Hydro Logic

Mary Anderson
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Estimating Groundwater Fluxes across Interfaces

Featured Faculty Research

Mary Anderson

Water is the most important substance on Earth. While not a mineral itself, water rules the mineral kingdom since interaction with water is fundamental to all geological processes. And water can even slip into the mineral kingdom by freezing into ice. Water occurs in the hydrologic cycle as soil water, groundwater and surface water. We also find water vapor in the atmosphere and frozen water in ice sheets and glaciers. The interactions among the various water reservoirs are receiving increased attention recently as researchers investigate fluxes of water across the interfaces between reservoirs.

Groundwater/surface water interaction has long been a topic of interest among hydrologists. Much attention has been given to both the theory and measurement of groundwater fluxes to and from surface water bodies, yet there are still many difficulties in obtaining accurate estimates of the spatial and temporal distribution of these fluxes, including fluxes to and from rivers and streams, reservoirs and lakes, wetlands, and the ocean. Similarly, there are no standard procedures for measuring recharge to the groundwater system from precipitation.

Recharge/discharge estimates are of interest at many different scales and for many different purposes. These fluxes affect physical, chemical and biological processes in the subsurface. Furthermore, basin scale biogeochemical cycles are determined in part by recharge/discharge patterns and the physiology of vegetation is strongly linked to recharge/discharge zones. Inflow of groundwater to surface water bodies carries nutrients important to biological communities. Recent work at the groundwater-stream interface (the hyporheic zone) and at the groundwater/lake interface has demonstrated that most of the chemical transformation occurs within a few inches of the interface. Improved measurements of groundwater fluxes and associated biogeochemical processes within these interfaces are needed. Understanding the spatial and temporal distribution of 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.

Our research group, with the help of Ken Bradbury (Wisconsin Geological and Natural History Survey) and Randy Hunt (USGS, Middleton, WI office) is addressing the problem of recharge estimation through both field investigations and modeling studies. PhD student, Wes Dripps, is quantifying the spatial and temporal distribution of recharge in the Pheasant Branch Watershed near Madison and in the Allequash Basin in northern Wisconsin. Allequash Basin is a study site within the Northern Temperate Lakes Long Term Ecological Research (NTL - LTER) Program and the United States Geological Survey's Water, Energy, Biogeochemical Budget (WEBB) Program. Wes has instrumented several sites in the basin to measure recharge rates. He uses hourly measurements of water level, subsurface temperature, and soil moisture to calculate recharge and then compares results obtained from the various methods. With Ken Bradbury, he has developed a simple soil-water balance model that combines a daily soil water-balance with a three-dimensional digital elevation model within a Geographic Information System framework. He is applying this model, as well as a terrestrial biosphere model, to calculate the regional distribution of recharge across the Trout Lake watershed. Master's student Tina Pint is revising and up-dating a regional flow model of the Trout Lake watershed (Cheng, 1994; Champion, 1998, Hunt et al., 1998) and will use information from Wes Dripps' work to study regional flow patterns and groundwater discharge to lakes within the watershed, building on earlier work by our group (Kenoyer and Anderson, 1989; Krabbenhoft et al., 1990; Anderson and Cheng, 1993, 1998; Kim et al., 1999, 2000).

PhD student Yu-Feng Lin, who is in the Geological Engineering Program, is working on a method to estimate spatial patterns of recharge and discharge zones from information on the configuration of the water-table, building on earlier work by our group (Stoertz and Bradbury, 1989; Stoertz, 1989). He is using data from the Sand Plain of central Wisconsin to test his method. Master's student Paul Juckem is working with Randy Hunt to identify changing patterns of recharge in Coon Valley, Wisconsin. PhD student Tim Eaton is working with Ken Bradbury to study hydrogeological properties of the Maquoketa Shale, which forms an important confining bed to the system of sandstones that form an important aquifer in eastern Wisconsin. Part of his work involves estimating the amount of recharge through the shale.

The methods being developed by our group are not limited to Wisconsin but are generally applicable to humid zone problems. Our results will provide insights into the recharge process and will provide water resource management tools capable of giving spatially and temporally distributed estimates of the rates and distribution of groundwater recharge. In addition, these techniques might be used by regional planners and hydrogeologists to evaluate the impacts of urbanization, land use changes, and climate change on the patterns and rates of recharge as well as to provide groundwater modelers with a method for estimating the spatial and temporal distribution of recharge for regional groundwater flow models.

