ground water

Flowpath Delineation and Ground Water Age, Allequash Basin, Wisconsin

by Christine D. Pint[1,2], Randall J. Hunt[3], and Mary P. Anderson[1]

Abstract

An analysis of ground water flowpaths to a lake and creek in northern Wisconsin shows the flow system in a geologically simple basin dominated by lakes can be surprisingly complex. Differences in source area, i.e., lakes or terrestrial, combined with the presence of intervening lakes, which may or may not capture underflowing ground water as water moves downgradient from recharge areas, contribute to a complex mix of flowpaths. The result is water of different chemistry and vastly different ages may discharge in close proximity. Flowpaths, travel times, and capture zones in the Allequash Basin in northern Wisconsin were delineated using particle tracking based on a calibrated steady-state ground water flow model. The flowpath analysis supports the conclusions of Walker et al. (2003) who made inferences about flowpath characteristics from isotope and major ion chemistry. Simulated particle tracking agreed with Walker et al.'s measurements of water source (lake or terrestrial recharge) in the stream subsurface and also supported their assertion that ground water with a high calcium concentration in the lower basin of Allequash Lake is derived from long flowpaths. Numerical simulations show that ground water discharging in this area originates more than 5 km away in a source area located upgradient of Big Muskellunge Lake, which is upgradient of Allequash Lake. These results graphically illustrate that in settings with multiple sources of water with different age characteristics and converging flowlines (like the Allequash Basin) it may be difficult to obtain accurate estimates of ground water age by chemical analyses of ground water.

Introduction

Walker et al. (2003) found surprising variability in major ion chemistry in the Allequash Creek Basin, a small, geologically simple watershed in northern Wisconsin. The aquifer in this watershed consists mainly of outwash sand and gravel comprised of predominantly silicate minerals and a relatively stable flow system. They attributed the chemical variability to differences in length of subsurface flowpaths, as well as differences in ground water velocity and weathering rates. Specifically, they found high calcium concentrations at what they inferred to be the end of long subsurface flowpaths and low δ^{87}Sr concentrations at what they inferred to be the end of flowpaths characterized by fast ground water velocities.

In the work reported in this paper, we show that flowpaths delineated with the help of a three-dimensional, steady state ground water flow model support the conclusions of Walker et al. Furthermore, our results graphically illustrate that in settings like the Allequash Basin it may be difficult to obtain an accurate estimate of ground water age by chemical analysis of a sample of ground water, owing to the fact that water samples are composed of a mix of waters of different ages. In previous work by others, ground water age has been treated as a quantity known as age mass (Goode 1996), which is the product of the age of a ground water sample and its mass. Ground water age can be modeled as a solute, allowing for mixing of ground water of different ages owing to dispersion in heterogeneous aquifers (Weissmann et al. 2002; Fogg et al. 1999) or mixing of waters originating in aquifers and confining beds (Bethke and Johnson 2002a, 2002b). This type of mixing causes underestimation of the mean ground water age because age dating techniques such as chlorofluorocarbons (CFCs) and tritium-based methods preferentially detect the relatively younger water in

[1]Department of Geology and Geophysics, University of Wisconsin-Madison, 1215 W. Dayton St., Madison, WI, 53705; andy@geology.wisc.edu
[2]Now with Barr Engineering Company, 4700 West 77th St., Minneapolis, MN 55435; cpint@barr.com
[3]U.S. Geological Survey, WRD, 8505 Research Way, Middleton, WI, 53562; rjhunt@usgs.gov

the sample (Weissman et al. 2002). Previous workers have pointed out that the piston flow model traditionally used to calculate ground water age can be flawed (Bethke and Johnson 2002a, 2002b). In our work, however, we assume piston flow and show that mixing of ground water of different ages occurs because convergent flowpaths cause waters of vastly different ages to discharge in close proximity.

Background

The Allequash Creek Basin (Figure 1) is located within the North Temperate Lakes Long Term Ecological Research (NTL-LTER) site and the USGS's Northern Temperate Lakes Water, Energy, and Biogeochemical Budgets (WEBB) site. The system is ground water dominated, with ground water derived base flow accounting for more than 90% of total streamflow (USGS, unpublished data). The aquifer consists of 40 to 60 m of unconsolidated Pleistocene glacial deposits, mostly glacial outwash sands and gravel (Attig 1985). Horizontal hydraulic conductivities are estimated to be ~10 m/day (Okwueze 1983; Hunt et al. 1998). Vertical anisotropy in hydraulic conductivity is relatively small, with the ratio of horizontal to vertical conductivity ranging from 4:1 to 8:1 at a scale of a couple of meters (Kenoyer 1988). The lakes occupy depressions in the glacial deposits that may penetrate more than 80% of the aquifer. Trout Lake, the largest lake in the basin with an area of 11 km^2, is drained by the Trout River (Figure 1) and is fed by four streams, including Allequash Creek. Annual precipitation averages about 79 cm/year (Cheng 1994) and average ground water recharge is estimated to be 27 cm/year (Hunt et al. 1998). Annual evaporation off the lakes is ~54 cm/year (Krabbenhoft et al. 1990; Wentz and Rose 1991). Lakes are well connected to the ground water system and many lakes are flow-through lakes with respect to ground water.

The Trout Lake Basin has been the focus of several modeling studies (Cheng 1994; Hunt et al. 1998; Champion and Anderson 2000; Pint 2002) that represent stages in the development and refinement of a regional ground water model, which will be used in future studies to address a variety of research problems including the effects of climate change.

