by the author to an unnamed tributary to Blackberry Creek. Blacksheep Creek drains land occupied by the Blacksheep Golf Course.)

For case 3, the GFLOW-predicted flow is too low for Blacksheep Creek, too high for Lake Run, and reasonable for East Run (Table 5). Matching these calibration targets was the focus for our next model case. In case 4, the groundwater discharge area introduced in case 3 was reshaped (see the magenta polygon in Figure 15) to improve the modeled streamflow, and the relative proportion of flow from surficial recharge and groundwater discharge was adjusted as shown in Table 5. The overall recharge was decreased to 2.5×10^{-4} ft/day (1.1 inches/yr), and the area within the magenta polygon has a discharge of 4.3×10^{-3} ft/day and hydraulic conductivity of 150 ft/day. The much larger groundwater discharge area now allows discharge to enter Blackberry Creek and Blacksheep Creek. The model then matches three of the four flow calibration targets, but flow remains too high for Lake Run. The reduced overall recharge results in lower groundwater levels (i.e., greater depth to water), with 2-ft declines observed at the Elburn and Aurora Airport locations when comparing cases 3 and 4.

Evaluating Other Features of the Watershed

For case 5, the effect of geologic materials with lower hydraulic conductivity was evaluated. These materials (orange polygon in Figure 15) are the Yorkville Member of the Lemont Formation and are found near Aurora. Dey et al. (2007e) noted that the Yorkville Member found in the St. Charles Moraine (Figure 5) tends to be finer grained and contain fewer coarse-grained lenses than that unit present in the Minooka Moraine (Figure 5) east of the Fox River. For case 5, the overall recharge rate was increased to 2.8×10^{-4} ft/day or 1.2 inches/yr to maintain streamflow. Hydraulic conductivity within the orange area was 37.5 ft/day, and recharge was -2.5×10^{-4} ft/day, which produces a net recharge (local recharge plus overall recharge) of 3.0×10^{-5} ft/day for this area. The flow predicted by GFLOW for case 5 (Table 5) matched flow at the Blackberry Creek outlet and Blacksheep Creek but was a bit too high for Lake Run. The predicted flow for East Run was zero, which was too low. The increased overall recharge resulted in higher groundwater levels (i.e., lower depth to water): a 2-ft increase at the Aurora Airport and a 1-ft increase at Elburn.

Cases 3, 4, and 5 explored the effects of the Quaternary geology on the watershed, but the bedrock geology may also impact water flow. The potentiometric surface map of the shallow bedrock aquifer (Figure 16) (Locke and Meyer 2007) showed several anomalies in southern Kane County. Case 6 focuses on the anomaly in the 680-ft contour in the northwest corner of T38N, R8E. At this location, the Silurian bedrock was mapped at higher elevations as shown in the southern end of cross section G–G′ by Dey et al. (2007a) (Figure 17). Additionally, this bedrock high appears to be connected with Quaternary sand and gravel deposits. For case 6, an area of higher head was added in the yellow polygon beneath the orange polygon (Figure 15). The yellow polygon represents an area where the bedrock aquifer is hydraulically connected to the shallow aquifer and could increase the head in the shallow aquifer. The head for the yellow polygon was set at 680 ft, and the overall recharge was reduced slightly to 2.45×10^{-4} ft/day. The recharge for the orange area was changed to -2.45×10^{-4} ft/day, yielding a net recharge of zero in this polygon.

