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WR01R005

# IMPACTS OF LAND USE AND GROUNDWATER FLOW ON THE TEMPERATURE OF WISCONSIN TROUT STREAMS

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# Impacts of Land Use and Groundwater Flow on the Temperature of Wisconsin Trout Streams

## Final Report

## Prepared for

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## PROJECT SUMMARY

| | |
|---|---|
| **Title** | Impacts of Land Use and Groundwater Flow on the Temperature of Wisconsin Trout Streams |
| **Project I.D.** | WRI #: R/UW-GSI-005, GCC #: 02-GSI-3 |
| **Investigator(s)** | *Principal Investigators:*<br>Stephen J. Gaffield, Hydrogeologist, Wisconsin Geological and Natural History Survey<br><br>Lizhu Wang, Supervisory Research Biologist, Michigan Department of Natural Resources<br><br>*Other Contributors:*<br>Todd W. Rayne, Professor, Hamilton College Department of Geology<br><br>Kenneth R. Bradbury, Hydrogeologist, Wisconsin Geological and Natural History Survey |
| **Period of Contract** | July 1, 2001 – June 30, 2003 |
| **Background/Need** | Groundwater discharge to streams is critical for maintaining coldwater fisheries. Habitat management is made difficult by a lack of detailed understanding of the controls over summer stream temperature. |
| **Objectives** | We evaluated the utility of models of stream temperature, groundwater flow, and groundwater recharge as decision-making tools for stream and watershed management. |
| **Methods** | We adapted the method used in the existing stream-temperature models SSTEMP and SNTEMP for application to small Wisconsin streams. Our stream-temperature model predicts water temperature as a function of groundwater inflow, channel shape, weather conditions, and shade from riparian vegetation. We tested model parameters previously calibrated for the Driftless Area to determine their suitability for use in the Northern Lakes and Forests, the North-Central Hardwood Forest, and the Southeast Wisconsin Till Plain Ecoregions of Wisconsin. Model simulations were compared to field data collected from five streams in the summer of 2001.<br><br>For one of these streams, Rowan Creek in Columbia County, we linked the stream-temperature model to models of groundwater |

recharge and groundwater flow. By jointly using these three models, we evaluated the impact of future land-use changes on the infiltration of rain and snowmelt into the soil, stream baseflow supplied by the groundwater flow system, and stream temperature.

**Results and Discussion**

The stream-temperature model matched measured temperatures for three streams reasonably well, but it performed poorly for two streams with extensive wetlands. Assumptions upon which the model is based may not be valid for wetland stream channels.

Linked models of groundwater recharge, groundwater flow, and stream temperature for Rowan Creek predicted changes in stream temperature of up to 0.8°C related to drought, conversion from native vegetation to agricultural land use, and groundwater extraction from a well near the stream. Simulations of increased urban and suburban land covers predicted little change in temperature.

**Conclusions, Implications, and Recommendations**

Our stream-temperature model is well suited for assessment of many small Wisconsin streams. Where extensive wetlands are present, caution must be used in applying the model because it may not adequately represent the processes controlling stream temperature. More research is needed to determine the best approach for simulating the temperature of streams flowing through large wetlands.

The linked models indicate that daily mean stream temperature is rather insensitive to changes in the groundwater flow system related to human activities. Daily maximum temperature is likely to be more sensitive, but is not simulated by our technique. Human land use can have numerous other impacts on stream habitat that are not represented by our models, including changes in channel width, burial of pools and gravel spawning beds by sediment, and inflows of runoff heated by paved surfaces.

**Related Publications**

Rayne, T.W., S.J. Gaffield and K.R. Bradbury (in press). Linking Groundwater Recharge, Flow, and Stream-Temperature Models to Simulate the Effects of Local Land-Use on a Stream. Geological Society of America 2003 Annual Meeting, Abstracts and Programs, abstract 65887.

**Key Words**

Stream temperature; groundwater; recharge; land use; coldwater fisheries; mathematical models

**Funding**

University of Wisconsin System

## INTRODUCTION

One of the most difficult challenges in managing coldwater stream fisheries is understanding the controls of summer water temperature, which typically limits the distribution of brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) (Becker, 1983). It is widely recognized that Midwestern streams are cooled by groundwater (e.g., Field and Graczyk, 1990; McRae and Edwards, 1994); however, stream-channel shape and shade from riparian vegetation also have an important impact (Younus and others, 2000; Blann and others, 2001). Human activities in the riparian zone and throughout a watershed can impact stream temperature by altering shade from vegetation, increasing stormwater runoff and channel erosion, and reducing groundwater recharge and stream baseflow. A lack of detailed understanding of these interactions and the tools to evaluate them makes habitat-management decisions difficult.

The objective of this study was to develop decision-making tools for watershed managers by combining field monitoring during the summer of 2001 with two mathematical modeling exercises. First, we tested the model developed for the Driftless Ecoregion of Wisconsin (Gaffield, 2000), based on a stream-temperature modeling technique developed by Theurer and others (1984), for the other three major ecoregions in Wisconsin. This model predicts stream temperature as a function of groundwater inflow, channel shape, weather conditions, and shade from riparian vegetation. The five streams tested are in the Northern Lakes and Forests, the North-Central Hardwood Forest, and the Southeast Wisconsin Till Plain Ecoregions (fig. 1).

Second, we linked this stream-temperature model to two additional models of groundwater recharge and groundwater flow for the Rowan Creek watershed in Columbia County (fig. 1). Groundwater recharge is affected by human land uses (such as the addition of paved surfaces) that change the ability of the soil to absorb precipitation and snowmelt. Changes in recharge to the groundwater flow system can affect the groundwater discharge that maintains stream baseflow in dry weather. We tested these linked models as a decision-making tool for watershed managers to predict the impact of future land-use changes on stream temperature.

## PROCEDURES AND METHODS

### *Data Collection*

Groundwater inflow rates to the streams were determined indirectly by measuring stream flow several locations on each stream (fig. 1). We chose measurement dates during baseflow periods, several days after major precipitation events, to ensure that groundwater inflow was the only source of water in the streams. We measured discharge with Price “mini” current meters using the standard wading technique of the U.S. Geological Survey (Buchanan and Somers, 1969).

We monitored water temperature at each flow-measurement site. Air temperature at one site for each study stream was also monitored using continuously recording thermographs. The temperature recording intervals ranged from 4 to 90 minutes, depending upon equipment capabilities, and the recording period was from late June to mid-September of 2001.