Watershed Model Design and Calibration

The term watershed model is used by hydrologists in a wide variety of applications to refer to models of varying degrees of sophistication. Traditionally, watershed models include regression analysis and a "black box" approach to estimate streamflows, e.g., the SPARROW model (Smith et al. 1997). These methods are typically applied to analyze streamflow in large basins where deterministic models are unwieldy owing to the regional scale of the problem. Regression models may have limited predictive capability, however, because they rely on relations developed from past events to predict the future. Furthermore, they cannot directly simulate flowpaths and associated lag times within the basin. Watershed models also include rainfall-runoff models, which approximate the ground water system as a simple linear reservoir, e.g., the PRMS model (Leavesley et al. 1983), or use Darcy's law with the assumption that the slope of the water table approximates the land-surface slope, e.g., TOPMODEL (Beven and Kirkby 1979; Beven et al. 1995).

These watershed models, which calculate streamflow as the major output, may be adequate when the watershed is dominated by surface water flows but have limited

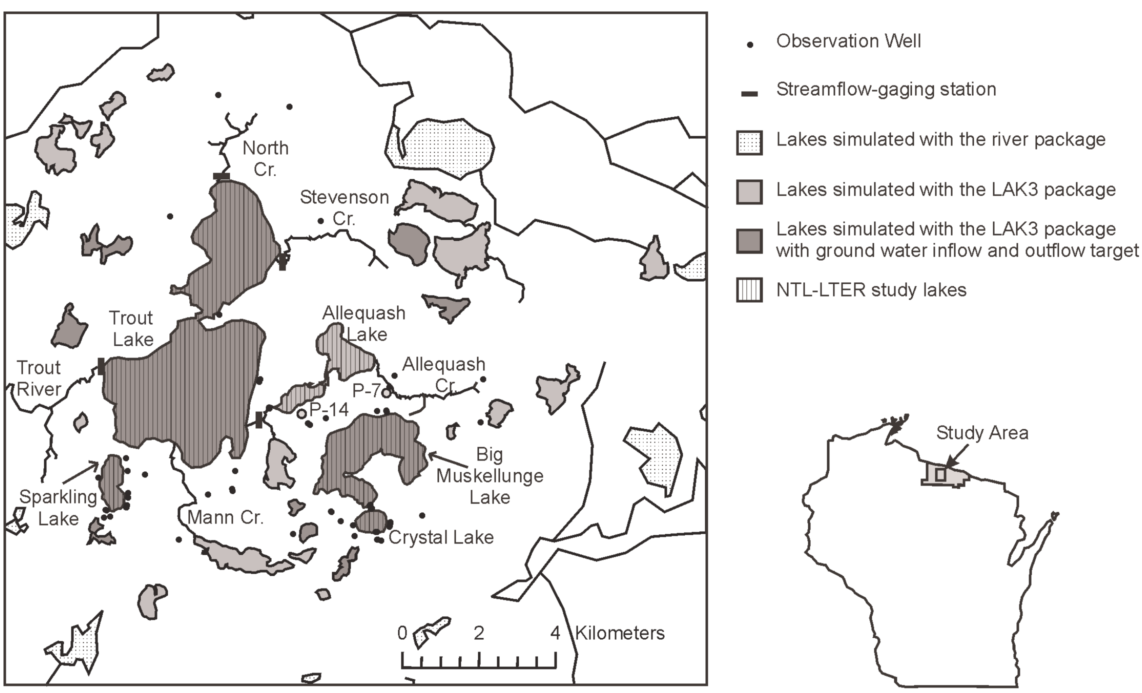

Figure 1. Extent of the domain used in the watershed model of the Trout Lake Basin, Wisconsin, showing location of Allequash Lake and Allequash Creek.

predictive and interpretive power when the basin of interest has an important ground water component. In ground water-dominated basins, a process-based, ground water flow model that incorporates links to surface waters is best suited for investigating flux distribution, flowpaths and residence times, chemical evolution, solute budgets, and basin yield. Hence, in the work reported here, we used a ground water-based watershed model.

The Allequash Basin, which includes Allequash Creek and Allequash Lake (Figure 1), was simulated within a regional ground water flow model of the Trout Lake Basin (Pint 2002) developed using MODFLOW–2000 (Harbaugh et al. 2000). The model was run using the pre- and post-processor MODFLOW GUI (Shapiro et al. 1997) within Argus Open Numerical Environments, i.e., Argus ONE (Argus Interware Inc. 1997). Particle tracking was performed using MODPATH (Pollock 1994).

The three-dimensional model used a uniform horizontal nodal spacing of 75 m and four layers (Figure 2). The bottom three layers ranged in thickness from 5 to 15 m, while the upper layer was relatively thick, with a saturated thickness between 8 and 35 m, to minimize the possibility of nodes drying during calibration and during transient simulations. A two-dimensional analytic element (AE) model using GFLOW (Haitjema 1995) was modified from an existing regional model of the Trout Lake area (Hunt et al. 1998) and was used to derive boundary conditions for the finite difference model using the methodology of Hunt et al. (1998). Briefly, ground water fluxes calculated at the boundaries of the MODFLOW grid by the AE model were distributed to the upper three layers of the finite difference model based on layer transmissivity and were input to MODFLOW's well package. The crystalline bedrock, assumed to be impervious, formed the bottom boundary of the model. Recharge flux was specified across the water table, which formed the upper boundary.