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photos: Carl Bowser

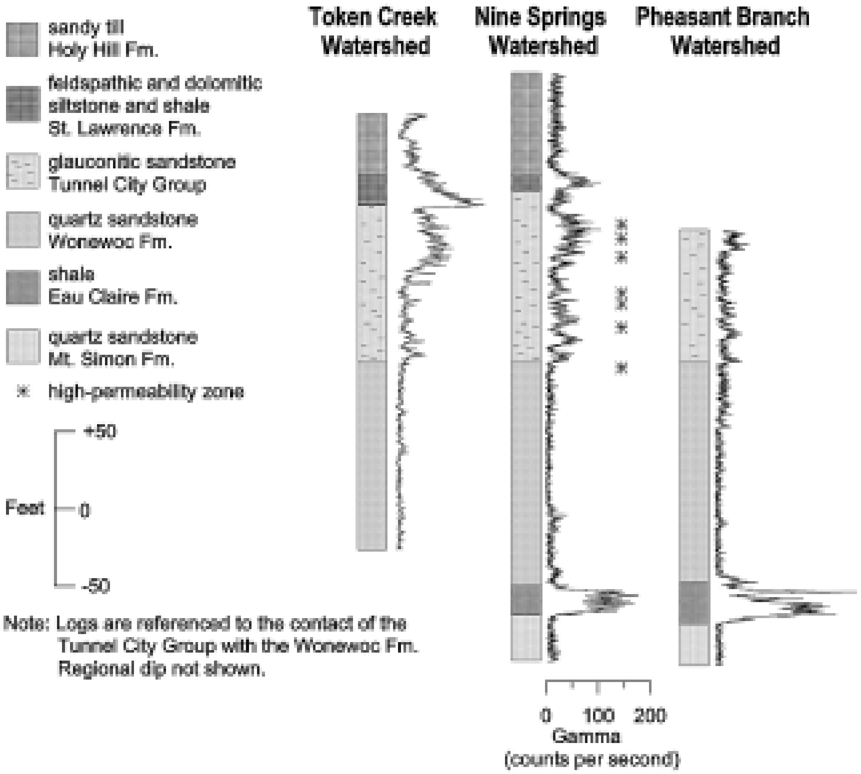
Unraveling the Mysteries of Springs in Dane County

Featured Faculty Research

Jean Bahr

Spring-fed wetlands once covered large areas of the watersheds surrounding the Madison lakes, but many of these have been lost to agricultural drainage and filling for urban development. As urban and suburban developments continue to expand into areas near the remaining wetlands, there has been increasing public interest in the aesthetic and ecological value of these features. This has prompted creation of several citizen groups dedicated to protecting, and possibly restoring, several of the larger springs. Water Resources Management Practicum studies in 1996 and 1997 provided background hydrogeologic information to these citizen groups on the Nine Springs Watershed, south of Madison, and to the Token Creek Watershed, northeast of Lake Mendota. In each of these watersheds, a few high volume springs appear to provide the majority of stream baseflow. There is concern that increased municipal pumping and paving over of recharge areas could significantly reduce springflow and threaten the remaining wetlands as well as stream quality.

Over the last four years my students and I have been following up on these initial studies with research designed to identify sources of water to major spring complexes and to develop more detailed groundwater flow models with which to evaluate potential adverse impacts of pumping and development. In 2000, we expanded our efforts to a third watershed, Pheasant Branch, to the northwest. What has emerged from this work is evidence that all of the major springs in these three watersheds are associated with preferential flow zones in a relatively shallow bedrock unit, the Tunnel City Group. The accompanying figure provides a summary of lithologic and hydrogeologic information obtained from bedrock wells in the three watersheds. Flow meter logging in existing wells at the DNR Fish Hatchery in the Nine Springs watershed indicated that the majority of the water from the flowing artesian wells enters the boreholes in a few short intervals within the Tunnel City. Interval packer tests in new bedrock wells we installed about a mile away in the same watershed revealed thin, high permeability intervals that correlate with the flow zones in the DNR wells. Geophysical logging and drill cuttings show that the Tunnel City group also occurs in the shallow bedrock near the major springs of the Pheasant Branch and Token Creek watersheds. We are in the process of completing interval packer tests in the other two watersheds to determine if high permeability zones can also be correlated at the county scale.