Other meteorological parameters, including dew point temperature, wind speed, cloud cover, and atmospheric pressure, were obtained from NOAA weather stations in Green Bay, La Crosse and

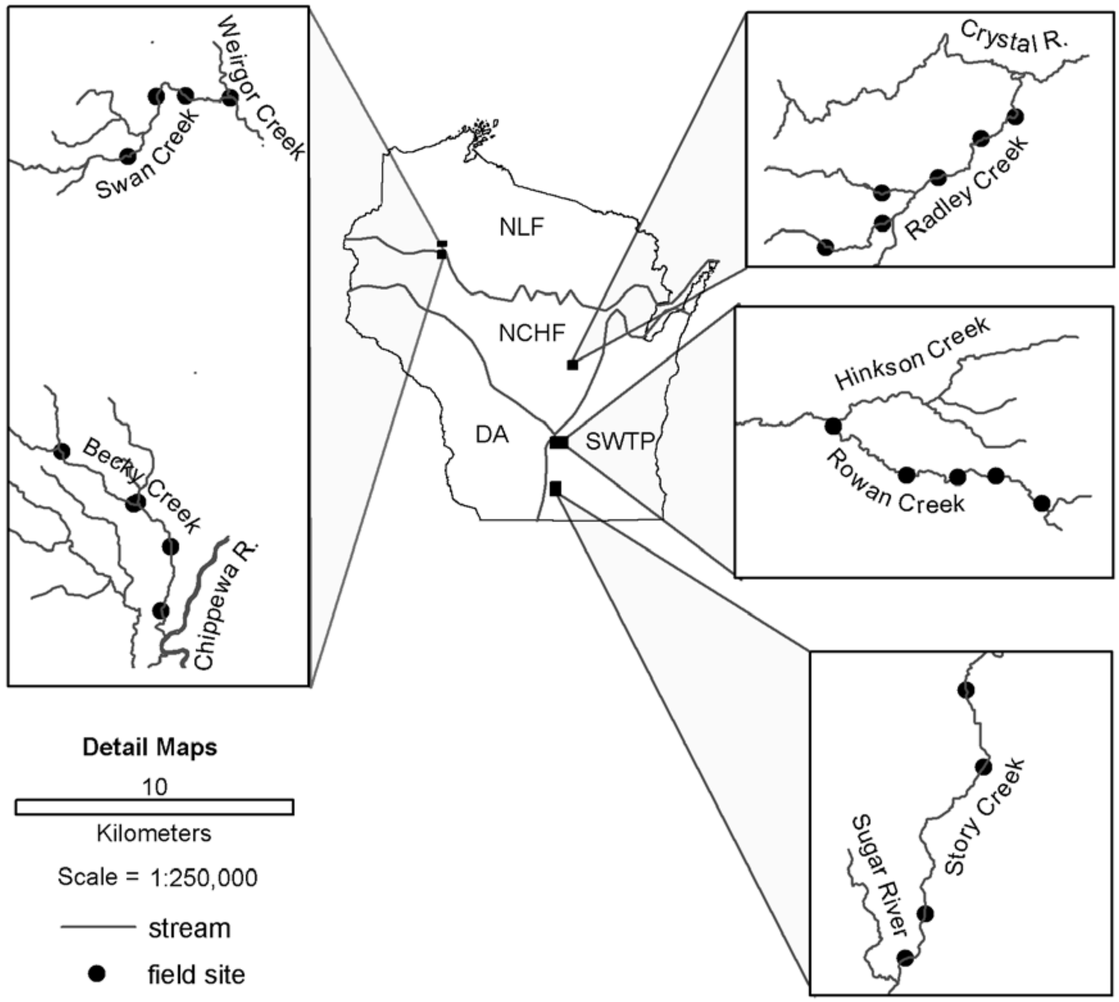


Figure 1. Locations of five study watersheds and stream monitoring sites in Wisconsin ecoregions. NLF = Northern Lakes and Forests. NCHF = North Central Hardwood Forests. SWTP = Southeastern Wisconsin Till Plains. DA = Driftless Area.

Madison in Wisconsin, and Duluth and Minneapolis in Minnesota. We estimated solar radiation with the method described by Campbell and Norman (1997).

We described riparian vegetation qualitatively by identifying stream reaches with fairly homogeneous vegetation cover separated by major transitions in vegetation. We supplemented field observations with analysis of aerial photographs. Descriptive categories included forest, open woodlands, buffer strips of trees and shrubs, grazed pasture, and wetlands.

*Stream-Temperature Modeling*

We simulated mean daily stream temperature for dates on which we measured stream baseflow and temperature. We adapted the method used in the Stream Network Temperature Model (SNTEMP; Theurer and others, 1984) for our application by translating it into a spreadsheet environment. SNTEMP is a FORTRAN model designed for complex stream networks. A simplified Microsoft Windows version, the Stream Segment Temperature Model (SSTEMP) can simulate one stream segment with uniform conditions (Bartholow, 1999). Applying this method in a spreadsheet allowed us greater ease of use than SNTEMP and more power to simulate changing downstream conditions (e.g., shade, baseflow) than SSTEMP.

The model approximates the daily mean temperature with an analytical solution to the heat transport equation, assuming steady-state streamflow and meteorological conditions. It predicts the temperature in one dimension along the length of a stream reach. The reach must be divided into segments with uniform width, groundwater inflow rate, and vegetation, requiring judgment by the modeler. Also required as input are the water temperature at the head of the reach and meteorological conditions. Details are discussed by Theurer and others (1984) and Gaffield (2000).

We obtained input parameters from a combination of field measurements and readily available data. Groundwater inflow rates were determined indirectly from stream-flow measurements. For all streams except Becky Creek, we fit a linear function to the data and used this function as input for the model. Because measured flows for Becky Creek were very small and varied widely, we simply used a constant discharge equal to the mean of four field measurements. For Swan Creek, streamflow at the site farthest upstream was too low to measure, so we estimated it to be 0.014 $m^3/s$ (0.5 $ft^3/s$). Because flows were measured during dry periods, we assumed that any downstream increase in flow was the result of groundwater discharge. We developed a relationship, in the form of a power function, between channel width and discharge using field measurements for each stream. We measured air temperature at one site in each watershed, and we obtained other meteorological parameters from the nearest NOAA weather station.

Because shade from riparian vegetation is difficult to measure or estimate along an entire stream reach, we treated shade as a calibration parameter. Gaffield (2000) determined shade values for different types of vegetation by calibrating the model for summer conditions in the Driftless Area Ecoregion (Appendix B). In this study, we evaluated the performance of the model using those calibrated values to determine whether they can be applied to other Wisconsin ecoregions.

*Recharge Modeling*

We modeled land-use impacts on groundwater recharge using a soil-water mass-balance model developed by Bradbury and others (2000). The model calculates spatially variable annual recharge rates by tracking soil moisture gains and losses throughout a year, simulating infiltration and surface runoff by the runoff curve number method (Soil Conservation Service, 1986) and evapotranspiration by Thornthwaite-Mather method (1957). It uses readily available geographic information system (GIS) data, including daily precipitation, land cover and soil properties, and land-surface elevation.

In our study, we used the soil-water mass-balance model to test the impact of land use on groundwater recharge in the Rowan Creek watershed. We held the model inputs of precipitation, elevation, soil texture, antecedent soil moisture, and meteorological factors constant and varied the land cover. Forest and agricultural lands currently cover most of the model area. We simulated groundwater recharge for 10 different scenarios involving different sizes and locations of residential and commercial developments. (See Appendix B for details.) For comparison, we also simulated recharge for drought conditions using precipitation data from 1988 and for the native vegetation present before European settlement (Finley, 1976).

*Groundwater Modeling*

The goal of the groundwater modeling was to accurately simulate the flow system in the Rowan Creek basin, with particular emphasis on groundwater discharge to the creek, using recharge rates computed with the soil-water mass-balance model.