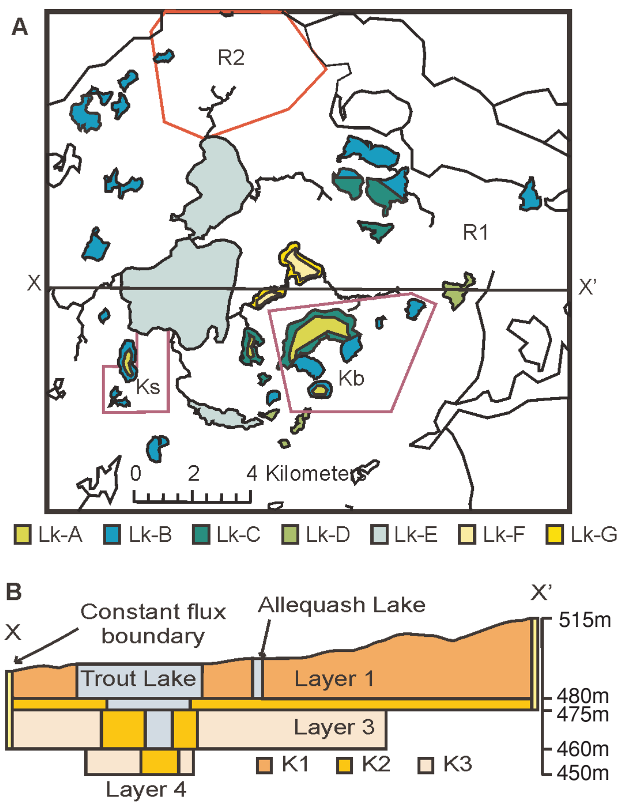

Figure 2. (a) Model domain showing location of high hydraulic conductivity (Kb, Ks), recharge (R1, R2), and lakebed leakance (Lk-A through Lk-G) zones. (b) Cross section shows the vertical layering of hydraulic conductivity zones. Vertical exaggeration is 90.

Thirty lakes within the Trout Lake Basin, or near its boundary, were simulated using the LAK3 Lake Package (Merritt and Konikow 2000), which calculates lake stages based on volumetric water budgets. Simulating lake stages within the model is superior to specifying lake stages using constant head nodes because it helps ensure that heads are not overly specified in the immediate area of interest. Similarly, streams located within the Trout Lake Basin were simulated using a beta version of the Streamflow Routing Package (Prudic et al., in press), thereby allowing calculation of stream stage. For convenience, other lakes and streams distant from the area of interest were represented as specified heads using the River Package (McDonald and Harbaugh 1988). The streambed sediments were assumed to have a uniform thickness of 1 m and a vertical hydraulic conductivity of 8.63 m/day. All aquifer hydraulic conductivity zones were assumed to have a vertical anisotropy ratio (Kx/Kz) equal to four. Effective porosity, used in particle tracking, was set equal to 0.29 (Krabbenhoft and Babiarz 1992).

The steady-state model was calibrated to average conditions as represented by ground water levels measured in July 2001 (which are representative of average conditions during the period of record, 1985–2001), average lake stages for the period of record, and average base flows for the period 1991–2000. We used nonsynchronous measurements in order to maximize the number of calibration targets, especially to include wells that were newly installed in 2001 in the northern portions of the watershed. This is considered acceptable as 2001 was representative of average conditions as calculated from records of head in wells with longer data sets. Because lake and stream levels can be influenced by short-term transient events, average values of lake and stream levels were used for the calibration. Additionally, estimates of ground water fluxes to and from lakes (Ackerman 1992), the depth of an oxygen isotope plume emanating from Big Muskellunge Lake as measured in well nests P–7 and P–14 (Figure 1), and travel time between Big Muskellunge Lake and well P–7 (Figure 1) estimated from CFC and tritium sampling (Walker et al., in review) were used as calibration targets.

Values of hydraulic conductivity, recharge, and lakebed leakance were estimated during calibration with the help of the parameter estimation code UCODE (Poeter and Hill 1998) (Table 1 and Figure 2). The root mean squared errors for the calibrated model were 0.56 m for head, 0.14 m for lake stage of the five principal LTER lakes and 0.77 m for 20 other lakes. Simulated base flows were within 1% of measured flows and the depth of the lake plume and travel times were also close to measured values. Values of lakebed leakance are poorly known, but sensitivities calculated during calibration with UCODE showed

Table 1 Calibrated Parameter Values for the Steady State Watershed Model	
Parameter*	**Value**
R1 (cm/yr)	24.9
R2 (cm/yr)	25.8
K1 (m/day)	9.67
Kb (m/day)	37.0
Ks (m/day)	26.2
K2 (m/day)	3.44
K3 (m/day)	38.2
Lk-A (day^{-1})	0.004
Lk-B (day^{-1})	0.1
Lk-C (day^{-1})	0.0043
Lk-D (day^{-1})	0.023
Lk-E (day^{-1})	0.00037
Lk-F (day^{-1})	0.7
Lk-G (day^{-1})	0.1

*See Figure 2 for explanation of symbols and location of parameter zones.

