# Temporal and Spatial Variability

# of

# Natural Groundwater Recharge

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**Groundwater Research Project**

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## Project Summary

**Title:** The Spatial and Temporal Variability of Groundwater Recharge

**Project ID:** R/UW-HDG-004

**Investigators:** Dr. Mary P. Anderson, Professor, Geology and Geophysics; Dr. Kenneth W. Potter, Professor, Civil and Environmental Engineering; Weston Dripps, Research Assistant, Geology and Geophysics.

**Period of Contract:** July 2000 – June 2001

**Background / Need:** Understanding the spatial and temporal distribution of groundwater recharge is a pre-requisite for effective groundwater management and modeling. Recharge, defined as the entry of water into the saturated zone, is influenced by a wide variety of factors including the vegetation, topography, climate, geology, and soils. Despite its dependence on these spatially variable parameters, recharge is typically assumed to be constant and uniform within a watershed. The recharge estimate is usually empirically derived, is a fitted parameter determined by calibration, or is calculated using baseflow of streams as a surrogate.

Since the distribution, rate, and timing of recharge are dictated by the interaction of these variable parameters, recharge should vary temporally and spatially at the watershed scale and the use of a constant value for an entire watershed may be inappropriate. Using a combination of field work and integrated modeling, we developed a suite of techniques for estimating recharge and tested our methods by quantifying the spatial and temporal distribution of recharge at the watershed scale and a daily time step for the Trout Lake basin, a small forested watershed in northern Wisconsin.

**Objective:** Our main objective was to develop a methodology for estimating the spatial and temporal distribution of groundwater recharge. The methodology was tested by application to the Trout Lake basin for the period 1996 – 2000.

**Methods:** We estimated the spatial and temporal distribution of recharge using: (1) a daily soil water balance (SWB) model, (2) an integrated terrestrial biosphere model (IBIS, (3) a two-dimensional analytic element groundwater flow model (GFLOW) linked to a parameter estimation code (UCODE) and (4) field techniques (water level fluctuations and time domain reflectometry).

**Results and Discussion:** The three models (SWB, IBIS, and GFLOW/UCODE) gave comparable recharge estimates, which also agreed well with estimates calculated from water-level fluctuations measured in wells. The SWB and IBIS models calculated an average annual recharge rate for the Trout Lake basin that varied more than two-fold, as well as large monthly variations. Spatial variations were not as significant although heterogeneity attributed to variability in soil and vegetation type was evident.

**Conclusions / Implications / Recommendations:**

- There is significant annual variation in recharge rate to the Trout Lake basin but spatial variability is less pronounced.

- Water level fluctuations and reflectometers are useful in estimating recharge amounts and the timing of recharge events.
- The IBIS model, originally designed as a global dynamic ecosystem model, can be successfully applied at a watershed scale.
- Assuming a linear correlation between precipitation and recharge is inappropriate since soil moisture conditions and the timing of precipitation events are more important in controlling recharge rates than the actual amount of precipitation that falls.
- Collectively the models used in this research, particularly the less rigorous soil water balance model, give modelers, planners, and policy makers practical water resource management tools for estimating spatially and temporally distributed recharge for modeling and water resource planning purposes.
- Training in the use of these models and methods would be a useful follow up to this project.

**Related Publications:**

Dripps, W. R., Expected May 2002. The Spatial and Temporal Variability of Natural Groundwater Recharge. PhD thesis, University of Wisconsin – Madison, Department of Geology and Geophysics.

Dripps, W.R., Kucharik, C.J., Lenters, J.D., Anderson, M.P. and Foley, J.A., 2001. Modeling the Spatial and Temporal Distribution of Groundwater Recharge Across a Forested Watershed in northern Wisconsin. Abstract. American Geophysical Union, 2001 Spring Meeting, Boston, MA, Eos, Vol. 82

Dripps, W.R., Anderson, M.P., and Hunt, R.J., 2001. The Use of Temperature Profiles through Unsaturated Soils to Estimate Short-term Rates of Natural Groundwater Recharge. Abstract. American Geophysical Union, 2001 Spring Meeting, Boston, MA, Eos, Vol. 82

Dripps, W.R, Anderson, M.P., and Hunt, R.J., 2001. Use of a Coupled Heat and Water Transport Model (VS2DH) for Estimating Rates of Natural Groundwater Recharge. Abstract. American Water Resources Association – Wisconsin Section, 25th Annual Meeting, Green Lake, WI, abstracts, p. 27.

Dripps, W.R., Anderson, M.P., and Hunt, R.J., 2000. Incorporating Recharge Variability into Groundwater Flow Models. Abstract. Geological Society of America, 2000 Fall Meeting, Reno, NV, Abstracts with Programs, Vol. 33, p. 335.

Awards given to Wes Dripps for work on this project: Horton Grant, Hydrology Section of the American Geophysical Union, Bailey Distinguished Graduate Fellowship, UW-Madison, Outstanding student paper award, AGU Spring 2001 meeting.

**Key Words:** Groundwater recharge, recharge estimation, groundwater hydrology, groundwater management, groundwater modeling, water resource management, IBIS, GFLOW, analytic element modeling, UCODE, parameter estimation

**Funding:** UWS Groundwater Research Program

## Introduction

Understanding the spatial and temporal distribution of groundwater recharge is a basic pre-requisite for effective groundwater management and modeling. Recharge, defined as the entry of water into the saturated zone, is influenced by a wide variety of factors including vegetation, topography, climate, geology, and soils. Despite its dependence on these spatially variable parameters, typically a constant value of recharge is assumed for an entire watershed. The recharge estimate is usually empirically derived, is a fitted parameter determined by calibration, or is calculated using stream baseflow as a surrogate.

