Can δ^{18}O of lakes be used to measure lake water residence times? Simulation of groundwater-lake interactions and lake water budgets at the catchment scale

Peter Engesgaard, Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark
Trine Enemark, College of Science and Engineering, Flinders University South Australia
Thomas Demant Lübbers, Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark

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Introduction

The water residence time of lakes is important for many in-lake chemical and biological processes. Wouldn’t it be nice if it was possible to estimate the water residence time of lakes by simply measuring a constituent in the lake water?

We are currently exploring the possibility of using δ^{18}O as a tracer for this for groundwater-dominated lakes. The hypothesis is that lakes with short residence times (T) will have a δ^{18}O signal near that of groundwater, while lakes with longer residence times will be enriched in δ^{18}O due to evaporative fractionation. This is only possible if we at the same time can estimate water residence time by some other means so that a δ^{18}O-T relation can be derived. We pursue this by applying integrated 3D catchment-scale groundwater-stream-lake modelling. If such a relation can be established we then also have the ability to predict how future changes in climate will affect catchment hydrology, groundwater-lake interactions, lake water budget, and, thus, future changes in lake water residence time.

Isotopic data

The monthly changes in δ^{18}O in 13 lakes in two catchments (total size of 160 km²) were determined for 1 year. The two catchments are separated by the main North-South water shed boundary in Jutland, Denmark, Figure 1. Based on the isotopic data it was possible to derive the mean δ^{18}O lake concentrations and standard deviations.

Figure 1: The two catchments of the study area. The Western catchment (Holtum, 126 km²) with the two major lakes; the topographically high-lying Lake Hampen and the lower-lying lake Ejstrup. The Eastern catchment (Mattrup, 38 km²) with the remaining 11 lakes.
A 3D steady-state groundwater-stream-lake model was developed with Modflow using the SFR (stream) and LAK (lake) packages. Drains were specified at one meter depth everywhere (but were only active in near-stream areas). The hydrogeological model was built in GeoScene3D. The upper geology consist of permeable Quaternary sands (in direct contact with streams and lakes) followed by Quaternary clay, and then Miocene sand. The model was calibrated using PEST (hydraulic conductivities) and manually (lake conductance) and with the use of mean heads from 326 wells and mean lake stages from the 13 investigated lakes. As an output we get the lake water budgets and can compute residence time as \( T = \frac{V}{Q} \), where \( V \) is the simulated lake volume and \( Q \) is the simulated total discharge or recharge. The parameter uncertainties obtained by PEST allowed for the quantification of the uncertainty on estimates of lake water residence times.

**Results: \( \delta^{18}O-T \) relation**

Figure 2 shows the \( \delta^{18}O-T \) relation. A group of lakes (Ejstrup, Stigholm, and Halle) fall near \( \delta^{18}O \) of groundwater with very short residence times (few weeks to months). These three lakes are all located at the downstream/discharge end of the two catchments (with large catchments). Lake Grane Langsø, Hampen and Kalgaard, on the other hand, are located near the topographical divide (with small catchments) and have much longer residence times (> 5 years). The remaining lakes fall in-between. Parameter uncertainty may lead to uncertainties of up to close to 2 years (Lake Kongso). Residence times for lakes with a \( \delta^{18}O > -4^\circ/oo \) can be difficult to estimate except that \( T > \sim 2-3 \) years.

![Figure 2: \( \delta^{18}O-T \) relation (purple symbols and line). The estimated uncertainty on \( T \) is shown by the horizontal dashed line. The measured standard deviation of lake \( \delta^{18}O \) is shown by vertical dashed line. Average groundwater \( \delta^{18}O \) is shown by blue circle. Light blue line is measured variability in rain over the catchment [1].](image)

**Conclusion**

The \( \delta^{18}O-T \) relationship could provide a mean for easily ‘measuring’ the lake water residence time by simply sampling the lake and using a relationship like this for estimating the residence time. Groundwater-dominated lakes can also be important for the export of nutrients from catchments. Specifically for this study area, a lake like Lake Ejstrup receives roughly 10% of the recharge across the whole catchment and, as such, not only has an impact on the hydrology and flow system, but also on the nutrient turn-over in the agricultural-dominated landscape. The study also shows that it is possible to integrate the use of regional tracers (such as water stable isotopes) with 3D integrated hydrologic modelling.

Currently, we are working in another catchment with groundwater-dominated lakes to test the general applicability of this idea.

**References**