Note: Logs are referenced to the contact of the Tunnel City Group with the Wonewoc Fm. Regional dip not shown.

This recognition of a relatively shallow bedrock source for the springs is counter to our initial hypothesis that the steady flow rates observed in these springs requires a connection to the deeper regional flow system. In addition to the field evidence for a shallow bedrock source, analytical modeling results derived by Sue Swanson as part of her PhD research indicate the feasibility of generating steady spring flow of the volumes observed via preferential flow through relatively shallow, high permeability bedrock layers. From a perspective of protecting these springs, the good news is that a shallow bedrock source may be somewhat buffered from impacts of municipal pumping, which is concentrated in the deeper bedrock. However, the shallower source also makes the springs more vulnerable to local sources of contamination and to reductions in recharge associated with paving over the nearby hilltops.

Hydrogeochemistry and Its Contribution to Ecosystem Science at the Long-Term Ecological Research Study Site in Northern Wisconsin

Featured Faculty Research

Carl Bowser

PROLOGUE—Think of water as a mineral, but a very special kind of a mineral:

Most likely you learned what a mineral is from your first course in elementary geology or mineralogy. No doubt it's stretching it to suggest that liquid water could be called a mineral, and, of course, by any strict reading of the rules it's not. However, a check of any number of standard dictionaries will reveal that the definition of a mineral is loose enough to accommodate the thought that water could be considered a special form of a mineral. Ironically, we commonly use the term "mineral water" or refer to water as having "minerals" in it, when we've long known that dissolved substances in liquid water aren't really minerals.

On the other hand in and of itself water has many of the attributes of minerals. Only the requirement that it is must be a solid phase, denies it status among the realm of minerals we all know. As a natural, inorganic compound, and thanks to the unique character of the directed hydrogen bond, its liquid form has a weakly ordered "crystal" structure and a well-defined and limited range of chemical composition. By solid phase mineralogical standards, the elements dissolved in water at low to moderate temperatures would be given the status of minor trace elements. Water is arguably the most important "mineral" on earth yet few are willing to give it status in the realm of the mineral kingdom. It's unique solvent properties, abundance, and ample opportunity to move easily among the various geospheres of the earth to interact with rocks and other minerals, are well known. Water serves as both a transporting medium and a powerful solvent interacting with the minerals through which it moves, no matter what the temperature and pressure. The concept of water as a "mineral" is merely definitional, but its role in earth process is what really matters.

Hardly any ”mineral” has such ambiguity in terms of its respect among earth scientists. Clearly revered by the metamorphic petrologist when it reacts with other minerals to form assemblages that provide insights into the P-T conditions under which it formed, it is equally despised by these same scientists for similar reactions that, under very low P/T conditions, allow it to reduce their "pristine" rocks to a nearly unrecognizable and poorly consolidated collection of thoroughly corroded minerals mixed with plant roots, invertebrates, bacteria and other unmentionables that we call soil.

Up until fairly recently all too many "surficial geologists, hydrogeologists, and soil scientists" viewed this hard rock "underburden" only in terms of its ability to contain and transmit water, and paid less attention to the possibility that these waters would actually react with the rocks they were moving through. Sedimentologists are forced to recognize water's importance in weathering, but to them water just aids the process well enough to help sort, and purify the minerals that will ultimately find their way to becoming sedimentary rocks. Only when water moves fast enough to transport mineral grains, to sort them, or to provide nutrients for growth of carbonate secreting shells do sedimentologists again find water interesting.

To a biologist water is equally ambiguous in its importance and appreciation, but they have long recognized that it is essential to all forms of life that we know. Water is largely viewed as the medium either in which organisms live or on which they depend for life. Few have treated water chemically as anything more than a source of nutrients and other critical minerals necessary for sustsaining growth and reproduction or as an agent that can contain various dissolved organic and in organic substancs that are a threat to the very life of the organism. Largely oriented toward just a few critical solute species (phosphorus, nitrogen, carbon, and perhaps silica and potassium, or a variety of organic compounds) biologists, biogeochemists, and ecologists have less concern for an ion balanced total chemical analysis of a water or for questions about what the other ions tell about where the water came from, and what sort of rocks and minerals it came in contact with along its way.