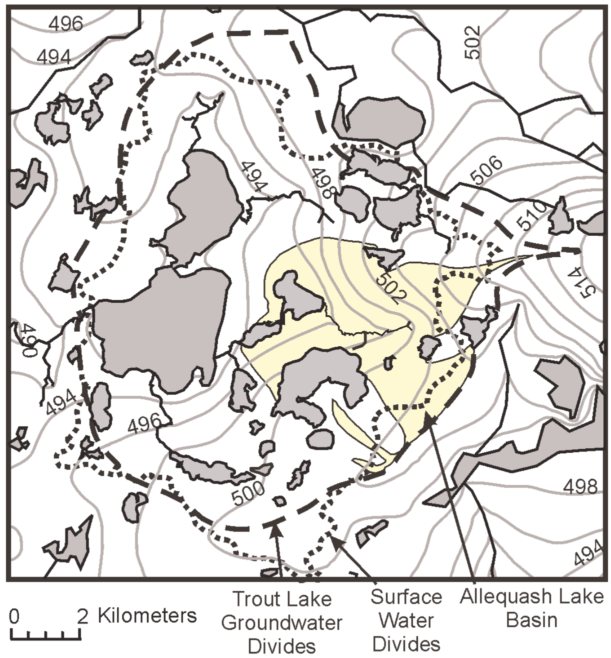

Figure 3. Simulated water table contour map. Ground water divides (delineated using particle tracking) and surface water divides for the Trout Lake Basin are shown. Boundaries of the Allequash Subbasin are also shown. Names of lakes and streams are shown in Figure 1.

that lakebed leakance is not a sensitive parameter for any lake except near the north shore of Big Muskellunge Lake. Details on the calibration of the model are given by Pint (2002).

Flowpath Analysis

Water table contours (Figure 3) show that ground water in the Trout Lake Basin flows toward Trout Lake. Within the Allequash Subbasin, ground water flows northwest from Big Muskellunge Lake to Allequash Lake; water from Allequash Lake drains to Trout Lake primarily via Allequash Creek.

The water isotope work of Walker et al. (2003) yields subsurface flowpaths in three categories according to point of origin—lake, terrestrial, or a mixture of the two (Figure 4). Distinction is also made between short and long flowpaths and fast and slow ground water velocities, as inferred from chemical analyses of water samples collected in the stream and in the streambed and lakebed during 1991–1994. Particle tracking simulations were performed using the calibrated steady-state ground water flow model to test the validity of Walker et al.'s conclusions. Particles were inserted below the Allequash Creek streambed and tracked backward to their points of origin using MODPATH (Figure 5).

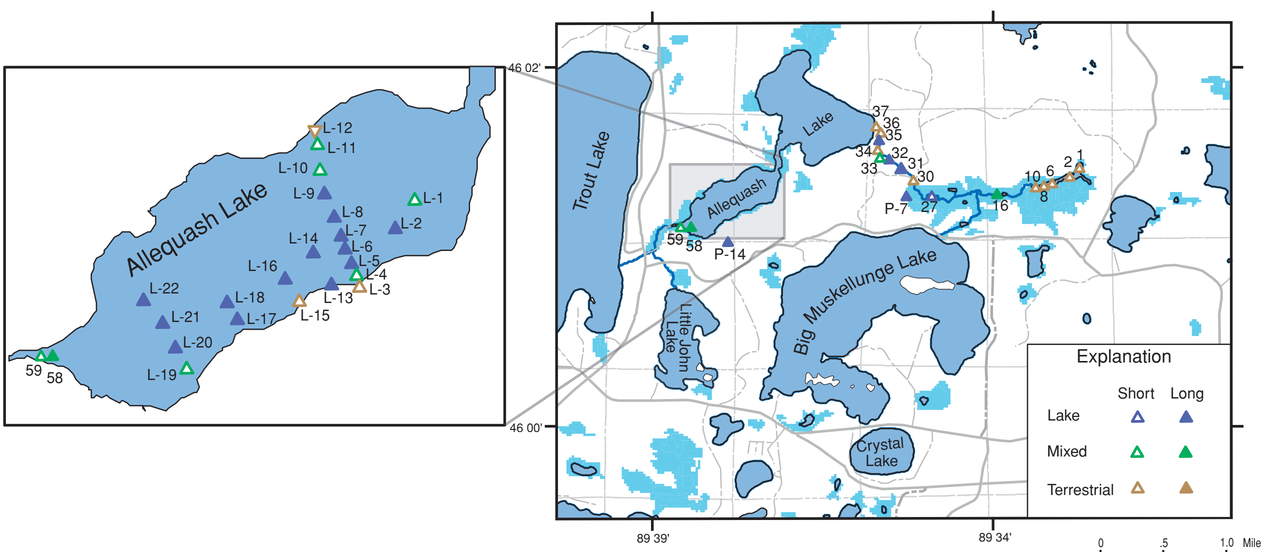

Figure 4. Results of flowpath analysis derived from results of Walker et al. (2003) showing origin, and relative length and time of travel for water entering Allequash Creek and Allequash Lake. Numbers correspond to sampling locations used by Walker et al., except points P–7 and P–14, which are based on work reported by Bullen et al. (in review).