We simulated groundwater flow using MODFLOW (McDonald and Harbaugh, 1988), a modular, three-dimensional, finite-difference model. The basis of our model was a larger model of the Dane County region (Krohelski and others, 2000), to which we added more detail for the Rowan Creek area (fig. 3). The model aquifer is divided into four layers corresponding to geologic divisions. The uppermost layer represents the unconsolidated glacial and alluvial sediments and varies in thickness from less than 1 ft to greater than 100 ft. The upper bedrock layer (layer 2) represents the Ordovician and Cambrian sandstones above the Eau Claire Formation. A shale unit that makes up part of the Eau Claire Formation is a lower-permeability third layer. The bottom layer represents the lower Eau Claire and Mount Simon sandstones that overlie the crystalline Precambrian basement rock, which we assumed to be impermeable. Bedrock layers 2 and 3 have a constant thickness throughout the model. The thickness of layer 4 varies; its bottom elevation is used as the approximate elevation of the Precambrian basement. Boundary conditions include specified head boundaries at Lake Wisconsin, Mud Lake, and several smaller lakes in the model area, head-dependent flux boundaries at Rowan Creek and its main tributaries, and no-flow boundaries at groundwater divides and at areas far from the Rowan Creek watershed. The locations of divides were determined from a water-table map of Columbia County (Harr and others, 1978) and from the Dane County model.

We calibrated the model to head values from the Columbia County water-table map and to baseflow measurements from 13 locations in Rowan and Hinkson Creeks taken in the spring and summer of 2002 by the Water Resources Management Practicum (in press). Parameters adjusted to produce the best fit between modeled and measured heads and fluxes were the hydraulic conductivity of each aquifer layer, stream width, stream-sediment thickness, and the hydraulic conductivity of the stream sediment. We constrained these parameters within plausible limits based on previous work in Dane and Sauk Counties (Krohelski and others, 2000, Gotkowitz and others, 2002). We consider the measured baseflows to be more accurate than the head values, which were determined mainly by domestic well drillers and are subject to seasonal variations, inaccuracies in locating the wells, and different measuring techniques employed by drillers. Therefore, we placed greater importance on calibrating the model to the baseflow measurements.

To simulate the impact of changes in land use, we used the results of the soil-water mass-balance model for different scenarios to generate recharge input to the groundwater model. For comparison, we also simulated the addition of a groundwater pumping well at three different depths and distances from Rowan Creek.

## RESULTS AND DISCUSSION

*Stream-Temperature Model Performance*

The model performed reasonably well for Rowan and Story Creeks (fig. 2; table B-2), with root-mean-square (RMS) errors of 1.3°C and 2.4°C, respectively. The predicted temperature is several degrees too high in the headwaters of both streams, suggesting the need for collection of additional field data to improve the resolution of model input. The predicted temperature profiles exhibit unrealistically sharp changes in slope that are caused by representing the stream reach as a series of segments with uniform conditions.

The simulation for Becky Creek demonstrates that the model can be useful even with very limited input data. Although the predicted temperature profile exhibits unrealistically sharp changes in slope due to discrete breaks between vegetation types, it is reasonably close to the measured temperatures (RMS error of 2.0°C) and generally follows the observed trend, warming in the first 7 km of the reach with little change farther downstream.

The model was less successful at matching observed temperatures for Swan and Radley Creeks. Extensive wetlands in the middle segments of Swan Creek and near the downstream end of Radley Creek coincide with elevated temperatures that could not be reproduced by the model. For Swan Creek, the predicted temperature was up to 6.5°C too low (RMS error of 5.4°C), and simulated temperatures were as much as 4.1°C low for Radley Creek (RMS error of 2.8°C). These errors are beyond the sensitivity of the model to changes in the shade parameter; even with shade parameter values to set to zero, predicted temperatures at wetland sites were nearly 3°C low for Swan Creek and more than 2°C low for Radley Creek. The field data appear to be accurate, because measurements with a handheld thermometer closely match the thermograph data for both streams.

The wetlands could affect stream temperature in several ways. The stream channel tends to be wide and pond-like in several locations, so the model assumption that the stream is completely mixed is probably violated. Temperature stratification and lateral differences in temperature across the channel cannot be accounted for in the model. It is also possible that the temperature of shallow groundwater flowing through the wetlands into the stream is greater than the mean regional value used in the model. To test the sensitivity of the model, we increased the groundwater temperature to the mean daily air temperature (17°C for Radley Creek and 20°C for Swan Creek) in the wetland segments. This resulted in an improved fit to the field data, but predicted temperatures were still low (2°C for Radley Creek and 4.5°C for Swan Creek). This suggests that the observed increase in temperature may be due to the combined effects of changes in groundwater temperature, shade, and channel width.

*Groundwater Model Calibration*

In general, the modeled heads reproduce the measured heads reasonably well, particularly in the areas near Rowan and Hinkson Creeks (fig. 3). Simulated streamflow was within 10 percent of values measured in April 2002 (table B-3), which we considered to be within measurement error. The difference between simulated and measured streamflow was slightly greater for July 2002.