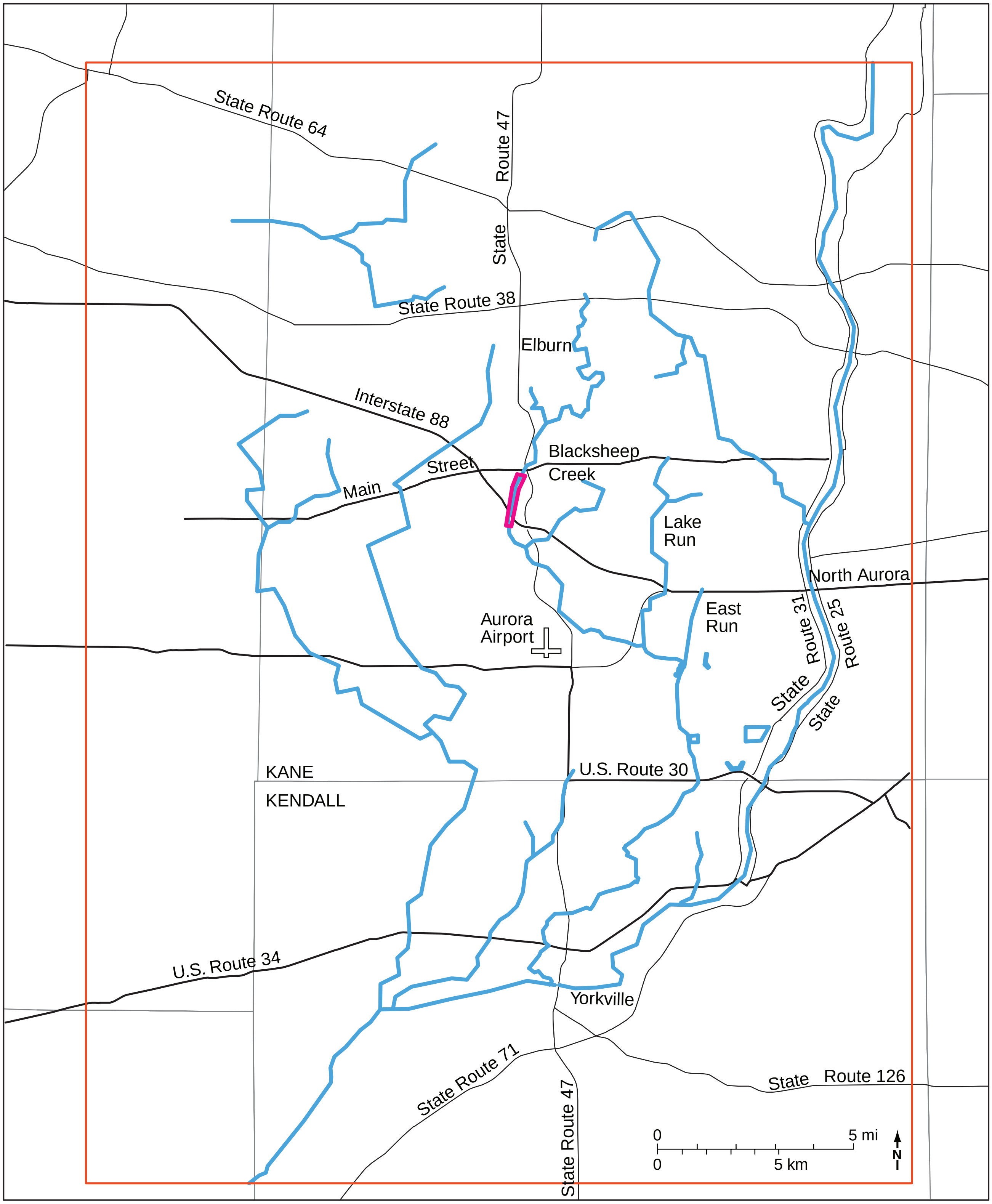

Figure 13 GFLOW model setup for case 3 with an area of different geology along Blackberry Creek (magenta polygon just south of Main Street). This is an area where deep groundwater discharges through the shallow aquifer and to the stream.

