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# Groundwater - the disregarded component in lake water and nutrient budgets. Part 1: effects of groundwater on hydrology

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## Abstract:

Lake eutrophication is a large and growing problem in many parts of the world, commonly due to anthropogenic sources of nutrients. Improved quantification of nutrient inputs is required to address this problem, including better determination of exchanges between groundwater and lakes. This first of a two-part review provides a brief history of the evolution of the study of groundwater exchange with lakes, followed by a listing of the most commonly used methods for quantifying this exchange. Rates of exchange between lakes and groundwater compiled from the literature are statistically summarized for both exfiltration (flow from groundwater to a lake) and infiltration (flow from a lake to groundwater), including per cent contribution of groundwater to lake-water budgets. Reported rates of exchange between groundwater and lakes span more than five orders of magnitude. Median exfiltration is 0.74 cm/day, and median infiltration is 0.60 cm/day. Exfiltration ranges from near 0% to 94% of input terms in lake-water budgets, and infiltration ranges from near 0% to 91% of loss terms. Median values for exfiltration and infiltration as percentages of input and loss terms of lake-water budgets are 25% and 35%, respectively. Quantification of the groundwater term is somewhat method dependent, indicating that calculating the groundwater component with multiple methods can provide a better understanding of the accuracy of estimates. The importance of exfiltration to a lake budget ranges widely for lakes less than about 100 ha in area but generally decreases with increasing lake area, particularly for lakes that exceed 100 ha in area. No such relation is evident for lakes where infiltration occurs, perhaps because of the smaller sample size. 

KEY WORDS groundwater; lake; water balance; water budget; seepage

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## INTRODUCTION

Eutrophication is one of the most important threats to lakes situated in temperate climatic zones (Wetzel, 2001; Brönmark and Hansson, 2002). Excess nutrients usually are to blame. Effective management for nutrient reduction in lakes requires that all water and nutrient source and loss terms be identified and quantified. An accurate water balance is a prerequisite for determining relative magnitudes of nutrient inputs. Surface inflows and outflows via streams, rivers and ditches usually can be quantified with relatively small errors. Nearby or on-site weather data often are available for obtaining precipitation and calculating evaporation. Overland flow is almost always assumed to be irrelevant, and it often is.

Quantifications of flow between groundwater and surface water are nearly always much more difficult. In some settings, groundwater contributions are small relative to other water-budget terms and can justifiably be ignored, but exchange with groundwater can be a large component of a lake-water or nutrient budget. Perhaps in part because of the difficulty of determining groundwater exchanges, groundwater has been assumed to be irrelevant for many lake-water-budget and nutrient-budget studies (Rosenberry and Winter, 2009). There are several reasons that this onerous term has often been neglected:

1. Groundwater exchange is far less visible (invisible except in the case of springs) compared with all other terms of a lake-water budget.
2. Rates of exchange between groundwater and lake water can be exceptionally small. However, the area over which this exchange occurs often is a large percentage of the lake-surface area, making even very small rates of exchange relevant to a lake-water budget.
3. The distribution of exchange between groundwater and a lake is heterogeneous both spatially and temporally. This can make quantification difficult and often requires multiple approaches.

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4. The groundwater–lake interface can be difficult to access, particularly in deep lakes or lakes set in rocky terrain or lakes fringed with extensive wetland areas.
5. In lakes where groundwater exfiltration (defined here as flow from groundwater to a lake) and infiltration (flow from a lake to groundwater) both occur, net flow between groundwater and the lake could be small, whereas both exfiltration and infiltration are large (e.g. Kenoyer and Anderson, 1989; LaBaugh *et al.*, 1997; Sutula *et al.*, 2001).
6. Although several new techniques have been developed in the past few decades for quantifying exchange between groundwater and surface water (reviews by Kalbus *et al.*, 2006; Rosenberry and LaBaugh, 2008; Fleckenstein *et al.*, 2010), numerous challenges remain. In some lake settings, no suitable method exists for adequately quantifying groundwater exchange, leading to the hope, and assumption by default, that groundwater exchange is small because it cannot reasonably be quantified (e.g. Song *et al.*, 2014).
7. Historical compartmentalization of scientific disciplines is slow to overcome. Hydrogeologists, surface-water hydrologists and ecologists have long approached the interface between groundwater and surface water from different perspectives. Although groundwater and surface water are now more commonly considered as a single resource (Winter *et al.*, 1998), lack of integration of scientific disciplines can impede progress in understanding flows and processes at the groundwater–surface water interface (Hayashi and Rosenberry, 2002; Fleckenstein *et al.*, 2010).

In spite of these assumptions, groundwater dominates some lake-water budgets. For example, groundwater represented 94% of inflows to a 14-ha lake in northern Minnesota (Stets *et al.*, 2010) and 90% of all inputs to a 9-ha lake in Montana (Gurrieri and Furniss, 2004). Groundwater infiltration also can be a large percentage of a lake-water budget, particularly for lakes that lack a surface-water outlet. Groundwater infiltration made up 91% of all loss terms at a 480-ha lake in Minnesota (Rosenberry, 2000) and 84% of loss terms for a lake in Florida (Grubbs, 1995). Even for the very large (201 700 ha) Lake Nam Ko in the Tibetan Plateau, groundwater infiltration comprised 56–70% of loss terms (Zhou *et al.*, 2013). Groundwater infiltration at Lake Nam Ko may have been larger yet because no data were available for groundwater exfiltration, which was assumed to be zero. Groundwater can be a large water-budget component even if there is a surface-water inlet or outlet. At a 16-ha lake in Denmark where annual streamflow to the lake was 7.5 times larger than annual precipitation, groundwater exfiltration was larger yet, comprising 66% of all inputs to the lake (Kidmose *et al.*, 2013). At a 15-ha lake in New Hampshire where three streams enter the lake, more water left the lake via groundwater infiltration than via surface-water outflow or evaporation; groundwater infiltration averaged 51% of the loss terms in the lake-water budget (Rosenberry and Winter, 2009).

The importance of groundwater to a lake nutrient budget depends on both the volume of groundwater exchange and the concentration of nutrients associated with that exchange. In some settings where groundwater exfiltration is small from a water-budget perspective, it can be the largest input term from a nutrient-budget perspective (LaBaugh *et al.*, 2000; Lewandowski *et al.*, this issue; Jarosiewicz and Witek, 2014).

This first of a two-part review presents a brief history of the study and quantification of groundwater exchange. A listing of methods for measuring this exchange is then presented, followed by a discussion of continuing challenges due primarily to heterogeneity of groundwater–lake exchange in both space and time. Rates of groundwater exchange reported from a broad survey of the literature are listed and summarized to provide an idea of rates of groundwater–lake exchange that are common or extreme. Because lakes occupy low places in the landscape, they often are thought to only receive flow from groundwater. However, a large percentage of lakes both receive water from groundwater and also lose water to groundwater. Descriptions of direction of flow can be confusing and depend on one's perspective. In both parts of this two-part paper, we describe flow from a groundwater perspective. Flow from groundwater to a lake (also known as lacustrine groundwater discharge) is termed exfiltration; flow from a lake to groundwater is termed infiltration. Percentage contributions of groundwater to lake-water budgets are also listed and summarized to demonstrate the importance of the groundwater component to lake-water budgets.

The companion paper by Lewandowski *et al.* (2014, this issue) presents similar information, but from a nutrient-budget perspective. Numerous reasons exist for conducting detailed water and chemical budgets, such as concerns over mercury in lakes and fish, acid deposition or too much or too little water in a lake. However, it is likely that concerns over excess nutrients exceed all others, hence the emphasis on nutrients in the companion paper. Lewandowski *et al.* emphasize exfiltration and the associated nutrient loading to lakes.

## QUANTIFYING GROUNDWATER EXCHANGE WITH LAKES

Groundwater and surface water historically have been viewed and managed as separate entities. Although submerged springs have been recognized as a linkage between groundwater and surface water for thousands of years, less obvious linkages between the two resources either were unknown or assumed to be of little consequence. Only since the mid-1800s have the processes and conditions that control exchange between groundwater and surface water been discovered and investigated more thoroughly. During the past four decades, increased interest has been directed to flows of water and solutes across the sediment–water interface of lakes, which has led to an increased understanding of the physical, chemical and biological linkages at this interface (Winter, 1996; Wetzel, 1999; Jones and Mulholland, 2000; Mann and Wetzel, 2000).

There are at least three primary reasons for the growing interest in and importance of the connection between groundwater and surface water.

1. The global use of both groundwater and surface water continues to increase. In most parts of the world, the inexpensive, easily attainable water resources already have been exploited (Alley *et al.*, 1999; Sophocleous, 2000). We now are faced with utilizing water resources that have higher economic, social and environmental costs. Continuing increases in the extraction of both groundwater and surface water are inducing greater flows across the interface between groundwater and surface water.
2. Contamination of groundwater and surface water increasingly threatens the supply of water for human use and consumption. Three quarters of excessively contaminated groundwater sites (‘Superfund sites’) in the USA are within 0.8 km (0.5 mi) of a surface-water body (Tomassoni, 2000). Municipal water-supply wells increasingly are designed to induce flow from nearby river water (Lindgren and Landon, 2000; Hiscock and Grischek, 2002; Sheets *et al.*, 2002; Ray *et al.*, 2003) and from lake water (Miettinen *et al.*, 1997; Wiese and Nützmann, 2009) to meet water-supply demands. Movement of contaminants from the adjacent river or lake to these water-supply wells is a growing concern.
3. Exchange of groundwater and surface water at and near the sediment–water interface occurs at an important ecotone where aquatic plant, invertebrate and vertebrate (fish and amphibians) communities have evolved to depend upon exchanges between surface water and their terrestrial surroundings (Gardner, 1999; Gurnell *et al.*, 2000; Hayashi and Rosenberry, 2002). Many rare and endangered plants thrive in and near springs where groundwater discharges rapidly to surface water (Goslee *et al.*, 1997; Rosenberry *et al.*, 2000; Hall *et al.*, 2001). However, exploitation of groundwater resources has greatly reduced the discharge of groundwater to some of these ecologically sensitive areas and has altered the communities that have evolved at this ecotone (Brunke and Gonser, 1997; Alley *et al.*, 1999; Sophocleous, 2000).

Scientists have made substantial progress in quantifying flows and understanding processes that control the flow of fluid and solutes across the sediment–water interface. Advances in computer modelling, water-quality analytical techniques and our understanding of hydrological, hydrogeological, biogeochemical and ecological processes have served as foundations for this growth, but perhaps more importantly, a growing interest in interdisciplinary collaboration has been responsible for much of this recent progress. Although significant progress has been driven by needs related to water-supply and contaminant hydrology, perhaps the greatest impetus for advancements has come from the ecological disciplines.

A relatively new field, ecohydrology, has evolved to focus on the biological communities and ecological processes that exist at this ecotone (Wassen and Grootjans, 1996; Gurnell *et al.*, 2000; Hayashi and Rosenberry, 2002; Nuttle, 2002). Baird and Wilby (1999), in the preface of their book on ecohydrology, demonstrate the interdisciplinary nature of this field by stating that only by collaboration between allied disciplines can substantial environmental problems and important research questions be addressed. Jones and Mulholland (2000) reach similar conclusions in their summary of the collaborative findings of ecological studies conducted in stream settings. The impressive collection of recent research focused at the sediment–water interface provides water-resource managers with many new ideas and methods with which to better manage these linked resources from ecological and human-health perspectives.

Interest in managing surface water and groundwater as a linked resource spawned a US Geological Survey publication titled *Ground Water and Surface Water: A Single Resource* (Winter *et al.*, 1998), which generated considerable additional interest in the topic. This publication, oriented for the lay reader and the water-resource manager as well as the research scientist, has greatly increased public awareness of the importance of quantifying the degree of interaction between groundwater and surface water in many hydrologic settings. However, although the interest in and understanding of this important linkage has grown remarkably during recent years, the development of new tools with which to quantify these exchanges has grown more slowly. Accurate, reliable and scale-independent methods have yet to be developed for many physical settings where quantification of flow between groundwater and surface water is needed.

## METHODS FOR QUANTIFYING FLOW BETWEEN GROUNDWATER AND SURFACE WATER – A BRIEF OVERVIEW OF THE PAST 100 YEARS

Many of the advances in understanding of processes and quantification of flows at the sediment–water interface are the result of new methodologies. As new methods are developed, processes are viewed from different perspectives, and a new understanding is generated. The list of methods available for quantification of flow between groundwater and surface water is still surprisingly small, however, given the historical and growing interest in the topic. Most of the methods rely on indirect measurement of water flow across the sediment–water interface, and the most frequently used methods provide information scaled to entire watersheds or entire surface-water bodies. The most commonly used methods can be categorized as follows (Kalbus *et al*., 2006; Rosenberry and LaBaugh, 2008):

- watershed-scale studies
- lake-water budgets
- combined lake-water and chemical budgets
- wells and flow-net analysis
- groundwater flow modelling
- tracer studies
- thermal methods
- biological indicators
- seepage meters

The aforementioned methods are arranged approximately according to spatial scale, although considerable scale overlap occurs among several of the methods. The evolution of these methods also generally follows a progression in scale, with the largest-area methods being developed earliest, followed by local-scale approaches as studies have evolved to focus on questions and problems that are more site specific. A brief description and history of the evolution of each of these methods follow. Some of the methods were developed for use in other types of settings, but all are wholly suitable for lake applications.

### *Watershed-scale studies*

This method is basically a water-budget approach, but from the perspective of the watershed (also called catchment) that supplies water to a lake. By using the topographically determined watershed divide as the boundary of the area of interest, inputs from precipitation are assumed to be distributed to a lake via stream and groundwater input minus evapotranspiration over the watershed area. Groundwater exfiltration is calculated as the residual of all other hydrological components. Most early efforts distributed groundwater exfiltration along a stream reach above a gauging station, but the method works equally well distributing the result along all or part of a lake shoreline.

Perhaps the earliest efforts that determined the interaction between groundwater and surface water at this scale were watershed studies that came into vogue during the 1920s through the 1960s. The first likely was the Wagon Wheel Gap study near Creede, Colorado, USA, begun by the US Forest Service in 1910 (Bates and Henry, 1928). This watershed-hydrology approach grew in popularity for several decades; studies were conducted by the US Forest Service, US Soil Conservation Service and US Agricultural Research Service. Watershed-scale research also grew in scope and scale to include studies of biology, biogeochemistry and general ecology of entire basins and sub-basins. Programmes initiated by the US Geological Survey (e.g. Mast and Clow, 1995; Baedecker and Friedman, 1999), US National Park Service (Herrmann, 1997) and the US National Science Foundation (Greenland *et al*., 2003) emphasized inter-site comparisons to address the concern of uniqueness of data and applicability of results to other watersheds.

A significant attraction of watershed-scale studies is the relative ease of defining the study on the basis of watershed boundaries, and the ability to scale the study on the basis of where streamflow is measured. One of the earliest streamflow-based approaches, commonly called the Rorabaugh (1964) method, segments the streamflow hydrograph to determine groundwater discharge to the stream. This method has since been modified and automated by applying computer programs to streamflow time-series data (Rutledge, 1998, 2000).

Numerous distributed-area ‘rainfall–runoff’ models have been developed that areally divide watersheds and subwatersheds and calculate hydrologic parameters for each area; some models include the groundwater component of each area (e.g. Federer and Lash, 1978; Leavesley *et al*., 1983; Beven *et al*., 1984; Leavesley *et al*., 2002). The current trend is to couple distributed-area watershed-scale models with groundwater flow models to better determine the temporal and spatial variability of the interaction between groundwater and surface water (Leavesley and Hay, 1998; Beven and Feyen, 2002; Markstrom *et al*., 2008).

A combined water and chloride budget was used on a watershed scale to determine the volume of groundwater that discharged from the watershed to Lake Stechlin (Nützmann *et al*., 2003). This method was similar to those that make use of conservative chemical constituents described in the section on combined lake-water and chemical budgets.

### *Lake-water budgets*

Quantifying all of the easier-to-measure components of a lake-water budget, and solving for the groundwater component as a residual, is a relatively simple concept that has been commonly used only since about the 1970s. The earliest examples of a lake-water budget being conducted to determine the groundwater components include a study of Lake Stechlin and other nearby lakes in eastern Germany to determine the suitability of the lake for cooling a proposed nuclear power plant (Heitmann and Schubert, 1965; Schumann, 1973) and a study of Lake Sallie in northern Minnesota to determine the role of groundwater in delivering excess nutrients to the lake (Mann and McBride, 1972). Prior to the early 1970s, most lake-water budgets were conducted for the purpose of determining evaporation (e.g. Harbeck *et al.*, 1958; Ficke, 1972), perhaps because lakes were generally considered to be minimally influenced or even separated from groundwater (Broughton, 1941).

The water-budget equation can be written as

$$\frac{\Delta V}{\Delta t} + R = P + S_{\mathrm{i}} + G_{\mathrm{i}} - ET - S_{\mathrm{o}} - G_{\mathrm{o}} \tag{1}$$

where $\Delta V/\Delta t$ is the change in volume of water in the lake per time, $P$ is precipitation, $S$ is surface-water flow, $ET$ is evaporation plus transpiration from emergent vegetation in the lake, $G$ is groundwater flow and $R$ is the residual, or unaccounted water, in the water budget. Subscripts $i$ and $o$ refer to water flowing *into* and *out* of the lake, respectively. Missing in the equation are overland flow and flow through unsaturated sediments, the latter also known as interflow. If we make the common assumption that these terms are negligible (or are included in $R$), then groundwater exfiltration minus groundwater infiltration can be grouped with $R$ to write

$$G_i - G_o - R = \frac{\Delta V}{\Delta t} + ET + S_o - P - S_i \tag{2}$$

Net groundwater is indicated on the left-hand side of Equation (2); neither groundwater exfiltration nor infiltration can be determined with this equation. However, both groundwater terms can be determined if water and chemical budgets are solved together, as described in the next section.

This equation is particularly well suited for settings where two of the three terms on the left-hand side of Equation (2) can be assumed to be small. For water budgets of reservoirs, where surface-water inputs and losses are the largest terms and can be measured relatively accurately, solving for groundwater as the residual can often be performed with relatively small errors. If surface flows become very large or are difficult to measure, errors associated with the surface-water terms can be so large that the resulting groundwater component is of little value (e.g. LaBaugh and Winter, 1984). Settings with surface-water input but no surface-water outlet (e.g. Rosenberry, 2000; Zhou *et al.*, 2013) or where there is a surface-water outlet but no inlets (e.g. Stets *et al.*, 2010) make it more likely that a determination of the net groundwater component can be reasonably accurate.