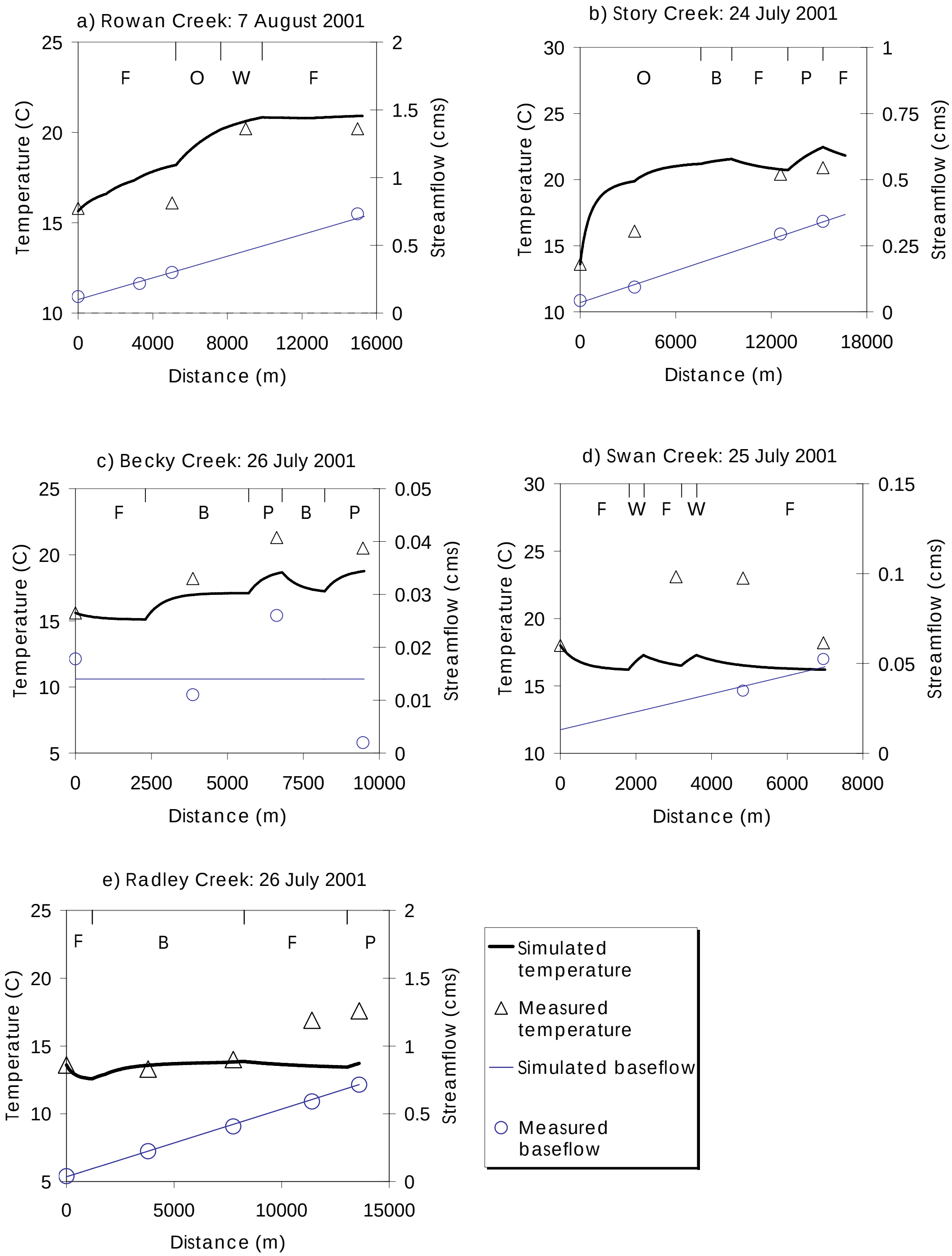


Figure 2. Mean daily stream-temperature simulations, with streamflow and riparian vegetation. B = buffer strip. F = forest. O = open woodland. P = grazed pasture. W = wetland.

*Impact of Land Use*

As we expected, a change in land cover from rural (pasture, cropland, forested land) to urban (residential and commercial) resulted in a decrease in the recharge rate predicted by the soil-water mass-balance model. The change was minor for low-lying areas adjacent to streams because recharge was already low for these wet, fine-grained soils. Upland areas with well drained, permeable soils showed a much greater change in recharge rates when land cover was converted to urban categories (fig. 4).

The groundwater model predicted decreased baseflow for all scenarios involving the addition of impervious areas (residential and industrial) in the watershed (fig. 5). Only the simulation of native vegetation throughout the watershed predicted greater baseflow than for current conditions. Model runs with less than 25 percent of the watershed converted to urban land covers (cases 1–5) produced little change (<10%) in the baseflow at most locations. However, small areas of residential or industrial development did decrease the baseflow in nearby reaches. Simulations of more extensive land-use change (cases 5–9) produced more than a 10 percent change in baseflow. For a given total developed area, fewer large developments had more impact than scattered smaller developments.

In comparison, simulations of a high-capacity well pumping from the deep sandstone aquifer and of smaller domestic wells had a slightly greater impact on stream baseflow (fig. 5). The impact decreased with distance to the stream. Finally, a severe drought with annual precipitation of 20 inches (approximately 33% less than the long-term average) produced the greatest decrease in baseflow. This scenario was run using the present-day land use; the addition of residential or industrial land use would

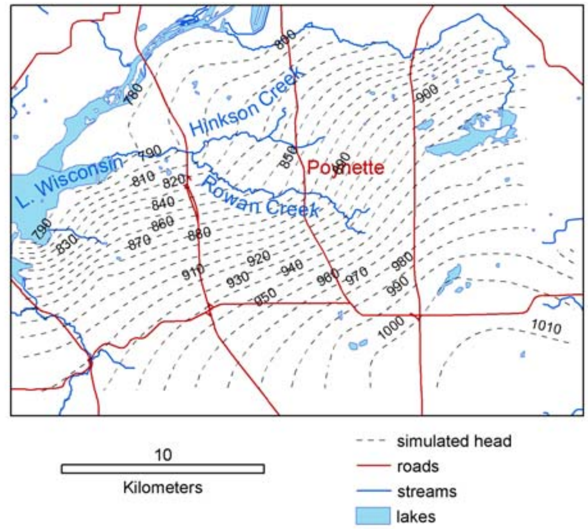


Figure 3. Simulated hydraulic head for groundwater in the Rowan Creek watershed.

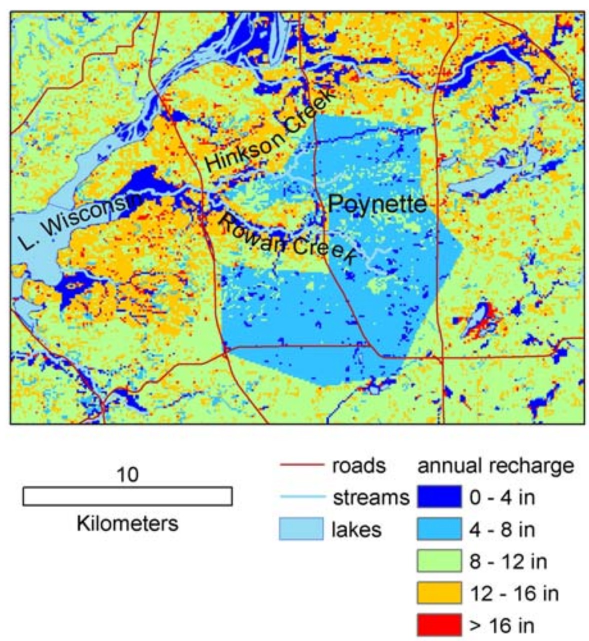


Figure 4. Simulated groundwater recharge for hypothetical residential development. Crescent-shaped area of reduced recharge near Rowan Creek coincides with location of development.

increase the negative impact on baseflow values.

We used the temperature model for Rowan Creek to evaluate the impact of these changes in land use and baseflow. We simulated temperature for the four scenarios that resulted in the greatest changes in baseflow: widespread residential development (case 9), pumping wells near the stream (cases 8w, PWA-C), drought conditions (case 10), and native vegetation (fig. 6). Reductions in baseflow due to drought conditions had the greatest impact on temperature, causing an increase of 0.8°C at the downstream end of the reach. The pumping well scenario resulted in a temperature increase of 0.3°C, and the simulation of widespread residential development produced no appreciable change in temperature. The simulated temperature for native vegetation present in the 1800s was 0.5°C cooler than for 2001.

Although the sensitivity of daily mean stream temperature predicted by these linked models is relatively low, it is important to keep in mind the limitations of this approach. First, the temperature model does not simulate daily maximum, which is likely to be more sensitive. Second, the accuracy of the runoff calculation method in the recharge model is uncertain. Third, stream habitat is affected by other impacts related to land use, including changes in channel width, and burial of pools and gravel spawning beds by sediment. Finally, the greatest impact on stream temperature in urban areas may occur during storms, which these models do not represent, when large discharges of runoff over hot paved surfaces enter the stream.

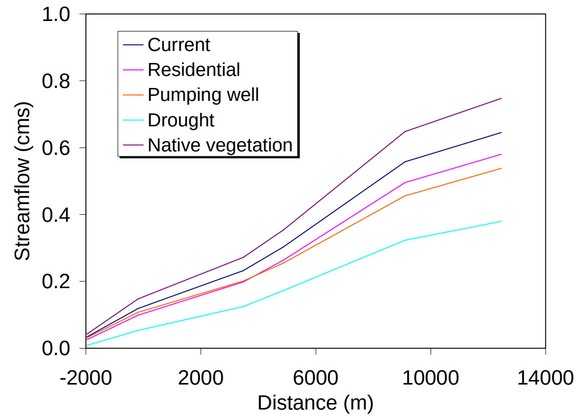


Figure 5. Simulated baseflow of Rowan Creek for different land-cover and climatic conditions.