Since the distribution, rate, and timing of recharge are dictated by the interaction of multiple spatially and temporally variable parameters, recharge should also vary temporally and spatially at the watershed scale and the use of a constant value may be inappropriate. Using a combination of field work and integrated modeling, we developed a suite of techniques for estimating recharge and tested our methods by quantifying the spatial and temporal distribution of recharge at the watershed scale and a daily time step for the Trout Lake basin, a small forested watershed in northern Wisconsin (Fig. 1).

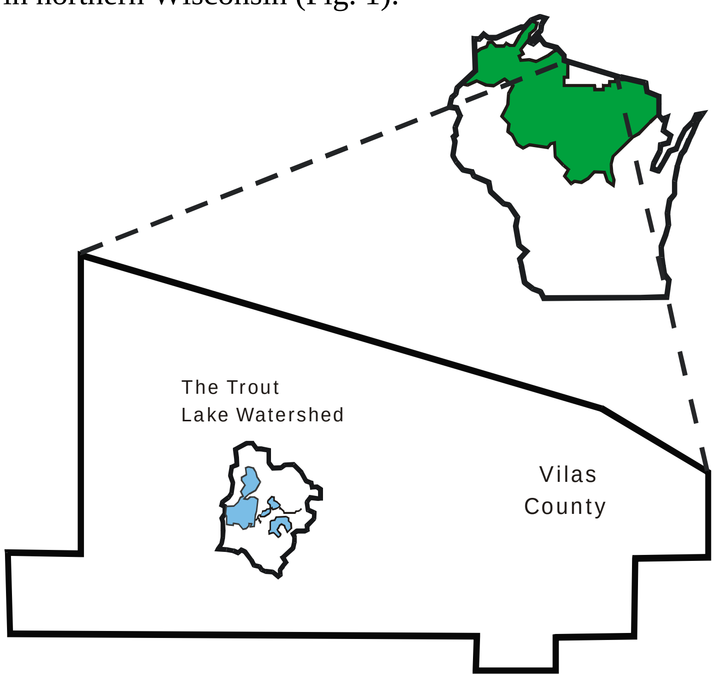



**Figure 1**. Location of the Trout Lake Watershed in Vilas County, Wisconsin.

Our main objective was to develop a methodology for estimating the spatial and temporal distribution of groundwater recharge. The methodology was tested by application to the Trout Lake basin for the period 1996 – 2000. We estimated the spatial and temporal distribution of recharge using: (1) a daily soil water balance (SWB) model, that we had previously developed for estimating recharge distributions in humid regions (Dripps et al., 2002), (2) an integrated terrestrial biosphere model (IBIS) run using hourly time steps (Foley et al., 1996; Kucharik et al., 2000; Lenters et al., 2000), (3) a two-dimensional analytic element groundwater flow model, GFLOW (Haitjema and Kelson, 1994; Hunt et al., 1998), linked to an inverse parameter estimation code, UCODE (Poeter and Hill, 1998) and (4) various field techniques (temperature profile modeling, water level fluctuations, and time domain reflectometry).

## Procedures and Methods

### *Regional Recharge Modeling*

We tested the ability of three different models (the SWB model, IBIS, and GFLOW/UCODE) to estimate spatial and temporal distributions in groundwater recharge in the Trout Lake basin.

#### SWB Model

Dripps et al. (2002) developed a physically-based, modified Thornthwaite – Mather soil water balance (SWB) model that uses daily time steps and based on methods presented in Thornthwaite and Mather (1957), Eaton (1995) and Swanson (1996). The SWB model estimates the temporal and spatial distribution of groundwater recharge at the watershed scale for humid areas like Wisconsin. The model uses readily available soil, land cover, topographic, and climatic data to estimate daily groundwater recharge for each grid cell using a simple mass balance (Fig. 2). Specifically, recharge is calculated as precipitation minus the sum of interception, runoff, evapotranspiration and changes in soil moisture. The model uses the Soil Conservation Service (SCS) rainfall-runoff algorithm to calculate runoff and a digital elevation model (DEM) to route runoff allowing for re-infiltration downslope. Unlike most other recharge models, the SWB model uses readily available data, does not require extensive parameterization, can be designed in a relatively short time, and is easy to use. The code is written in Visual Basic and requires Microsoft Excel 2000 to run. ArcView is used to generate the model input grids.