Working at the boundaries between the geologist, soil scientist, hydrologist, biologist and ecologist are a growing group of people dedicated toward understanding the movement of water through the lithosphere, processes of weathering, mineral/water interface reactions, and contaminant transport in the near earth environment. The department has a 20 year involvement in the Long Term Ecological Research program (LTER), both from the perspective of our campus' research involvement, and as one involved in national and international LTER activities. Encouraged by this highly interdisciplinary, campus-wide research program I have been one of the principal proponents of studies of the linkage between geochemistry, limnology, biology, hydrogeology, and the environmental sciences. Geology has many links outside of our traditional disciplines, and but one example of such is the LTER program, summarized below.

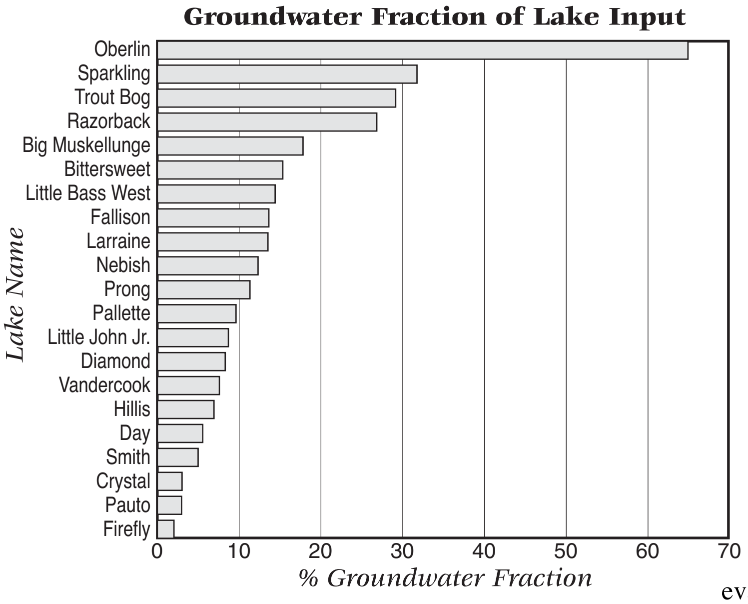


Figure 1. Groundwater input fraction of total lake budgets for lakes across northern Wisconsin.

This year marks the 20th year of the Long-Term Ecological Research program at Wisconsin, an appropriate time to highlight some of the geochemical approaches to study of lake-groundwater interaction in the Northern Highlands forest of Wisconsin.

Over these years we have made substantial progress in our understanding of lake-groundwater interaction, and the role of groundwater in buffering against human induced change (forest clearcutting, acid rain, roadsalting). Students from the department have conducted research on groundwater since inception of the LTER program, and include: Galen Kenoyer, David Krabbenhoft, Louis Marin, Jeff Ackerman, Susannah Michaels, Kangjoo Kim, John Schindler, Emeka Okwueze, Xiangxue Cheng, Glen Champion, Wesley Dripps, Kuopo Chung, and Christine Pint. Jokingly referred to as “outcrops of groundwater” the many lakes in the deglaciated terrain of northern Wisconsin provide a key workshop in which to pursue studies on groundwater flow, lake-groundwater interaction, and geochemical consequences of mineral-water interaction in this important weathering “ecosystem”. As such our work has significantly influenced the character and direction of research at our site, and at a number of other LTER study sites across the US, Puerto Rico, and Antarctica.

The focus of my work and students (Krabbenhoft, Ackerman, Michaels, Kim) has been to use stable isotopes to solve for groundwater budgets to lakes, to understand regional variation in lake/groundwater isotope chemistry, and to use isotopes as tracers along flow paths to allow geochemical modeling of mineral-water interaction (weathering). The strength of the lake-groundwater interaction is critical to understand the solute and nutrient chemistry of most lakes in the area. Similarly the pathways of water through the groundwater flow system, the rates of flow, and mineral phases that react with these waters along the way are just as critical in helping to better understand the controls on the chemistry of lakes and streams in the area, as well as more general problems of mineral weathering in field settings.