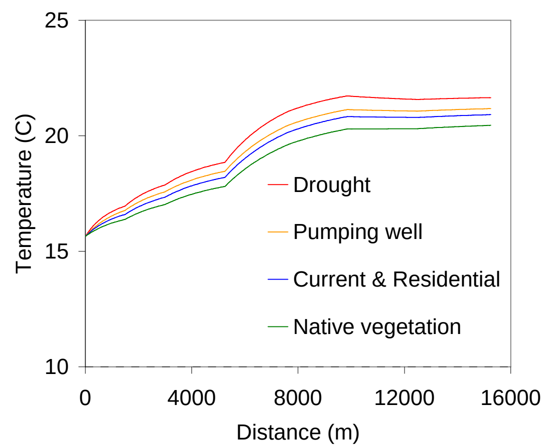


Figure 6. Simulated daily mean temperature of Rowan Creek in summer for different land-cover and climatic conditions.

## CONCLUSIONS AND RECOMMENDATIONS

The stream-temperature model used in this study performed well for three streams but poorly for two other streams flowing through extensive wetlands. Two likely causes of this problem are insufficient input data and violation of model assumptions. It is possible that collection of additional field data to better define the channel width, shade, and local groundwater temperature in wetland reaches would lead to acceptable simulations with this method. However, where wetland channels are wide, poorly defined, and have slow flow velocities, it is likely that this modeling technique is invalid. More research is needed to determine the best approach for simulating the temperature of streams flowing through large wetlands.

Linked models are useful for evaluating the impacts of human activities on complex hydrologic systems. Although this approach has inherent limitations and requires further validation, it appears to be capable of predicting the general magnitude of the impacts of land use and groundwater pumping on stream baseflow and temperature. Models of the Rowan Creek watershed predicted changes in stream temperature that were small, but potentially important for fish habitat, related to drought conditions, conversion from native vegetation to agricultural land use, and groundwater extraction from a well near the stream. Simulations of increases in urban and suburban land covers in the watershed resulted in little change in temperature. It is possible that conversion of agricultural land to suburbs would not further reduce groundwater recharge, as indicated by a modeling study for rural Ohio (Liu and others, 2000). However, the true impact of urbanization in this watershed will depend heavily on the design of urban areas, including the use of best management practices to maintain groundwater recharge; the modeling techniques that can accurately simulate these impacts remain to be developed.

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## APPENDIX A: Awards, Publications, Reports, Patents, and Presentations

Rayne, T.W., S.J. Gaffield and K.R. Bradbury (in press). Linking Groundwater Recharge, Flow, and Stream-Temperature Models to Simulate the Effects of Local Land-Use on a Stream. Geological Society of America 2003 Annual Meeting, Abstracts and Programs, abstract 65887.

## APPENDIX B: Supplemental Information

Table B-1
Shade Values Use in Stream-Temperature Model

| Vegetation Type | Shaded Fraction |
|---|---|
| forest | 0.8 |
| buffer strip | 0.5 |
| open woodlands | 0.5 |
| grazed pasture | 0.2 |
| grassland/ wetland | 0.3 |

Table B-2
Stream-Temperature Model Performance Statistics

| | | Temperature ( $^{o}$C) | | Errors ( $^{o}$C) | | |
|---|---|---|---|---|---|---|
| | Dist (m) | Measured | Simulated | Individual | Maximum | RMS |
| Rowan Creek | 5035 | 16.1 | 18.2 | 2.1 | 2.1 | 1.3 |
| | 8984 | 20.2 | 20.6 | 0.4 | | |
| | 14982 | 20.2 | 20.9 | 0.7 | | |
| Story Creek | 3417 | 16.1 | 19.9 | 3.8 | 3.8 | 2.4 |
| | 12577 | 20.4 | 20.8 | 0.4 | | |
| | 15240 | 20.9 | 22.5 | 1.6 | | |
| Becky Creek | 3864 | 18.2 | 17 | -1.2 | 2.7 | 2.0 |
| | 6621 | 21.3 | 18.6 | -2.7 | | |
| | 9460 | 20.5 | 18.8 | -1.7 | | |
| Swan Creek | 3059 | 23.1 | 16.6 | -6.5 | 6.5 | 5.4 |
| | 4830 | 23 | 16.5 | -6.5 | | |
| | 6958 | 18.2 | 16.2 | -2 | | |
| Radley Creek | 3796 | 13.3 | 13 | -0.3 | 4.1 | 2.8 |
| | 7754 | 14 | 13.1 | -0.9 | | |
| | 11408 | 16.9 | 13.2 | -3.7 | | |
| | 13603 | 17.6 | 13.5 | -4.1 | | |

Table B-3.
Measured and modeled values of stream discharge during baseflow conditions (cfs). See figure 1 for field site locations.

| Field site | Measured baseflow (cfs) 6-Apr-02 | Measured baseflow (cfs) 12-Jul-02 | Simulated baseflow (cfs) |
|---|---|---|---|
| 1 | 35.1 | 29.7 | 37.6 |
| 2 | 10.5 | 7.4 | 9.7 |
| 3 | 7 | 5.3 | 8.6 |
| 4 | 4.9 | 3.3 | 6.9 |
| 5 | 1.9 | 0.7 | 1.8 |
| 6 | 1.2 | 0.7 | 1.2 |
| 8 | 21.4 | 21.4 | 22.8 |
| 9 | 19.5 | 19.4 | 19.7 |
| 11 | 16.5 | 8.9 | 10.7 |
| 12 | 9.4 | 9.4 | 8.2 |
| 13 | 4.4 | 4.4 | 4.2 |
| 14 | 1.1 | 0.9 | 1.2 |
| 15 | 0.5 | 0.4 | 0.6 |

Table B-4. Simulated baseflow for changes in land use.

| | Simulated streamflow (cubic meters per second) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Field Site | Base | 5 | 6 | 7 | 8 | 8w | 9 | PWA | PWB | PWC | 10 | Orig Veg |
| 1 | -1.06 | -1.05 | -0.94 | -1.00 | -1.03 | -1.01 | -0.94 | -0.92 | -0.92 | -0.92 | -0.59 | 1.23 |
| 2 | -0.27 | -0.27 | -0.23 | -0.26 | -0.27 | -0.25 | -0.23 | -0.25 | -0.25 | -0.25 | -0.13 | 0.33 |
| 3 | -0.24 | -0.24 | -0.20 | -0.23 | -0.23 | -0.22 | -0.20 | -0.21 | -0.22 | -0.19 | -0.11 | 0.29 |
| 4 | -0.20 | -0.19 | -0.15 | -0.18 | -0.18 | -0.17 | -0.15 | -0.17 | -0.17 | -0.17 | -0.08 | 0.24 |
| 5 | -0.05 | -0.05 | -0.02 | -0.05 | -0.05 | -0.03 | -0.02 | -0.04 | -0.04 | -0.04 | 0.00 | 0.08 |
| 6 | -0.03 | -0.03 | -0.03 | -0.03 | -0.03 | -0.03 | -0.03 | -0.03 | -0.03 | -0.03 | -0.01 | 0.04 |
| 8 | -0.64 | -0.64 | -0.58 | -0.62 | -0.63 | -0.62 | -0.58 | -0.53 | -0.54 | -0.54 | -0.38 | 0.75 |
| 9 | -0.56 | -0.55 | -0.49 | -0.53 | -0.54 | -0.53 | -0.49 | -0.45 | -0.45 | -0.46 | -0.32 | 0.65 |
| 11 | -0.30 | -0.30 | -0.27 | -0.30 | -0.29 | -0.28 | -0.26 | -0.26 | -0.26 | -0.25 | -0.17 | 0.35 |
| 12 | -0.23 | -0.23 | -0.20 | -0.23 | -0.22 | -0.21 | -0.20 | -0.21 | -0.21 | -0.20 | -0.12 | 0.27 |
| 13 | -0.12 | -0.12 | -0.10 | -0.12 | -0.11 | -0.11 | -0.10 | -0.11 | -0.11 | -0.11 | -0.05 | 0.15 |
| 14 | -0.03 | -0.03 | -0.03 | -0.03 | -0.03 | -0.03 | -0.03 | -0.03 | -0.03 | -0.03 | -0.01 | 0.04 |
| 15 | -0.02 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | 0.02 |

