6. Mass balance of lakes and wetlands

Water level and chemical composition in lakes are controlled by the input and output. We will examine the mass balance of lakes in the context of the hydrologic cycle.

Water balance of a lake

IN - OUT = ΔS (storage change)

IN = P + IS + IG
  + other terms (sewer outlet, snow drift, etc.)

OUT = E + OS + OG
  + other terms (pumping, etc.)

ΔS = Change in the volume of water
Determining the storage

The volume of water in a lake is estimated from the water level (stage) using the stage-volume relationship.

Water level

Water level is measured by a staff gauge or an automatic water level recorder. Float-pulley system is commonly used in automatic recorders. Computer-controlled pressure transducers are becoming popular.

Stage-volume relationship

The stage \((h)\) is measured from the lowest point in the lake.

If the topography of the lake bottom has been surveyed, \(h-V\) and \(h-A_L\) functions can be determined from a digital elevation map (DEM).
Precipitation and evaporation

Precipitation is relatively easy to measure.

Evaporation is estimated or measured by;
- Evaporation map, e.g. Morton (1983).
- Penman method
- Class-A pan on the shore, or on a raft on the lake.

Surface inflow

If no stream discharge data is available, one can estimate annual runoff from a hydrological atlas.

For example, if annual runoff is 700 mm, then annual surface inflow is; \( I_s = 0.7 \times (A_C - A_L) \) m³.

It is desirable to construct gauging stations in inflow and outflow streams and install water level recorders (see D&L, Fig. 16-2). We can estimate stream discharge from a stage-discharge rating curve.

To construct a rating curve, we need to measure the water level \((h)\) and the discharge \((Q)\) in a stream under various conditions.

Velocity-area method

Total discharge \((Q)\) is given by;

\[ Q = A_1 v_1 + A_2 v_2 + \ldots \]

Velocity \((v)\) is measured at “six-tenth” depth.
Dilution gauging

A tracer, commonly NaCl, is injected into the stream at a constant rate. After a sufficient time and travel length, the tracer is mixed completely with stream water. The mass balance of the tracer in the stream is given by;

\[ Q_{inj} C_{inj} + Q_{str} C_b = (Q_{str} + Q_{inj}) C_{str} \]

- \( Q_{inj} \): rate of injection (L/min).
- \( C_{inj} \): concentration in injected water (mg/L).
- \( Q_{str} \): stream discharge
- \( C_{str} \): concentration in water sampled down stream.
- \( C_b \): background concentration in stream water

If \( Q_{str} \) is reasonably constant with time and travel distance,

\[ Q_{str} = Q_{inj} (C_{inj} - C_{str})/(C_{str} - C_b) \]

An excellent description on the area-velocity method, dilution gauging, and other methods can be found in Dingman (2002, Physical Hydrology, Prentice-Hall, pp. 608-623).
Groundwater inflow

Two methods are commonly used to measure groundwater flow.

Seepage meter

Seepage from the bottom sediment is corrected in a plastic bag to estimate specific discharge \( q \) [m/s].

\[
q = \frac{Q}{A}
\]

where \( Q \) [m³/s] is the flow rate and \( A \) [m²] is the area covered by the seepage meter.

Mini-piezometer

A shallow piezometer is installed in the sediment to measure hydraulic head. From Darcy’s law;

\[
q = K \frac{\Delta h}{L}
\]

where \( K \) [m/s] is hydraulic conductivity.

Both of these methods measure a local value of \( q \), which may not represent an entire lake. It is necessary to install a network of the instrument covering the lake and estimate the average \( q \).

When direct measurement is impossible, groundwater flow is assumed to be equal to the residual term in the water balance equation.
Surface outflow and groundwater outflow

These terms are measured or estimated by the same method used to measure or estimate inflow terms.

Water balance equation

\[ P + I_S + I_G - E - O_S - O_G = \Delta V \]  

(1)

Note that; \( P = p \times A_L \) \( E = e \times A_L \)

where \( p \) [m] and \( e \) [m] are the quantity per unit area, and \( P \) [m³] and \( E \) [m³] are total volumes

Note also that \( V \) and \( A_L \) are functions of the water level \( h \). The graphs show an example of such functions for a wetland near Saskatoon.

Application of balance equations

Water balance equation (1) and solute mass balance equation (2, next page) can be used to estimate unknown components in the hydrologic cycle; for example, groundwater inflow and outflow terms.
Solute mass balance of a lake

Solute mass balance is similar to water balance. Each term is multiplied by the concentration. For example;

\[ C_P \text{ (g/m}^3\text{)} \times P \text{ (m}^3\text{)} = \text{mass coming in as precip. (g)} \]

Mass balance equation is

\[ C_P P + C_IS I_S + C_{IG} I_G - C(O_S + O_G) + R_{XN} = \Delta(CV) \quad (2) \]

The concentration of outflow terms are equal to that of lake water, \( C \). The solute mass storage is given by the concentration and the volume of water in the lake \((CV)\).

Measurement of concentration

Samples of stream, groundwater, and lake water provide estimates of \( C_{IS}, C_{IG}, \) and \( C \). The amount of solute coming in as precipitation is usually negligible. If necessary, the value can be estimated from the data of Canadian Air and Precipitation Monitoring Network (CAPMoN) published by Atmospheric Environment Service. For chloride, \( C_P \simeq 0.04 \text{ mg/L} \) in southern Alberta and Saskatchewan.
Chemical reaction term

This term $R_{XN}$ can be positive or negative. For example, dissolved CO$_2$ is generated by biochemical reactions in summer and $R_{XN} > 0$, while SO$_4^{2-}$ is consumed by microorganisms and $R_{XN} < 0$. It is very difficult, if not impossible, to estimate this term. In hydrology, we look at conservative tracer, which do not participate in reactions and $R_{XN} = 0$. Chloride (Cl$^-$) is a commonly used conservative tracer. Deviation of other species from the conservative tracer indicates the sign and magnitude of $R_{XN}$ term.

This diagram shows the mass of each species stored in a wetland near Saskatoon. The mass ($M$) is normalized to the value ($M_0$) on April 12, 1994. Compared to Cl$^-$, CO$_2$ mass increases in summer ($R_{XN} > 0$) and SO$_4^{2-}$ mass decreases in summer ($R_{XN} < 0$).
Reading assignment

Quantifying time-varying ground-water discharge and recharge in wetlands of the northern Florida Everglades


(1) Why is it important to evaluate the flux of groundwater in wetlands?

(2) How is $G_i - G_o$ estimated in this paper? How is the method similar to and different from our laboratory exercises?

(3) What is the tracer being used in this study?

(4) What is the magnitude of $G_i - G_o$ and $G_i$ in terms of mm/day?

(5) Did they find significant groundwater recharge that was not captured by the seepage canal? If so, what is its implication on groundwater quality?