Exchange of Water, Solutes, and Nutrients at the Sediment-Water Interface Affects a Northern Minnesota Watershed at Multiple Scales

D.O. Rosenberry, W.E. Dean, J.H. Duff, J.W. LaBaugh, M.M. Reddy, P.S. Schuster, R.G. Striegl, F.J. Triska, T.C. Winter

Abstract

Flow of water, solutes, and nutrients across the sediment-water interface at two lakes, a stream, and a wetland (fen) in a northern Minnesota watershed has variable influence on their hydrology, geochemistry and ecology, depending on the scale that is considered. Ground water provides chemicals to a closed-basin lake that are sequestered by biological processes in the lake, but calcium, removed from the water column as a result of photosynthesis, is not present in profundal lake sediments. Biological and chemical processes deposit and then dissolve calcium in the near-shore margins, and it can leave the lake basin by advection in areas where lake water flows to ground water. At a nearby lake, inputs of dissolved inorganic carbon from a river and from ground water increase fluxes of carbon from the lake to the atmosphere. Ground-water discharge of iron and manganese also sequesters phosphorus in the profundal sediments. Much of the ground-water discharge to that lake is focused at near-shore springs, which are conspicuously absent of aquatic vegetation. Upstream of the lake, strong ground-water discharge reduces the thickness of the hyporheic zone, where microbes consume ammonium and reduce the amount of nitrogen that reaches the stream. Ground-water discharge also provides nutrients and a stable environment for establishment of aquatic vegetation in the streambed. At a nearby fen, ground-water discharge provides a stable environment for rare and protected plants. Locally, most of the discharge occurs at the break in slope along the fen margin, where other aquatic plants thrive. These results indicate that exchanges between ground water and surface water need to be well understood at multiple scales if the watershed as a whole is to be managed effectively.

Introduction

Increasing demands on our natural resources require greater understanding of ecosystem-scale processes that interact to generate landscape characteristics. Water-resource managers typically manage on a watershed or even regional scale, whereas field scientists typically conduct research at much smaller scales. Resolving this scale conflict remains a significant challenge to scientists and managers alike. Watershed-scale research has evolved to include scientists from numerous disciplines. Many hydrologists, biogeochemists, and ecologists have adopted an ecosystem perspective and now work together to solve site-scale and watershed-scale research questions (Likens and Bormann 1995). Ecohydrology is a rapidly growing subdiscipline that often is conducted at a watershed-scale (Wassen and Grootjans 1996, Baird and Wilby 1999, Gurnell et al. 2000, Nuttle 2002).

Quantification of hydrological and chemical fluxes, and biological processes, commonly is scale dependent. Scale-dependence problems are well documented and exist in many disciplines from ground-water hydrology (e.g. Rovey II and Cherkauer 1995) to chemistry (e.g. Capel and Larson 2001) to biology (e.g. Angermeier and Winston 1998). Interpretations resulting from a local-scale study can be greatly different from those resulting from a larger-scale study. Better understanding of the effects of scale on interpretation of research results can be achieved by studying processes at multiple scales, within a single watershed. This paper presents results from the Shingobee River headwaters area in northern

---

Rosenberry, Dean, Reddy, Striegl, and Winter are with the U.S. Geological Survey (USGS), Lakewood, CO 80225. E-mail: rosenber@usgs.gov. Duff and Triska are with the USGS, Menlo Park, CA 94025. LaBaugh is with the USGS, Reston, VA 20192. Schuster is with the USGS, Boulder, CO 80303.

Minnesota that demonstrate how interpretations can differ depending on the scale of the study. Flow of water and solutes between ground water and surface water is a common emphasis for all of the studies described herein. A better understanding of the effects of this exchange on ecosystem processes at a watershed scale results from taking a comprehensive view of these studies conducted at sub-watershed scales.