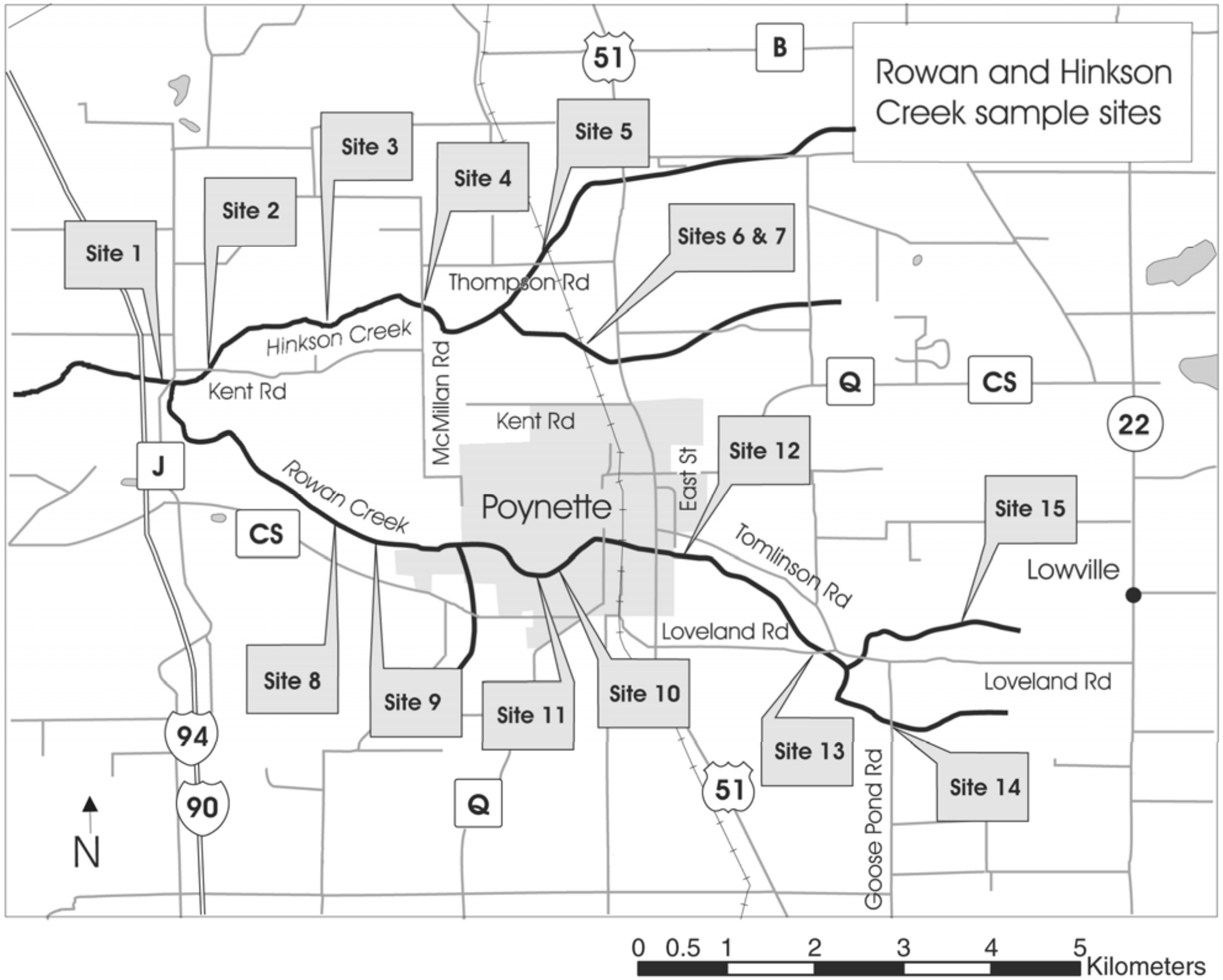
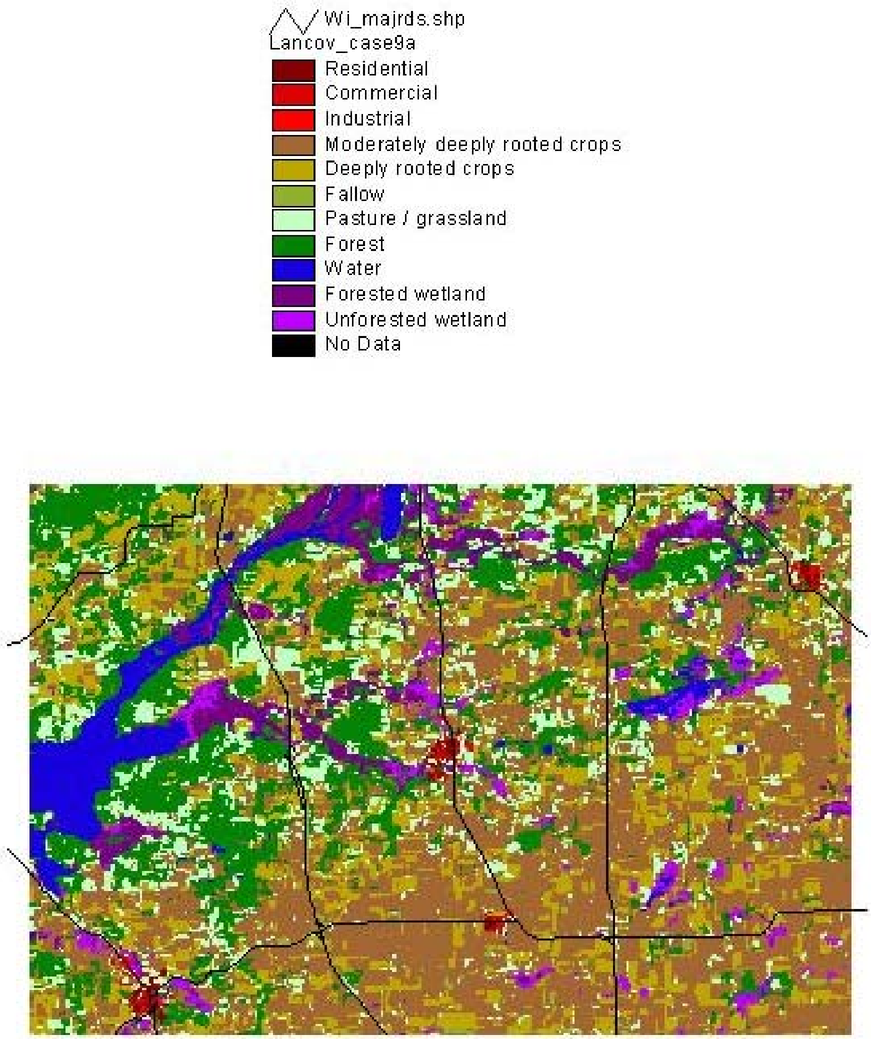



Figure B-1. Rowan Creek locations monitored in 2002 (adapted from Water Resources Management Practicum, in press).