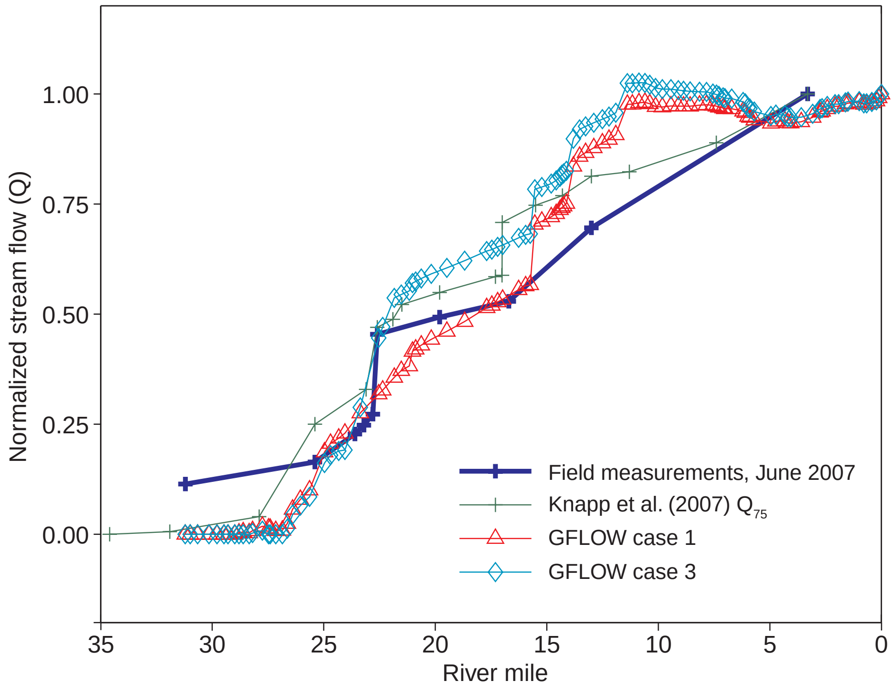

Figure 14 Normalized flow in Blackberry Creek where flow at the Yorkville gage equals 1.00. Field data and model results are presented.

When comparing modeling results from case 6 with case 5, no change was observed in flow at the outlet, higher flow was observed in East Run and Lake Run, and slightly lower flow was observed in Blacksheep Creek. The depth to water value increased by 1 ft at the airport and at Elburn. Overall, the inclusion of the bedrock window leads to a slightly better model of the watershed.

A review of the normalized flow in Blackberry Creek (Figure 18) showed that the GFLOW model results plotted closer to the ISWS model results as the complexity of the GFLOW models increased. However, all GFLOW model results underestimated flow in the upper end of the watershed (above river mile 25) and overpredicted flow in the lower stretch of the watershed (river mile 15 to 10). To boost flow in the upper end of the watershed, an area of higher recharge was added. This area is shown as a cluster of violet polygons (Figure 15) and represents areas where nearly 700 homes use septic tanks for wastewater treatment. For the areas shown in violet, satellite images from Google Maps were reviewed, and residences were counted. Assumptions were that 3 people lived in each residence and each person used 75 gal/day of water. Thus, each residence discharged 225 gal/day to the septic system, which was then available for recharging groundwater. Dividing the septic tank flow by the land area yielded a recharge rate of 2.0×10^{-4} ft/day, which is comparable to the overall recharge rate (Table 5). The area north of Elburn was modified by adding two surface water features, Lily Lake (head at 885 ft) and Ferson Creek (head at 900 to 811 ft). These changes did not modify streamflow at the flow calibration targets (comparing cases 6 and 7), but higher groundwater heads (depth to water) were noted at Elburn (17 ft) and the airport (5 ft). These changes were not adopted in the final model because they did not increase flow in the headwaters region of Blackberry Creek.

In case 8, the focus was to reduce flow in the southern end of the watershed. In this case, an area of higher hydraulic conductivity (yellow polygon in Figure 15) was added, representing an area with more sand and gravel (Figure 17). For this unique area, hydraulic conductivity was increased to 150 ft/day, but recharge was not changed. This area of higher hydraulic conductivity significantly changed flow in the watershed and increased streamflow in Blackberry Creek. The peak flow observed in Figure 19 increased due to this change. Because the desired effect would have been to reduce this peak, this change was not adopted. Also, the depth to water at the Aurora Airport dropped to 22 ft below ground (Table 5), which is outside its calibration target of 5 to 10 ft.

