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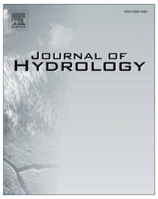

An approach to improve direct runoff estimates and reduce uncertainty in the calculated groundwater component in water balances of large lakes

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SUMMARY

Groundwater is important in the overall water budget of a lake because it affects the quantity and quality of surface water and the ecological health of the lake. The water balance equation is frequently used to estimate the net groundwater flow for small lakes but is seldom used to determine net groundwater flow components for large lakes because: (1) errors accumulate in the calculated groundwater term, and (2) there is an inability to accurately quantify the direct runoff component. In this water balance study of Lake Pyhäjärvi (155 km^2) in Finland, it was hypothesized a hydrograph separation model could be used to estimate direct runoff to the lake and, when combined with a rigorous uncertainty analyses, would provide reliable net groundwater flow estimates. The PART hydrograph separation model was used to estimate annual per unit area direct runoff values for the watershed of the inflowing Yläneenjoki River (a subwatershed of the lake) which were then applied to other physically similar subwatersheds of the lake to estimate total direct runoff to the lake. The hydrograph separation method provided superior results and had lower uncertainty than the common approach of using a runoff coefficient based method. The average net groundwater flow into the lake was calculated to be +43 mm per year (+3.0% of average total inflow) for the 38 water years 1971–2008. It varied from −197 mm to 284 mm over that time, and had a magnitude greater than the uncertainty for 17 of the 38 years. The average indirect groundwater contribution to the lake (i.e., the groundwater part of the inflowing rivers) was 454 mm per year (+32% of average total inflow) and demonstrates the overall importance of groundwater. The techniques in this study are applicable to other large lakes and may allow small net groundwater flows to be reliably quantified in settings that might otherwise be unquantifiable or completely lost in large uncertainties.

1. Introduction

The flow of groundwater into lakes is important because it can affect: the quantity and quality of the surface water (LaBaugh et al., 1995; Winter, 1999; Dubrovsky et al., 2010; Fruh, 1967; Bruce et al., 2009); the ecosystem health (Hayashi and Rosenberry, 2002); the distribution of aquatic life (Baird and Wilby, 1999; Rosenberry et al., 2000); and the quality of the fish habitat (Power et al., 1999). Estimates of net groundwater discharge to a lake can indicate the relative importance of groundwater in the water budget, but accurately quantifying total discharge can be a challenge. Groundwater flows into and out of lakes can be estimated using: direct point measurements of flow (Cartwright et al., 1979; Cherkauer and Nader, 1989; Harvey et al., 1997, 2000); water balance calculations (Winter, 1981; Sacks et al., 1998; Zacharias et al., 2003); isotopic tracers (Walker and Krabbenhoft, 1998; Stets et al., 2010), and numerical modeling of the lake and its watershed (Feinstein et al., 2010; Hoaglund et al., 2002; Mylopoulos et al., 2007). Point measurement techniques are useful but impractical to employ on a lake-wide basis, particularly when the lake is large and there is substantial spatial heterogeneity in lakebed deposits and flows. Likewise, geochemical methods are difficult to use in large lakes because of spatial variability in water quality and challenges in defining appropriate end member concentrations for calculating mixing ratios. Numerical models that quantify groundwater flow are potentially very useful and can handle considerable spatial and temporal complexities; however, the lack of field data to constrain and populate

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these models generally results in major simplifying assumptions which produce uncertainties and errors that are either unknown or not readily quantifiable. The water balance method requires the quantification of inflows (precipitation, direct runoff, surface water inflows), outflows (evaporation, surface water outflows), and change in lake storage to calculate net groundwater flow. If properly done, the water balance equation has the potential to provide accurate estimates of the net groundwater flow (i.e., groundwater inflow minus groundwater outflow, which represents a minimum value for groundwater discharge) with potentially less effort and uncertainty than is associated with the other techniques. Despite this potential, the water balance method tends not to be used to determine net groundwater discharges for large lakes (Quinn and Guerra, 1986; Neff and Killian, 2003; Lenters, 2004; Neff and Nicholas, 2005).

There are two main reasons why water balances performed on large lakes do not attempt to quantify groundwater–surface water exchanges and, instead, either assume groundwater contributions are insignificant (i.e., are zero) or simply lump them together with the direct runoff into a combined runoff term. The first reason is that net groundwater flow is usually solved for as an unknown in the water balance equation, which means all the uncertainty in other components translates to and accumulates in the uncertainty of the groundwater component. Even what appear to be small relative errors on large components (e.g., precipitation or evaporation) may result in errors of substantial absolute magnitude that are larger than the groundwater component being quantified (Winter, 1981; Thodal, 1997). Unfortunately, many studies do not perform the uncertainty analysis necessary to assess the reliability of results even though several studies discuss how to quantify uncertainties (Winter, 1981; Lee and Swancar, 1997; Winter and Rosenberry, 2009; Neff and Nicholas, 2005). Even in studies where the net groundwater flow in the water budget as a percent of total inflow appeared to be important (e.g., Zacharias et al., 2003; Demlie et al., 2007; Ayenew and Gebreegziabher, 2006), uncertainty analysis of the groundwater term has not been included. Without the uncertainty analyses, it is not known if the calculated values of net groundwater flow are accurate and representative.