Study Area

The Shingobee River headwaters area (Figure 1) is the site of long-term research initiated by the U.S. Geological Survey in 1989. The purpose of the study is to examine the linkages that allow atmospheric water, surface water, and ground water to function as an integrated system (Averett and Winter 1997). Initial study was focused on two lakes within the watershed, one (Williams Lake) with no surface-water exchange and a relatively long water residence time, and one (Shingobee Lake) with a relatively short water residence time because it exchanges water with the Shingobee River. Processes in lakes integrate many physical, chemical, and biological processes that occur in watersheds; therefore, lakes were a natural focal point for concentrating investigations. Research also has focused on a reach of the Shingobee River upstream from Shingobee Lake, and at a wetland fen that discharges into the Shingobee River.

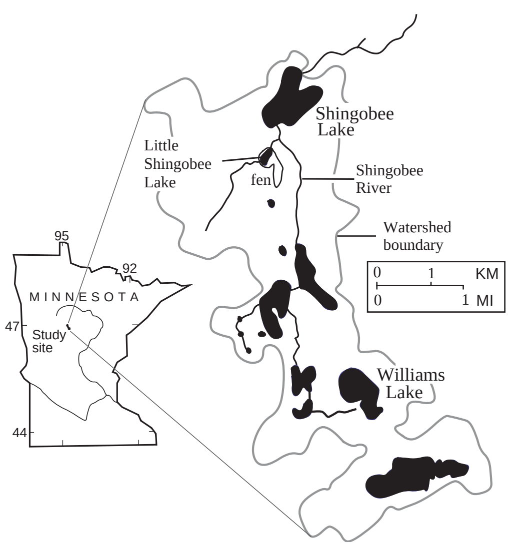

Figure 1. Shingobee River headwaters area.

The watershed boundary for the Shingobee River headwaters area encompasses 28 km^2 of hummocky glaciated terrain situated in a humid continental climate where evaporation and precipitation are about equal. Precipitation averages 640 mm yr^{-1} with about 12 percent falling as snow (Siegel and Winter 1980, Rosenberry et al. 1993). Discharge from Shingobee Lake to the Shingobee River has averaged 0.4 m^3 s^{-1} since 1989 and is relatively stable except following large rain events and during spring snowmelt. The watershed is covered primarily with mixed deciduous and coniferous forest, interspersed with pasture and fallow fields.

Exchange Between Ground Water and Surface Water in a Closed-Basin Lake

Williams Lake (39 ha, 9.8 m maximum depth) receives diffuse ground-water discharge along the south and east shoreline, but loses water to ground water along much of the west and north shoreline (Siegel and Winter 1980). Ground water dominates the water budget for Williams Lake, providing 58-76 percent of the annual water inputs (LaBaugh et al. 1995).

From a lake-basin perspective, ground-water discharge to Williams Lake supplies silica, calcium, and alkalinity that are removed from the lake water column by biological processes (McConnaughey et al. 1994). Those constituents are then deposited in the lake sediment. However, data from sediment transects indicate that very little calcium carbonate is present in sediments near the sediment-water interface beyond about 5-m depth (Dean and Bradbury 1997).

Local-scale, near-shore investigations indicated that calcium carbonate precipitate was deposited in the near-shore littoral sediments of the lake (Schuster et al. 2003). Sediment pore-water samplers were used to collect sediment-water chemistry data beneath the lakebed at 5-cm intervals. Calcium concentrations in pore waters of the near-shore, littoral sediments were substantially greater than lake-water or ground-water concentrations. In addition, calcium concentrations in the pore waters of these surficial sediments varied seasonally. Data indicated that plants sequester calcium in the littoral zone and deposit it in shallow sediment following senescence. Calcium deposited in the littoral sediments is dissolved by the acidic, anoxic pore water. It then mixes with the more dilute lake water or is lost to ground water, depending on the local hydraulic gradient.