Accurate determination of $ET$ can be difficult and requires a substantial amount of instrumentation and data. Depending on the anticipated magnitude of $ET$ relative to other components of a lake-water budget, several methods are available, the accuracies of which generally are commensurate with the cost of implementation (Rosenberry *et al.*, 2007).

*Combined lake-water and chemical budgets*

Conservative chemicals in a watershed are those that are not altered by chemical reaction with the porous media through which they flow or by chemical or biological processes that occur in surface waters. Conservative chemicals can be used to determine the volume of groundwater that flows into or out of a surface-water body, provided that all other fluxes are known. This method has been used for decades in many stream, lake and wetland studies but, perhaps because of advances in analytical methods, has grown rapidly in use since the 1980s (e.g. Stauffer, 1985; Bukaveckas *et al.*, 1993; LaBaugh *et al.*, 1995; Wentz *et al.*, 1995; Brunke and Gonser, 1997; Katz *et al.*, 1997; LaBaugh *et al.*, 1997). The accuracy of the method depends greatly on the accuracy of the flow and chemical-concentration measurements. LaBaugh (1985) and Choi and Harvey (2000) provide thorough examples of proper use of error analysis to quantify the uncertainty associated with flux results obtained using this method.

The concept and procedure for determining a chemical budget are similar to a water-budget equation; the chemical concentration is multiplied by the mass (or volume) of each water-budget component to determine the chemical mass:

$$\frac{\Delta(C_L V)}{\Delta t} + R = C_P P + C_{Si} S_i + C_{Gi} G_i - C_{ET} ET - C_{So} S_o - C_{Go} G_o \tag{3}$$

where $C$ is the concentration of the chemical constituent in each of the water-budget components as indicated by the subscript that follows $C$ and the other terms are the same as for Equation (1) except for $R$, which now indicates concentration times water volume. The equation can be simplified for shallow, well-mixed lakes where the concentrations for $S_o$ and $G_o$ equal the lake-water concentration, $C_L$, and for all lakes, assuming no chemical mass is lost in the evaporation process:

$$\frac{\Delta(C_L V)}{\Delta t} + R = C_P P + C_{Si} S_i + C_{Gi} G_i - C_L (S_o + G_o) \tag{4}$$

 

Equation (1) can be rearranged to isolate $G_o$ and then substituted for $G_o$ in Equation (4) (again, without the $ET$ term, assuming no chemical mass is lost in the $ET$ process) to solve for $G_i$:

$$G_i + \varepsilon = \frac{C_L \frac{\Delta V}{\Delta t} + (C_L - C_P)P + (C_L - C_{Si})S_i}{C_{Gi} - C_L} \tag{5}$$

where $\varepsilon$ is the combined errors of measurements of water mass and chemical concentration. $R$ is lumped with $\varepsilon$ in Equation (5) for convenience. $G_i$ determined with Equation (5) can now be inserted in Equation (1) or (2) to solve for $G_o$.

This method is particularly well suited for settings where the concentration of the chemical constituent of interest is spatially consistent within the groundwater that discharges to the lake. If this is not the case, the groundwater flow field that discharges to the lake can be segmented into areas where the chemical concentration is relatively consistent, and $C_{Gi}G_i$ can be determined for each area where $C_{Gi}$ is relatively uniform. This method is not well suited for settings where $C_{Gi}$ is nearly the same as $C_L$ because as the denominator in Equation (5) approaches zero, measurement errors cause the result to become unstable.

Combining water and chemical budgets to determine $G_i$ and $G_o$ separately requires the use of a conservative constituent dissolved in the water. Chloride is commonly used in this application, although it is not always conservative (e.g. LaBaugh *et al.*, 1997). Isotopes of oxygen and hydrogen have been used for the last several decades to determine various source and loss terms of surface-water bodies, including groundwater exfiltration and infiltration (Dincer, 1968; Krabbenhoft *et al.*, 1990, 1994; Kendall *et al.*, 1995; Katz *et al.*, 1997; LaBaugh *et al.*, 1997; Sacks *et al.*, 1998). These isotopes are inherently conservative because they are part of the water as opposed to solutes dissolved in the water. The method works well when the degree of isotopic fractionation of the water is different for different sources of water (Kendall *et al.*, 1995). The simple mixing models described earlier then can be used to identify sources of water, with one caveat. The isotopic signature of the evaporating water needs to be determined, and the term $C_{ET}ET$ needs to be subtracted on the right-hand side of Equation (4). Additional variables, such as air temperature at the water–atmosphere interface, relative humidity and the isotopic content of local atmospheric water vapour, need to be determined (e.g. Krabbenhoft *et al.*, 1990), making $C_{ET}ET$ particularly difficult to determine accurately. This method was rarely used until the mid-1980s when new analytical tools, such as the mass spectrometer, became less expensive and more readily available. Data richness in some locations has grown to the point that decadal-scale studies of seasonal and inter-annual variability in groundwater–surface water exchange are now possible using this isotope-mass-budget approach (Sacks *et al.*, 2014).

### *Wells and flow-net analysis*

The flow-net analysis, sometimes called the 'Darcy approach', is probably the most frequently used field-based method for quantifying flow between groundwater and surface water. This method requires determination of horizontal hydraulic gradient and hydraulic conductivity in the portion of the aquifer near the lake, so calculations can be made on the basis of Darcy's law. The method uses a combination of near-shore water-table wells along with a device to measure surface-water stage to determine water-table gradients between the wells and the shoreline of the surface-water body. Hydraulic conductivity commonly is determined from single-well slug tests (e.g. Bouwer and Rice, 1976) conducted in the same wells used to obtain hydraulic gradients. A multiple-well aquifer test would provide a better indication of hydraulic conductivity, but the greater cost usually precludes this option. Other options include grain-size analysis of sediments removed during well installation (e.g. Shepherd, 1989) or a lab analysis of an intact sediment core collected during well installation. One of two approaches is commonly used to determine spatial distribution of hydraulic properties. One approach segments the shoreline of the surface-water body according to the number and location of nearby wells, and flows to or from the lake are determined for the lake segment attributed to each monitoring well on the basis of data collected from that well. Another approach uses hydraulic-head and surface-water-stage data to generate equipotential lines and flow paths. Flows to and from the surface-water body are then calculated using flow-net analysis (Fetter, 1994; Cedergren, 1997; Rosenberry *et al.*, 2008). Flow-net analysis has existed for many decades, but prior to the mid-1990s, use of the method required subjective hand-drawn lines to generate equipotential lines and groundwater flow paths (e.g. Kenoyer and Anderson, 1989; Schafran and Driscoll, 1993). Commercially or freely available computer programs (e.g. Hsieh, 2001) have made the method much more popular during recent years.

This method typically is used for all or a portion of a watershed or a lake or wetland basin. It is relatively expensive for use with large lakes or where the depth to groundwater makes well installations costly. Detail and accuracy of the method are directly proportional to the density of the well network (Rosenberry and Hayashi, 2013). The literature contains numerous examples of the method being used successfully to quantify exchange of water (and also solutes) between groundwater and surface water (e.g. Pfannkuch and Winter, 1984; Belanger and Kirkner, 1994; Lee and Swancar, 1997). One benefit of this method over many others is the ability to determine flow direction and magnitude for specific shoreline segments or portions or embayments of irregularly shaped lakes. An even finer-scale approach has been to use small-diameter portable wells that are driven into the shallow lakebed to determine the vertical hydraulic-head gradient (Winter *et al.*, 1988). This local-scale approach can be far less expensive and less labour-intensive than typical well installations.

### *Groundwater flow modelling*

Prior to the mid-1970s, most people concerned with modelling flow between groundwater and surface water used analytical models or electric analogue models, both of which were limited to relatively simple flow geometry and boundary conditions. Early finite-difference and finite-element numerical models were a substantial improvement in modelling groundwater fluid flow, but they also were relatively restrictive regarding the physical settings that could be modelled. One of the limitations was the requirement that the elevation of the water table and surface-water body be specified and fixed. Although this restriction did not substantially affect most watershed-scale studies, it severely limited simulations of local-scale, near-shore processes adjacent to surface-water bodies. Richard Cooley developed a two-dimensional, variably saturated, transient finite-element model that allowed the water table to fluctuate in response to temporally variable recharge conditions (Cooley, 1983), and Thomas Winter used this model to simulate groundwater flow adjacent to lakes in response to snowmelt (Winter, 1976, 1978, 1981, 1983). Winter's (1976, 1978) results indicated that flow conditions adjacent to lakes were highly variable and that a hydraulic-head dam could form in the aquifer, reverse the direction of flow between groundwater and the lake and hydraulically isolate the lake from other nearby lakes. Winter's (1983) subsequent modelling further developed this new concept and initiated a rapid increase in research on processes that control flow between groundwater and surface water.

Groundwater-flow models are now commonly used to assess the interaction between groundwater and surface water, in part because the popular US Geological Survey MODFLOW finite-difference code (McDonald and Harbaugh, 1984; Harbaugh *et al.*, 2000) is modular in implementation and relatively easy to use. The newest (circa 2014) version of this model (http://water.usgs.gov/ogw/modflow/) includes modules for simulating flows to or from a river, detailed stream–groundwater interaction, flows to and from reservoirs, and two modules exist for simulating flows to and from lakes. For some settings, other simpler modelling approaches (e.g. analytical element, Strack, 1999, and high conductivity) can produce similar results (Hunt *et al.*, 2003). Detailed simulations of the spatial distribution of groundwater discharge to a lake were recently made for a lake in Kenya using the high-conductivity modelling method and setting hydraulic conductivity of the lake domain at three orders of magnitude larger than the surrounding porous media (Yihdego and Becht, 2013). Anderson *et al.* (2002) indicated a four-orders-of-magnitude contrast between lake and aquifer hydraulic conductivity would be better but less efficient than using the MODFLOW lake package. Temporal variability also has been emphasized in many modelling studies. Some studies have investigated the importance of temporal variability in groundwater divides (Holzbecher, 2001), which commonly diverge substantially from surface-water divides (Winter *et al.*, 2003). Other studies investigated the effects of climate change on the groundwater contribution to lake-water budgets (Hunt *et al.*, 2013) and on near-shore processes that control exchanges between groundwater and a lake underlain by karst, the latter incorporating simulated changes in lake-surface area that accompany simulated changes in lake stage (Virdi *et al.*, 2013). Near-shore temporal variability in hydraulic gradients also was shown to enhance dispersion of solutes when groundwater flow between an upgradient and nearby downgradient lake was modelled (Kim *et al.*, 2000).

Many studies that are primarily field oriented also include a groundwater flow model, often in an attempt to further verify the results of the study. However, problems arise when insufficient field data exist to properly calibrate the models (Munter and Anderson, 1981; Hill, 1991; Konikow and Bredehoeft, 1992; Tiedeman and Gorelick, 1993). Alternately, overly complex models can be developed with the intent of matching field data as opposed to increasing understanding of hydrogeological processes (Voss, 2011a, b). Rapidly increasing computer power allows newer calibration methods that were unheard of only a few years ago (e.g. Hunt and Zheng, 2012).

### *Tracer studies*

The addition of chemicals to streams and rivers, and subsequent sampling of water downgradient of the source to determine the mean flow velocity, has been used for many years in the surface-water community. However, only since the 1980s, and the concern with discovery and movement of groundwater-contamination plumes, has the use of tracers become widespread among groundwater scientists. Tracers have been used in several ways to track the movement of groundwater, including single-point (slug-type) tracer injection and constant-discharge tracer injection. Naturally occurring tracers also can be used if the chemical signature of groundwater is sufficiently different from lake water. Perhaps the first well-documented use of tracers to determine the discharge of groundwater to a lake was at Perch Lake, Ontario. Salt was injected in an upgradient line of wells, and a dense grid of monitoring wells installed adjacent to and in the lake was sampled to determine the route and velocity of the salt mass as it moved towards and discharged to the lake (Lee *et al*., 1980). Other studies have used fluorescent dye (Smart and Smith, 1976), as well as other conservative chemical constituents, to track movement of groundwater to surface water (Bertin and Bourg, 1994; Harvey *et al*., 1996; Hayashi *et al*., 1998; Thies *et al*., 2002). Studies have even made use of contaminant plumes to determine rates of discharge of groundwater to surface water (Ferrey *et al*., 2001).

Tracers also can be injected into a lake to determine movement of surface water to groundwater (a 'whole-lake' injection test). If a tracer is selected that has exceptionally low natural, or background, concentrations in all of the other water-budget terms (lithium or bromide commonly meets this criterion), then Equation (3) reduces to

$$\frac{\Delta(C_L V)}{\Delta t} + R = C_L(S_o + G_o) \tag{6}$$

Lithium bromide solution, for example, was injected into several small lakes in Michigan in order to quantify water movement from the lakes to groundwater (Cole and Pace, 1998).

Despite their wide applicability, tracer studies are not as commonly used to study the interaction between groundwater and surface water as some of the other available methods. This likely is due, in part, to the relative cost, in both equipment and time, for application and monitoring of tracer movement or to restrictions that prohibit addition of chemicals to a lake. Another problem with use of tracers at the sediment–water interface is detection of the tracer once it enters or leaves the surface-water body. Tracer dilution in the surface water often results in tracer concentrations that are below detection limits.

### *Thermal methods*

Temperature is one of the simplest and most accurately measured properties of water. Temperature anomalies long have been used to locate near-shore springs in surface-water bodies (Lee, 1985). Commonly, temperature has been used qualitatively as an indicator of groundwater discharge (Bundschuh, 1993; Baskin, 1998), especially in karstic terrain where spring discharge is focused and rapid. Remote sensing temperature-measurement methods have proven useful for identifying areas of rapid groundwater discharge to shallow surface water (Lee and Tracey, 1984; Baskin, 1998; Gosselin *et al*., 2000; Kang *et al*., 2005; Lewandowski *et al*., 2013), including hand-held thermal-infrared units (Cardenas *et al*., 2012). Spatial variability in temperature also has been used to locate areas of rapid groundwater discharge in deeper portions of lakes and rivers (Lee, 1985; Stark *et al*., 1994). This is accomplished by towing a tethered temperature (and sometimes also specific-conductance, Lee, 1985) probe and recording temperature anomalies. Relatively new technology, commonly referred to as distributed temperature sensing, is now routinely used to map temperatures at the sediment–water interface of lakebeds with 0.25- to about 1-m spatial resolution and about 0.05–0.1° temperature resolution along distances of up to several kilometres, providing the ability to identify areas where groundwater exfiltration is likely focused (e.g. Day-Lewis *et al*., 2006; Selker *et al*., 2006; Fleckenstein *et al*., 2010; Blume *et al*., 2013; Sebok *et al*., 2013).

Previously mentioned temperature-measurement methods have primarily been qualitative. Recent analytical methods have provided convenient means for temperature to be used quantitatively to determine rates of groundwater discharge. Several authors (Conant, 2004; Schmidt *et al*., 2006; Anibas *et al*., 2009) assumed steady-state conditions when they measured thermal-depth profiles and applied a one-dimensional analytical solution of the heat conduction–advection equation to the measured profiles. Others have made use of seasonal differences between shallow groundwater and surface-water temperature (Lapham, 1989; Bartolino and Niswonger, 1999) or diurnal changes in temperature difference (Silliman and Booth, 1993; Constantz *et al*., 1994; Stonestrom and Constantz, 2003; Briggs *et al*., 2012; Gordon *et al*., 2012). Because measurement of temperature is so simple and inexpensive, it is one of the fastest-growing methods for determining the interaction between groundwater and surface water on a small scale (e.g. Hatch *et al*., 2010; Briggs *et al*., 2012; Gordon *et al*., 2012; Lautz, 2012; Briggs *et al*., 2013). Several recent local-scale studies have used thermal methods in lake settings (Kidmose *et al*., 2011; Blume *et al*., 2013; Sebok *et al*., 2013). However, geologic heterogeneity often makes the results from temperature methods difficult to extrapolate to scales at which watershed managers typically are interested (Conant, 2000; Fryar *et al*., 2000; Rau *et al*., 2012).

Analogous to thermal profiles discussed earlier, vertical profiles of conservative, natural chemicals also can be used to calculate rates of exchange between groundwater and surface water. Several authors have used conservative constituents, such as chloride, bromide, tritium and the water isotopes deuterium and oxygen-18, to determine fluxes at the sediment–water interface of lakes (Cornett *et al*., 1989; Mortimer *et al*., 1999; Schuster *et al*., 2003).

 

*Biological indicators*

The biological response to flow at the sediment–water interface can be used as an indicator of direction of flow and relative magnitude of groundwater exfiltration or infiltration. Hydrologists have used plants to locate areas of groundwater discharge for many years, as evidenced by O. E. Meinzer's classic report titled *Plants as Indicators of Ground Water* (Meinzer, 1927). Numerous more recent examples from the growing field of ecohydrology use distributions of specific types of plants and animals to indicate areas of groundwater–surface water interaction (Danielopol, 1984; Loeb and Hackley, 1988; Lodge *et al*., 1989; Lillie and Barko, 1990; Malard *et al*., 1996; Danielopol *et al*., 1997; Goslee *et al*., 1997; Wetzel, 1999; Rosenberry *et al*., 2000; Sebestyen and Schneider, 2004). The density of submerged macrophytes also can be related to groundwater exfiltration, particularly if nutrients are being supplied by groundwater (Lodge *et al*., 1989; Frandsen *et al*., 2012). These methods provide a qualitative indication of the direction and magnitude of flow between groundwater and surface water and are good reconnaissance tools to aid in locating areas in need of more detailed investigations. Typically, they involve identifying species or groups of species of plants or animals that are known to thrive in places where groundwater discharges to surface water, but some of the species also indicate areas where surface water flows into groundwater. Although identification of specific plant and animal species is necessary for use of these methods, some of the species are so simple to identify that biological or ecological training is not required (Rosenberry *et al*., 2000).

A considerable impetus for the increased interest in quantifying flows between groundwater and surface water is related to fish. Fisheries biologists for years have suspected that many species of fish position spawning redds on the basis of water flow across the sediment–water interface in streams, commonly termed hyporheic exchange (e.g. Pollard, 1955; Vaux, 1968; Shepard *et al*., 1986; Malcolm *et al*., 2004). Some fish species construct spawning redds in locations of focused groundwater discharge (e.g. Warren *et al*., 2005), and others seemingly do not. More recent research is advancing the understanding of this linkage with regard to fish in lake settings (Ridgway and Blanchfield, 1998; Warren *et al*., 2005).