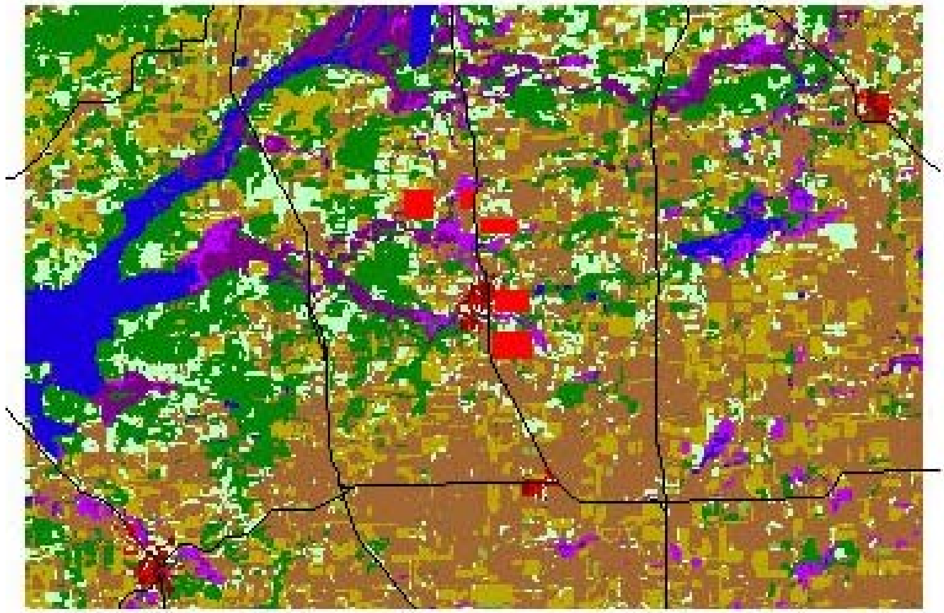
Figure B-2. Land cover arrays used as input for recharge model of Rowan Creek watershed.



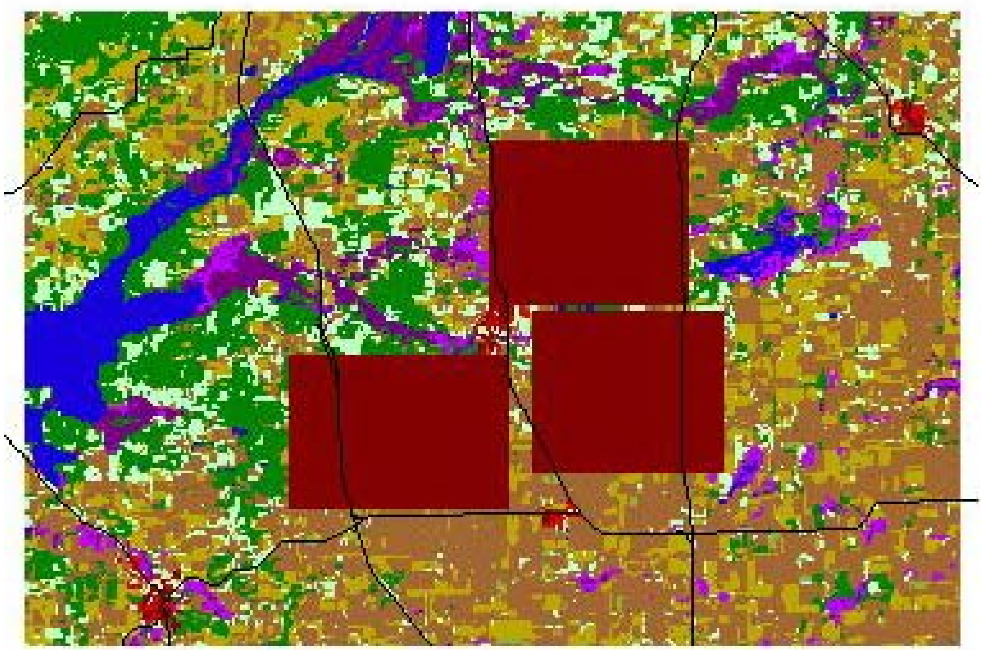

Base case. This represents current land cover.

Cases PWA, PWB, and PWC are modifications in which a municipal well pumps at a substantially higher rate than the current Poynette well (4,000,000 gal/day) in three different locations: (A) present location (~1,000 ft from Rowan Creek), (B) 2,000 ft from the creek, and (C) 3,000 ft from Rowan Creek. Land cover and recharge are the same as the base case.

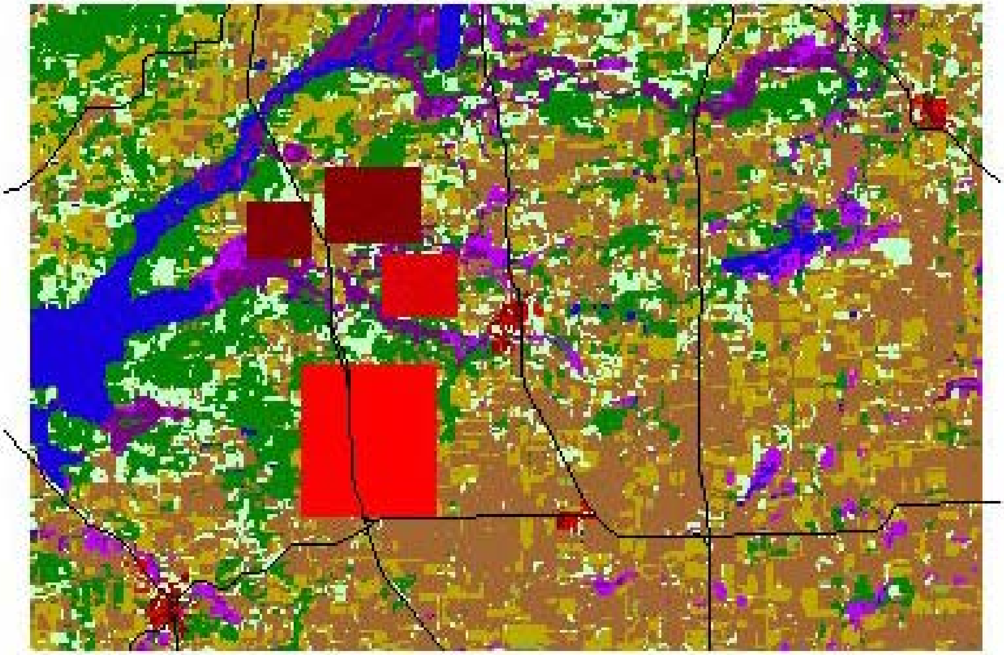
Cases 1 – 4 (not shown). Residential development for these scenarios is less extensive than the following cases.