Results shown in Figure 18 indicate that additional work is needed to improve the match between modeled and measured streamflow, but the modeling effort ends here. A number of models have been developed to explain the field data (Table 5). A simple model with uniform geologic properties (case 1) was developed to match streamflow at the outlet and groundwater heads. A model with more complex geology (case 6) was developed that matches the streamflow at the outlet and other streamflow calibration targets. People may argue which model is better. The more detailed model (case 6) may be more useful to land-use planners interested in environmental planning, and the simple model (case 1) may be useful to others. Although development of a better model for the watershed is possible, the major goal of this effort was to demonstrate the utility of the modeling process to test various conceptual models of the watershed geology.

Summary and Conclusions

The AE modeling process provided an efficient technique to develop a steady-state flow model of the Blackberry Creek watershed. The AE model allowed an integrated groundwater-surface water flow model to be developed in much less time than needed for a more common, finite difference model (i.e., MODFLOW). The process of modeling shallow groundwater and surface water flow through the watershed helped improve our understanding of the water flow through the watershed and thus improved our understanding of the geologic framework. Through the modeling process,

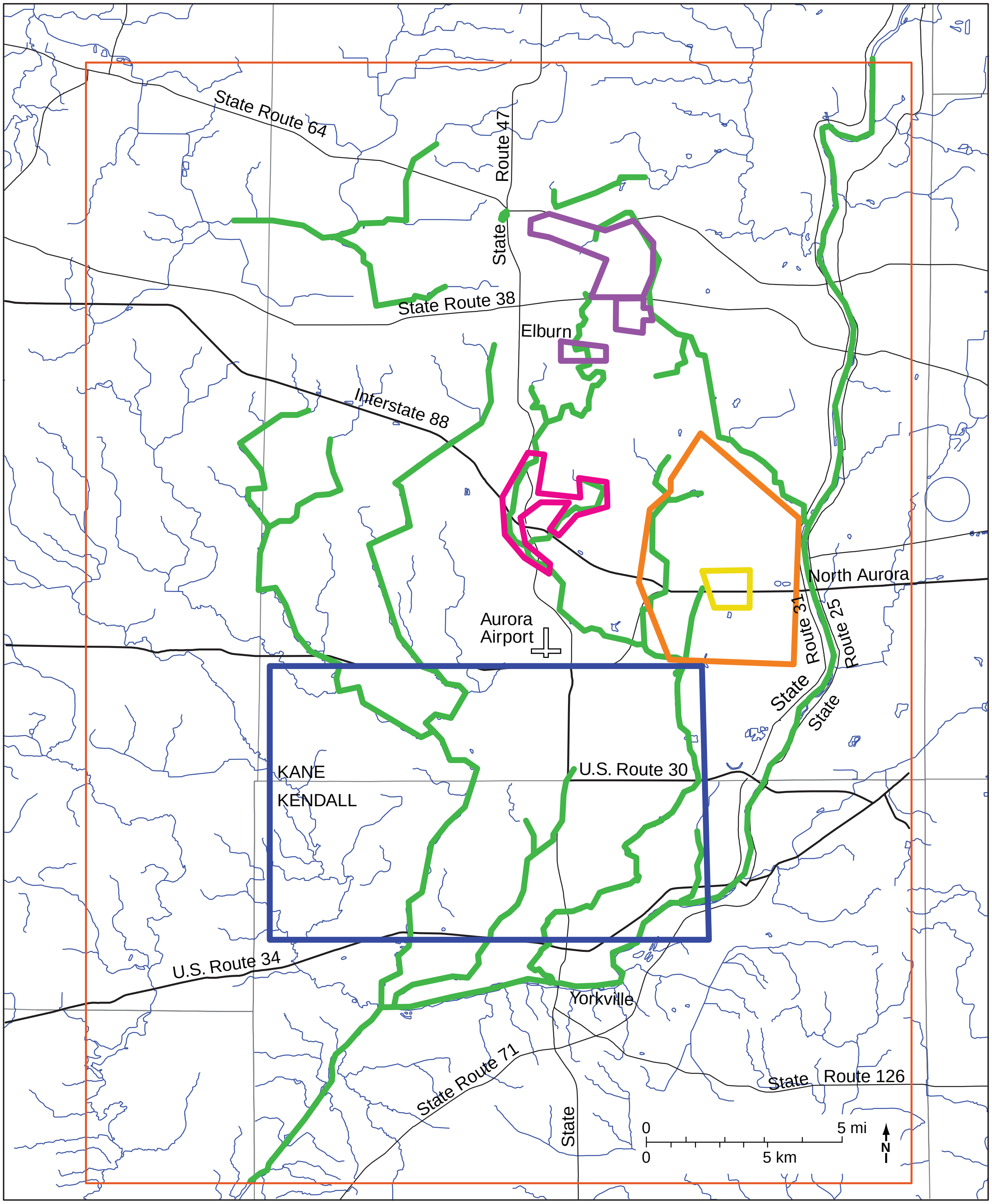

Figure 15 Map showing features of more complex GFLOW models. The red rectangle shows the area for the overall recharge. The magenta polygon shows the area of deep groundwater discharge to Blackberry and Blacksheep Creeks. The navy blue rectangle shows an area of higher hydraulic conductivity. The orange polygon shows an area of reduced recharge. The yellow polygon inside (beneath) the orange polygon represents an area of higher head. The violet polygons represent an area of higher recharge accounting for an area with septic systems.