*Seepage meters*

The seepage meter is a device placed over the sediment of a surface-water body, in this case a lake, that records the net flow of water to or from the lake through the bed area covered by the meter. The device funnels all flow through the isolated portion of the lakebed either to or from a collection bag, depending on whether water is flowing to or from the lake. The change in volume of water contained in the bag during the bag-attachment period gives a time-integrated and space-integrated indication of seepage. Of all the methods listed in this review, the seepage meter alone provides a direct measurement of water flow across the sediment–water interface. All other methods rely on measurement of related parameters that indirectly determine flow across the sediment–water interface. The seepage meter provides a local-scale measurement, integrating flow over a lakebed area typically between 0.03 and 1.7 $m^2$, with 0.25 $m^2$ being the area covered by the most commonly used type of seepage meter (Lee, 1977).

Early versions of the seepage meter developed during the 1940s and 1950s were designed to measure seepage losses in irrigation canals (Israelson and Reeve, 1944; Warnick, 1951; Robinson and Rohwer, 1952; Rasmussen and Lauritzen, 1953). Many of these devices were expensive and unwieldy and were little used beyond the application to canals. David Lee (1977) developed an inexpensive and simple meter that has evolved little in the decades since its inception. Lee's meter consists of the cut-off end of a 208-l (55-gal) storage drum, to which a plastic bag that is partially filled with a known volume of water is attached. The bag is attached to the chamber for a measured amount of time, after which the bag is removed and the volume of water contained in the bag is re-measured. The change in volume per bag-attachment time is the volumetric rate of flow through the portion of the bed covered by the chamber, which then can be divided by the approximately 0.25-$m^2$ area covered by the chamber to obtain a flux velocity (distance/time). Values commonly are expressed as cubic metre per square metre per second or centimetre per day. This value typically is multiplied by a coefficient that compensates for inefficiencies in flow within the meter as well as restrictions to flow through the connector between the bag and the chamber and any resistance to movement of the bag. Correction factors reported in the literature have ranged from 1.05 to 1.74 (Rosenberry and Menheer, 2006). This basic design is used in most seepage-meter studies, although several modifications exist for use in a variety of specific stream and lake settings, including shallow, near-shore waters (Lee and Cherry, 1978), deep lakes (Boyle, 1994) and large lakes with large waves (Cherkauer and McBride, 1988). Placing the bag inside a shelter minimizes velocity-head effects associated with waves and currents in lakes (Sebestyen and Schneider, 2001; Rosenberry, 2008). Increasing the area covered by the seepage meter better integrates local-scale seepage heterogeneity (Rosenberry, 2005), whereas seepage meters that cover a smaller bed area are far easier to install. Additional information regarding methods of use and sources of error is presented by Rosenberry *et al*. (2008).

 

Several automated seepage meters have been developed that replace the seepage bag with a flow meter. Taniguchi and Fukuo (1993) introduced the first automated seepage meter when they used heat-pulse sensors, originally designed to measure sap flow in trees, to measure lakebed seepage. They were able to extend the range over which they could measure seepage by using pairs of thermistor thermometers that were various distances away from a heat source. They also logged results from this system with a digital data logger. Taniguchi and others have used this device to investigate temporal variability in seepage responses to seiches in lakes and ocean tides (Taniguchi and Fukuo, 1996; Taniguchi *et al*., 2002). Although information regarding this device has been readily available for nearly two decades, only a few similar devices have been built (Krupa *et al*., 1998), likely because considerable engineering and electronics expertise is required. Ultrasonic flow sensors have been used to measure seepage with good results (Paulsen *et al*., 2001; Menheer, 2004; Fritz *et al*., 2009). An electromagnetic flow meter designed for use in boreholes has been used to measure seepage in several freshwater and marine settings (Rosenberry and Morin, 2004; Swarzenski *et al*., 2007). This device is capable of measuring seepage on the order of seconds to minutes, which allows investigation of short-term temporal variability in response to rainfall, evapotranspiration, lake seiches and other processes (Rosenberry *et al*., 2013).

## DISTRIBUTION OF EXCHANGE BETWEEN GROUNDWATER AND LAKES IN SPACE AND TIME

Seepage, whether exfiltration or infiltration, is focused near the shoreline of lakes and decreases exponentially with distance from shore (McBride and Pfannkuch, 1975; Pfannkuch and Winter, 1984), but only if the geology beneath and adjacent to the lake is homogeneous. Lakebeds rarely are homogeneous for a wide variety of reasons, including (1) wave-induced erosion of sediments focused at the shoreline, which can remove fines and leave behind the coarser-grained fraction; (2) deposition of sediments focused at the shoreline brought in via overland flow associated with intense rainfall events; (3) changes in lake stage that result in lateral movement of the shoreline, as well as the associated near-shore processes listed in 1 and 2; (4) erosion and deposition of sediment caused by seiche-induced, wind-induced and wave-induced currents; (5) accumulation of biomass and/or woody debris from the adjacent upland; (6) manipulation of near-shore sediments by physical (e.g. ice shove, Rosenberry *et al*., 2010) or biological processes such as plant roots, benthic invertebrates, freshwater mussels, crayfish, fish and ducks; (7) geologic heterogeneity; and (8) anthropogenic manipulations (e.g. shoreline alteration and/or stabilization). Anisotropy, the ratio of horizontal to vertical hydraulic conductivity, also is common in lacustrine sediments. The greater the anisotropy, the less that seepage is focused near the shoreline (Pfannkuch and Winter, 1984; Genereux and Bandopadhyay, 2001). Numerous studies have indicated atypical distribution of seepage with distance from shore in lake settings (e.g. Woessner and Sullivan, 1984; Cherkauer and Nader, 1989; Schneider *et al*., 2005; Kidmose *et al*., 2013), including increase in seepage with distance from shore. In all of these cases, geologic controls were stronger than the local or regional physiographic setting that otherwise would control seepage distribution (Winter, 1999).

In addition to spatial heterogeneity, temporal variability also confounds determination and interpretation of exchange between groundwater and lakes. Seepage rates are affected by numerous hydrologic processes that commonly are focused at or near the shoreline, such as troughs of depression in the adjacent groundwater system resulting from evapotranspiration (Rosenberry and Winter, 1997). Near-shore hydraulic gradients and seepage change when rainfall infiltrates through an unsaturated zone that thins to zero with proximity to the lake. Enhanced groundwater recharge near the shoreline can also create water-table mounds that reverse seepage direction in near-shore margins. Anthropogenic effects, such as withdrawal of groundwater for private or municipal water supply or addition of water associated with septic leachate, can locally affect exchange between lakes and the adjacent groundwater. Some large-volume water-supply wells are intentionally placed near a lake to induce flow from the lake to the well; this process is commonly termed bank filtration (Miettinen *et al*., 1997; Wiese and Nützmann, 2009). Fine-grained sediments that accumulate in lakes are re-suspended by waves and currents focused in the near-shore margins; the net effect of this frequent process is that fines are preferentially deposited in the deeper portions of the lake. Suspension of fines by waves and currents increases sediment permeability and enhances the focusing of seepage in the near-shore margins. For all these reasons, lakebeds are notoriously heterogeneous, which creates one of the greatest challenges in determining representative seepage rates for lakeshore segments, embayments or entire lakes.

## SEEPAGE VALUES COMMONLY MEASURED IN LAKES

Rates of exchange between groundwater and lakes were obtained from the published literature to statistically summarize seepage in lake settings. Data presented in Table I are indicative almost entirely of variability among lakes. In a few instances, multiple values are presented for the same lake, either because different methods were used to indicate seepage or because multiple studies were conducted by different groups of authors. These multiple values for a single lake additionally provide an indication of either methodological biases or temporal variability.

Seepage, when determined as part of a lake-water budget, commonly is reported in units of volume per time. However, for the purpose of comparing seepage among lakes that vary over many orders of magnitude in surface area or to compare seepage that has been determined with a variety of methods, each of which has a different measurement scale, it is useful to normalize seepage values by dividing the volumetric seepage value by the surface area of the lake, or the area over which the measurement represents, to determine a seepage rate. Here (Table I), we present seepage in units of volume per area per time, or distance per time, in centimetre per day (equivalent to 10 l/m$^2$/day).

On the basis of studies conducted in 102 lakes where exfiltration was measured (Figure 1 and Table I), the median value for exfiltration is 0.74 cm/day (Table II). Far fewer studies have been conducted in lakes where infiltration occurs. The median value for 18 lakes where infiltration was measured is 0.60 cm/day, nearly the same as at exfiltration locations. These values represent average seepage rates reported for a wide range of lakes situated around the world, with 70% of the studied lakes being in the USA. Although data in Table I are extensive, they are by no means an exhaustive representation of the seepage literature. Median values would better represent seepage than average values because seepage datasets commonly are skewed. However, data from the ‘Average value’ column in Table I were used to summarize data because median values were only rarely reported in the literature. The same comparison of seepage rates can be made on the basis of maximum rather than average values from the literature. The median of 59 maximum exfiltration values reported in the literature is 5.10 cm/day. The median of 18 maximum infiltration seepage rates is 1.64 cm/day (Table II). In the case of maximum values, the largest reported exfiltration seepage rate is 745 cm/day; the largest reported infiltration rate is 263 cm/day.

Interestingly, extreme values for maximum seepage are larger for infiltration than for exfiltration. Four of the 18 values of reported maximum infiltration are larger than 100 cm/day, whereas only one of the 59 maximum values for exfiltration is larger than 100 cm/day (Figure 1C, D). The largest exfiltration value based on our literature review is 745 cm/day at Lake Væng in central Jutland, Denmark (Kidmose *et al*., 2013). The largest value for infiltration is 263 cm/day at Lake Belle Taine, in northern Minnesota (Rosenberry, 2000). Bed sediment at both lakes is medium-to-coarse-grained sand.

Early measurements of seepage indicated substantially smaller seepage rates. Not until 1990 were rates as large as 100 cm/day reported (Figure 1D), and maximum-measured seepage rates generally increase with time after 1990, particularly for lakes where exfiltration was measured (Figure 1). This trend may be in part due to improving measurement methods. For example, the efficiency of seepage meters has improved substantially since the mid-1970s (Rosenberry and Menheer, 2006). Some scientists also have focused more on the larger seepage rates found in near-shore margins or in unusual geologic settings. Seepage rates one to two orders of magnitude larger than those presented here have been reported for fluvial settings, and also in lakes where infiltration occurs and the sediment has been disturbed or altered (Rosenberry *et al*., 2010).

## SIGNIFICANCE OF THE GROUNDWATER COMPONENT IN LAKE-WATER BUDGETS

The significance of the groundwater component of a lake-water budget varies greatly and often is larger than expected. On the basis of 110 determinations of the groundwater component of a lake-water budget, including 73 for groundwater exfiltration and 37 for groundwater infiltration, groundwater as a percentage of the water budget ranged from 0.01 to 94.4 with a median value of 31.0%. Groundwater exfiltration determined at 65 lakes (some lakes had multiple determinations) ranged from 0.01% to 94.4% of the lake-water-budget input terms, with a median value of 25.0%. Groundwater infiltration determined at 44 lakes ranged from 0.1% to 91.0% of the lake-water-budget loss terms, with a median value of 34.5% (Table III). As with Table I, this gleaning of lakes for which water budgets have been determined is comprehensive but by no means exhaustive. Given the broad range of lake sizes represented in the table, it is likely that adding data from other studies would not substantially affect the statistical summaries of the results. However, there may be some overall bias in this dataset because some of these studies were conducted in lakes where quantification of exchange with groundwater was a goal of the study, likely because the groundwater component of the lake budget was substantial. In other studies, the groundwater component was so small as to be ‘negligible’ (e.g. Schindler *et al*., 1976) and was, therefore, not included in this analysis because no value for a groundwater component was given.

Because exchange between groundwater and lake water commonly is focused near the shoreline, it is logical to expect that groundwater would be a larger

 

Table I. Summaries of rates of groundwater exfiltration and infiltration reported in the literature

| Reference | Location | Average value | Median value | Minimum value | Maximum value | Measurement method |
|---|---|---|---|---|---|---|
| Rates of groundwater exfiltration | | | | | | |
| (Mitchell *et al*., 1988) | 11 lakes in Massachusetts, USA | | | | 10.6 | Seepage meter |
| (Ala-aho *et al*., 2013) | L. Ahveroinen, Finland | 1.49 | 0.78 | 0 | 4.92 | Seepage meter |
| (Boyle, 1994) | Alexander Lake, Ontario, Canada | 0.65 | | 0.5 | 0.8 | Seepage meter |
| (McCobb *et al*., 2009) | Ashumet Pond, Massachusetts, USA | 47.7 | | 25 | 80.4 | Seepage meter |
| (Rosenberry and Morin, 2004) | Ashumet Pond, Massachusetts, USA | 33 | | 11 | 56 | Seepage meter |
| (Rosenberry *et al*., 2013) | Ashumet Pond, Massachusetts, USA | | | | 55 | Seepage meter |
| (Herczeg *et al*., 2003) | Blue Lake, Australia | 2.07 | | | | Isotopes |
| (Dimova *et al*., 2013) | Butler Lake, Florida, USA | 0.3 | | | | Radon |
| (Dimova *et al*., 2013) | Clear Lake, Florida, USA | 0.3 | | | | Radon |
| (Simpkins, 2006) | Clear Lake, Iowa, USA | 2.9 | | 0 | 14.9 | Model |
| (Piña-Ochoa and Álvarez-Cobelas, 2009) | Colgada Lake, Spain | 10.2 | | 6.8 | 13.6 | Flow meters |
| (Stauffer, 1985) | Columbia Lake, Wisconsin, USA | 0.329 | | | | Chemistry |
| (Schafran and Driscoll, 1993) | Dart's Lake, Pennsylvania, USA | 1.8 | | 0.35 | 5.1 | Seepage meter |
| (Stauffer, 1985) | Deep Lake, Wisconsin, USA | 0.274 | | | | Chemistry |
| (Lillie and Barko, 1990) | Devils Lake, Wisconsin, USA | 0.34 | 0.24 | 0.02 | 1.76 | Seepage meter |
| (Ridgway and Blanchfield, 1998) | Dickson Lake, Ontario, Canada | 15.5 | | | | Seepage meter |
| (Mitchell *et al*., 1988) | Dimmock Pond, Massachusetts, USA | 1.74 | | | | Seepage meter |
| (Belanger *et al*., 1985) | East Lake Tohopekaliga, Florida | 0.411 | 0.488 | 0.016 | 0.708 | Seepage meter |
| (Cole and Pace, 1998) | East Long Lake, Michigan, USA | 0.4 | | | | Chemistry |
| (Stauffer, 1985) | Emrick Lake, Wisconsin, USA | 0.123 | | | | Chemistry |
| (Stauffer, 1985) | Fish Lake, Wisconsin, USA | 0.027 | | | | Chemistry |
| (Mitchell *et al*., 1988) | Five Mile Pond, Massachusetts, USA | 1.42 | | | | Seepage meter |
| (Weilhartner *et al*., 2012) | Gravel Pit Lake 1, Austria | 1.11 | | | | Budget |
| (Weilhartner *et al*., 2012) | Gravel Pit Lake 2, Austria | 1.19 | | | | Budget |
| (Weilhartner *et al*., 2012) | Gravel Pit Lake 3, Austria | 2.54 | | | | Budget |
| (Weilhartner *et al*., 2012) | Gravel Pit Lake 4, Austria | 1.32 | | | | Budget |
| (Weilhartner *et al*., 2012) | Gravel Pit Lake 5, Austria | 4.17 | | | | Budget |
| (Anderson *et al*., 2014) | Great Salt Lake, Utah, USA | 0.8 | | 0.1 | 2.4 | Seepage meter |
| (Rosenberry *et al*., 2013) | Great Salt Lake, Utah, USA | | | | 24 | Seepage meter |
| (Dimova *et al*., 2013) | Haines Lake, Florida, USA | 1 | | 0.3 | 1.1 | Radon |
| (Harvey *et al*., 2000) | Hamilton Harbor, Lake Ontario, Ontario, Canada | 3.8 | | | | Budget |
| (Harvey *et al*., 2000) | Hamilton Harbor, Lake Ontario, Ontario, Canada | 0.27 | | | | Darcy |
| (Dimova *et al*., 2013) | Josephine Lake, Florida, USA | 1.6 | | 1 | 3.1 | Radon |
| (Mitchell *et al*., 1988) | Knopp's Pond, Massachusetts, USA | 2.62 | | | | Seepage meter |
| (Cherkauer and McBride, 1988) | Lake Michigan, Wisconsin, USA | 0.01 | | | | Seepage meter |
| (Lee, 1977) | Lake Sallie, Minnesota, USA | 2.37 | 1.90 | 0.03 | 6.91 | Seepage meter |
| (Loeb and Goldman, 1979) | Lake Tahoe, California, USA | 18 | | | | Darcy |
| (Loeb and Hackley, 1988) | Lake Tahoe, California, USA | 0.04 | 0.01 | 0.004 | 0.10 | Seepage meter |
| (Connor and Belanger, 1981) | Lake Washington, Florida, USA | 0.2 | | −0.3 | 1 | Seepage meter |
| (Bruckner *et al*., 1989) | Lake Anna, Virginia, USA | 0.019 | 0.016 | 0.002 | 0.043 | Seepage meter |
| (Fellows and Brezonik, 1980) | Lake Apopka, Florida, USA | 1.4 | | 0.1 | 8.5 | Seepage meter |
| (Taniguchi and Fukuo, 1993) | Lake Biwa, Japan | 8 | | 0 | 22.5 | Seepage meter |