Dean and Schwalb (2002) reached a similar conclusion through analyses of lake-sediment cores collected from near the center of the lake. They indicated that dissolution of calcium carbonate, caused by organic acids created by decomposition of organic matter, constitutes a “carbon pump” that has significant implications regarding cycling of other elements. The sediment record also indicates that very little calcium carbonate has been deposited in the lake sediments for the past 4000 years (Schwalb et al. 1995). However, older, deeper sediments contain abundant calcium carbonate, indicating that the lake had a different hydrologic setting prior to 4000 years ago. The carbon and oxygen isotopic composition of that older carbonate material tracks the hydrologic evolution of Williams Lake (Schwalb and Dean 2002). These results also have been extended from a watershed to a global scale (Dean and Gorham 1998). Based on data and understanding gained from studies of Williams and Shingobee Lakes (as well as from nearby Elk Lake and several other sites), lakes, reservoirs and peatlands, which collectively cover less than 2 percent of the Earth’s surface, bury organic carbon at an annual rate that is three times the carbon burial rate in all oceans, which cover 71% of the Earth’s surface.

Influence of Ground-water Discharge to a Lake Dominated by Streamflow

Shingobee Lake (66 ha, 10.7 m maximum depth) is hydrologically dominated by exchange with the Shingobee River (Rosenberry et al. 1997) and its chemistry is greatly affected by that of the river. Major-ion concentrations are 2-4 times greater, total phosphorus is 2.3 times greater, and ammonium concentration is about 3.6 times greater than at Williams Lake (LaBaugh 1997). Total kjeldahl nitrogen and nitrate plus nitrite concentrations are about the same at both lakes. In spite of the surface-water dominance, Shingobee Lake receives four times as much ground-water than does Williams Lake (Rosenberry et al. 1997). Because much of the water that discharges to Shingobee Lake has a ground-water origin, the water chemistry of Shingobee Lake has a surprisingly strong ground-water signature for a surface-water dominated lake. This leads to some interesting chemical and biological responses.

Dissolved inorganic carbon (DIC) in Shingobee Lake, expressed as alkalinity, is more than twice that in Williams Lake, and is also greater than DIC in the Shingobee River upstream from the lake. About 60-80 percent of the carbon input to Shingobee Lake is from DIC in ground water (Striegl and Michmerhuizen 1998). The large concentration of DIC results in large partial pressure of carbon dioxide, which generates carbon fluxes from the lake to the atmosphere that are about double the fluxes that would occur without ground-water discharge to Shingobee Lake. Therefore, ground-water discharge may be of potential significance to studies of global climate change.

Ground-water discharge also may indirectly sequester phosphorus in the lake sediments, which could reduce lake photosynthesis. Ground water supplies iron and manganese that reach concentrations in the oxygen-depleted hypolimnion of Shingobee Lake that are hundreds of times greater than in the epilimnion (Dean et al. 2003). The large concentrations of iron and manganese precipitate iron and manganese oxyhydroxides at fall turnover. These oxyhydroxides efficiently adsorb phosphorus and sequester it in the profundal sediments of the lake, thus removing it from the lake-water column.

Ground-water discharge to Shingobee Lake has local-scale effects as well. A significant portion of the ground water discharges at springs, many of which are situated near the shoreline of the lake (Rosenberry et al. 2000, Kishel and Gerla 2002). Nearly 30 percent of the estimated 57 L s^{-1} of ground water that discharges to Shingobee Lake originates from the near-shore springs located along the south and west shoreline of the lake. These springs provide stable habitat for aquatic plants where they discharge immediately landward of the shoreline. However, they create conspicuous “dead zones,” lakebed areas where no macrophytes are present, where they discharge immediately lakeward of the shoreline (Rosenberry et al. 2000).

Influence of Ground-water Discharge on Nutrient Flux in a Gaining Stream

Flow in the Shingobee River increases by about 20 percent, from 180 to 216 L s^{-1}, along a 1200-m reach upstream from Shingobee Lake (Jackman et al. 1997). This large gain in flow is caused mainly by ground water that discharges to the river at rates varying from 0.006 to 0.06 L s^{-1} per meter of river reach. Large hydraulic-head gradients beneath the streambed limit surface-water exchange and restrict the thickness of the hyporheic zone. During summer, microbes in the relatively thin hyporheic zone reduce the amount of nitrogen that reaches the stream by decreasing ground-water derived ammonium through coupled nitrification-denitrification (Duff and Triska 2000).