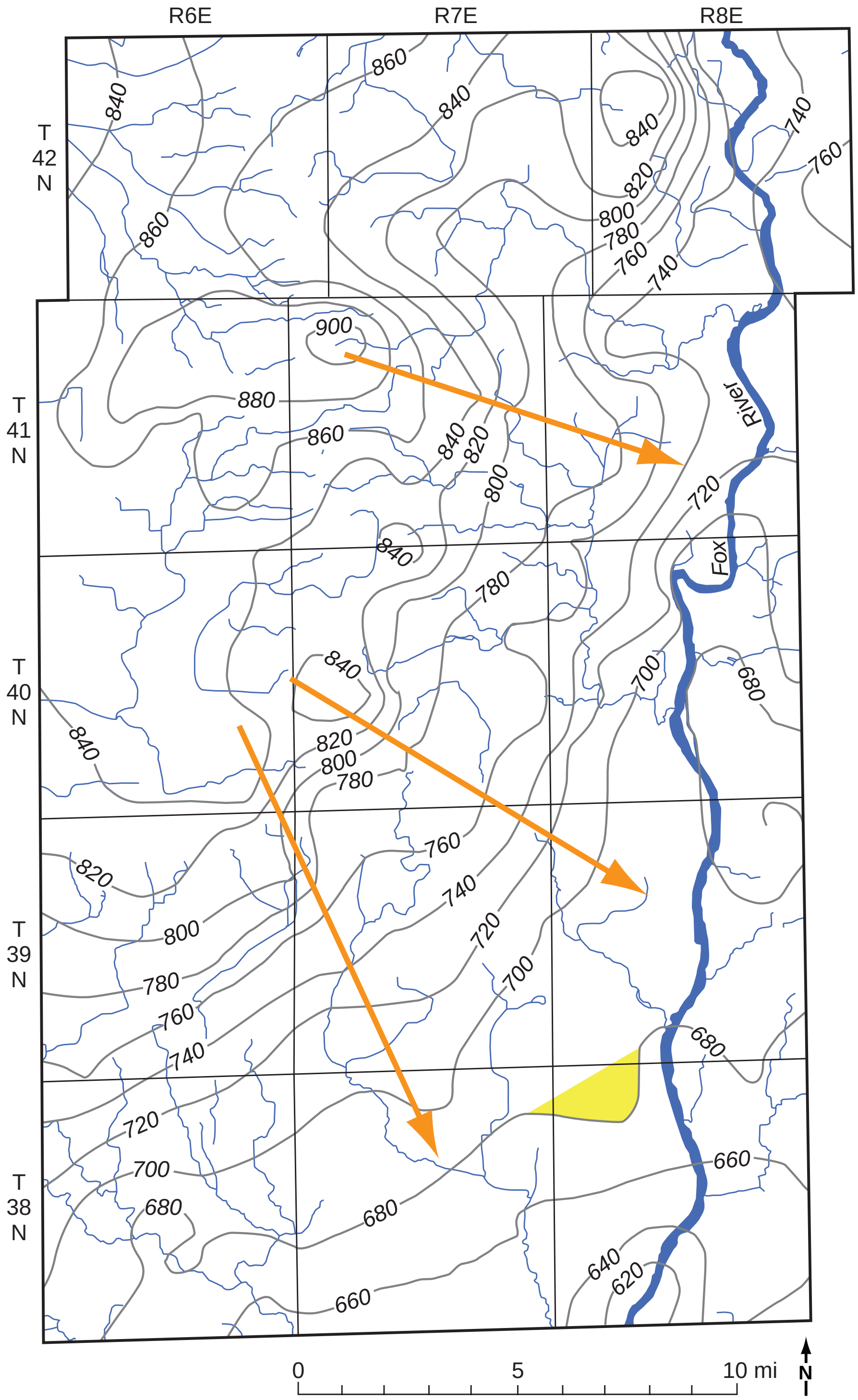

Figure 16 Potentiometric surface of the shallow bedrock aquifer in northeastern Illinois (Locke and Meyer 2007). The orange arrows show the general direction of groundwater flow in the aquifer. The northwest corner of T38N, R8E shows an area of high head and may indicate a possible connection between the shallow bedrock aquifer and a shallower, sand and gravel aquifer. The contour interval is 20 ft.

various features of the watershed were evaluated with respect to improving the description of water flowing through the watershed. In the end, a more complex (and hopefully more accurate) description of streamflow, groundwater recharge, and groundwater flow was developed. For this watershed, streamflow data for the stream and three tributaries were needed to test and calibrate the final flow model. These streamflow data were collected by two workers over 2 days and were relatively inexpensive to collect.

A model of shallow groundwater flow and streamflow through the Blackberry Creek watershed was initially developed and calibrated using streamflow data at the outlet. This model with uniform hydrologic properties (case 1) was considered to be inadequate because it did not include significant hydrologic features. The first added feature to improve the flow model was an area where groundwater discharged from a deep aquifer to the alluvial sediments beneath Blackberry Creek and a tributary (Blacksheep Creek). Multiple solutions (similar to case 3) could be developed to match the target flow at the outlet by varying overall recharge and discharge from the deep aquifer. Adding flow calibration targets (such as those for tributaries of Blackberry Creek) allowed a unique solution (case 4) to be developed. To further improve the flow model, two features were added—an area of reduced recharge (orange polygon in case 5) and an area of higher head to represent groundwater discharge from the Silurian dolomite (yellow polygon in case 6). Two more features, higher recharge for an area served with septic tanks east of Elburn (violet polygons in case 7) and an area of higher hydraulic conductivity in the southern end of the watershed (navy blue polygon in case 8), were also tested. These features were not adopted as they did not yield the desired changes in the GFLOW model of the watershed.

The overall modeling process could be improved with additional data collected within and around the watershed. Surrogate groundwater levels