Table I. Summaries of rates of groundwater exfiltration and infiltration reported in the literature

| Reference | Location | Average value | Median value | Minimum value | Maximum value | Measurement method |
|---|---|---|---|---|---|---|
| (Vanek, 1991) | Lake Bysjon, Sweden | 0.216 | | | | recharge |
| (Lesack, 1995) | Lake Calado, Brazil | 3.9 | | 0.12 | 33.5 | Seepage meter |
| (Cullmann *et al*., 2006) | Lake Camaleao, Brazil | 0.7 | | | | Budget |
| (Cullmann *et al*., 2006) | Lake Camaleao, Brazil | 1.73 | 1.42 | 1.22 | 2.86 | Chemistry |
| (Cullmann *et al*., 2006) | Lake Camaleao, Brazil | 3.48 | | | 67.8 | Seepage meter |
| (Fellows and Brezonik, 1980) | Lake Conway, Florida, USA | 1.2 | | 0.3 | 5.5 | Seepage meter |
| (Kidmose *et al*., 2011) | Lake Hampen, Denmark | 1.5 | | 0 | 8.6 | Seepage meter |
| (Oliveira Ommen *et al*., 2012) | Lake Hampen, Denmark | 0.64 | | 0.05 | 8.3 | |
| (Mortimer *et al*., 1999) | Lake Kinneret, Israel | 0.33 | 0.323 | 0.226 | 0.444 | Chemistry |
| (Mortimer *et al*., 1999) | Lake Kinneret, Israel | 0.16 | 0.157 | 0.049 | 0.266 | Seepage meter |
| (Mitchell *et al*., 1988) | Lake Lorraine, Massachusetts, USA | 1.75 | | | | Seepage meter |
| (Lee and Swancar, 1997) | Lake Lucerne, Florida, USA | 0.07 | | 0.003 | 0.17 | Darcy |
| (Woessner and Sullivan, 1984) | Lake Mead, Nevada, USA | 4.30 | 3.06 | 0.20 | 12.63 | Seepage meter |
| (Sonzogni and Lee, 1974) | Lake Mendota, Wisconsin, USA | 0.19 | | | | Budget |
| (Brock *et al*., 1982) | Lake Mendota, Wisconsin, USA | 0.18 | | 0.6 | 44.5 | Seepage meter |
| (Downing and Peterka, 1978) | Lake Metigoshe, North Dakota, USA | 0.04 | | | 0.19 | Seepage meter |
| (Schneider *et al*., 2005) | Lake Oneida, New York, USA | 0.2 | | 0 | 2.8 | Seepage meter |
| (Kang *et al*., 2005) | Lake Persimmon, Florida, USA | 0.0063 | | | | Chemistry |
| (Misztal *et al*., 1992) | Lake Piaseczno, Poland | 0.047 | | | | Darcy |
| (McBride, 1987) | Lake St Clair, Michigan, USA | 0.08 | | 0.03 | 0.17 | Seepage meter |
| (Lee *et al*., 2014) | Lake Starr, Florida, USA | 0.24 | | | | Model |
| (Kidmose *et al*., 2013) | Lake Væng, Denmark | 124.1 | 19.0 | 0.3 | 745 | Seepage meter |
| (Kidmose *et al*., 2013) | Lake Væng, Denmark | 3.8 | | | | Budget |
| (Mitchell *et al*., 1988) | Little Sandy Bottom Pond, Massachusetts, USA | 0.87 | | | | Seepage meter |
| (Menheer, 2004) | Long Lake, Minnesota, USA | 13 | | 1.8 | 26 | Seepage meter |
| (Attanayake and Waller, 1988) | Long Lake, Nova Scotia, Canada | 4.0 | | 1.3 | 6.7 | Seepage meter |
| (Mitchell *et al*., 1988) | Loon Pond, Massachusetts, USA | 1.38 | | | | Seepage meter |
| (Mitchell *et al*., 1988) | Lost Lake, Massachusetts, USA | 1.16 | | | | Seepage meter |
| (Cherkauer and Zager, 1989) | Lower Nashotah Lake, Wisconsin, USA | 0.6 | | 0.02 | 1 | Seepage meter |
| (Sebestyen and Schneider, 2001) | Lower Sylvan Pond, New York, USA | 0.005 | | 0 | 1.5 | Seepage meter |
| (Stauffer, 1985) | Marl Lake, Wisconsin, USA | 0.356 | | | | Chemistry |
| (Hofmann *et al*., 2008) | Mining Lake Plessa 117, Germany | 0.22 | | | | Budget |
| (Hofmann *et al*., 2008) | Mining Lake Plessa 117, Germany | 0.26 | | | | Isotopes |
| (Hofmann *et al*., 2008) | Mining Lake Plessa 117, Germany | 0.23 | | | | Model |
| (Asbury, 1990) | Mirror Lake, New Hampshire, USA | | 0.0115 | 0.004 | 0.094 | Seepage meter |
| (Toran *et al*., 2010) | Mirror Lake, New Hampshire, USA | 0.125 | | 0.01 | 0.17 | Seepage meter |
| (Belanger and Kirkner, 1994) | Mountain Lake, Florida, USA | 0.813 | 0.432 | 0.0336 | 2.64 | Seepage meter |
| (Ridgway and Blanchfield, 1998) | Mykiss Lake, Ontario, Canada | 2.9 | | | | Seepage meter |
| (Shaw *et al*., 1990) | Narrow Lake, Alberta, Canada | 0.091 | | | | Budget |
| (Shaw *et al*., 1990) | Narrow Lake, Alberta, Canada | 0.054 | | | | Darcy |
| (Shaw and Prepas, 1990) | Narrow Lake, Alberta, Canada | 0.26 | 0.22 | 0.14 | 0.44 | Seepage meter |

*(Continues)*

Table I. (Continued)

| Reference | Location | Average value | Median value | Minimum value | Maximum value | Measurement method |
|---|---|---|---|---|---|---|
| (Shaw *et al*., 1990) | Narrow Lake, Alberta, Canada | 0.036 | | | | Seepage meter |
| (Mitchell *et al*., 1988) | Nashawannuck Pond, Massachusetts, USA | 0.43 | | | | Seepage meter |
| (Dimova *et al*., 2013) | Newnans Lake, Florida, USA | 0.5 | | | | Radon |
| (Stauffer, 1985) | Parker Lake, Wisconsin, USA | 0.383 | | | | Chemistry |
| (Lee and Cherry, 1978) | Perch Lake, Ontario, Canada | 4.1 | | | | Seepage meter |
| (Lee *et al*., 1980) | Perch Lake, Ontario, Canada | 4.04 | 4.63 | 1.42 | 6.56 | Seepage meter |
| (Cole and Pace, 1998) | Peter Lake, Michigan, USA | 0.65 | | | | Chemistry |
| (Stauffer, 1985) | Pickerel Lake, Wisconsin, USA | 0.055 | | | | Chemistry |
| (Mitchell *et al*., 1988) | Richmond Pond, Massachusetts, USA | 0.74 | | | | Seepage meter |
| (John and Lock, 1977) | Rotorua Lake, New Zealand | 2.09 | 0.96 | 0.27 | 12.8 | Seepage meter |
| (Stauffer, 1985) | Round Lake, Wisconsin, USA | 0.548 | | | | Chemistry |
| (Ridgway and Blanchfield, 1998) | Scott Lake, Ontario, Canada | 3.4 | | 0.86 | 13 | Seepage meter |
| (Rosenberry *et al*., 2013) | Shingobee Lake, Minnesota, USA | | | | 45 | Seepage meter |
| (Rosenberry *et al*., 2000) | Shingobee Lake, Minnesota, USA – nonsprings | 1.4 | | 0.09 | 7.8 | Seepage meter |
| (Rosenberry *et al*., 2000) | Shingobee Lake, Minnesota, USA – springs | 13.8 | | 0.39 | 47.5 | Seepage meter |
| (Dimova *et al*., 2013) | Shipp Lake, Florida, USA | 0.1 | | | | Radon |
| (Mitchell *et al*., 1988) | Silver Lake, Massachusetts, USA | 1.64 | | | | Seepage meter |
| (Hagerthey and Kerfoot, 1998) | Sparkling Lake, Wisconsin, USA | 3.45 | | 0.04 | 10.4 | Seepage meter |
| (Krabbenhoft *et al*., 1990) | Sparkling Lake, Wisconsin, USA | 1.18 | 1.21 | 0.8 | 1.39 | Seepage meter |
| (Lodge *et al*., 1989) | Sparkling Lake, Wisconsin, USA | 1.3 | | 0.17 | 9.5 | Seepage meter |
| (Menheer, 2004) | Square Lake, Minnesota, USA | 13.1 | | 5.9 | 18.3 | Seepage meter |
| (Mitchell *et al*., 1988) | Stetson Pond, Massachusetts, USA | 1.3 | | | | Seepage meter |
| (Ridgway and Blanchfield, 1998) | Stringer Lake, Ontario, Canada | 5.1 | | | | Seepage meter |
| (Krabbenhoft and Anderson, 1986) | Trout Lake, Wisconsin, USA | 1.87 | 1.47 | 0.86 | 3.97 | Seepage meter |
| (Wentz *et al*., 1995) | Vandercook Lake, Wisconsin, USA | 0.008 | 0.005 | 0 | 0.02 | Darcy |
| (Cole and Pace, 1998) | West Long Lake, Michigan, USA | 0.5 | | | | Chemistry |
| (LaBaugh *et al*., 1995) | Williams Lake, Minnesota, USA | 0.64 | | | | Darcy |
| (Schuster *et al*., 2003) | Williams Lake, Minnesota, USA | 0.271 | | | | Darcy |
| (Schuster *et al*., 2003) | Williams Lake, Minnesota, USA | | | 0.234 | 0.39 | Isotopes |
| (Erickson, 1981) | Williams Lake, Minnesota, USA | 0.3 | | 0 | 0.71 | Seepage meter |
| (Schuster *et al*., 2003) | Williams Lake, Minnesota, USA | | | 0.013 | 0.665 | Seepage meter |
| (Stauffer, 1985) | Wolf Lake, Wisconsin, USA | 0.137 | | | | Chemistry |
| (Stauffer, 1985) | Wood Lake, Wisconsin, USA | 0.137 | | | | Chemistry |
| Rates of groundwater infiltration | | | | | | |
| (Mitchell *et al*., 1988) | 11 lakes in Massachusetts, USA | | | | −4.3 | Seepage meter |
| (Ala-aho *et al*., 2013) | L. Ahveroinen, Finland | −1.76 | −0.6 | −0.09 | −8.21 | Seepage meter |
| (Boyle, 1994) | Alexander Lake, Ontario, Canada | −0.65 | | −0.02 | −1.18 | Seepage meter |
| (Choi and Harvey, 2000) | Everglades, Florida, USA | −0.84 | | −0.004 | −14 | Seepage meter |
| (Rosenberry, 2000) | Lake Belle Taine, Minnesota, USA | −37 | | −0.08 | −263 | Seepage meter |
| (Isiorho and Matisoff, 1990) | Lake Chad, Cameroon, Chad, Niger and Nigeria, Africa | −0.19 | −0.11 | −0.002 | −1.2 | Seepage meter |
| (Lee and Swancar, 1997) | Lake Lucerne, Florida, USA | −0.09 | | −0.006 | −0.15 | Budget |
| (Dorrance, 1989) | Lake Mary, Arizona, USA | −0.44 | −0.34 | −0.15 | −0.96 | Seepage meter |

Table I. Summaries of rates of groundwater exfiltration and infiltration reported in the literature

| Reference | Location | Average value | Median value | Minimum value | Maximum value | Measurement method |
|---|---|---|---|---|---|---|
| (Woessner and Sullivan, 1984) | Lake Mead, Nevada, USA | −1.05 | −1.02 | −0.61 | −1.83 | Seepage meter |
| (Lee *et al*., 2014) | Lake Starr, Florida, USA | −0.18 | | | | Model |
| (Isiorho *et al*., 1996) | Long Lake, Indiana, USA | −0.11 | | −0.002 | −0.19 | Seepage meter |
| (Sebestyen and Schneider, 2001) | Lower Sylvan Pond, New York, USA | −0.73 | | 0 | −1.45 | Seepage meter |
| (Asbury, 1990) | Mirror Lake, New Hampshire, USA | −11.52 | | −0.008 | −100.12 | Seepage meter |
| (Rosenberry *et al*., 2010) | Mirror Lake, New Hampshire, USA | −31.2 | | −1.9 | −137 | Seepage meter |
| (Rosenberry *et al*., 2013) | Mirror Lake, New Hampshire, USA | | | | −148 | Seepage meter |
| (Belanger and Kirkner, 1994) | Mountain Lake, Florida, USA | −4.69 | −1.008 | −0.067 | −36 | Seepage meter |
| (Krabbenhoft and Webster, 1995) | Nevins Lake, Michigan, USA | −0.001 | | | | Chemistry |
| (Hagerthey and Kerfoot, 1998) | Sparkling Lake, Wisconsin, USA | −0.12 | | −0.02 | −0.20 | Seepage meter |
| (Krabbenhoft *et al*., 1990) | Sparkling Lake, Wisconsin, USA | −0.24 | −0.24 | −0.2 | −0.28 | Seepage meter |
| (Erickson, 1981) | Williams Lake, Minnesota, USA | −0.55 | | 0 | −0.91 | Seepage meter |

Values are in centimetres per day.

component of the water budget for small lakes where the ratio of perimeter to surface area is larger. One would be hard pressed to make this case for lakes smaller than about 100 ha. Percentages of the groundwater component of a lake-water budget range from nearly 0% to nearly 95% of inputs to lakes (Figure 2A) and from nearly 0% to 91% of losses from lakes (Figure 2B). For lakes larger than about 100 ha, groundwater as a percentage of a lake-water budget rarely exceeds 40%. A log-normal fit of the exfiltration data shown in Figure 2A indicates a poor relation between per cent groundwater component of a lake-input budget and lake-surface area, explaining only 25% of the variance. If the data are binned and surface area is averaged for each order of magnitude range in surface area, a log-normal regression shows a good relation and explains 85% of the variance (Figure 3). However, no such relation is evident, no matter the data manipulation, for lakes where groundwater infiltration occurs (Figure 2B). One particularly interesting lake is Lake Nam Co on the Tibetan plateau with a lake-surface area greater than 100 000 ha. In spite of the large surface area for evaporating water, groundwater makes up over 60% of the water-budget loss terms (Zhou *et al*., 2013).

## INFLUENCE OF MEASUREMENT METHOD ON DETERMINATION OF GROUNDWATER EXFILTRATION AND INFILTRATION

The interpreted exchange between groundwater and surface water depends substantially on the method of quantification. Calculating a groundwater component as the residual of a water budget or using a conservative water or chemical tracer or combining water and chemical budgets provides a value that is integrated across the entire lake, or in some cases an entire bay or other lake component that may be reasonably isolated from the rest of the lake. Segmenting a lakeshore according to locations of monitoring wells (Darcy approach), from which hydraulic gradients and estimates of hydraulic conductivity are obtained, including incorporating that information into a groundwater-flow model, provides groundwater exfiltration and infiltration data for specific portions of lakes that then need to be summed to represent the whole lake. Although conceptually sound, this method comes with the large uncertainty in the scale-appropriate value for hydraulic conductivity (e.g. Rovey and Cherkauer, 1995). Calculating a groundwater component on the basis of seepage-meter measurements is only representative of the portion of the lakebed covered by the seepage cylinders; results from multiple meters must then be extrapolated across the rest of the lakebed area.

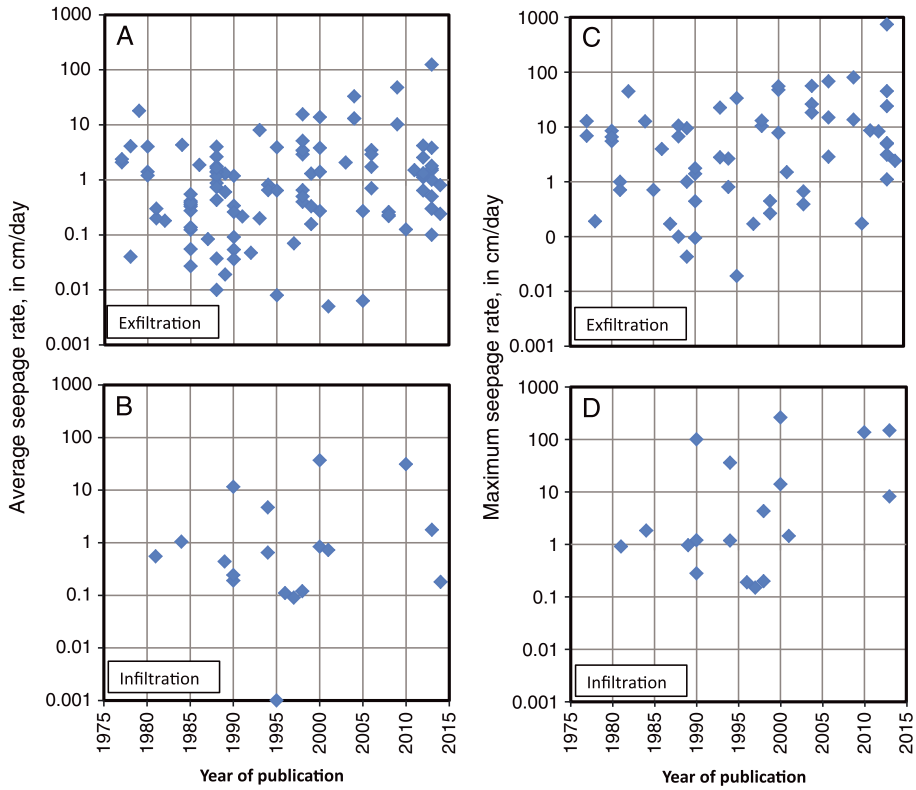


Figure 1. Published rates of groundwater exfiltration (A, C) and infiltration (B, D). References are listed in Table III. Panels A and B are based on average values reported in the literature for specific study lakes. Panels C and D list maximum values from each studied lake

Table II. Seepage rates for upward seepage (exfiltration) and downward seepage (infiltration) at 108 lakes across the world

| | Exfiltration average | Exfiltration maximum | Infiltration average | Infiltration maximum |
|---|---|---|---|---|
| Count | 109 | 59 | 18 | 18 |
| Minimum | 0.005 | 0.019 | 0.001 | 0.15 |
| 25th percentile | 0.23 | 0.76 | 0.18 | 0.92 |
| Median | 0.74 | 5.10 | 0.60 | 1.64 |
| 75th percentile | 2.09 | 13.30 | 1.58 | 30.5 |
| Maximum | 124.1 | 745.0 | 37.0 | 263.0 |

Data culled from the literature are average and maximum values reported for particular lakes. Values are in centimetres per day.