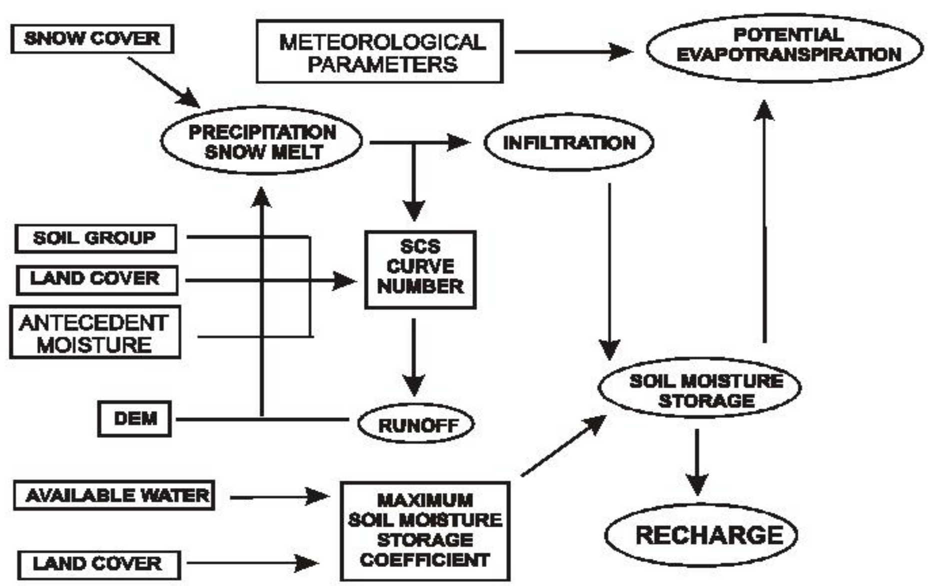



**Figure 2**. Flow chart for the SWB model.

The SWB model was run at a daily time step for 1995 – 2000 for the entire Trout Lake basin at a grid spacing of 120 meters. The model requires six input grids: (1) the available soil water capacity, (2) the hydrologic soil group based on the Soil Conservation Service Curve Number method, (3) land cover, (4) surface flow direction, (5) snow cover distribution, and (6) initial soil moisture content. The first four grids were generated from a geographic information system (GIS) database that included spatial coverage of the soils, land cover, hydrography, and elevation. The latter two input grids were generated for each year by running the model with the previous year's climatic data. The final soil moisture and snow cover distributions as of

December 31 served as input to the model for the next year's model run beginning on January 1. The required climatic data, which included temperature and precipitation, were taken from a composite climate data set assembled specifically for this project. Simulated daily recharge was averaged to yield an annual recharge distribution for each year of interest.

IBIS

The IBIS (Integrated BIosphere Simulator) model is a comprehensive, modular terrestrial biosphere model (Fig. 3) that explicitly links land surface and hydrologic processes, terrestrial biogeochemical cycles, and vegetation dynamics within a single, physically consistent framework (Foley et al., 1996). IBIS was originally designed as a global scale model, but recently was successfully applied at a regional scale (Kucharik, personal communication). The equations used in the model are independent of scale such that application at the watershed scale is possible, but had not been attempted prior to the application to the Trout Lake basin reported here.

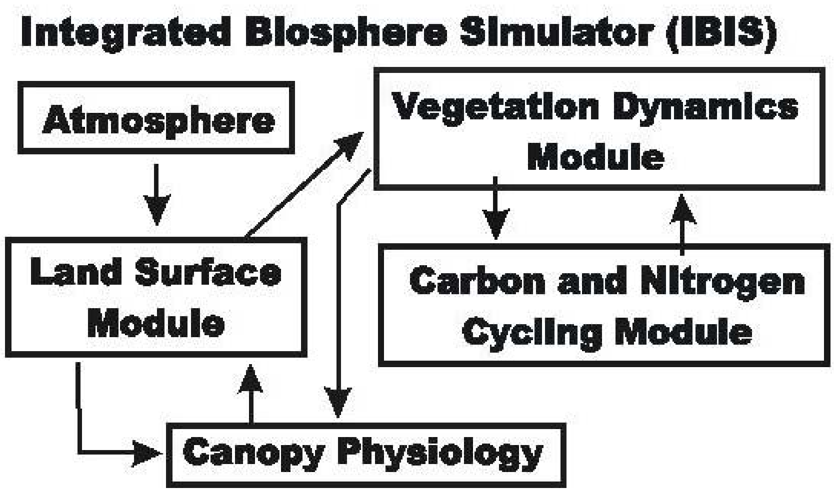



**Figure 3**. Schematic diagram of IBIS.

We used IBIS to calculate spatially and temporally variable recharge for the Trout Lake basin for 1996 – 2000, utilizing the atmosphere, land surface, and vegetation phenology modules to calculate the basin's water balance. Hourly climatic data were used to drive the land surface module, which simulates energy, water, carbon, and momentum balances of the soil – vegetation – atmosphere system. The land surface module allows for two vegetation layers (an upper and lower canopy), six soil layers, and a three layer thermodynamic snow melt system. Inputs to the module include vegetation variables (land cover physiology), soil variables (type and hydrologic characteristics), and meteorological variables including precipitation, temperature, relative humidity, solar radiation, and wind speed. The required vegetation, soil and meteorological inputs were obtained from the same data set assembled for the SWB model. The model was run using hourly time steps for 1989 – 2000 and a grid cell spacing of roughly 120 meters. There were some small gaps in the hourly climate record for 1989 – 1995, so these six years were used as spin up data, and the 1996 – 2000 model output was used for the recharge analysis.

The model was calibrated to baseflow of streams tributary to Trout Lake (North Creek, Stevenson Creek, Allequash Creek, and the Trout River) as well as to snow cover depths, interception, and actual evapotranspiration as measured at comparable sites across northern Wisconsin.

GFLOW/UCODE

A nonlinear parameter estimation code, UCODE Poeter and Hill (1998), was coupled to a two-dimensional analytic element (AE) code, GFLOW (Haitjema and Kelson, 1994), to estimate annual recharge rates for 1996 – 2000 by optimizing the AE model to estimated baseflow at the four tributary streams to Trout Lake. The AE model used in this study was adapted from an existing AE model of the basin developed by Hunt et al. (1998). In this application of GFLOW, we did not consider spatial variability but did assess temporal fluctuations of recharge.

Following Hunt et al. (1998) streams and lakes in the immediate vicinity of Trout Lake were simulated as a series of interconnected linesinks with resistance (Fig. 4). Stream elevations and lake stages were assigned based on the USGS topographic map of the area. The interior of each of the major lakes was assigned a high hydraulic conductivity to prevent mounding and a higher precipitation rate to account for the lack of vegetative transpiration. Hunt et al. (1998) calibrated the model to 1991 head measurements and streamflows using a uniform hydraulic conductivity of 8.64 m/day, which we also used in simulations performed in our study for the period 1996-2000.