The second reason why net groundwater discharge is not calculated for lakes is because it requires the direct runoff component (i.e., non-channelized overland flow and interflow) be quantified and this is often neglected or cannot be done with confidence or certainty due to a lack of suitable methods. The direct runoff component is usually ignored for large lakes (Neff and Nicholas, 2005; Lenters, 2004; Neff and Killian, 2003), and little work has been done in the last three decades to specifically estimate non-channelized runoff to lakes despite its inclusion in data-intensive time-stepping models such as SWAT (e.g., Menking et al., 2003), MOD-HMS (e.g., Panday and Huyakorn, 2004), and WATLAC (e.g., Zhang, 2011). The few methods that have been applied have been for small lakes and were originally developed for streams. The methods include: the curve number (CN) method (Natural Resources Conservation Service, 2004; Motz et al., 2001), the use of coefficients associated with varying land use and permeability (Sacks et al., 1998; Dames and Moore, 1992), and the extrapolation of hydrograph separation results (Newbury and Beaty, 1980; Schindler et al., 1976). The hydrograph separation model approach is appealing because it represents an empirical relationship derived from and calibrated to a portion of that particular lake's watershed and takes into account the actual physical and climatological conditions at the site without relying on models that extrapolate and use empirical runoff relationships derived at other sites with different conditions. The hydrograph separation method has not been applied to large lakes, and there is a need to determine its applicability and accuracy when applied to large lakes.

An opportunity to examine these issues concerning quantification of net groundwater discharge and direct runoff to large lakes was presented when concerns were expressed regarding the current and future water quality of Lake Pyhäjärvi (155 km^2), located in glacial terrain near Säkylä, Finland. The concerns focused on the eutrophication of the lake resulting in part from the effects of the agricultural watershed around the lake, along with impacts on the fishing industry, recreational enjoyment, and overall ecological integrity of the lake (Kirkkala, 2014). Early studies of the lake (Hyvärinen et al., 1973; Kuusisto, 1975; Järvinen, 1978; Eronen et al., 1982) either insufficiently assessed the net groundwater component of the lake's water budget or assumed it was negligible (i.e., zero); however, recent work indicated significant groundwater discharge might occur through an esker that intersects Lake Pyhäjärvi and at other specific locations along the shoreline (Rautio, 2009; Korkka-Niemi et al., 2011; Rautio and Korkka-Niemi, 2011). Moreover, indirect groundwater discharge, where groundwater discharges to a river and then is transported into the lake by the river, can also influence the quantity and quality of water in large lakes (Holtschlag and Nicholas, 1998; Neff et al., 2005). It was hypothesized that using historical climatological and hydrological data, a carefully conducted water balance study could be used to successfully estimate the net groundwater flow into the lake, provided that a rigorous uncertainty analysis was performed to characterize potential errors and that a suitable method for determining direct runoff could be used. A specific objective of this study was to evaluate whether a hydrograph separation method that has been applied to streams and small lakes to estimate direct runoff could be successfully applied to a large lake. This study (1) provides the first rigorous water balance and estimates of net groundwater flow and indirect groundwater discharge for Lake Pyhäjärvi, (2) demonstrates the importance of uncertainty analyses, and (3) successfully tests the hypothesis that using a hydrograph separation method to estimate the direct runoff component to a large lake is a viable approach for water balances. This approach could be applicable to other large water bodies in various landscape settings.

2. Background

Lake Pyhäjärvi (60°54′–61°06′N, 22°09′–22°25′E) is the largest lake in southwestern Finland (155 km^2) and is a valuable fishery and recreational area (Ventelä et al., 2007, 2005). The lake is quite shallow (5.4 m on average) with a maximum depth of 26 m (e.g., Kirkkala, 2014), and it makes up a large percentage (25%) of its watershed (Fig. 1). Lake Pyhäjärvi's watershed (616 km^2) is predominately agricultural land (Luoto, 2000; Häkkinen, 1996). The ground elevations in the watershed range from about 40 to 145 masl, and it is relatively flat with an average topographic slope of 2.8% (MML, 2009c; ESRI, 2010). Two rivers (Yläneenjoki and Pyhäjoki) are gauged, drain the agricultural lands in the south and east, and flow into the lake; while one river (Eurajoki, also gauged) flows from the northern end of the lake at Kauttua Falls and flows to the Baltic Sea. The remaining area (304 km^2) of the lake's watershed is ungauged and consists of four subwatersheds with single channels that drain water into the lake and another six subwatersheds that do not have significant drains or channels (Fig. 1).

The landscape around Lake Pyhäjärvi has been sculpted by glacial erosion and deposition. The surficial geology around the lake is shown in Fig. 2 and consists primarily of thin, discontinuous till layers, numerous granite and sandstone bedrock outcrops, and to a lesser extent clays, peats, and silts. Fig. 3 shows that the watershed contains very few coarse grained aquifer deposits. Among these is the Kuivalahti-Säkylä esker, which is connected to the

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