Ground-water discharge is relatively high in nitrogen, phosphorus, and DIC compared to concentrations in the Shingobee River, which aids in the establishment of *Elodea canadensis* hummocks during spring following snowmelt. On a local scale, *Elodea* hummocks affect patterns of ground-water discharge (Duff and Triska 2000). Ground-water discharge is greater at the downstream end than at the upstream end of the *Elodea* hummocks because sediment that accumulates at the upstream end is finer and thicker than the surrounding streambed. Rates of nitrification and denitrification are greater beneath the *Elodea* hummocks, indicating that greater microbial activity occurs in those areas.

Influence of Ground-water Discharge to a Calcareous Fen

Little Shingobee Fen is a 13-ha wetland adjacent to and surrounding Little Shingobee Lake (Figure 1). The fen is vegetated primarily by a tamarack and black spruce forest with sphagnum covering the fen surface and a grass sedge zone adjacent to Little Shingobee Lake. Peat and marl deposits up to 14-m thick underlie the fen surface and sand and silt underlie the peat (Carter et al. 1997a). The sloping surface is saturated in most of the fen, and small pools occur throughout. Calcium carbonate concentration in the shallow ground water is about 10 times greater than that of typical fens (Puckett et al. 1997). Three streams discharge 360,000 m^3 yr^{-1} from the fen to Little Shingobee Lake (Winter et al. 2001). Ground-water discharge to the fen is remarkably constant, providing a stable habitat for several rare and protected wetland species, including pitcher plants, sundews, and orchids (Carter et al. 1997b). The steady ground-water discharge indicates that the source of water is distant from the fen and is little affected by seasonal or longer-term climate change.

Much of the ground-water discharge occurs along the eastern margin of the fen where the steeply sloping upland meets the gently sloping fen. Hydraulic-head gradients are strongly upward in this portion of the fen and heads in many of the wells are above land surface (Puckett et al. 1997). *Caltha palustris*, an indicator of areas of rapid ground-water discharge, grows in abundance along this break in slope and almost nowhere else in the fen (Rosenberry et al. 2000). It is likely that much of the central portion of the fen receives water that discharges near the break in slope along the eastern margin. This water then flows overland, down the sloping surface, until it is intercepted by one of the small streams that drain the fen.

Implications for watershed management

Watersheds are appealing to many environmental managers because they provide well-defined boundaries that allow determination of relatively well-constrained water and solute budgets. The budget values of interest generally are for the watershed as a whole, as determined by the major inputs (largely precipitation) and outputs (a stream or lake) that receive the water and solutes derived from the watershed. As presented here, surface-water bodies in relatively flat glacial terrain can have substantial interaction with ground water, and the interaction can vary greatly locally. Ground-water input to a surface-water body can be diffuse, allowing major biochemical interactions to take place in the sediments, or it can be focused at springs, resulting in a different chemical signature and ecological response than the diffuse input. The differences in water and solute residence times in lakes within a watershed can result in the development of substantially different lake ecosystems. Thus, to manage watersheds such as the Shingobee River headwaters area, the small-scale processes such as those discussed herein need to be well understood if the watershed as a whole is to be managed effectively. The challenge is to be able to integrate and scale up understanding of the small-scale processes that are the focus of much research, into broader understanding of the watershed that is useful to environmental managers.

References

Angermeier, P.N., and M.R. Winston. 1998. Local vs. regional influences on local diversity in stream fish communities of Virginia. Ecology 79:911-927.

Averett, R.C., and T.C. Winter. 1997. History and status of the U.S. Geological Survey Interdisciplinary Research Initiative in the Shingobee River Headwaters Area, Minnesota. In T.C. Winter, Interdisciplinary Research Initiative: Hydrological and Biogeochemical Research in the Shingobee River Headwaters Area, North-Central Minnesota, pp. 1-2. U.S. Geological Survey Water-Resources Investigations Report 96-4215, Denver, CO.