In spite of these issues of scale, parsing 110 quantifications of the groundwater component of a lake budget (data from Table III) on the basis of the measurement method results in surprisingly little difference in the method-averaged groundwater component for the lake-water budgets available for this analysis (Table IV). When exfiltration and infiltration are lumped together, median values based on water budget, chemical budget, Darcy or seepage-meter measurements range from about 20% to 52%. The scale of measurement appears to have little to do with the range in percentages. The median groundwater percentages resulting from the two methods that integrate the whole lake, the lake-water and lake-chemistry budget methods, are 23% and 52%, respectively. Similar ranges occur for both exfiltration-only and infiltration-only analyses (Table IV). The median groundwater percentage based on the most locally determined measurements, seepage meters, is 20% if both exfiltration and infiltration lakes are considered, 18% for exfiltration-only lakes and 60% for infiltration-only lakes. Although generally smaller, the seepage-meter percentages are not appreciably smaller given the range of percentages indicated by the methods that integrate a larger portion of the lake area.

Some studies have quantified groundwater exfiltration and/or infiltration using several methods. Results often

 

Table III. Groundwater exfiltration and infiltration as a percentage of a lake-water budget

| Reference | Lake | Lake area (ha) | Percentage of groundwater exfiltration/infiltration | Measurement method |
|---|---|---|---|---|
| Exfiltration | | | | |
| (Brown and Cherkauer, 1991) | Beaver Lake, Wisconsin, USA | 132 | 70 | Budget |
| (Ozyavas *et al*., 2010) | Caspian Sea | 38350000 | 0.01 | Budget |
| (Simpkins, 2006) | Clear Lake, Iowa, USA | 1468 | 32 | Model |
| (Gurrieri and Furniss, 2004) | Cliff Lake, Montana, USA | 9 | 90 | Budget |
| (Piña-Ochoa and Álvarez-Cobelas, 2009) | Colgada Lake, Spain | 103 | 50 | Flow meter |
| (Stets *et al*., 2010) | Crystal Lake, Minnesota, USA | 77 | 52 | Isotopes |
| (Field and Duerk, 1988) | Delavan Lake, Wisconsin, USA | 725 | 17.8 | Budget |
| (Mitchell *et al*., 1988) | Dimmock Pond, Massachusetts, USA | 4.2 | 10.5 | Seepage meter |
| (Belanger *et al*., 1985) | East Lake Tohopekaliga, Florida, USA | 4680 | 14.3 | Seepage meter |
| (Cole and Pace, 1998) | East Long Lake, Michigan, USA | 2.3 | 57 | Chemistry |
| (Mitchell *et al*., 1988) | Five Mile Pond, Massachusetts, USA | 14.3 | 19.7 | Seepage meter |
| (Sacks *et al*., 1998) | Grassy Lake, Florida, USA | 30.4 | 35 | Isotopes |
| (Arnow, 1985) | Great Salt Lake, Utah, USA | 440000 | 3 | Budget |
| (Harvey *et al*., 2000) | Hamilton Harbor, Ontario, Canada | 2150 | 7 | Darcy |
| (Bayer *et al*., 2008) | Hayes Lake, New Zealand | 276 | 9 | Seepage meter |
| (Stets *et al*., 2010) | Island Lake, Minnesota, USA | 32 | 45 | Isotopes |
| (Mitchell *et al*., 1988) | Knopp's Pond, Massachusetts, USA | 25.1 | 56.2 | Seepage meter |
| (Sacks *et al*., 1998) | Lake Annie, Florida, USA | 36.8 | 85 | Isotopes |
| (Fellows and Brezonik, 1980) | Lake Apopka, Florida, USA | 12400 | 2 | Seepage meter |
| (Colman, 1998) | Lake Baikal, Russia | 31722 | 4.5 | Budget |
| (Lee, 1996) | Lake Barco, Florida, USA | 11.7 | 1 | Model |
| (Yihdego and Webb, 2012) | Lake Buninjon, Australia | 290 | 5 | Budget |
| (Yihdego and Webb, 2012) | Lake Burrumbeet, Australia | 2300 | 1.3 | Budget |
| (Wentz and Rose, 1991) | Lake Clara, Wisconsin, USA | 33.6 | 9 | Darcy |
| (Fellows and Brezonik, 1980) | Lake Conway, Florida, USA | 739 | 17.5 | Seepage meter |
| Grubbs, 1995 | Lake Five-O, Florida, USA | 10.9 | 78 | Model |
| (Sacks *et al*., 1998) | Lake George Florida, USA | 23.6 | 51 | Isotopes |
| (Sacks *et al*., 1998) | Lake Hollingsworth, Florida, USA | 142.4 | 50 | Isotopes |
| (Sacks *et al*., 1998) | Lake Isis, Florida, USA | 20 | 67 | Isotopes |
| (Yihdego and Webb, 2012) | Lake Linlithgow, Australia | 1010 | 1 | Budget |
| (Mitchell *et al*., 1988) | Lake Lorraine, Massachusetts, USA | 11.5 | 18.4 | Seepage meter |
| (Lee and Swancar, 1997) | Lake Lucerne, Florida, USA | 18 | 20 | Darcy |
| (Brock *et al*., 1982) | Lake Mendota, Wisconsin, USA | 3940 | 33 | Seepage meter |
| (Grannemann *et al*., 2000) | Lake Michigan, Michigan, USA | 58000 | 2.6 | Budget |
| (Hood *et al*., 2006) | Lake O'Hara, British Columbia, Canada | 26 | 38 | Budget |
| (Sacks *et al*., 1998) | Lake Olivia, Florida, USA | 34.4 | 46 | Isotopes |
| (McBride *et al*., 2011) | Lake Panasoffkee, Florida, USA | 2280 | 22 | Budget |
| (Mann and McBride, 1972) | Lake Sallie, Minnesota, USA | 492 | 14.5 | Darcy |
| (Dalton *et al*., 2004) | Lake Seminole, Georgia, USA | 15040 | 18 | Model |
| (Lee *et al*., 2014) | Lake Starr, Florida, USA | 54 | 42 | Budget |

*(Continues)*

Table III. (Continued)

| Reference | Lake | Lake area (ha) | Percentage of groundwater exfiltration/infiltration | Measurement method |
|---|---|---|---|---|
| (Sacks *et al*., 1998) | Lake Starr, Florida, USA | 53.6 | 29 | Isotopes |
| (Kidmose *et al*., 2013) | Lake Væng, Denmark | 16 | 66 | Budget |
| (Connor and Belanger, 1981) | Lake Washington, Florida, USA | 2700 | 0.7 | Seepage meter |
| (Mitchell *et al*., 1988) | Little Sandy Bottom Pond, Massachusetts, USA | 21.9 | 14.9 | Seepage meter |
| (Mitchell *et al*., 1988) | Loon Pond, Massachusetts, USA | 10.2 | 22.65 | Seepage meter |
| (Mitchell *et al*., 1988) | Lost Lake, Massachusetts, USA | 57.5 | 24.8 | Seepage meter |
| (Motz *et al*., 2001) | Lowry Lake, Florida, USA | 519 | 19 | Darcy |
| (Jarosiewicz and Witek, 2014) | Mały Borek Lake, Poland | 7.6 | 46.2 | Darcy |
| (Stets *et al*., 2010) | Mary Lake, Minnesota, USA | 14 | 94 | Isotopes |
| (Hofmann and Lessmann, 2006) | Mining Lake Plessa 117, Germany | 95 | 70 | Isotopes |
| (Hofmann *et al*., 2008) | Mining Lake Plessa 117, Germany | 95 | 42 | Model |
| (Hofmann *et al*., 2008) | Mining Lake Plessa 117, Germany | 95 | 47 | Isotopes |
| (Rosenberry and Winter, 2009) | Mirror Lake, New Hampshire, USA | 15 | 16 | Darcy |
| (Shaw *et al*., 1990) | Narrow Lake, Alberta, Canada | 110 | 17 | Seepage meter |
| (Shaw *et al*., 1990) | Narrow Lake, Alberta, Canada | 110 | 25 | Darcy |
| (Shaw *et al*., 1990) | Narrow Lake, Alberta, Canada | 110 | 42 | Budget |
| (Mitchell *et al*., 1988) | Nashawannuck Pond, Massachusetts, USA | 11.3 | 1.2 | Seepage meter |
| (Cole and Pace, 1998) | Peter Lake, Michigan, USA | 2.7 | 67 | Chemistry |
| (Mitchell *et al*., 1988) | Richmond Pond, Massachusetts, USA | 86.6 | 2.1 | Seepage meter |
| (Gurrieri and Furniss, 2004) | Rock Lake, Montana, USA | 18.9 | 33 | Budget |
| (Sacks *et al*., 1998) | Round Lake, Florida, USA | 12.4 | 12 | Isotopes |
| (Sacks *et al*., 1998) | Saddle Blanket Lake, Florida, USA | 2.4 | 44 | Isotopes |
| (Stets *et al*., 2010) | Shingobee Lake, Minnesota, USA | 65 | 18 | Isotopes |
| (Mitchell *et al*., 1988) | Silver Lake, Massachusetts, USA | 11.5 | 44.8 | Seepage meter |
| (Stets *et al*., 2010) | Steel Lake, Minnesota, USA | 25 | 19 | Isotopes |
| (Mitchell *et al*., 1988) | Stetson Pond, Massachusetts, USA | 33.8 | 42.6 | Seepage meter |
| (Sacks *et al*., 1998) | Swim Lake, Florida, USA | 2 | 78 | Isotopes |
| (Wentz and Rose, 1991) | Vandercook Lake, Wisconsin, USA | 38.8 | 17 | Darcy |
| (Wentz *et al*., 1995) | Vandercook Lake, Wisconsin, USA | 43 | 7 | Darcy |
| (Cole and Pace, 1998) | West Long Lake, Michigan, USA | 3.4 | 63 | Chemistry |
| (LaBaugh *et al*., 1995) | Williams Lake, Minnesota, USA | 36 | 66 | Darcy |
| (LaBaugh *et al*., 1997) | Williams Lake, Minnesota, USA | 36 | 74 | Darcy |
| (Stets *et al*., 2010) | Williams Lake, Minnesota, USA | 40 | 55 | Isotopes |
| Infiltration | | | | |
| (Deevey, 1988) | 10 lakes in central Florida, USA | 1317 | 30 | Budget |
| (Brown and Cherkauer, 1991) | Beaver Lake, Wisconsin, USA | 132 | 59 | Budget |
| (Simpkins, 2006) | Clear Lake, Iowa, USA | 1468 | 21 | Model |
| (Gurrieri and Furniss, 2004) | Cliff Lake, Montana, USA | 9 | 78 | Budget |
| (Stets *et al*., 2010) | Crystal Lake, Minnesota, USA | 77 | 52 | Isotopes |
| (Choi and Harvey, 2000) | Everglades Nutrient Removal Project, Florida, USA | 1544 | 23 | Seepage meter |
| (Sacks *et al*., 1998) | Grassy Lake, Florida, USA | 30.4 | 35 | Budget |
| (Sacks *et al*., 1998) | Lake Annie, Florida, USA | 36.8 | 23 | Budget |

| | | | | |
|---|---|---|---|---|
| (Lee, 1996) | Lake Barco, Florida, USA | 11.7 | 29 | Model |
| (Rosenberry, 2000) | Lake Belle Taine, Minnesota, USA | 480 | 91 | Seepage meter |
| (Yihdego and Webb, 2012) | Lake Buninjon, Australia | 290 | 0.8 | Budget |
| (Yihdego and Webb, 2012) | Lake Burrumbeet, Australia | 2300 | 12 | Budget |
| (Wentz and Rose, 1991) | Lake Clara, Wisconsin, USA | 33.6 | 15 | Darcy |
| (Grubbs, 1995) | Lake Five-O, Florida, USA | 10.9 | 84 | Model |
| (Sacks *et al*., 1998) | Lake George, Florida, USA | 23.6 | 16 | Budget |
| (Sacks *et al*., 1998) | Lake Hollingsworth, Florida, USA | 142.4 | 43 | Budget |
| (Sacks *et al*., 1998) | Lake Isis, Florida, USA | 20 | 48 | Budget |
| (Yihdego and Webb, 2012) | Lake Linlithgow, Australia | 1010 | 0.1 | Budget |
| (Lee and Swancar, 1997) | Lake Lucerne, Florida, USA | 18 | 18 | Budget |
| (Dorrance, 1989) | Lake Mary, Arizona, USA | 240 | 42 | Seepage meter |
| (Zhou *et al*., 2013) | Lake Nam Co, Tibet | 201700 | 61 | Budget |
| (Sacks *et al*., 1998) | Lake Olivia, Florida, USA | 34.4 | 35 | Budget |
| (Lee *et al*., 2014) | Lake Starr, Florida, USA | 54 | 30 | Budget |
| (Sacks *et al*., 1998) | Lake Starr, Florida, USA | 53.6 | 27 | Budget |
| (Vallet-Coulomb *et al*., 2001) | Lake Ziway, Ethiopia | 50000 | 10 | Budget |
| (Motz, 1998) | Lowry Lake, Florida, USA | 519 | 35 | Budget |
| (Jarosiewicz and Witek, 2014) | Mały Borek Lake, Poland | 7.6 | 42.3 | Darcy |
| (Healy *et al*., 2007) | Mirror Lake, New Hampshire, USA | 15 | 51 | Darcy |
| (Rosenberry and Winter, 2009) | Mirror Lake, New Hampshire, USA | 15 | 50 | Darcy |
| (Belanger and Kirkner, 1994) | Mountain Lake, Florida, USA | 483 | 77 | Seepage meter |
| (Gurrieri and Furniss, 2004) | Rock Lake, Montana, USA | 18.9 | 21 | Budget |
| (Sacks *et al*., 1998) | Round Lake, Florida, USA | 12.4 | 2 | Budget |
| (Sacks *et al*., 1998) | Saddle Blanket Lake, Florida, USA | 2.4 | 32 | Budget |
| (Hines and Brezonik, 2007) | Spring Lake, Minnesota, USA | 8.9 | 9 | Budget |
| (Sacks *et al*., 1998) | Swim Lake, Florida, USA | 2 | 78 | Budget |
| (Wentz and Rose, 1991) | Vandercook Lake, Wisconsin, USA | 38.8 | 39 | Darcy |
| (Stets *et al*., 2010) | Williams Lake, Minnesota, USA | 40 | 57 | Isotopes |

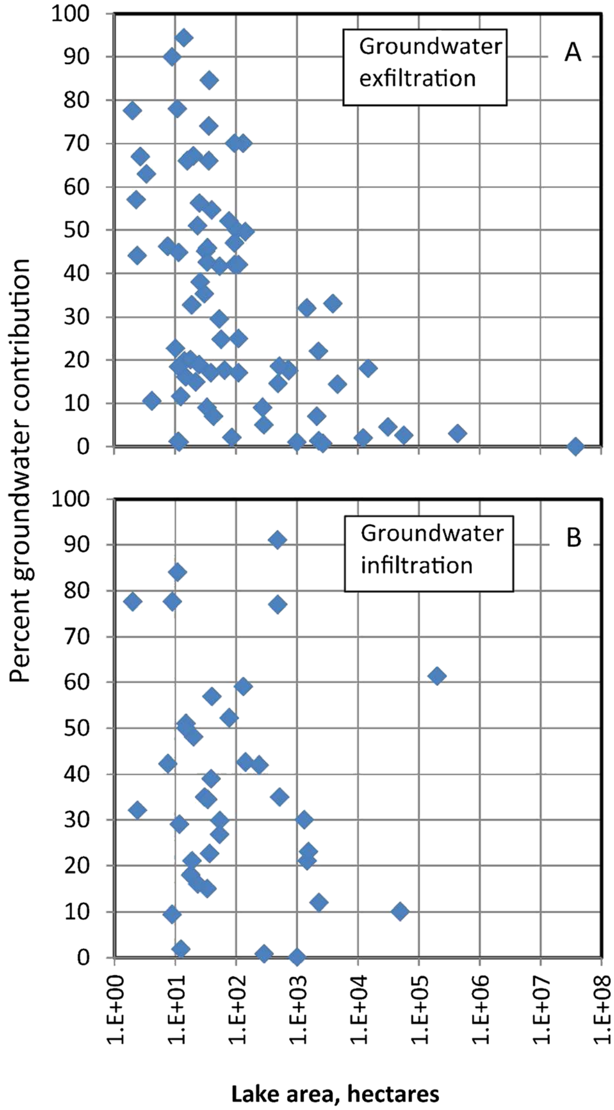


Figure 2. Groundwater exfiltration (A) and infiltration (B) as a percentage of a lake-water budget versus lake-surface area

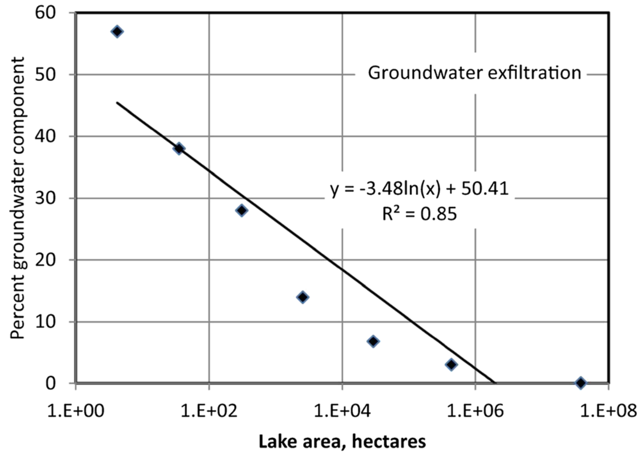


Figure 3. Average groundwater exfiltration as a percentage of the lake-water budget when data are grouped into orders of magnitude of lake-surface area

are substantially different among methods. LaBaugh *et al.* (1997) determined exfiltration and infiltration using Darcy calculations, and also with combined water and chemical budgets using several chemical constituents, including water isotopes. The Darcy-based estimate of groundwater exfiltration was close to 400 $m^3$/year. The best estimate using oxygen isotopes of water was 525, although that value ranged from 320 to 650, depending on the range in estimates of the isotopic value of evaporating water. Values for groundwater exfiltration using major ions ranged from 60 based on chloride to 300 based on sodium. An estimate using dissolved organic carbon was over 1000. Precipitation, at 140 $m^3$/year, was the only other input term. Therefore, the Darcy-based best estimate for groundwater exfiltration was 74% of the water-budget input terms. Estimates from combined water and chemical mass budgets ranged from 30% to 88% (LaBaugh *et al.*, 1997). Meinikmann *et al.* (2013) compared groundwater exfiltration rates to a lake using temperature-depth profiles with watershed-scale equipotential lines drawn from field data. As might be expected, spatial variability of exfiltration rates was greater on the basis of temperature; however, the temperature-based results also indicated that the largest rates of groundwater exfiltration were not always located where hydraulic gradients were largest. Discrepancies likely arose from limited opportunities for measurement of hydraulic head in groundwater, especially near the shoreline.