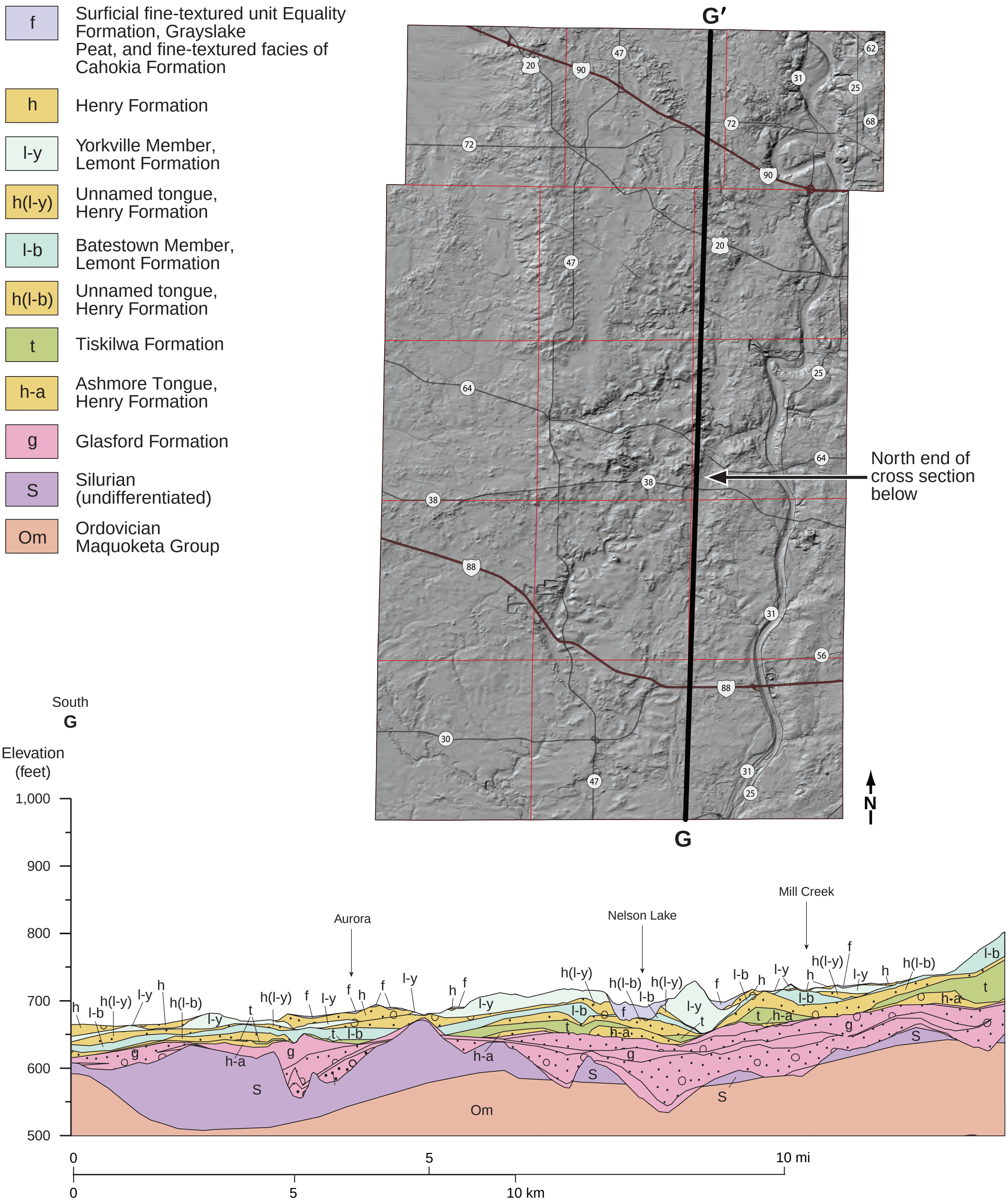

Figure 17 A portion of cross section G–G′ from Dey et al. (2007a) showing higher bedrock in an area northwest of Aurora, Illinois, near Interstate 88. This bedrock high appears to be hydraulically connected with Quaternary sand and gravel deposits.