Baird, A.J., and R.L. Wilby. 1999. Eco-Hydrology, Plants and Water in Terrestrial and Aquatic

Environments. Routledge Physical Environment Series, edited by K. Richards, Routledge, London.

Capel, P.D., and S.J. Larson. 2001. Effect of scale on the behavior of atrazine in surface waters. Environmental Science and Technology 35:648-657.

Carter, V., S.M. Locke, T.A. McConnaughey, and T.C. Winter. 1997a. Stratigraphy and Biological Characteristics of Sediments in Little Shingobee Fen. In T.C. Winter, Interdisciplinary Research Initiative: Hydrological and Biogeochemical Research in the Shingobee River Headwaters Area, North-Central Minnesota, pp. 193-197. U.S. Geological Survey Water-Resources Investigations Report 96-4215, Denver, CO.

Carter, V.P., P.T. Gammon, and N.B. Rybicki. 1997b. Vegetation of Little Shingobee Fen. In T.C. Winter, Interdisciplinary Research Initiative: Hydrological and Biogeochemical Research in the Shingobee River Headwaters Area, North-Central Minnesota, pp. 161-165. U.S. Geological Survey Water-Resources Investigations Report 96-4215, Denver, CO.

Dean, W.E., and J.P. Bradbury. 1997. Transects of Organic Carbon, Calcium Carbonate, and Diatoms in Surface Sediments of Williams and Shingobee Lakes. In T.C. Winter, Interdisciplinary Research Initiative: Hydrological and Biogeochemical Research in the Shingobee River Headwaters Area, North-Central Minnesota, pp. 117-129. U.S. Geological Survey Water-Resources Investigations Report 96-4215, Denver, CO.

Dean, W.E., and E. Gorham. 1998. Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. Geology 26:535-538.

Dean, W.E., B.P. Neff, D.O. Rosenberry, T.C. Winter, and R.S. Parkhurst. 2003. The significance of ground water to the accumulation of iron and manganese in the sediments of two hydrologically distinct lakes in north-central Minnesota: A geological perspective. Ground Water (in press).

Dean, W.E., and A. Schwalb. 2002. The lacustrine carbon cycle as illuminated by the waters and sediments of two hydrologically distinct headwater lakes in north-central Minnesota, USA. Journal of Sedimentary Research 72:416-431.

Duff, J.H., and F.J. Triska. 2000. Nitrogen Biogeochemistry and Surface-Subsurface Exchange in Streams. In J.B. Jones and P.J. Mulholland, eds., Streams and Ground Water, pp. 197-220. Academic Press, San Diego, CA.

Gurnell, A.M., C.R. Hupp, and S.V. Gregory. 2000. Linking hydrology and ecology. Hydrological Processes 14:2813-2815.

Jackman, A.P., F.J. Triska, and J.H. Duff. 1997. Hydrologic Examination of Ground-water Discharge into the Upper Shingobee River. In T.C. Winter, Interdisciplinary Research Initiative: Hydrological and Biogeochemical Research in the Shingobee River Headwaters Area, North-Central Minnesota, pp. 137-142. U.S. Geological Survey Water-Resources Investigations Report 96-4215, Denver, CO.

Kishel, H.F., and P.J. Gerla. 2002. Characteristics of preferential flow and groundwater discharge to Shingobee Lake, Minnesota, USA. Hydrological Processes 16:1921-1934.

LaBaugh, J.W. 1997. Chemical Fluxes Between Williams and Shingobee Lakes and their Watersheds.
In T.C. Winter, Interdisciplinary Research Initiative: Hydrological and Biogeochemical Research in the Shingobee River Headwaters Area, North-Central Minnesota, pp. 55-58. U.S. Geological Survey Water-Resources Investigations Report 96-4215, Denver, CO.