David Krabbenhoft (MS ‘84, PhD ‘88) developed techniques to measure the groundwater fraction of input to a flow through lake, Sparkling Lake, using the stable oxygen isotopic composition of precipitation, lake water, groundwater, and water vapor from lake evaporation. With the help of a groundwater flow model we were able to demonstrate that the results from traditional flow analysis compared well with results using isotopes. Encouraged by this success with Sparkling Lake, Jeff Ackermann (MS ’92) was able to extend the isotopic technique to a larger group of lakes in the county and model lake water budgets for over 19 lakes. The isotopic composition of groundwater is surprisingly uniform in composition, simplifying the estimates of budgets considerably. Susannah Michaels (MS ’95) extended the range of lake and groundwater isotopic measurements to much of northern Wisconsin, and included important shifts in the composition of precipitation due to the “lake effect” snows from Lake Superior. Estimates of groundwater inputs to over 40 lakes now exist (figure 1) and values of groundwater input range from nearly zero to nearly 50 percent. The strength of this groundwater contribution weighed heavily in the development of the concept of landscape position of lakes, an ecological concept that has driven several LTER workshops and publications in recent years.

Returning to the Crystal Lake–Big Muskelluge Lake isthmus, a 100 meter strip of land separating the two lakes, Kangjoo Kim (PhD 96), Mary Anderson and I elaborated on the earlier work of Galen Kenoyer (PhD ’86) with an emphasis on mapping the detailed groundwater flow trajectories, and their rates, to develop a better understanding of the processes that control a 4-8 meter wide dispersion zone marking the boundary between lake and isthmus recharge waters (figure 2). Again isotopes provided a key calibration, owing to the distinctly different composition of lake and recharge water. The flow paths identified allowed us to chose a series of wells along a flow path from which we could measure the total ion chemical

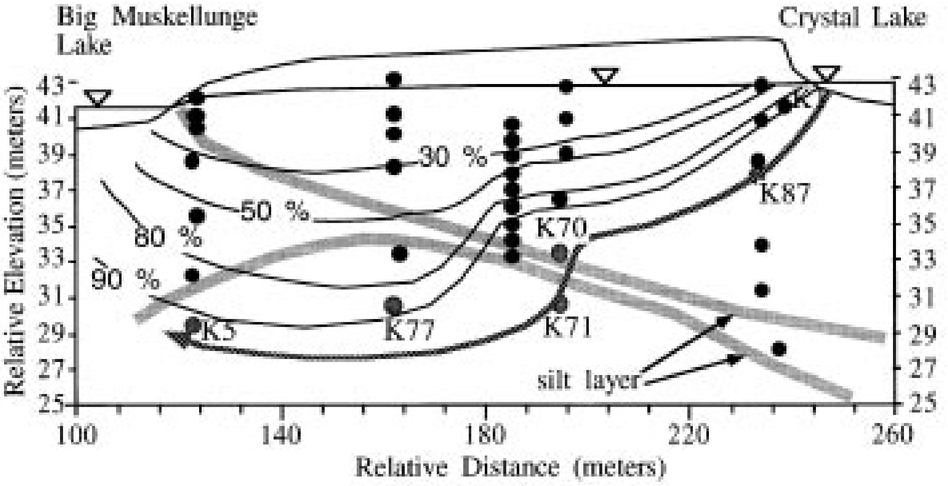


Figure 2. Cross-section of isthmus between Crystal and Big Muskellunge Lakes. Contoured percentage of lake water (vs isthmus recharge water) are shown as well as well point locations and a generalized flow-path for water across the isthmus.

changes along the flow path and to quantify the mineral mass transfers reflecting weathering along the flow path. Working with the data of G. Kenoyer and K. Kim, my colleague Blair Jones (USGS) and I have incorporated a mass balance model of the Trout Lake area with five other sites across the US to look broadly at silicate weathering processes, relative mineral weathering rates, and comparisons across a range of climatic and geologic settings. Our mass-balance modeling efforts are currently being finalized into a manuscript that will be submitted to the *American Journal of Science* by the end of February.

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