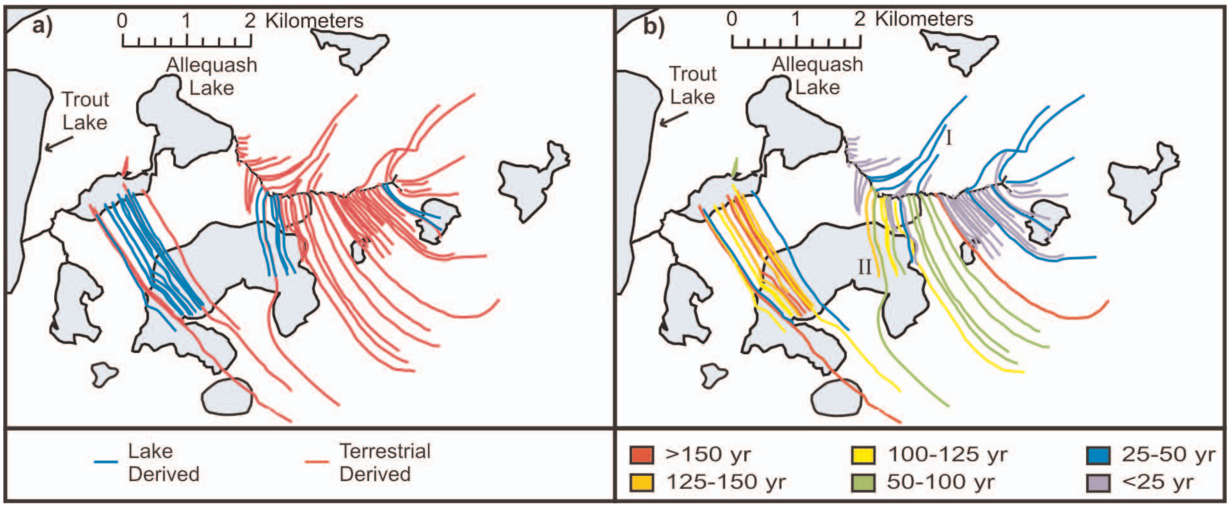

Figure 5. Simulated flowpaths in the Allequash Creek Basin: (a) origin of water entering Allequash Creek and the lower basin of Allequash Lake; (b) travel times for simulated flowpaths; flowpaths I and II discharge near each other, but have travel times of 26 and 128 years, respectively.

Walker et al. (2003) also used oxygen isotopes to infer that water discharging to the headwaters area of Allequash Creek, from site 1 to site 10, originates from a terrestrial source (Figure 4), a finding that is confirmed by the simulated flowpaths (Figure 5a). Walker et al. found that downgradient of site 10, water samples had oxygen isotope signatures indicative of terrestrial, lake, and mixed origins, with lake-derived water discharging at sites 27, 31, 32, and 35 (Figure 4). Our flowpath simulation similarly shows a mix of waters downgradient of site 10 with lake-derived flowpaths discharging at sites 27, 31, and 32 (Figure 5a). Walker et al. inferred that terrestrial and water of mixed origin discharges into the shoreline areas of the lower basin of Allequash Lake and that lake-derived water discharges into the areas farther from shore (Figure 4). Our simulation also shows that both terrestrial and lake-derived flowpaths discharge into the lake with a spatial distribution similar to that observed by Walker et al. (Figure 5a).

Walker et al. inferred that the headwaters area of Allequash Creek from site 1 to site 10 receives flowpaths of intermediate length, that subsurface water near site 18 had relatively long flowpaths, and that the reach from site 27 to site 37 receives both long and short flowpaths. Our simulations agree with this interpretation (Figure 5). Moreover, Walker et al. also concluded that the portions of the lower basin of Allequash Lake, e.g., site 58, and parts of the creek downstream of Allequash Lake receive very long flowpaths. Our simulation shows that flowpaths discharging in the lower lake basin can be more than 5 km long and originate upgradient of Big Muskellunge Lake.

Capture Zone Analysis

MODPATH was used to delineate the capture zones of Allequash Lake and Allequash Creek (Figure 6). While a capture zone is a three-dimensional surface (Townley and Trefry 2000), for our purposes a capture zone is defined as the land surface area that contributes flow that discharges directly into the relevant lake or stream. It should be noted, however, that Allequash Lake and Allequash Creek also receive water from flowpaths that originate in Big Muskellunge Lake. Furthermore, Big Muskellunge Lake receives water from flowpaths that originate from upgradient terrestrial sources as well as from upgradient lakes. In effect, the system of lakes acts as a conveyor moving water downgradient toward Trout Lake, so that water in Allequash Lake and Allequash Creek may ultimately originate at the ground water divide of Trout Lake Basin, or anywhere in between.

In our simulation, one particle was introduced at the water table in the center of every active node in the top layer of the model. Particles were tracked forward in time to their points of discharge and capture zones were delineated based on discharge location. Travel time information recorded by MODPATH was used to construct contour lines of equal travel time, representing the time required for water to flow from point of origin to the lake or creek. The contours also provide relative information on ground water velocities inasmuch as closely spaced contours indicate low velocities and widely spaced contours indicate high velocities.

The capture zone for Allequash Lake (Figure 6) is surprisingly complex and includes an area upgradient of Big Muskellunge Lake; this area appears to be the source of the long, slow terrestrial and mixed flowpaths that discharge to the southern shoreline area of the lower basin of Allequash Lake (Figures 4 and 5). The capture zone analysis also indicates short flowpaths and low velocities along the northwestern shoreline of the lower basin of Allequash Lake, supporting the conclusion of Walker et al. (2003) that this part of the lake basin receives terrestrial and mixed water with slow ground water velocities. Furthermore, Walker et al. (2003) inferred that fast flowpaths discharge to Allequash Creek between site 16 and site 30, and slow flowpaths discharge to the creek downgradient of site 30, which is supported by the capture zone analysis (Figure 6) where time of travel contour lines are more closely spaced downgradient of site 30, indicating slower flowpaths.