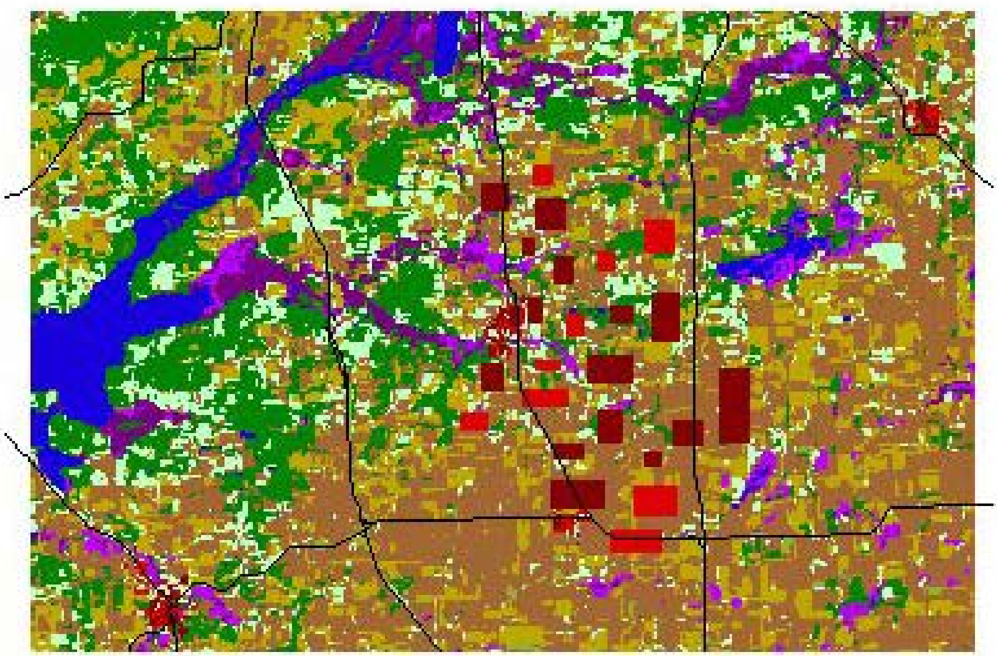
Case 5.  Five rectangular developments in headwaters of Hinkson and Rowan Creeks, to the north, east, and south of Poynette.



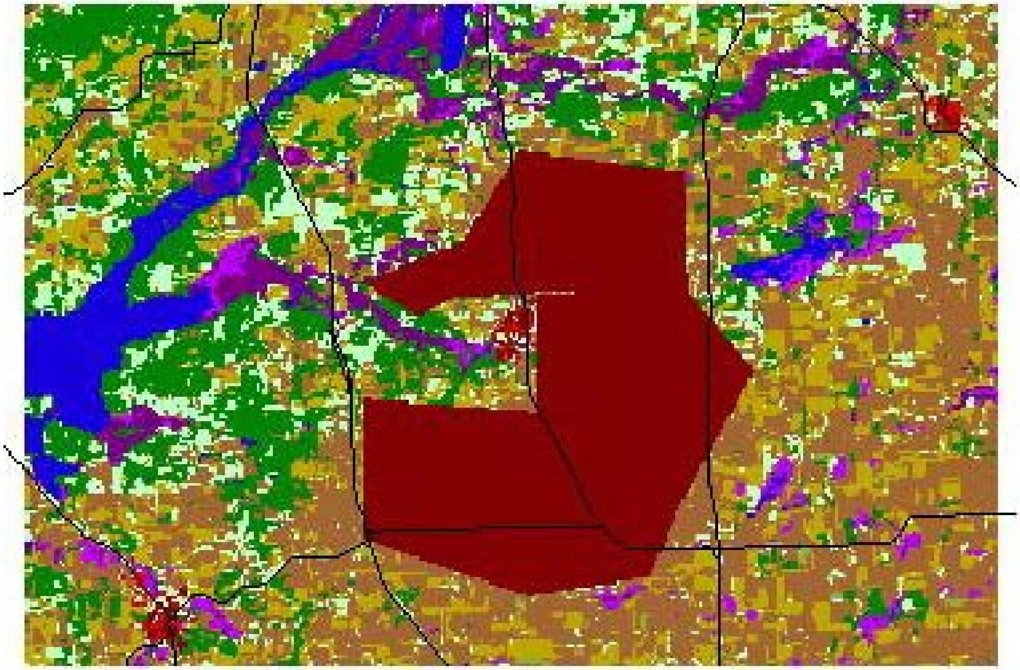
Case 6.  Three large residential developments that cover much of the upland areas of the creeks.



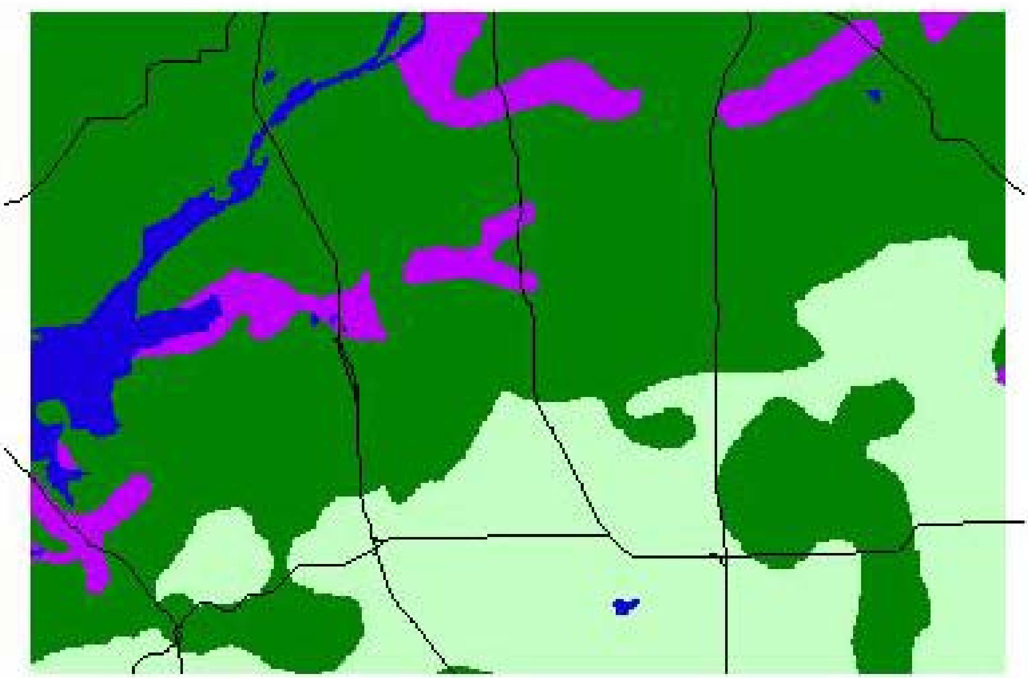
Case 7.  Four large rectangular developments with residential, commercial, and industrial land use located midstream.



Case 8.  Numerous small rectangular developments with residential and commercial land use located in upstream areas.  Case 8w used same land use and includes a well for each development pumping from layer 2 at 6,700 $ft^3$/d (i.e., each pumping well in the model represents 100 households pumping at 500 g/d).



Case 9.  Large residential area in nearly all the uplands surrounding Rowan and Hinkson Creeks.



Land cover before European settlement, from Findley (1976).