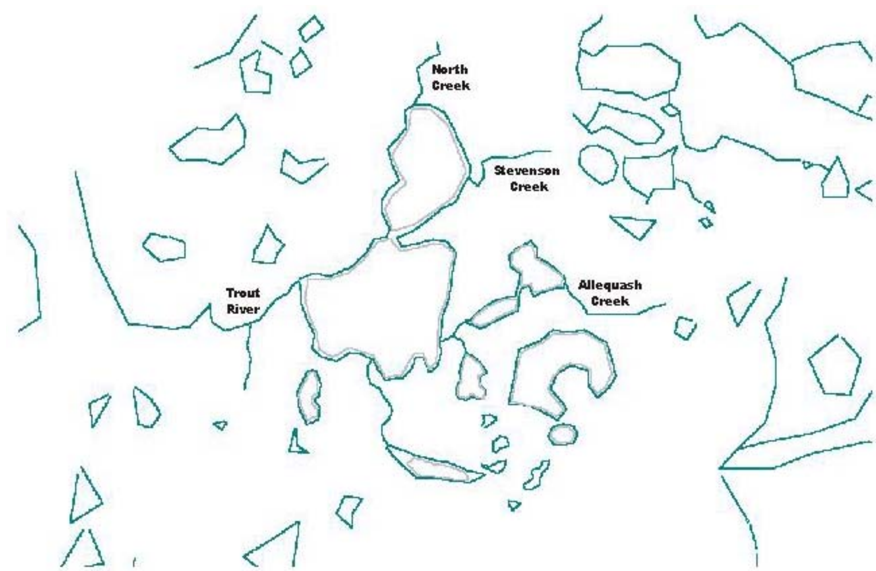



**Figure 4**. Analytic element model of the Trout Lake basin showing location of tributary streams.

Beginning in Fall 1999, we made field measurements of recharge at numerous well-instrumented sites in the Trout Lake basin covering a range of different vegetation, soil, geologic, and topographic features. At each site we recorded precipitation, water levels in wells, and soil moisture at three depths (10 inches, 3 feet, and 7 feet), as well as temperature profiles at depths of 0.05, 0.2, 0.5, 1, 3, and 5 meters below the surface, all at hourly intervals.

## ***Field Methods***

Water Level Fluctuations

Fluctuations in the water table contain a continuous record of the recharge process and in areas where precipitation is the only source of recharge, can provide a means to track the timing and spatial distribution of precipitation-induced recharge. Rainfall timing, intensity, and amounts, antecedent soil moisture conditions, properties of the soil and aquifer, types of vegetation, topography, and thickness of the unsaturated zone affect the water-table response.

Water levels were monitored hourly in 23 wells from September 1999 - June 2001 using 0 – 3 foot range, Global Water Waterloggers (WL14X). Manual water-level measurements, using chalk and a steel tape, were made roughly once every two months to correct for electronic drift in the sensors. The rise in the water table through time in response to recharge events can be converted to volumes of recharge by multiplying the magnitude of each rise by the aquifer's specific yield. Analysis is relatively straightforward, but interpretation of the water-table response can be complicated by the presence of lateral groundwater flow and by the removal of groundwater directly from the saturated zone by plant roots.

An approach similar to that described by Johannson (1987) was used to interpret the water-table response for those wells where precipitation-induced recharge appeared to dominate. A water-table recession curve was derived using water-level data during extended times when recharge did not occur (i.e., in winter when the ground was frozen and covered with snow). For each recharge period, the recession curve was then used to extrapolate what the water level would have been had recharge not occurred. The difference between the projected water level without recharge and the actual measured water level at the end of the recharge period represented the rise in the water table due to a particular recharge event. This difference was multiplied by an estimate of the aquifer's specific yield to generate a volume of recharge for each period. Estimates of specific yield were constrained by the porosity (~ 0.29) and by values of specific yield for similar material reported in the literature (Duke, 1972). A range of 0.20 –0.26 was used for the recharge calculations.

### Temperature Profiles

Following work by Stallman (1965), many researchers attempted to use changes in the temperature profile, measured below the water table, to quantify recharge rates. In this study, we attempted to use a two-dimensional coupled water and heat flow mode, VS2DH (Healy et al., 1996), to analyze temperature measurements in the unsaturated zone in order to quantify recharge through model calibration.

### Reflectometers

Soil moisture reflectometers use time domain reflectometry to measure the soil moisture content. Reflectometers were placed at multiple depths and the moisture data at numerous sites provided a record of the timing of recharge events, denoted by sharp rises in the soil moisture content as pulses of infiltrating recharge moved through the unsaturated zone en route to the water table.

## Results and Discussion

Average annual recharge estimates generated by the three models and from analysis of water-table fluctuations are summarized in Table 1.

**Table 1: Range in Annual Recharge Values (in/yr) generated by the various methods. The annual rainfall and percentage of rainfall that represents recharge are also included.**

| Year | SWB | IBIS | GFLOW | Water Levels | Rainfall | % of Rainfall |
|---|---|---|---|---|---|---|
| 1996 | 14.5 - 16.5 | 14.75 – 17 | 16.45 | | 38.59 | 38 - 44% |
| 1997 | 13.5 - 15.25 | 14.25 - 16.75 | 15.24 | | 30.64 | 44 - 55% |
| 1998 | 4.75 - 6 | 6.75 – 8 | 8.52 | | 22.51 | 21 - 38% |
| 1999 | 6 - 10.75 | 6 – 10 | 7.02 | | 31.79 | 19 - 34% |
| 2000 | 8.25 - 10.75 | 9.25 - 11.25 | | 6 – 12 | 31.19 | 19 - 39% |

Soil moisture measurements were useful in estimating the timing of recharge events (Fig. 5) and were used to constrain the SWB and IBIS models. Recharge events could be detected qualitatively on our measured temperature profiles but even for large rainfall events, there was no temperature response below about one meter from the land surface. Furthermore, the likely occurrence of heterogeneities and finger flow in the unsaturated zone complicated attempts to simulate the temperature response in the upper meter. The model was unsuccessful in matching the field measured profiles and consequently we were not able to quantify recharge using the measured temperatures.