The particle tracking results also allowed us to delineate the Trout Lake ground water basin (Figure 3). The boundaries of the ground watershed differ somewhat from the surface watershed, providing additional justification for using a ground water-based watershed model whose boundaries contain both the ground water and surface water basins.

Ground Water Age

Several workers recently called attention to the fact that ground water age, as determined from well water samples, may deviate from ages calculated assuming a simple piston flow model (Goode 1996; Bethke and Johnson 2002a, 2002b; Weissmann et al. 2002). They maintain a ground water sample is a complex mixture of water of various ages, comparable to water samples analyzed for solute concentrations. The deviation from piston flow is usually related to the degree of aquifer heterogeneity, including heterogeneity caused by the presence of confining layers (Bethke and Johnson 2002b) and large hydraulic conductivity contrasts within a heterogeneous aquifer, for example, five orders of magnitude (Fogg et al. 1999; Weissmann et al. 2002). Walker et al. (2003) found complex age relations in the relatively homogeneous, simple outwash sand and gravel aquifer system in the Allequash Basin. We assumed piston flow and used particle tracking to show that in the Allequash Basin, flowpaths carrying water of vastly different ages discharge in close proximity creating the potential for mixing of age mass within a particular ground water sample.

The capture zones for Allequash Lake and Allequash Creek (Figure 6) indicate that ground water discharging to these surface waters is as much as 200 years old. While, in general, recharge from distant areas has longer travel times than recharge originating in areas near Allequash Lake and Allequash Creek, particle tracking results (Figure 5) graphically illustrate that flowpaths that discharge close together may have very different ages and points of origin. For example, ground water that flows under Big Muskellunge Lake may have a shorter time of travel than water that originates in Big Muskellunge Lake, e.g., the two flowpaths in the vicinity of flowpath II (Figure 5b). Moreover, flowpath II (colored gold) with a travel time of 128 years, discharges close to flowpath I (colored blue), which has traveled only 26 years (Figure 5b). The travel times for lake-derived water are longer than for terrestrial-derived water with the same flowpath length because water originating in the lake

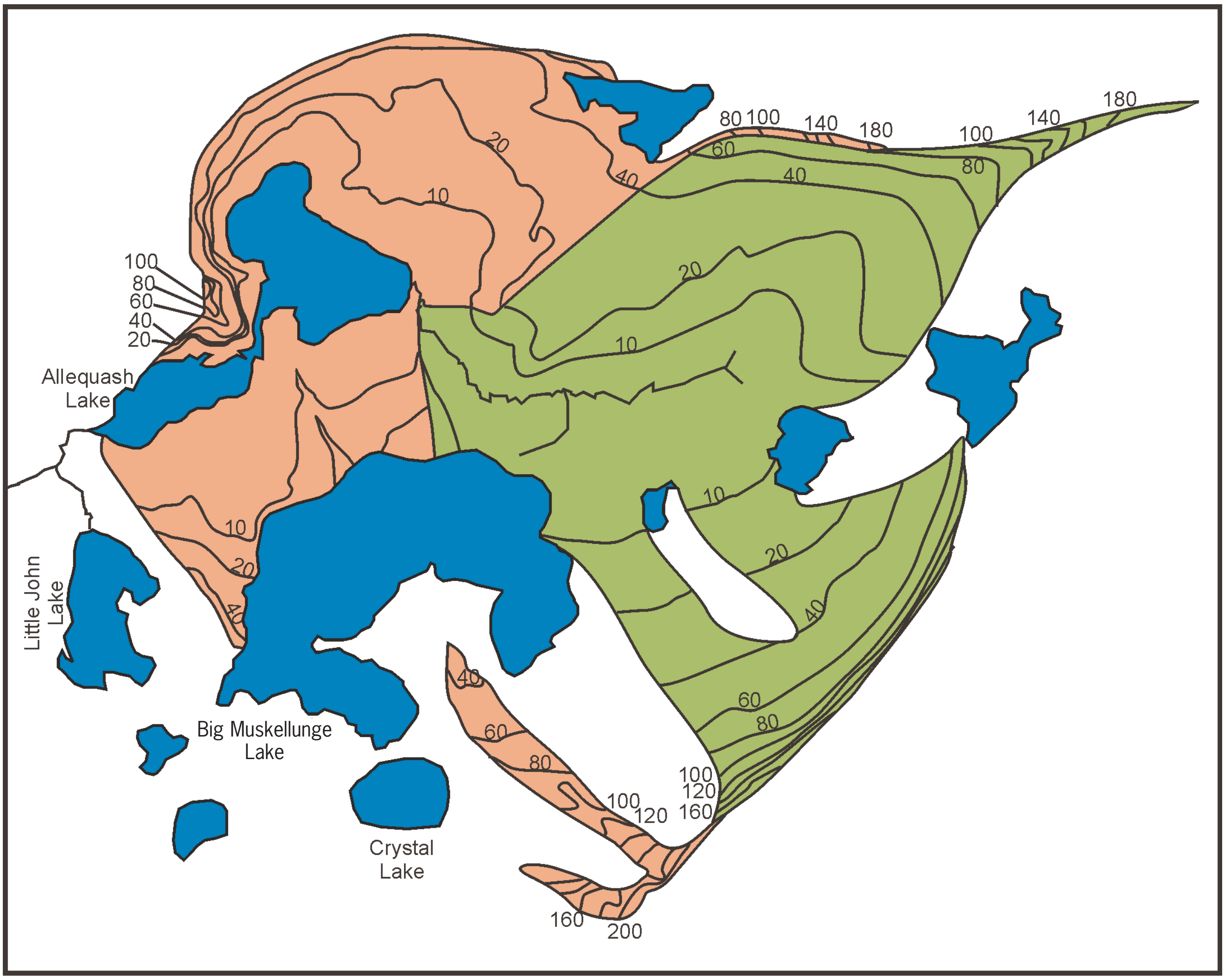

Figure 6. Capture zones for Allequash Lake (pink) and Allequash Creek (green) delineated using particle tracking. Contours indicate time of travel in years.

must travel through low-conductivity lake sediments when leaving the lake.