Others have combined Darcy-based flow determinations with water-budget calculations to reduce the uncertainty associated with estimates of hydraulic conductivity. Lee and Swancar (1997), in a very detailed study of a lake in Florida, used a flow-net analysis based on an extensive network of monitoring wells to calculate flows of groundwater to and from the lake. They determined that groundwater exfiltration occurred around the entire perimeter of the lake and groundwater infiltration occurred in the middle, deepest portion of the lake. Darcy-based estimates were determined to be too small when compared with an analysis of water-budget terms over a period of several months. By comparing net groundwater flow based on the residual of monthly water budgets with net groundwater flow from their Darcy-based flow-net calculations, they were able to determine that actual groundwater exfiltration was about 1.2 times larger than their flow-net estimates. Others also have adjusted Darcy-based calculations of groundwater flows to match more closely values from combined water and chemical budgets (e.g. Sacks *et al.*, 1998). Combining results from multiple methods often reduces the uncertainty of estimates of groundwater exfiltration or infiltration (e.g. Hines and Brezonik, 2007; Hofmann

Table IV. Groundwater component of lake-water budget based on measurement method

| | Water budget | Chemistry budget | Darcy method | Seepage meter |
|---|---|---|---|---|
| All data | | | | |
| *n* | 37 | 23 | 27 | 23 |
| Average | 28.8 | 51.8 | 33.1 | 27.6 |
| Median | 22.6 | 52.0 | 29.0 | 19.7 |
| Maximum | 89.9 | 94.4 | 84.0 | 91.0 |
| Minimum | 0.01 | 11.5 | 1.0 | 0.7 |
| Exfiltration only | | | | |
| *n* | 15 | 21 | 18 | 19 |
| Average | 26.4 | 51.5 | 29.6 | 21.1 |
| Median | 17.8 | 50.9 | 19.3 | 17.5 |
| Maximum | 89.9 | 94.4 | 78.0 | 56.2 |
| Minimum | 0.01 | 11.5 | 1.0 | 0.7 |
| Infiltration only | | | | |
| *n* | 22 | 2 | 9 | 4 |
| Average | 30.5 | 54.5 | 40.1 | 58.3 |
| Median | 28.4 | 54.5 | 39.0 | 59.5 |
| Maximum | 77.6 | 56.9 | 84.0 | 91.0 |
| Minimum | 0.10 | 52.2 | 15.0 | 23.0 |

Values in percentage of the sum of all input or loss terms of the lake-water budget. Chemistry budget includes entries listed as ‘Isotopes’ in Table III. Darcy method includes entries listed as ‘Model’ in Table III. Seepage meter includes entries listed as ‘Flow meter’ in Table III.

*et al*., 2008; Kidmose *et al*., 2011; Yihdego and Webb, 2012). Perhaps the greatest potential for advancement in understanding and quantification of flow across the groundwater–lakebed interface will come from combining measurement methods in clever new ways.

## SUMMARY

Measured rates of groundwater exfiltration and groundwater infiltration vary by five orders of magnitude in lacustrine settings, on the basis of 127 values gleaned from the literature. Of these values, 85% were groundwater exfiltration, and 15% were groundwater infiltration. The median rate of exfiltration (0.74 cm/day) was nearly the same as the median rate of infiltration (0.60 cm/day). Maximum measured exfiltration (745 cm/day) was almost three times larger than the maximum infiltration rate of 263 cm/day. However, four values for maximum infiltration were larger than 100 cm/day, whereas the second largest value for maximum exfiltration was 80 cm/day.

The groundwater component of 110 measured lake-water budgets ranged from near 0% to just under 95%, with a median value of 31%. Although surprisingly large, this value may be somewhat biased; several of the cited studies were conducted for the specific purpose of determining what was suspected to be a substantial groundwater contribution to a lake-water budget. The percentage of the groundwater component generally decreased as lake area increased, but only in the case of groundwater exfiltration and only for lakes greater than about 100 ha in area. No percentage-versus-lake area relation was evident for groundwater infiltration on the basis of 37 lake-water budget calculations.

Determination of per cent groundwater contribution to a lake budget depends substantially on the method used to quantify the groundwater term. Use of multiple methods to estimate the groundwater component is suggested to reduce this uncertainty.

## REFERENCES


Ala-aho P, Rossi PM, Kløve B. 2013. Interaction of esker groundwater with headwater lakes and streams. *Journal of Hydrology* **500**: 144–156.

Alley WM, Reilly TE, Franke OL. 1999. Sustainability of ground-water resources. *U.S. Geological Survey Circular* **1186**: 79.

Anderson MP, Hunt RJ, Krohelski JT, Chung K. 2002. Using high hydraulic conductivity nodes to simulate seepage lakes. *Ground Water* **40**: 117–122.

Anderson RB, Naftz DL, Day-Lewis FD, Henderson RD, Rosenberry DO, Stolp BJ, Jewell P. 2014. Quantity and quality of groundwater discharge in a hypersaline lake environment. *Journal of Hydrology* **512**: 177–194.

Anibas C, Fleckenstein JH, Volze N, Buis K, Verhoeven R, Meire P, Batelaan O. 2009. Transient or steady-state? Using vertical temperature profiles to quantify groundwater–surface water exchange. *Hydrological Processes* **23**: 2165–2177.

Arnow T. 1985. Water-level and water-quality changes in Great Salt Lake, Utah 1843–1985. In *Orogenic Patterns and Stratigraphy of North-central Utah and Southeastern Idaho*. Kerns GJ, Kerns Jr. RL (eds). Utah Geological Association: Salt Lake City; 227–236.

Asbury CE. 1990. The role of groundwater seepage in sediment chemistry and nutrient budgets in Mirror Lake, New Hampshire. PhD, Cornell University.

Attanayake MP, Waller DH. 1988. Use of seepage meters in a groundwater–lake interaction study in a fractured rock basin – a case study. *Canadian Journal of Civil Engineering* **15**: 984–989.

Baedecker MJ, Friedman LC. 1999. Water, energy, and biogeochemical budgets: a watershed research program. *U.S. Geological Survey Fact Sheet* **FS 165-99**: 4.

Baird AJ, Wilby RL (eds). 1999. *Eco-hydrology, Plants and Water in Terrestrial and Aquatic Environments*. Routledge: London; 402.

Bartolino JR, Niswonger RG. 1999. Numerical simulation of vertical ground-water flux of the Rio Grande from ground-water temperature profiles, central New Mexico. *U.S. Geological Survey Water-Resources Investigations Report* **99-4212**; 40.

Baskin RL. 1998. Locating shoreline submarine springs in two Utah lakes using thermal imagery. In *Modern & Ancient Lake Systems; New Problems and Perspectives*. Pitman JK, Carroll AR (eds). Utah Geological Association: Salt Lake City, Utah; 51–57.

Bates CG, Henry AJ. 1928. Forests and streamflow at Wagon Wheel Gap, Colorado. *Monthly Weather Review* **30**: 1–79.

Bayer TK, Schallenberg M, Martin CE. 2008. Investigation of nutrient limitation status and nutrient pathways in Lake Hayes, Otago, New Zealand: a case study for integrated lake assessment. *New Zealand Journal of Marine and Freshwater Research* **42**: 285–295.

Belanger TV, Kirkner RA. 1994. Groundwater/surface water interaction in a Florida augmentation lake. *Lake and Reservoir Management* **8**: 165–174.

Belanger TV, Mikutel DF, Churchill PA. 1985. Groundwater seepage nutrient loading in a Florida Lake. *Water Research* **19**: 773–781.

Bertin C, Bourg ACM. 1994. Radon-222 and chloride as natural tracers of the infiltration of river water into an alluvial aquifer in which there is


 

significant river/groundwater mixing. *Environmental Science and Technology* **28**: 794–798.
Beven K, Feyen J. 2002. The future of distributed modeling. *Hydrological Processes* **16**: 169–172.
Beven KJ, Kirkby MJ, Schofield N, Tagg AF. 1984. Testing a physically-based flood forecasting model (TOPMODEL) for three U.K. catchments. *Journal of Hydrology* **69**: 119–143.
Blume T, Krause S, Meinikmann K, Lewandowski J. 2013. Upscaling lacustrine groundwater discharge rates by fiber-optic distributed temperature sensing. *Water Resources Research* **49**: 7929–7944.
Bouwer H, Rice RC. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. *Water Resources Research* **12**: 423–428.
Boyle DR. 1994. Design and seepage meter for measuring groundwater fluxes in the nonlittoral zones of lakes – evaluation in a boreal forest lake. *Limnology and Oceanography* **39**: 670–681.
Briggs MA, Lautz LK, McKenzie JM, Gordon RP, Hare DK. 2012. Using high-resolution distributed temperature sensing to quantify spatial and temporal variability in vertical hyporheic flux. *Water Resources Research* **48**: W02527.
Briggs MA, Voytek EB, Day-Lewis FD, Rosenberry DO, Lane JW. 2013. Understanding water column and streambed thermal refugia for endangered mussels in the Delaware River. *Environmental Science & Technology* **47**: 11423–11431.
Brock TD, Lee DR, Janes D, Winek D. 1982. Groundwater seepage as a nutrient source to a drainage lake: Lake Mendota, Wisconsin. *Water Resources* **16**: 1255–1263.
Brönmark C, Hansson L-A. 2002. Environmental issues in lakes and ponds: current state and perspectives. *Environmental Conservation* **29**: 290–307.
Broughton W. 1941. The geology, ground water, and lake basin seal of the region south of the Muskellunge Moraine, Vilas County, Wisconsin. *Transactions of the Wisconsin Academy of Sciences, Arts and Letter* **33**: 5–20.
Brown BE, Cherkauer DS. 1991. Phosphate and carbonate mass balances and their relationships to groundwater inputs at Beaver Lake, Waukesha County, Wisconsin. *University of Wisconsin Water Resources Center Technical Completion Report* **G1458-04**: 43.
Bruckner AE, Hornberger GM, Mills AL. 1989. Field measurement and associated controlling factors for ground water seepage in a piedmont impoundment. *Hydrological Processes* **3**: 223–235.
Brunke M, Gonser T. 1997. The ecological significance of exchange processes between rivers and groundwater. *Freshwater Biology* **37**: 1–33.
Bukaveckas PA, Likens GE, Buso DC, Winter TC. 1993. *Hydrologic Controls of Chemical Flux Rates in the Mirror Lake Watershed.* Verhandlungen des Internationalen Verein Limnologie. **25**: 419–422.
Bundschuh J. 1993. Modeling annual variations of spring and groundwater temperatures associated with shallow aquifer systems. *Journal of Hydrology* **142**: 427–444.
Cardenas MB, Lagmay AMF, Andrews BJ, Rodolfo RS, Cabria HB, Zamora PB, Lapus MR. 2012. Terrestrial smokers: thermal springs due to hydrothermal convection of groundwater connected to surface water. *Geophysical Research Letters* **39**: L02403.
Cedergren HR. 1997. *Seepage Drainage and Flow Nets*, 3rd edition. John Wiley and Sons: New York; 496.
Cherkauer DA, McBride JM. 1988. A remotely operated seepage meter for use in large lakes and rivers. *Ground Water* **26**: 165–171.
Cherkauer DS, Nader DC. 1989. Distribution of groundwater seepage to large surface-water bodies: the effect of hydraulic heterogeneities. *Journal of Hydrology* **109**: 151–165.
Cherkauer DS, Zager JP. 1989. Groundwater interaction with a kettle-hole lake: relation of observations to digital simulations. *Journal of Hydrology* **109**: 167–184.
Choi J, Harvey JW. 2000. Quantifying time-varying ground-water discharge and recharge in wetlands of the northern Florida Everglades. *Wetlands* **20**: 500–511.
Cole JJ, Pace ML. 1998. Hydrologic variability of small, northern Michigan lakes measured by the addition of tracers. *Ecosystems* **1**: 310–320.
Colman SM. 1998. Water-level changes in Lake Baikal, Siberia: tectonism versus climate. *Geology* **26**: 531–534.
Conant Jr. B 2000. Ground-water plume behavior near the ground-water/surface water interface of a river. Proceedings of the Ground-water/Surface-water Interactions Workshop, Denver, Colorado, 23–30.
Conant Jr. B 2004. Delineating and quantifying ground water discharge zones using streambed temperatures. *Ground Water* **42**: 243–257.
Connor JN, Belanger TV. 1981. Ground water seepage in Lake Washington and the Upper St. Johns River Basin, Florida. *Water Resources Bulletin* **17**: 799–805.
Constantz J, Thomas CL, Zellweger G. 1994. Influence of diurnal variations in stream temperature on streamflow loss and groundwater recharge. *Water Resources Research* **30**: 3253–3264.
Cooley RL. 1983. Some new procedures for numerical solution of variably saturated flow problems. *Water Resources Research* **19**: 1271–1285.
Cornett RJ, Risto BA, Lee DR. 1989. Measuring groundwater transport through lake sediments by advection and diffusion. *Water Resources Research* **25**: 1815–1823.
Cullmann J, Junk WJ, Weber G, Schmitz GH. 2006. The impact of seepage influx on cation content of a Central Amazonian floodplain lake. *Journal of Hydrology* **328**: 297–305.
Dalton MS, Aulenbach BT, Torak LJ. 2004. Ground-water and surface-water flow and estimated water budget for Lake Seminole, northwestern Georgia and northwestern Florida. *U.S. Geological Survey Scientific Investigations Report* **2004-5073**: 49.
Danielopol DL. 1984. Ecological investigations on the alluvial sediments of the Danube in the Vienna area – a phreatobiological project. *Verhandlungen. Internationale Vereinigung fur theoretische und angewandte Limnologie* **22**: 1755–1761.
Danielopol DL, Rouch R, Pospisil P, Torreiter P, Moeszlacher F. 1997. Ecotonal animal assemblages; their interest for groundwater studies. In *Groundwater/Surface Water Ecotones: Biological and Hydrological Interactions and Management Options*. Gibert J, Mathieu J, Fournier F (eds). Cambridge University Press: Cambridge; 11–20.
Day-Lewis FD, White EA, Johnson CD, Lane Jr. JW, Belaval M. 2006. Continuous resistivity profiling to delineate submarine groundwater discharge – examples and limitations. *The Leading Edge* **25**: 724–728.
Deevey Jr. ES. 1988. Estimation of downward leakage from Florida lakes. *Limnology and Oceanography* **33**: 1308–1320.
Dimova NT, Burnett WC, Chanton JP, Corbett JE. 2013. Application of radon-222 to investigate groundwater discharge into small shallow lakes. *Journal of Hydrology* **486**: 112–122.
Dincer T. 1968. The use of oxygen-18 and deuterium concentrations in the water balance of lakes. *Water Resources Research* **4**: 1289–1306.
Dorrance DW. 1989. Streaming potential and seepage meter studies at Upper Lake Mary near Flagstaff, Arizona. MS, University of Arizona.
Downing JA, Peterka JJ. 1978. Relationship of rainfall and lake groundwater seepage. *Limnology and Oceanography* **23**: 821–825.
Erickson DR. 1981. A study of littoral groundwater seepage at Williams Lake, Minnesota using seepage meters and wells. MS, University of Minnesota.
Federer CA, Lash D. 1978. BROOK: a hydrologic simulation model for eastern forests. *Water Resources Research Center*, *University of New Hampshire Research Report no.* 19.
Fellows CR, Brezonik PL. 1980. Seepage flow into Florida lakes. *Water Resources Bulletin* **16**: 635–641.
Ferrey ML, Lundy JR, Estuesta P. 2001. The effect of groundwater aeration on PCE natural attenuation patterns. *Bioremediation Journal* **5**: 211–224.
Fetter Jr. CW. 1994. *Applied Hydrogeology*, 3rd edition. Prentice Hall: Englewood Cliffs; 691.
Ficke JF. 1972. Comparison of evaporation computation methods, Pretty Lake, Lagrange County, northeastern Indiana. *U.S. Geological Survey Professional Paper* **686-A**: 48.
Field SJ, Duerk MD. 1988. Hydrology and water quality of Delavan Lake in southeastern Wisconsin. *U.S. Geological Survey Water-Resources Investigations Report* **87-4168**: 61.
Fleckenstein JH, Krause S, Hannah DM, Boano F. 2010. Groundwater–surface water interactions: new methods and models to improve understanding of processes and dynamics. *Advances in Water Resources* **33**: 1291–1295.
Frandsen M, Nilsson B, Engesgaard P, Pedersen OLE. 2012. Groundwater seepage stimulates the growth of aquatic macrophytes. *Freshwater Biology* **57**: 907–921

 

Fritz BG, Mendoza DP, Gilmore TJ. 2009. Development of an electronic seepage chamber for extended use in a river. *Ground Water* **47**: 136–140.

Fryar AE, Wallin EJ, Brown DL. 2000. Spatial and temporal variability in seepage between a contaminated aquifer and tributaries to the Ohio River. *Ground Water Monitoring and Remediation* **20**: 129–146.

Gardner KM. 1999. The importance of surface water/groundwater interactions – issue paper. *U.S. Environmental Protection Agency*; 18.

Genereux D, Bandopadhyay I. 2001. Numerical investigation of lake bed seepage patterns: effects of porous medium and lake properties. *Journal of Hydrology* **241**: 286–303.

Gordon RP, Lautz LK, Briggs MA, McKenzie JM. 2012. Automated calculation of vertical pore-water flux from field temperature time series using the VFLUX method and computer program. *Journal of Hydrology* **420–421**: 142–158.

Goslee SC, Brooks RP, Cole CA. 1997. Plants as indicators of wetland water source. *Plant Ecology* **131**: 199–206.

Gosselin DC, Rundquist DC, McFeeters SK. 2000. Remote monitoring of selected ground-water dominated lakes in the Nebraska Sand Hills. *Journal of the American Water Resources Association* **36**: 1039–1051.

Grannemann NG, Hunt RH, Nicholas JR, Reilly TE, Winter TC. 2000. The importance of ground water in the Great Lakes region. *U.S. Geological Survey Water-Resources Investigations Report* **00-4008**: 14.