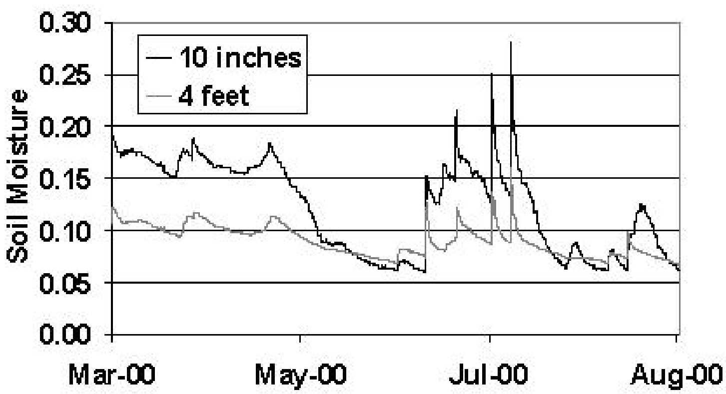



**Figure 5**. Soil moisture as measured using reflectometry at one of the field sites.

Results from the three models (Table 1) show that there is more than a two-fold difference in annual recharge over the five year period considered. These annual differences are significant, and must be considered for accurate and proper groundwater management. Furthermore, although there is general correlation between the amount of precipitation and the magnitude of the annual recharge, results suggest that the correlation between recharge and precipitation is nonlinear. For instance, in 1997, the Trout Lake watershed received less rainfall than in 1999, but received over 25% more recharge. This is probably because 1998 was a particularly dry year and most of the 1999 snowmelt and spring rain went towards replenishing the soil water deficit that had been carried over from the previous fall instead of recharging the groundwater system. Soil moisture conditions and the timing of precipitation events seem to be more important in controlling recharge rates than the actual amount of precipitation that falls.

The simulated average annual spatial distribution of recharge for 2000 for the Trout Lake watershed as calculated by the SWB model (Fig. 6a) and by IBIS (Fig. 6b) shows that while the spatial variability in the recharge distribution within the modeled region is relatively small, heterogeneity in the recharge pattern can be attributed to differences in soil and vegetation types.

The pattern produced by SWB model (Fig. 6a) has even less variability than the pattern generated by IBIS (Fig. 6b) because the current version of SWB does not distinguish between deciduous and coniferous forests. In a previous application of the SWB model to an urban/ agricultural watershed in south central Wisconsin, land cover was found to be a major source of variability in recharge (Dripps et al., 2002). The Trout Lake watershed, however, is covered almost entirely by forest. Recharge is typically larger in coniferous forests than in deciduous forests due to differences in evapotranspiration rates and shading effects on snow cover between the two types (Lenters, personal communication). The IBIS model distinguishes between deciduous and coniferous forest and some of the spatial variability in recharge rates evident in Fig. 6b is due to forest type.

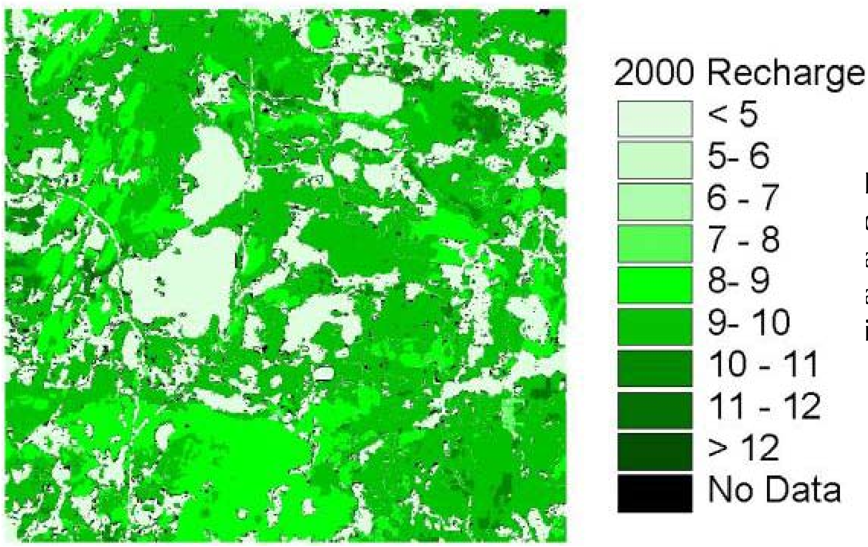
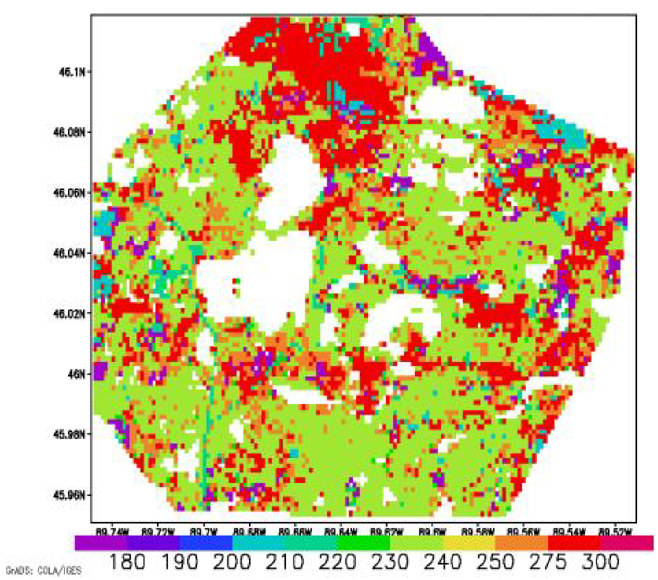



**Figure 6.** Spatial distribution of annual average recharge in 2000 as calculated by **a)** SWB, in/yr and **b)** IBIS, mm/yr.