In the Allequash Basin, it appears that diversity in source area (lake or terrestrial) and the presence of intervening lakes, which may or may not capture underflowing ground water, are significant contributing factors to complexity in ground water age. The aquifer in the Allequash Basin, although layered, contains no confining layers (Figure 3), except for low permeability sediments that underlie the lakes, and hydraulic conductivity varies within one order of magnitude (Table 1). Moreover, flowpaths were simulated using advective particle tracking; the results do not include the effects of diffusion, dispersion, or exchange processes commonly included in transport simulations, all of which would add to complexity in age dates.

Conclusions

Flowpaths delineated using a three-dimensional ground water flow model support the conclusions of Walker et al. (2003), who made inferences about length and origin of flowpaths and ground water velocities from chemical analyses of water samples. Discharge to Allequash Creek and Allequash Lake in northern Wisconsin originates both from recharge that flows exclusively through the subsurface and from water that originates in Big Muskellunge Lake. Moreover, flowpaths that discharge to the creek and lake are a mix of long and short flowpaths and a mix of flowpaths characterized by both slow and fast velocities.

This complexity confounds attempts to devise a simple correlation between chemical signatures and the discharge point of a specific flowpath; however, the simulated flowpaths provide support for deductions made from Walker et al.'s chemical analyses for discharge areas within the basin. For example, concentrations of high calcium in water in the lower basin of Allequash Lake agreed with model results showing a long flowpath (>5 km). Also, oxygen isotope concentrations correctly indicated that three of four sites along Allequash Creek receive water derived from Big Muskellunge Lake, and the headwaters area of the creek receives terrestrial-derived water from relatively short flowpaths.

The capture zone for Allequash Lake contains a terrestrial recharge area upgradient of Big Muskellunge Lake from which long flowpaths originate carrying water that takes up to 200 years to discharge to the lake. Moreover, there is a complex mix of long and short flowpaths discharging to Allequash Creek and Allequash Lake that is surprising because the aquifer is relatively homogeneous. Our results graphically illustrate that in settings such as the Allequash Basin, it may be difficult to obtain an accurate estimate of ground water age from chemical analysis of a sample of ground water because water of vastly different ages can be found in close proximity, especially in areas with converging flow lines (discharge areas).

In the Allequash Basin, it appears that diversity in source areas (lakes or terrestrial) and the presence of intervening lakes, which may or may not capture underflowing ground water, significantly contribute to age complexity in this relatively homogeneous, simple sand-and-gravel aquifer. Moreover, this variability in ground water age was inferred using only advective particle tracking; the results did not include consideration of diffusion, dispersion, or exchange processes commonly included in transport simulations. The flowpath analysis also illustrates that the variability in chemistry in this small watershed, found by Walker et al. (2003), reflects a complex three-dimensional flow system.

Acknowledgements

Support was provided by the Wisconsin Groundwater Coordinating Council, the North Highland Lakes Long Term Ecological Research (LTER) Project funded by the National Science Foundation (DEB–9632853), and the USGS Northern Temperate Lakes Water, Energy, and Biogeochemical Budgets (WEBB) project. We are grateful to Daniel Feinstein, Tom Johnson, and Tom Winter for insightful review comments.

Editor's Note: The use of brand names in peer-reviewed papers is for identification purposes only and does not constitute endorsement by the authors, their employees, or the National Ground Water Association.

References

Ackerman, J.A. 1992. Extending the isotope based ($\delta^{18}O$) mass budget technique for lakes and comparison with solute based lake budgets. Master's thesis, Department of Geology and Geophysics, University of Wisconsin-Madison.

Argus Interware Inc. 1997. *User's Guide Argus ONE™* for Argus Open Numerical Environments—A GIS Modeling System, Version 4.0. Jerico, New York: Argus Holdings Ltd.

Attig, J.W. 1985. Pleistocene geology of Vilas County, Wisconsin. Wisconsin Geological and Natural History Survey Information Circular 50.

Bethke, C.M., and T.M. Johnson. 2002a. Paradox of groundwater age. *Geology* 30, no. 2: 107–110.

Bethke, C.M., and T.M. Johnson 2000b. Ground water age. *Ground Water* 40, no. 4: 337–339.

Beven, K J., and M.J. Kirkby. 1979. A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin* 24, 43–69.

Beven, K.J., R. Lamb, P.F. Quinn, R. Romanowicz, and J. Freer. 1995. TOPMODEL. In *Computer Models of Watershed Hydrology*, ed. V.P. Singh, 627–668. Highlands Ranch, Colorado: Water Resources Publications.