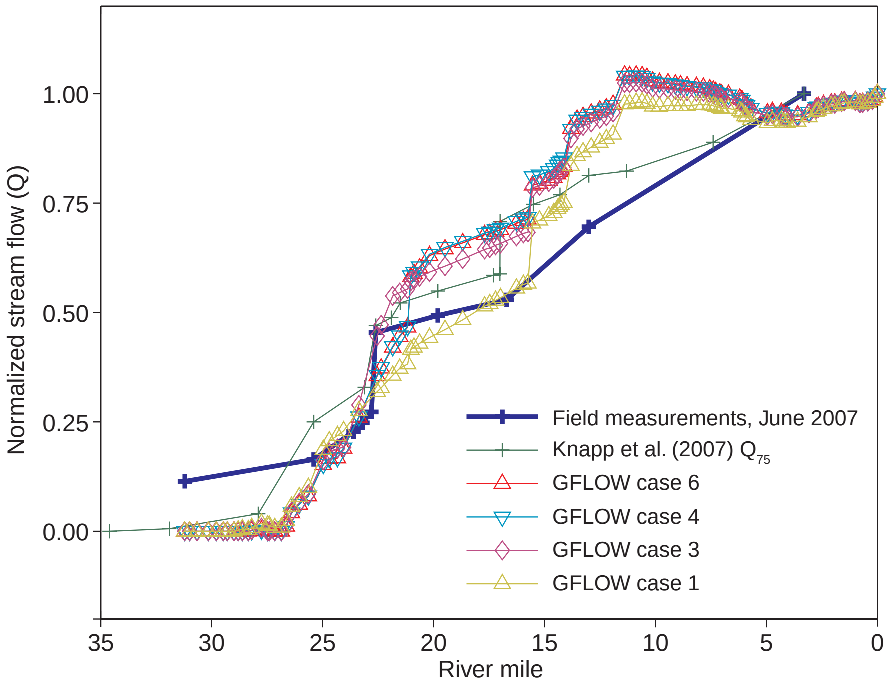

Figure 18 Normalized flow in Blackberry Creek comparing modeled values for cases 1, 3, 4, and 6 with field data. Illinois State Water Survey model results are from Knapp et al. (2007).

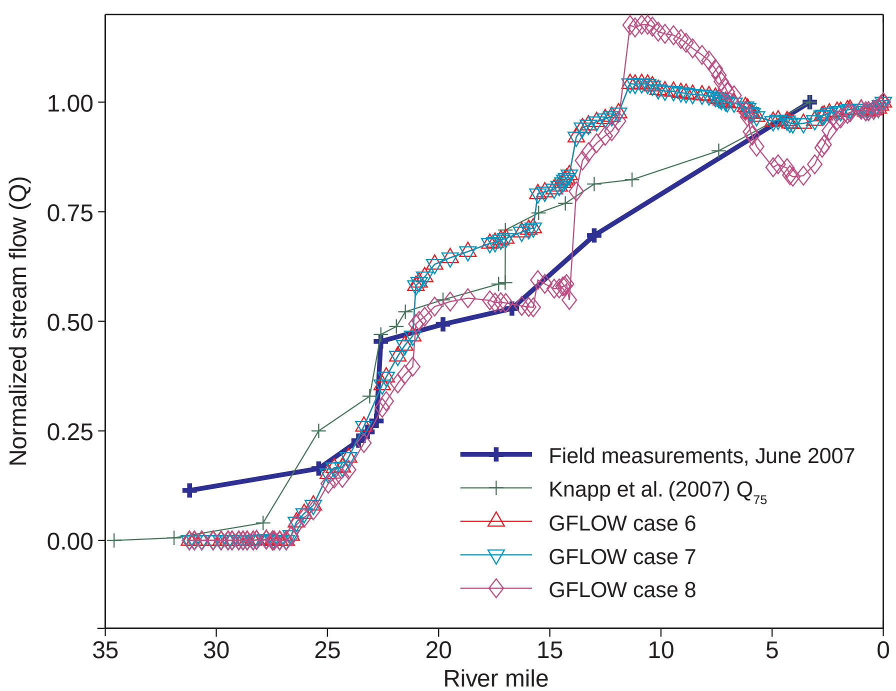

Figure 19 Normalized flow in Blackberry Creek comparing modeled values for cases 6, 7, and 8 with field data. Illinois State Water Survey model results are from Knapp et al. (2007).

based on ground elevations were used in this study, but the modeling process could be improved if shallow groundwater head data were available. These groundwater heads could be obtained through a network of shallow groundwater wells, which should be distributed throughout the watershed. The assumption that streamflow through the watershed remains constant across a wide variety of flow conditions is a topic for future research. Data to test this assumption could be obtained by measuring streamflow throughout the watershed at a variety of flow conditions (e.g., Q_{50}, Q_{75}, and Q_{90}). Additional modeling is needed to improve the fit of the GFLOW model with respect to the normalized flow of Blackberry Creek (Figures 18 and 19). Finally, the modeling effort would benefit from additional data to define the watershed boundaries, such as streamflow data for streams surrounding Blackberry Creek.

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