(a)




(b)

The absence of extensive spatial variability suggests that the use of a spatially constant recharge rate may be acceptable for more regionally based modeling studies in this area, although for site-specific studies that involve processes like nutrient cycling, contaminant transport, or construction of a detailed water budget, use of a single average recharge estimate would certainly produce erroneous results.

Monthly recharge rates calculated by the SWB and IBIS models vary widely not only within the same year, but also from year to year (Fig. 7). For this watershed, as is true for most watersheds in the northern United States, the spring snowmelt is typically the biggest single recharge event each year, occurring usually either in March or April although occasionally in February as it did in 1998 and 2000. There is typically little to no recharge during the winter months when the ground is frozen, negligible recharge during the summer months when evapotranspiration is high, and occasional small recharge events during the fall after evapotranspirative demands have diminished or ceased. The sporadic recharge events that occur during the summer and fall are almost always associated with major thunderstorms that drop a few inches of rain at a time. Although most years follow this general monthly pattern of recharge, there are exceptions. For example, in 2000 the highest monthly recharge rate occurred in July (Fig. 7).

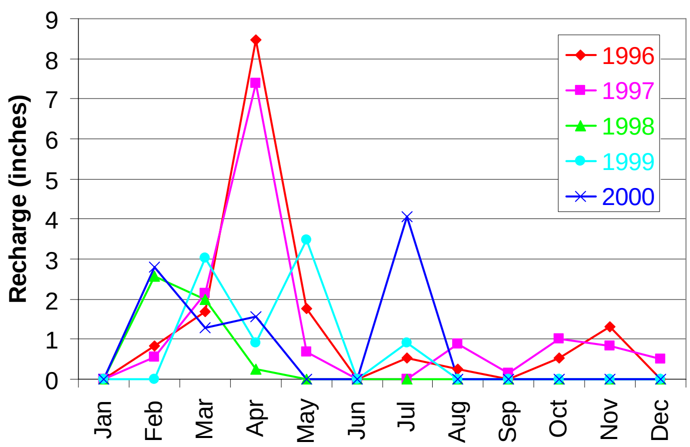



**Figure 7**. Monthly recharge as calculated by the SWB model for the Trout Lake basin.

## Conclusions and Recommendations

- The SWB, IBIS and GFLOW/UCODE models gave comparable recharge estimates that compared well to those calculated from measured water-table fluctuations.
- Temperature measurements in the unsaturated zone, while indicating the timing of major recharge events, were not useful in quantifying recharge rates in the Trout Lake basin, probably because of the presence of heterogeneities and finger flow.
- The SWB model is potentially a useful tool for estimating spatially and temporally distributed recharge arrays for input to groundwater flow models and for management decisions. The SWB model yielded recharge estimates and distributions similar to those calculated by the more rigorous IBIS and GFLOW/UCODE models but unlike those two models, the SWB model does not require extensive parameterization, can be designed and applied in a relatively short time, and is easy to use.
- IBIS, originally designed as a global dynamic ecosystem model, was successfully applied at the watershed scale.

- Annual average temporal variations in recharge in the Trout Lake watershed were significant (more than two-fold). Monthly variations were also large. These significant temporal variations have important implications for water resource planning and management. Spatial variability was primarily controlled by differences in soil and land cover type. This variability has significant implications regarding the potential impacts of land cover changes on the basin's water budget as well as implications for nutrient and contaminant transport processes.
- The standard practice of estimating recharge as a percentage of the annual precipitation provides only a crude approximation of the recharge process. Although there is typically a broad correlation between the amount of precipitation and the magnitude of annual recharge, assuming a linear correlation between the two is a bad assumption as soil moisture conditions and the timing of precipitation events are more important in controlling recharge rates than the actual amount of precipitation that falls.
- Collectively these models, particularly the SWB model, give modelers, planners, and policy makers practical water resource management tools for providing spatially and temporally distributed recharge estimates for purposes of water resources planning.

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## Appendix A: Awards, Dissertations, Presentations, Reports

**Awards**

Best Student Paper: Dripps, W.R., Kucharik, C.J., Lenters, J.D., Anderson, M.P. and Foley, J.A., 2001. Modeling the Spatial and Temporal Distribution of Groundwater Recharge Across a Forested Watershed in northern Wisconsin. American Geophysical Union, 2001 Spring Meeting, Boston, MA, Eos, Vol. 82

**Dissertations**

Dripps, W. R., Expected January 2002. The Spatial and Temporal Variability of Natural Groundwater Recharge. University of Wisconsin – Madison, Department of Geology and Geophysics.

**Conference Proceedings / Presentations**

Dripps, W.R., Kucharik, C.J., Lenters, J.D., Anderson, M.P. and Foley, J.A., 2001. Modeling the Spatial and Temporal Distribution of Groundwater Recharge Across a Forested Watershed in northern Wisconsin. American Geophysical Union, 2001 Spring Meeting, Boston, MA, Eos, Vol. 82

Dripps, W.R., Anderson, M.P., and Hunt, R.J., 2001. The Use of Temperature Profiles through Unsaturated Soils to Estimate Short-term Rates of Natural Groundwater Recharge. American Geophysical Union, 2001 Spring Meeting, Boston, MA, Eos, Vol. 82

Dripps, W.R, Anderson, M.P., and Hunt, R.J., 2001. Use of a Coupled Heat and Water Transport Model (VS2DH) for Estimating Rates of Natural Groundwater Recharge. American Water Resources Association – Wisconsin Section, 25$^{th}$ Annual Meeting, Green Lake, WI, abstracts, p. 27.