LaBaugh, J.W., D.O. Rosenberry, and T.C. Winter. 1995. Groundwater contribution to the water and chemical budgets of Williams Lake, Minnesota, 1980-1991. Canadian Journal of Fisheries and Aquatic Science 52:754-767.

Likens, G.E., and F.H. Bormann. 1995. Biogeochemistry of a Forested Ecosystem. Second Edition. Springer-Verlag, New York.

McConnaughey, T.A., J.W. LaBaugh, D.O. Rosenberry, R.G. Striegl, M.M. Reddy, P.F. Schuster, and V. Carter. 1994. Carbon budget for a groundwater-fed lake: calcification supports summer photosynthesis. Limnology and Oceanography 39:1319-1332.

Nuttle, W.K. 2002. Eco-hydrology's past and future in focus. EOS 83(205):211-212.

Puckett, L.J., V. Carter, D.O. Rosenberry, and D.A. Merk. 1997. Ground-water Surface-water

Interactions and Biogeochemistry of Little Shingobee Fen. In T.C. Winter, Interdisciplinary Research Initiative: Hydrological and Biogeochemical Research in the Shingobee River Headwaters Area, North-Central Minnesota, pp. 167-176. U.S. Geological Survey Water-Resources Investigations Report 96-4215, Denver, CO.

Rosenberry, D.O., J.W. LaBaugh, T.A. McConnaughey, R.G. Striegl, and T.C. Winter. 1993. The Interdisciplinary research initiative: Hydrologic research in the Shingobee River headwaters area, Minnesota. U.S. Geological Survey Open-File Report 93-446.

Rosenberry, D.O., R.G. Striegl, and D.C. Hudson. 2000. Plants as indicators of focused ground water discharge to a northern Minnesota lake. Ground Water 38:296-303.

Rosenberry, D.O., T.C. Winter, D.A. Merk, G.H. Leavesley, and L.D. Beaver. 1997. Hydrology of the Shingobee River Headwaters Area. In T.C. Winter, Interdisciplinary Research Initiative: Hydrological and Biogeochemical Research in the Shingobee River Headwaters Area, North-Central Minnesota, pp. 19-23. U.S. Geological Survey Water-Resources Investigations Report 96-4215, Denver, CO.

Rovey II, C.W., and D.S. Cherkauer. 1995. Scale dependency of hydraulic conductivity measurements. Ground Water 33:769-780.

Schuster, P.F., M.M. Reddy, J.W. LaBaugh, R.S. Parkhurst, D.O. Rosenberry, T.C. Winter, R.C. Antweiler, and W.E. Dean. 2003. Characterization of lake water and ground water movement in the littoral zone of Williams Lake, a closed-basin lake in north central Minnesota. Hydrological Processes 17:823-838.

Schwalb, A., and W.E. Dean. 2002. Reconstruction of hydrological changes and responses to effective moisture variations from north-central USA lake sediments. Quaternary Science Reviews 21:1541-1554.

Schwalb, A., S.M. Locke, and W.E. Dean. 1995. Ostracode □^{18}O and □^{13}C evidence of Holocene environmental changes in the sediments of two Minnesota lakes. Journal of Paleolimnology 14:281-296.

Siegel, D.I., and T.C. Winter. 1980. Hydrologic setting of Williams Lake, Hubbard County, Minnesota. U.S. Geological Survey Open-File Report 80-403.

Striegl, R.G., and C.M. Michmerhuizen. 1998. Hydrologic influence on methane and carbon dioxide dynamics at two north-central Minnesota lakes. Limnology and Oceanography 43:1519-1529.

Wassen, M.J., and A.P. Grootjans. 1996. Ecohydrology: an interdisciplinary approach for wetland management and restoration. Vegetation 126:1-4.

Winter, T.C., D.O. Rosenberry, D.C. Buso, and D.A. Merk. 2001. Water source to four U.S. wetlands: Implications for wetland management. Wetlands 21:462-473.