Greenland D, Goodin DG, Smith RC, Barondes SH (eds). 2003. *Climate Variability and Ecosystem Response at Long-term Ecological Research Sites (Long-term Ecological Research Network Series)*. Oxford University Press: New York City.

Grubbs JW. 1995. Evaluation of ground-water flow and hydrologic budget for Lake Five-O, a seepage lake in northwestern Florida. *U.S. Geological Survey Water-Resources Investigations Report* **94-4145**: 41.

Gurnell AM, Hupp CR, Gregory SV. 2000. Linking hydrology and ecology. *Hydrological Processes* **14**: 2813–2815.

Gurrieri JT, Furniss G. 2004. Estimation of groundwater exchange in alpine lakes using non-steady mass-balance methods. *Journal of Hydrology* **297**: 187–208.

Hagerthey SE, Kerfoot WC. 1998. Groundwater flow influences the biomass and nutrient ratios of epibenthic algae in a north temperate seepage lake. *Limnology and Oceanography* **43**: 1227–1242.

Hall BR, Raynal DJ, Leopold DJ. 2001. Environmental influences on plant species composition in ground-water seeps in the Catskill Mountains of New York. *Wetlands* **21**: 125–134.

Harbaugh AW, Banta ER, Hill MC, McDonald MG. 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water models; user guide to modularization concepts and the ground-water flow process. *U. S. Geological Survey Open-File Report* **00-0092**: 121.

Harbeck GEJ, Kohler MA, Koberg GE. 1958. Water-loss investigations: Lake Mead studies. *U.S. Geological Survey Professional Paper* **298**: 100.

Harvey JW, Wagner BJ, Bencala KE. 1996. Evaluating the reliability of the stream tracer approach to characterize stream–subsurface water exchange. *Water Resources Research* **32**: 2441–2451.

Harvey FE, Rudolph DL, Frape SK. 2000. Estimating ground water flux into large lakes: application in the Hamilton Harbor, Western Lake Ontario. *Ground Water* **38**: 550–565.

Hatch CE, Fischer AT, Ruehl CR, Stemler G. 2010. Spatial and temporal variations in streambed hydraulic conductivity quantified with time-series thermal methods. *Journal of Hydrology* **389**: 276–288.

Hayashi M, Rosenberry DO. 2002. Effects of ground water exchange on the hydrology and ecology of surface water. *Ground Water* **40**: 309–316.

Hayashi M, van der Kamp G, Rudolph DL. 1998. Water and solute transfer between a prairie wetland and adjacent uplands, 2. Chloride cycle. *Journal of Hydrology* **207**: 56–67.

Healy RW, Winter TC, LaBaugh JW, Franke OL. 2007. Water budgets: foundations for effective water-resources and environmental management. *U.S. Geological Survey Circular* **1308**: 98.

Heitmann M, Schubert H. 1965. *Lake Stechlin – a hydrometeorological research area*. Publ. IASH: Budapest; **66**: 429–440.

Herczeg AL, Leaney FW, Dighton JC, Lamontagne S, Schiff SL, Telfer AL, English MC. 2003. A modern isotope record of changes in water and carbon budgets in a groundwater-fed lake: Blue Lake, South Australia. *Limnology and Oceanography* **48**: 2093–2105.

Herrmann R. 1997. Long-term watershed research and monitoring to understand ecosystem change in parks and equivalent reserves. *Journal of the American Water Resources Association* **33**: 747–753.

Hill MC. 1991. A computer program (MODFLOWP) for estimating parameters of a transient, three-dimensional, ground-water flow model using nonlinear regression. *U.S. Geological Survey Open-File Report* **91-484**: 358.

Hines NA, Brezonik PL. 2007. Mercury inputs and outputs at a small lake in northern Minnesota. *Biogeochemistry* **84**: 265–284.

Hiscock KM, Grischek T. 2002. Attenuation of groundwater pollution by bank filtration. *Journal of Hydrology* **266**: 139–144.

Hofmann H, Lessmann D. 2006. Hydrogeochemistry of groundwater seepage into an acidic mining lake. *Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie* **29**: 1452–1456.

Hofmann H, Knöller K, Lessmann D. 2008. Mining lakes as groundwater-dominated hydrological systems: assessment of the water balance of Mining Lake Plessa 117 (Lusatia, Germany) using stable isotopes. *Hydrological Processes* **22**: 4620–4627.

Holzbecher E. 2001. The dynamics of subsurface water divides – watersheds of Lake Stechlin and neighbouring lakes. *Hydrological Processes* **15**: 2297–2304.

Hood JL, Roy JW, Hayashi M. 2006. Importance of groundwater in the water balance of an alpine headwater lake. *Geophysical Research Letters* **33**: L13405.

Hsieh PA. 2001. TopoDrive and ParticleFlow – two computer models for simulation and visualization of ground-water flow and transport of fluid particles in two dimensions. *U.S. Geological Survey Open-File Report* **01-286**: 30.

Hunt RJ, Zheng C. 2012. The current state of modeling. *Ground Water* **50**: 330–333.

Hunt RJ, Haitjema HM, Krohelski JT, Feinstein DT. 2003. Simulating ground water–lake interactions: approaches and insights. *Ground Water* **41**: 227–237.

Hunt RJ, Walker JF, Selbig WR, Westenbroek SM, Regan RS. 2013. Simulation of climate-change effects on streamflow, lake water budgets, and stream temperature using GSFLOW and SNTEMP, Trout Lake Watershed, Wisconsin. *U.S. Geological Survey Scientific Investigations Report* **2013-5159**: 118.

Isiorho SA, Matisoff G. 1990. Groundwater recharge from Lake Chad. *Limnology and Oceanography* **35**: 931–938.

Isiorho SA, Beeching FM, Stewart PM, Whitman RL. 1996. Seepage measurements from Long Lake, Indiana Dunes National Lakeshore. *Environmental Geology* **28**: 99–105.

Israelson OW, Reeve RC. 1944. Canal lining experiments in the Delta Area, Utah. Utah Agricultural Experimental Station; 15–35.

Jarosiewicz A, Witek Z. 2014. Where do nutrients in an inlet-less lake come from? The water and nutrient balance of a small mesotrophic lake. *Hydrobiologia* **724**: 157–173.

John PH, Lock MA. 1977. The spatial distribution of groundwater discharge into the littoral zone of a New Zealand lake. *Journal of Hydrology* **33**: 391–395.

Jones JB, Mulholland PJ. 2000. *Streams and Ground Waters*. Academic Press: San Diego; 425.

Kalbus E, Reinstorf F, Schirmer M. 2006. Measuring methods for groundwater – surface water interactions: a review. *Hydrology and Earth System Sciences* **10**: 873–887.

Kang WJ, Kolasa KV, Rials MW. 2005. Groundwater inflow and associated transport of phosphorus to a hypereutrophic lake. *Environmental Geology* **47**: 565–575.

Katz BG, Coplen TB, Bullen TD, Davis JH. 1997. Use of chemical and isotopic tracers to characterize the interactions between ground water and surface water in mantled karst. *Ground Water* **35**: 1014–1028.

Kendall C, Sklash MG, Bullen TK. 1995. Isotope tracers of water and solute sources in catchments. In *Solute Modelling in Catchment Systems*. Trudgill ST (ed). John Wiley & Sons Ltd: Chichester, UK; 261–303.

Kenoyer GJ, Anderson MP. 1989. Groundwater's dynamic role in regulating acidity and chemistry in a precipitation-dominated lake. *Journal of Hydrology* **109**: 287–306.

Kidmose J, Engesgaard P, Nilsson B, Laier T, Looms MC. 2011. Spatial distribution of seepage at a flow-through lake: Lake Hampen, Western Denmark. *Vadose Zone Journal* **10**: 110–124.

 

Kidmose J, Nilsson B, Engesgaard P, Frandsen M, Karan S, Landkildehus F, Søndergaard M, Jeppesen E. 2013. Focused groundwater discharge of phosphorus to a eutrophic seepage lake (Lake Væng, Denmark): implications for lake ecological state and restoration. *Hydrogeology Journal* **21**: 1787–1802.

Kim K, Anderson MP, Bowser CJ. 2000. Enhanced dispersion in groundwater caused by temporal changes in recharge rate and lake levels. *Advances in Water Resources* **23**: 625–635.

Konikow LF, Bredehoeft JD. 1992. Ground-water models cannot be validated. *Advances in Water Resources* **15**: 75–83.

Krabbenhoft DP, Anderson MP. 1986. Use of a numerical ground-water flow model for hypothesis testing. *Ground Water* **24**: 49–55.

Krabbenhoft DP, Webster KE. 1995. Transient hydrogeological controls on the chemistry of a seepage lake. *Water Resources Research* **31**: 2295–2305.

Krabbenhoft DP, Bowser CJ, Anderson MP, Valley JW. 1990. Estimating groundwater exchange with lakes 1. The stable isotope mass balance method. *Water Resources Research* **26**: 2445–2453.

Krabbenhoft DP, Bowser CJ, Kendall C, Gat JR. 1994. Use of oxygen-18 and deuterium to assess the hydrology of groundwater-lake systems. In *Environmental Chemistry of Lakes and Reservoirs*. LA Baker (ed). American Chemical Society: Washington DC; 67–90.

Krupa SL, Belanger TV, Heck HH, Brock JT, Jones BJ. 1998. Krupaseep – the next generation seepage meter. *Journal of Coastal Research* **26**: 210–213.

LaBaugh JW. 1985. Uncertainty in phosphorus retention, Williams Fork Reservoir, Colorado. *Water Resources Research* **21**: 1684–1692.

LaBaugh JW, Winter TC. 1984. The impact of uncertainties in hydrologic measurement on phosphorus budgets and empirical models for two Colorado reservoirs. *Limnology and Oceanography* **29**: 322–339.

LaBaugh JW, Rosenberry DO, Winter TC. 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.

LaBaugh JW, Winter TC, Rosenberry DO, Schuster PF, Reddy MM, Aiken GR. 1997. Hydrological and chemical estimates of the water balance of a closed-basin lake in north central Minnesota. *Water Resources Research* **33**: 2799–2812.

LaBaugh JW, Winter TC, Rosenberry DO. 2000. Comparison of the variability in fluxes of ground water and solutes in lakes and wetlands in central North America. *Verhandlungen Internationale Vereinigung fuer Theoretische und Angewandte Limnologie* **27**: 420–426.

Lapham WW. 1989. Use of temperature profiles beneath streams to determine rates of vertical ground-water flow and vertical hydraulic conductivity. *U. S. Geological Survey Water-Supply Paper* **2337**: 35.

Lautz LK. 2012. Observing temporal patterns of vertical flux through streambed sediments using time-series analysis of temperature records. *Journal of Hydrology* **464–465**: 199–215.

Leavesley GH, Hay L. 1998. The use of coupled atmospheric and hydrological models for water-resources management in headwater basins. Proceedings of the Hydrology, Water Resources and Ecology in Headwaters, Meran, Italy, 259–265.

Leavesley GH, Lichty RW, Troutman BM, Saindon LG. 1983. Precipitation–runoff modeling system; user's manual. *U.S. Geological Survey Water-Resources Investigations Report* **83-4238**: 207.

Leavesley GH, Markstrom SL, Restrepo PJ, Viger RJ. 2002. A modular approach to addressing model design, scale, and parameter estimation issues in distributed hydrological modelling. *Hydrological Processes* **16**: 173–187.

Lee DR. 1977. A device for measuring seepage flux in lakes and estuaries. *Limnology and Oceanography* **22**: 140–147.

Lee DR. 1985. Method for locating sediment anomalies in lakebeds that can be caused by groundwater flow. *Journal of Hydrology* **79**: 187–193.

Lee TM. 1996. Hydrogeologic controls on the groundwater interactions with an acidic lake in karst terrain, Lake Barco, Florida. *Water Resources Research* **32**: 831–843.

Lee DR, Cherry JA. 1978. A field exercise on groundwater flow using seepage meters and mini-piezometers. *Journal of Geological Education* **27**: 6–20.

Lee TM, Swancar A. 1997. Influence of evaporation, ground water, and uncertainty in the hydrologic budget of Lake Lucerne, a seepage lake in Polk County, Florida. *U.S. Geological Survey Water Supply Paper* **2439**: 61.

Lee DR, Tracey JP. 1984. Identification of groundwater discharge locations using thermal infrared imagery. Proceedings of the Ninth Canadian Symposium on Remote Sensing, Saint Johns, Newfoundland, 301–308.

Lee DR, Cherry JA, Pickens JF. 1980. Groundwater transport of a salt tracer through a sandy lakebed. *Limnology and Oceanography* **25**: 45–61.

Lee TM, Sacks LA, Swancar A. 2014. Exploring the long-term balance between net precipitation and net groundwater exchange in Florida seepage lakes. *Journal of Hydrology*, in press. DOI: 10.1016/j.jhydrol.2014.

Lesack LFW. 1995. Seepage exchange in an Amazon floodplain lake. *Limnology and Oceanography* **40**: 598–609.

Lewandowski J, Meinikmann K, Ruhtz T, Pöschke F, Kirillin G. 2013. Localization of lacustrine groundwater discharge (LGD) by airborne measurement of thermal infrared radiation. *Remote Sensing of Environment* **138**: 119–125.

Lewandowski J, Meinikmann K, Nützmann G, Rosenberry DO. 2014. Lacustrine groundwater discharge – the disregarded component in lake nutrient budgets. 2. Biogeochemical considerations. *Hydrological Processes*, in review.

Lillie RA, Barko JW. 1990. Influence of sediment and groundwater on the distribution and biomass of *Myriophyllum spicatum* L. in Devil's Lake, Wisconsin. *Journal of Freshwater Ecology* **5**: 417–426.

Lindgren RJ, Landon MK. 2000. Effects of ground-water withdrawals on the Rock River and associated valley aquifer, eastern Rock County, Minnesota. *U.S. Geological Survey Water-Resources Investigations Report* **99-4157**: 103.

Lodge DM, Krabbenhoft DP, Striegl RG. 1989. A positive relationship between groundwater velocity and submersed macrophyte biomass in Sparkling Lake, Wisconsin. *Limnology and Oceanography* **34**: 235–239.

Loeb SL, Goldman CR. 1979. Water and nutrient transport via groundwater from Ward Valley into Lake Tahoe. *Limnology and Oceanography* **24**: 1146–1154.

Loeb SL, Hackley SH. 1988. The distribution of submerged macrophytes in Lake Tahoe, California and Nevada, and the possible influence of groundwater seepage. *Verhandlungen. Internationale Vereinigung fur theoretische und angewandte Limnologie* **23**: 1927–1933.

Malard F, Plenet S, Gibert J. 1996. The use of invertebrates in ground water monitoring: a rising research field. *Ground Water Monitoring and Remediation* **16**: 103–113.

Malcolm IA, Soulsby C, Youngson AF, Hannah DM, McLaren IS, Thorne A. 2004. Hydrological influences on hyporheic water quality: implications for salmon egg survival. *Hydrological Processes* **18**: 1543–1560.

Mann WB, McBride MS. 1972. The hydrologic balance of Lake Sallie, Becker County, Minnesota. *U.S. Geological Survey Professional Paper* **800-D**: D189–D191.

Mann CJ, Wetzel RG. 2000. Hydrology of an impounded lotic wetland-subsurface hydrology. *Wetlands* **20**: 33–47.

Markstrom SL, Niswonger RG, Regan RS, Prudic DE, Barlow PM. 2008. GSFLOW – coupled ground-water and surface-water flow model based on the integration of the precipitation-runoff modeling system (PRMS) and the modular ground-water flow model (MODFLOW-2005). *U.S. Geological Survey Techniques and Methods* **Book 6, D1**; 240.

Mast MA, Clow DW. 1995. Environmental characteristics and water quality of hydrologic benchmark network stations in the Western United States, 1963–95. *U.S. Geological Survey Circular* **1173-D**: 114.

McBride JM. 1987. Measurement of ground water flow to the Detroit River, Michigan and Ontario. MS, University of Wisconsin–Milwaukee: 107.

McBride MS, Pfannkuch HO. 1975. The distribution of seepage within lakebeds. *U.S. Geological Survey Journal of Research* **3**: 505–512.

McBride WS, Bellino JC, Swancar A. 2011. Hydrology, water budget, and water chemistry of Lake Panasoffkee, west-central Florida. *U.S. Geological Survey Scientific Investigations Report* **2010-5237**: 96.

McCobb TD, LeBlanc DR, Massey AJ. 2009. Monitoring the removal of phosphate from ground water discharging through a pond-bottom permeable reactive barrier. *Ground Water Monitoring and Remediation* **29**: 43–55.


 

McDonald MG, Harbaugh AH. 1984. A modular three-dimensional finite-difference ground-water flow model. *U.S. Geological Survey Open-File Report* **83-0875**: 528.

Meinikmann K, Lewandowski J, Nützmann G. 2013. Lacustrine groundwater discharge: combined determination of volumes and spatial patterns. *Journal of Hydrology* **502**: 202–211.

Meinzer OE. 1927. Plants as indicators of ground water. *U.S. Geological Survey Water-Supply Paper* **577**: 95.

Menheer MA. 2004. Development of a benthic-flux chamber for measurement of ground-water seepage and water sampling for mercury analysis at the sediment-water interface. *U.S. Geological Survey Scientific Investigation Report* **2004-5298**: 14.

Miettinen IT, Vartiainen T, Martikainen PJ. 1997. Changes in water microbial quality during bank filtration of lake water. *Canadian Journal of Microbiology* **43**: 1126–1132.

Misztal M, Smal H, Górniak A. 1992. Ground water inflow of nutrients to a lake from differently utilized catchments. *Water Research* **26**: 1237–1242.

Mitchell DF, Wagner KJ, Asbury C. 1988. Direct measurement of groundwater flow and quality as a lake management tool. *Lake and Reservoir Management* **4**: 169–178.

Mortimer RJG, Krom MD, Boyle DR, Nishri A. 1999. Use of a high-resolution pore-water gel profiler to measure groundwater fluxes at an underwater saline seepage site in Lake Kinneret, Israel. *Limnology and Oceanography* **44**: 1802–1809.

Motz LH. 1998. Vertical leakage and vertically averaged vertical conductance for karst lakes in Florida. *Water Resources Research* **34**: 159–167.