Dripps, W.R., Anderson, M.P., and Hunt, R.J., 2000. Incorporating Recharge Variability into Groundwater Flow Models. Geological Society of America, 2000 Fall Meeting, Reno, NV, Abstracts with Programs, Vol. 33, p. 335.

**Reports**

Dripps, W.R., Bradbury, K.R., Anderson, M.P., and Hankley, D.W., in prep. A Modified Thornthwaite – Mather Soil Water Balance Model for Estimating the Spatial Distribution of Groundwater Recharge. 2002 Wisconsin Geological and Natural History Survey Circular.

Additional publications in peer-reviewed journals are expected to be submitted sometime during 2002.

**Appendix B**
**Abstracts cited in Appendix A**

## Modeling the Spatial and Temporal Distribution of Groundwater Recharge Across a Forested Watershed in northern Wisconsin

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The spatial and temporal distribution of groundwater recharge depends on the complex interaction of hydrologic, atmospheric, pedologic, vegetative, and geologic processes, making it one of the most difficult and uncertain hydrologic parameters to quantify, yet understanding its distribution is a basic prerequisite for effective groundwater resource management and modeling.

We use a modular terrestrial biosphere model (IBIS) (Kucharik et al., 2000), which couples carbon, nitrogen, water, and energy fluxes, to examine the spatial and temporal distribution and variability of groundwater recharge across a 400 $km^2$ forested watershed in northern Wisconsin. The model uses a two-layer vegetation (upper and lower canopy) and six-layer soil scheme to simulate the exchange of energy and water between the soil surface, vegetation canopies, and the atmosphere. Inputs to the model include vegetation land cover type, soil variables (soil type and hydrologic characteristics), and meteorological parameters (precipitation, temperature, relative humidity, solar radiation, and wind speed). For this study the model was run with an hourly time step.

The meteorological inputs were collected as part of the North Temperate Lakes Long Term Ecological Research (NTL-LTER) project, while the required vegetation and soil variables were taken from the literature and from other ongoing and previous vegetation studies in northern Wisconsin. Field measurements of recharge rates at numerous sites within the watershed were used to calibrate and verify the model results.

**The Use of Temperature Profiles through Unsaturated Soils to Estimate Short-term Rates of Natural Groundwater Recharge**

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It has long been recognized that infiltration influences the vertical subsurface temperature profile. Many researchers have used changes in the temperature profile to quantify the rate of groundwater flow in saturated systems, e.g. in wetlands and streambeds. Others have considered coupled heat and flow transport through the unsaturated zone, but we are aware of only two groups (Taniguchi and Sharma, 1993; Tabbagh et al., 1999) who have previously used temperature profiles through the unsaturated zone to estimate rates of areally extensive groundwater recharge. Both groups looked at seasonal changes in soil temperature to estimate annual recharge rates, but no attempt was made to analyze individual recharge events.

We collected hourly soil temperature measurements through the unsaturated zone at depths of 0.05, 0.2, 0.5, 1, and 3 meters at a site in the Trout Lake basin of northern Wisconsin for the past two years. VS2DH (Healy and Ronan, 1996), a two-dimensional, numerical, coupled heat and water flow model for variably saturated media, was used to simulate the thermocouple data and estimate rates of recharge for individual recharge events. Field studies including Guelph permeameter tests, slug tests, grain size analyses, bulk density estimates, and lab measurements of soil moisture characteristic curves were used to estimate the necessary hydraulic and thermal parameters for the model. The field data were supplemented by values reported in the literature, and further refined during model calibration. Recharge rates computed using temperature data were compared with estimates based on water level fluctuations and estimates obtained using simple water balance modeling.

## Use of a Coupled Heat and Water Transport Model (VS2DH) for Estimating Rates of Natural Groundwater Recharge

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It has long been recognized that infiltrating water influences the subsurface temperature profile. Many researchers have used changes in the temperature profile to quantify the rate of groundwater recharge in saturated systems, e.g. in wetlands and streambeds.

Others have considered coupled heat and flow transport through the unsaturated zone, but we are aware of only one group (Taniguchi and Sharma, 1993) who has previously used temperature profiles through the unsaturated zone to estimate rates of recharge. Taniguchi and Sharma (1993) looked at seasonal changes in soil temperature to estimate annual recharge rates, but no attempt was made to analyze individual recharge events.

We used thermocouple data from the unsaturated zone in conjunction with VS2DH (Healy and Ronan, 1996), a two-dimensional, numerical, coupled heat and water flow model for variably saturated media, to estimate rates of recharge for individual recharge events at a site in the Trout Lake basin of northern Wisconsin. Field data were used where available to estimate the necessary hydraulic and thermal parameters for the model. The field data were supplemented by values reported in the literature, hydrologic judgment, and model calibration. Recharge rates computed using temperature data were compared with estimates based on water level fluctuations and estimates obtained using simple water balance modeling.

**Incorporating Recharge Variability into Groundwater Flow Models**

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Understanding the spatial and temporal distribution of groundwater recharge is a prerequisite for effective groundwater resource management and modeling. For example, accurate representation of recharge variability in a groundwater model may be critical in predicting contaminant and nutrient transport. While there has been much work on recharge estimation, the measurement of recharge variability and its incorporation into regional groundwater models continue to present significant challenges. Hence, it is not uncommon in groundwater modeling studies to disregard recharge heterogeneity and use a single value of recharge for an entire watershed.