Bullen, T.D., R.J. Hunt, J.F. Walker, and D.P. Krabbenhoft. In review. Watershed-scale groundwater chemical evolution in a sandy silicate aquifer, northern Wisconsin. *Geochimica et Cosmochimica Acta.*

Champion, G., and M.P. Anderson. 2000. Assessment of impacts on groundwater/lake systems using MODFLOW with a lake package: Application to the Trout Lake Basin, northern Wisconsin. Water Resources Institute, University of Wisconsin-Madison, Groundwater Research Report WRI GRR 00–05.

Cheng, X. 1994. Numerical analysis of groundwater and lake systems with application to the Trout River Basin, Vilas County, Wisconsin. Ph.D. dissertation, Department of Geology and Geophysics, University of Wisconsin-Madison.

Fogg, G.E., E.M. LaBolle, and G.S. Weissmann. 1999. Groundwater vulnerability assessment: Hydrologic perspective and example from Salinas Valley, California. In *Assessment of non-point source pollution in the vadose zone.* American Geophysical Union, Geophysical Monograph 108, 45–61.

Goode, D.J., 1996. Direct simulation of groundwater age. *Water Resources Research* 32, no. 2: 289–296.

Haitjema, H.M. 1995. *Analytic Element Modeling of Groundwater Flow*. San Diego: Academic Press.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald. 2000. MODFLOW–2000, the U.S. Geological Survey modular ground-water model: User guide to modularization concepts and the ground-water flow process. USGS Open-File Report 00–92.

Hunt, R.J., M.P. Anderson, and V.A. Kelson. 1998. Improving a complex finite-difference ground water flow model through the use of an analytic element screening model. *Ground Water* 36, no. 6: 1011–1017.

Kenoyer, G.J. 1988. Tracer test analysis of anisotropy in hydraulic conductivity of granular aquifers. *Ground Water Monitoring Review* 8, no. 3: 67–70.

Krabbenhoft, D.P., M.P. Anderson, and C.J. Bowser. 1990. Estimating groundwater exchange with lakes, II: Calibration of a three-dimensional, solute transport model to a stable isotope plume. *Water Resources Research* 26, no. 10: 2455-2462.12.

Krabbenhoft, D.P., and C.L. Babiarz. 1992. Role of groundwater transport in aquatic mercury cycling. *Water Resources Research* 28, no. 12: 3119–3128.

Leavesley, G.H., R.W. Lichty, B.M. Troutman, and L.G. Saindon. 1983. Precipitation-runoff modeling system user's manual. USGS Water-Resources Investigations Report 83–4238.

McDonald, M.G., and A.W. Harbaugh. 1988. A modular three-dimensional finite-difference ground-water flow model. USGS Techniques of Water-Resources Investigations Report, Book 6, Ch. A1.

Merritt, M.L., and L.F. Konikow. 2000. Documentation of a computer program to simulate lake-aquifer interaction using the MODFLOW ground-water flow model and the MOC3D solute-transport model. U.S. Geological Survey Water-Resources Investigations Report 00-4167.

Okwueze, E. 1983. Geophysical investigation of the bedrock and groundwater-lake flow system in the Trout Lake region of Vilas County, northern Wisconsin. Ph.D. dissertation, Department of Geology and Geophysics, University of Wisconsin-Madison.

Pint, C.D., 2002. A groundwater flow model of the Trout Lake Basin, Wisconsin: Calibration and lake capture zone analysis. M.S. thesis, Department of Geology and Geophysics, University of Wisconsin-Madison.

Poeter, E.P., and M.C. Hill. 1998. Documentation of UCODE, a computer code for universal inverse modeling. USGS Water-Resources Investigation Report 98–4080.

Pollock, D.W. 1994. User's guide for MODPATH/MODPATH-PLOT, Version 3: A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model. USGS Open-File Report 94–464.

Prudic, D.E., L.F. Konikow, and A.W. Harbaugh. In press. A streamflow routing package (SFR1) to simulate stream-aquifer interaction with MODFLOW–2000 ground-water flow model and MODFLOW-GWT solute-transport model. USGS Open-File Report.

Shapiro, A.M., J. Margolin, S. Dolev, and Y. Ben-Israel. 1997. A graphical-user interface for the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model (MODFLOW–96) using Argus numerical environments. USGS Open-File Report 97–121.

Smith, R.A., G.E. Schwarz, and R.B. Alexander. 1997. Regional interpretation of water-quality monitoring data. *Water Resources Research* 33, no. 12: 2781–2798.

Townley, L.R., and M.G. Trefry. 2000. Surface water-groundwater interaction near shallow circular lakes. *Water Resources Research* 36, no. 4: 935–949.

Walker, J.F., R.J. Hunt, T.D. Bullen, C. Kendall, D.P. Krabbenhoft, and J.F. Elder. 2003. Spatial and temporal variability of isotope and major ion chemistry in the Allequash Creek basin, northern Wisconsin. *Ground Water* 41, no. 7: 883–894.

Walker, J.F., D.A. Saad, and R.J. Hunt. In review. Factors affecting CFCs in ground-water recharge derived from northern Wisconsin lakes. *Journal of Hydrology*.

Weissmann, G.S., Y. Zhang, E.M. La Bolle, and G.E. Fogg. 2002. Dispersion of groundwater age in an alluvial aquifer system. *Water Resources Research* 38, no 10: 16.1–16.8.

Wentz, D.A., and W.J. Rose. 1991. Hydrology of lakes Clara and Vandercook in north-central Wisconsin. USGS Water Resources Investigations Report 89–4204.