Motz LH, Sousa GD, Annable MD. 2001. Water budget and vertical conductance for Lowry (Sand Hill) Lake in north, central Florida, USA. *Journal of Hydrology* **250**: 134–148.

Munter JA, Anderson MP. 1981. The use of ground-water flow models for estimating lake seepage rates. *Ground Water* **19**: 608–616.

Nuttle WK. 2002. Eco-hydrology's past and future in focus. *Eos* **83**(205): 211–212.

Nützmann G, Holzbecher E, Pekdeger A. 2003. Evaluation of the water balance of Lake Stechlin with the help of chloride data. *Advances in Limnology* **58**: 11–23.

Oliveira Ommen DA, Kidmose J, Karan S, Flindt MR, Engesgaard P, Nilsson B, Andersen FØ. 2012. Importance of groundwater and macrophytes for the nutrient balance at oligotrophic Lake Hampen, Denmark. *Ecohydrology* **5**: 286–296.

Ozyavas A, Khan SD, Casey JF. 2010. A possible connection of Caspian Sea level fluctuations with meteorological factors and seismicity. *Earth and Planetary Science Letters* **299**: 150–158.

Paulsen RJ, Smith CF, O'Rourke D, Wong T. 2001. Development and evaluation of an ultrasonic ground water seepage meter. *Ground Water* **39**: 904–911.

Pfannkuch HO, Winter TC. 1984. Effect of anisotropy and groundwater system geometry on seepage through lakebeds, 1. Analog and dimensional analysis. *Journal of Hydrology* **75**: 213–237.

Piña-Ochoa E, Álvarez-Cobelas M. 2009. Seasonal nitrogen dynamics in a seepage lake receiving high nitrogen loads. *Marine and Freshwater Research* **60**: 435–445.

Pollard RA. 1955. Measuring seepage through salmon spawning gravel. *Journal of the Fisheries Research Board of Canada* **12**: 706–741.

Rasmussen W, Lauritzen CW. 1953. Measuring seepage from irrigation canals. *Agricultural Engineering* **34**: 326–330.

Rau GC, Andersen MS, Acworth RI. 2012. Experimental investigation of the thermal time-series method for surface water-groundwater interactions. *Water Resources Research* **48**: W03530.

Ray C, Melin G, Linsky RB (eds). 2003. *Riverbank Filtration: Improving Source-water Quality*. Kluwer Academic Publishers: Dordrecht; 364.

Ridgway MS, Blanchfield PJ. 1998. Brook trout spawning areas in lakes. *Ecology of Freshwater Fish* **7**: 140–145.

Robinson AR, Rohwer C. 1952. Study of seepage losses from irrigation channels. *U.S. Department of Agriculture*, *Soil Conservation Service Progress Report*; 42.

Rorabaugh MI. 1964. Estimating changes in bank storage and ground-water contribution to streamflow. *International Association of Scientific Hydrology Publication* **63**: 432–441.

Rosenberry DO. 2000. Unsaturated-zone wedge beneath a large, natural lake. *Water Resources Research* **36**: 3401–3409.

Rosenberry DO. 2005. Integrating seepage heterogeneity with the use of ganged seepage meters. *Limnology and Oceanography: Methods* **3**: 131–142.

Rosenberry DO. 2008. A seepage meter designed for use in flowing water. *Journal of Hydrology* **359**: 118–130.

Rosenberry DO, Hayashi M. 2013. Assessing and measuring wetland hydrology. In *Wetland Techniques Volume 1: Foundations*. Anderson JT, Davis CA (eds). Springer: Dordrecht; 87–225.

Rosenberry DO, LaBaugh JW. 2008. Field techniques for estimating water fluxes between surface water and ground water. *U.S. Geological Survey Techniques and Methods* **Chapter 4-D2**; 128.

Rosenberry DO, Menheer MA. 2006. A system for calibrating seepage meters used to measure flow between ground water and surface water. *U.S. Geological Survey Scientific Investigations Report* **2006-5053**: 21.

Rosenberry DO, Morin RH. 2004. Use of an electromagnetic seepage meter to investigate temporal variability in lake seepage. *Ground Water* **42**: 68–77.

Rosenberry DO, Winter TC. 1997. Dynamics of water-table fluctuations in an upland between two prairie-pothole wetlands in North Dakota. *Journal of Hydrology* **191**: 266–269.

Rosenberry DO, Winter TC. 2009. Hydrologic processes and the water budget. In *Mirror Lake: Interactions among Air, Land, and Water*. Winter TC, Likens GE (eds). University of California Press: Berkeley; 23–68.

Rosenberry DO, Striegl RG, Hudson DC. 2000. Plants as indicators of focused ground water discharge to a northern Minnesota lake. *Ground Water* **38**: 296–303.

Rosenberry DO, Winter TC, Buso DC, Likens GE. 2007. Comparison of 15 evaporation methods applied to a small mountain lake in the northeastern USA. *Journal of Hydrology* **340**: 149–166.

Rosenberry DO, LaBaugh JW, Hunt RJ. 2008. Use of monitoring wells, portable piezometers, and seepage meters to quantify flow between surface water and ground water. In *Field Techniques for Estimating Water Fluxes between Surface Water and Ground Water*, DO Rosenberry, JW LaBaugh (eds). U.S. Geological Survey Techniques and Methods 4-D2: Denver; 39–70.

Rosenberry DO, Toran L, Nyquist JE. 2010. Effect of surficial disturbance on exchange between groundwater and surface water in nearshore margins. *Water Resources Research* **46**: W06518. doi: 06510.01029/02009WR008755.

Rosenberry DO, Sheibley RW, Cox SE, Simonds FW, Naftz DL. 2013. Temporal variability of exchange between groundwater and surface water based on high-frequency direct measurements of seepage at the sediment–water interface. *Water Resources Research* **49**: 2975–2986.

Rovey II CW, Cherkauer DS. 1995. Scale dependency of hydraulic conductivity measurements. *Ground Water* **33**: 769–780.

Rutledge AT. 1998. Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow data – update. *U.S. Geological Survey Water-Resources Investigations Report* **98-4148**: 44.

Rutledge AT. 2000. Considerations for use of the RORA program to estimate ground-water recharge from streamflow records. *U.S. Geological Survey Open-File Report* **00-156**: 44.

Sacks LA, Swancar A, Lee TM. 1998. Estimating ground-water exchange with lakes using water-budget and chemical mass-balance approaches for ten lakes in ridge areas of Polk and Highlands Counties, Florida. *U.S. Geological Survey Water-Resources Investigations Report* **98-4133**: 52.

Sacks LA, Lee TM, Swancar A. 2014. The suitability of a simplified isotope-balance approach to quantify transient groundwater-lake interactions over a decade with climatic extremes. *Journal of Hydrology*, in press. DOI: 10.1016/j.jhydrol.2013.12.012.

Schafran GC, Driscoll CT. 1993. Flow path-composition relationships for groundwater entering an acidic lake. *Water Resources Research* **29**: 145–154.

Schindler DW, Newbury RW, Beaty KG, Campbell P. 1976. Natural water and chemical budgets for a small Precambrian lake basin in central Canada. *Journal of the Fisheries Research Board of Canada* **33**: 2526–2543.

 

Schmidt C, Bayer-Raich M, Schirmer M. 2006. Characterization of spatial heterogeneity of groundwater–stream water interactions using multiple depth streambed temperature measurements at the reach scale. *Hydrology and Earth System Sciences Discussions* **3**: 1419–1446.

Schneider RL, Negley TL, Wafer C. 2005. Factors influencing groundwater seepage in a large, mesotrophic lake in New York. *Journal of Hydrology* **310**: 1–16.

Schumann D. 1973. Annual variation of seepage of lakes in the moraine area of the German Democratic Republic. *Hydrology of Lakes IAHS Publication* **109**: 101–108.

Schuster PF, Reddy MM, LaBaugh JW, Parkhurst RS, Rosenberry DO, Winter TC, Antweiler RC, Dean WE. 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.

Sebestyen SD, Schneider RL. 2001. Dynamic temporal patterns of nearshore seepage flux in a headwater Adirondack lake. *Journal of Hydrology* **247**: 137–150.

Sebestyen SD, Schneider RL. 2004. Seepage patterns, pore water, and aquatic plants: hydrological and biogeochemical relationships in lakes. *Biogeochemistry* **68**: 383–409.

Sebok E, Duque C, Kazmierczak J, Engesgaard P, Nilsson B, Karan S, Frandsen M. 2013. High-resolution distributed temperature sensing to detect seasonal groundwater discharge into Lake Væng, Denmark. *Water Resources Research* **49**: 5355–5368.

Selker JS, Thévenaz L, Huwald H, Mallet A, Luxemburg W, van de Giesen N, Stejskal M, Zeman J, Westhoff M, Parlange MB. 2006. Distributed fiber-optic temperature sensing for hydrologic systems. *Water Resources Research* **42**: W12202.

Shaw RD, Prepas EE. 1990. Groundwater–lake interactions: I. Accuracy of seepage meter estimates of lake seepage. *Journal of Hydrology* **119**: 105–120.

Shaw RD, Shaw JFH, Fricker H, Prepas EE. 1990. An integrated approach to quantify groundwater transport of phosphorus to Narrow Lake, Alberta. *Limnology and Oceanography* **35**: 870–886.

Sheets RA, Darner RA, Whitteberry BL. 2002. Lag times of bank filtration at a well field, Cincinnati, Ohio, USA. *Journal of Hydrology* **266**: 162–174.

Shepard BG, Hartman GF, Wilson WJ. 1986. Relationships between stream and intragravel temperatures in coastal drainage, and some implications for fisheries workers. *Canadian Journal of Fisheries and Aquatic Sciences* **43**: 1818–1822.

Shepherd RG. 1989. Correlations of permeability and grain size. *Ground Water* **27**: 633–638.

Silliman SE, Booth DF. 1993. Analysis of time-series measurements of sediment temperature for identification of gaining vs. losing portions of Juday Creek, Indiana. *Journal of Hydrology* **146**: 131–148.

Simpkins WW. 2006. A multiscale investigation of ground water flow at Clear Lake, Iowa. *Ground Water* **44**: 35–46.

Smart PL, Smith DJ. 1976. Water tracing in tropical regions. The use of fluorometric techniques in Jamaica. *Journal of Hydrology* **30**: 179–195.

Song C, Huang B, Ke L, Richards KS. 2014. Seasonal and abrupt changes in the water level of closed lakes on the Tibetan Plateau and implications for climate impacts. *Journal of Hydrology* **514**: 131–144.

Sonzogni WC, Lee GF. 1974. Nutrient sources for Lake Mendota – 1972. *Transactions of the Wisconsin Academy Sciences Arts and Letters* **62**: 133–164.

Sophocleous M 2000. From safe yield to sustainable development of water resources – the Kansas experience. *Journal of Hydrology* **235**: 27–43.

Stark JR, Armstrong DS, Zwilling DR. 1994. Stream–aquifer interactions in the Straight River area, Becker and Hubbard Counties, Minnesota. *U.S. Geological Survey Water-Resources Investigations Report* **94-4009**: 83.

Stauffer RE. 1985. Use of solute tracers released by weathering to estimate groundwater inflow to seepage lakes. *Environmental Science and Technology* **19**: 405–411.

Stets EG, Winter TC, Rosenberry DO, Striegl RG. 2010. Quantification of surface water and groundwater flows to open- and closed-basin lakes in a headwaters watershed using a descriptive oxygen stable isotope model. *Water Resources Research* **46**: W03515. doi: 03510.01029/02009WR007793.

Stonestrom DA, Constantz J. 2003. Heat as a tool for studying the movement of ground water near streams. *U.S. Geological Survey Circular* **1260**: 96.

Strack ODL. 1999. Principles of the analytic element method. *Journal of Hydrology* **226**: 128–138.

Sutula M, Day JW, Cable J, Rudnick D. 2001. Hydrological and nutrient budgets of freshwater and estuarine wetlands of Taylor Slough in Southern Everglades, Florida (U.S.A.). *Biogeochemistry* **56**: 287–310.

Swarzenski PW, Simonds FW, Paulson AJ, Kruse S, Reich C. 2007. Geochemical and geophysical examination of submarine groundwater discharge and associated nutrient loading estimates into Lynch Cove, Hood Canal, WA. *Environmental Science and Technology* **41**: 7022–7029.

Taniguchi M, Fukuo Y. 1993. Continuous measurements of ground-water seepage using an automatic seepage meter. *Ground Water* **34**: 675–679.

Taniguchi M, Fukuo Y. 1996. An effect of seiche on groundwater seepage rate into Lake Biwa, Japan. *Water Resources Research* **32**: 333–338.

Taniguchi M, Burnett WC, Cable JE, Turner JV. 2002. Investigation of submarine groundwater discharge. *Hydrological Processes* **16**: 2115–2129.

Thies H, Nickus U, Arnold C, Psenner R. 2002. A hydrological tracer experiment with LiCl in a high mountain lake. *Hydrological Processes* **16**: 2329–2337.

Tiedeman C, Gorelick SM. 1993. Analysis of uncertainty in optimal groundwater contaminant capture design. *Water Resources Research* **29**: 2139–2153.

Tomassoni G. 2000. A federal statutory/regulatory/policy perspective on remedial decision-making with respect to ground-water/surface-water interaction. Proceedings of the Ground-Water/Surface-Water Interactions Workshop, Denver, Colorado, 13–14.

Toran L, Johnson M, Nyquist J, Rosenberry D. 2010. Delineating a road-salt plume in lakebed sediments using electrical resistivity, piezometers, and seepage meters at Mirror Lake, New Hampshire, U.S.A. *Geophysics* **75**: WA75–WA83.

Vallet-Coulomb C, Legesse D, Gasse F, Travi Y, Chernet T. 2001. Lake evaporation estimates in tropical Africa (Lake Ziway, Ethiopia). *Journal of Hydrology* **245**: 1–18.

Vanek V. 1991. Riparian zone as a source of phosphorus for a groundwater-dominated lake. *Water Research* **25**: 409–418.

Vaux WG. 1968. Intragravel flow and interchange of water in a streambed. *Fishery Bulletin* **66**: 479–489.

Virdi ML, Lee TM, Swancar A, Niswonger RG. 2013. Simulating the effect of climate extremes on groundwater flow through a lakebed. *Groundwater* **51**: 203–218.

Voss C. 2011a. Editor's message: groundwater modeling fantasies – part 1, adrift in the details. *Hydrogeology Journal* **19**: 1281–1284.

Voss C. 2011b. Editor's message: groundwater modeling fantasies – part 2, down to earth. *Hydrogeology Journal* **19**: 1455–1458.

Warnick CC. 1951. Methods of measuring seepage loss in irrigation canals. *University of Idaho Engineering Experiment Station Bulletin* **No. 8**; 42.

Warren DR, Sebestyen SD, Josephson DC, Lepak JM, Kraft CE. 2005. Acidic groundwater discharge and in situ egg survival in redds of lake-spawning brook trout. *Transactions of the American Fisheries Society* **134**: 1193–1201.

Wassen MJ, Grootjans AP. 1996. Ecohydrology: an interdisciplinary approach for wetland management and restoration. *Vegetatio* **126**: 1–4.

Weilhartner A, Muellegger C, Kainz M, Mathieu F, Hofmann T, Battin TJ. 2012. Gravel pit lake ecosystems reduce nitrate and phosphate concentrations in the outflowing groundwater. *Science of the Total Environment* **420**: 222–228.

Wentz DA, Rose WJ. 1991. Hydrology of Lakes Clara and Vandercook in north-central Wisconsin. *U.S. Geological Survey Water-Resources Investigations Report* **89-4204**: 24.

Wentz DA, Rose WJ, Webster KE. 1995. Long-term hydrologic and biogeochemical responses of a soft water seepage lake in north central Wisconsin. *Water Resources Research* **31**: 199–212.

Wetzel RG. 1999. Plants and water in and adjacent to lakes. In *Ecohydrology*. Baird AJ, Wilby RL (eds). Routledge: New York; 269–299.

Wetzel RG. 2001. *Limnology: Lake and River Ecosystems*. Academic Press: London; 1006.

 

Wiese B, Nützmann G. 2009. Transient leakance and infiltration characteristics during lake bank filtration. *Ground Water* **47**: 57–68.

Winter TC. 1976. Numerical simulation analysis of the interaction of lakes and ground water. *U.S. Geological Survey Professional Paper* **1001**: 45.

Winter TC. 1978. Numerical simulation of steady state three-dimensional groundwater flow near lakes. *Water Resources Research* **14**: 245–254.

Winter TC. 1981. Effects of water-table configuration on seepage through lakebeds. *Limnology and Oceanography* **26**: 925–934.

Winter TC. 1983. The interaction of lakes with variably saturated porous media. *Water Resources Research* **19**: 1203–1218.

Winter TC. 1996. Hydrological and biogeochemical research in the Shingobee River Headwaters Area, north-central Minnesota. *U.S. Geological Survey Water Resources Investigations Report* **96-4215**: 210.

Winter TC. 1999. Relation of streams, lakes, and wetlands to groundwater flow systems. *Hydrogeology Journal* **7**: 28–45.

Winter TC, LaBaugh JW, Rosenberry DO. 1988. The design and use of a hydraulic potentiomanometer for direct measurement of differences in hydraulic head between groundwater and surface water. *Limnology and Oceanography* **33**: 1209–1214.

Winter TC, Harvey JW, Franke OL, Alley WW. 1998. Ground water and surface water: a single resource. *U.S. Geological Survey Circular* **1139**: 79.

Winter TC, Rosenberry DO, LaBaugh JW. 2003. Where does the ground water in small watersheds come from? *Ground Water* **41**: 989–1000.

Woessner WW, Sullivan KE. 1984. Results of seepage meter and mini-piezometer study, Lake Mead, Nevada. *Ground Water* **22**: 561–568.

Yihdego Y, Becht R. 2013. Simulation of lake-aquifer interaction at Lake Naivasha, Kenya using a three-dimensional flow model with the high conductive technique and a DEM with bathymetry. *Journal of Hydrology* **503**: 111–122.

Yihdego Y, Webb J. 2012. Modelling of seasonal and long-term trends in lake salinity in southwestern Victoria, Australia. *Journal of Environmental Management* **112**: 149–159.

Zhou S, Kang S, Chen F, Joswiak DR. 2013. Water balance observations reveal significant subsurface water seepage from Lake Nam Co, south-central Tibetan Plateau. *Journal of Hydrology* **491**: 89–99.

 