At a site in northern Wisconsin, we combined extensive field instrumentation with modeling to characterize the spatial and temporal distribution of recharge across a 16 square mile watershed. We compare common direct methods (e.g., water-level fluctuations) and indirect methods (e.g., temperature profiling and time domain reflectometry) for assessing site estimates of groundwater recharge. Each technique is applied at more than one site to assess the relative significance of some of the factors (e.g. precipitation, vegetation, topography, soils, and geology) that control recharge and affect its spatial and temporal distribution. In addition, we developed a simple soil-water balance model to estimate the annual spatial distribution of groundwater recharge for the watershed. The model is based on a modified Thornthwaite – Mather approach and uses available soil, land cover, topographic, and climatic data.

**The Spatial Distribution of Groundwater Recharge: Its Estimation and Incorporation into Groundwater Flow Models**

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Understanding the spatial distribution of groundwater recharge is a basic prerequisite for effective groundwater resource management and modeling. The measurement of recharge variability and its incorporation into regional groundwater modeling projects remain the most important problems to be overcome in recharge analysis. Most groundwater modeling studies typically disregard recharge heterogeneity and use a single estimate of recharge for an entire watershed. The use of a single recharge estimate in a flow model may be inappropriate as recharge clearly varies at the watershed scale, due to its dependence on a wide variety of spatially variable parameters (e.g. precipitation, vegetation, topography, soils, and geology). Incorporating recharge variability into groundwater flow models is critical to constructing an accurate water balance as well as predicting contaminant and nutrient transport.

We have developed a GIS-based method for estimating spatially distributed, annual recharge rates for regional groundwater flow studies. The method links a simple Thornthwaite-Mather soil water balance to a three-dimensional gridded digital elevation model within a Geographic Information System. The model utilizes soil, land cover, topography, and climate data to calculate annual recharge rates for each model cell. The model accounts for gains (precipitation), losses (runoff, evapotranspiration), and changes in storage for each cell and uses a rainfall-runoff algorithm and a digital elevation model to route runoff and allow for reinfiltration downslope.

We tested our model in the Pheasant Branch watershed near Middleton, WI, where the United States Geological Survey has completed a field-intensive rainfall-runoff study. Our model produces recharge estimates comparable to those calculated in the USGS study. We are currently applying our model to the Trout Lake watershed of Boulder Junction, Wisconsin. An existing finite difference groundwater flow model of the watershed is being used to assess the differences between incorporating a spatially-variable recharge array relative to a single estimate array with respect to the water balance and contaminant transport in the watershed.

**A GIS-Based Method for Estimating Groundwater Recharge Over Large Areas**

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Understanding the spatial and temporal distribution of groundwater recharge is a basic prerequisite for effective groundwater resource management and modeling and is one of the keys to economic development in rapidly expanding urban, industrial, and agricultural regions. Recharge, defined as the entry of water into the saturated zone, depends on a wide variety of factors (e.g. vegetation, precipitation, climate, topography, geology, and soil type), making it one of the most difficult, complex, and uncertain hydrologic parameters to quantify in the evaluation of groundwater resources. Although many researchers have proposed techniques for estimating recharge, only a few studies have considered both its spatial and temporal variability, and still no standard accepted method exists to quantify recharge for regional groundwater studies.

We are attempting to estimate annual recharge rates using a modified Thornthwaite/Mather water balance method linked to a geographic information system (GIS). The water balance method is based on mapped soils information, and accounts for gains (precipitation), losses (runoff, evapotranspiration), and changes in storage over individual soil units. A grid-based rainfall-runoff algorithm uses a digital elevation model to route runoff between and across soil units. Water leaving the soil column through deep percolation is assumed to represent recharge. This modeling technique has the advantage of fairly rapid implementation using data widely available in Wisconsin and elsewhere (digital soils maps, digital elevation models). A preliminary version of the model using ARC/INFO GRID has been completed and is being tested in the Pheasant Branch watershed near Middleton, Wi, where the US Geological Survey has completed a field-intensive rainfall-runoff study and has independently developed recharge rates for comparison with our results. Initial model runs produce recharge estimates that are lower than field measurements, possibly because of coarse (monthly) time discretization in our model. We are currently modifying the model to handle finer time discretization.

**A Comparison of Multiple Methods for Estimating Groundwater Recharge in the Trout Lake Basin, Northern Wisconsin**

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Accurate measurements of groundwater recharge are a basic prerequisite for effective groundwater resource management and modeling. Although a wide variety of physical and chemical methods exists for estimating groundwater recharge, most recharge studies use a single technique to estimate recharge and thus lack corroborating evidence to substantiate recharge measurements. Consequently, we will apply and compare some of the common direct methods (water-level fluctuations and lysimeters) and some of the indirect methods (temperature profiling and time domain reflectometry) for assessing site estimates of groundwater recharge. Eight sites in the Allequash watershed of northern Wisconsin that differ in respect to vegetation and soil type have been instrumented with water-table wells, water-level recorders, in-situ zero tension (gravity) lysimeters, reflectometers, and thermocouple nests. The USGS, two-dimensional, numerical, coupled heat and water flow model VS2DH will be used to help interpret the thermocouple data.

The use of multiple methods will allow for a comparison of techniques and results and will provide a range of recharge estimates at each site. Thereafter, a comparison among the eight different sites will be used to assess the spatial and temporal distribution of recharge within the watershed as well as explore and determine the relative significance of some of the different factors (e.g. precipitation, vegetation, topography, soils, and geology) that influence this distribution.