Watershed, hydrologic cycle, water budgets for lakes

See Kalff Chapters 4 and 5

A variety of watershed characteristics (e.g. area, slope, vegetation cover, disturbance) have been shown to impact lake ecology. Sample reference: Thierfelder, T. 1999 "Empirical/statistical modeling of water quality in dimictic glacial/boreal lakes." Journal of Hydrology **220**:186-208. We found that watershed characteristics, such as the amount of wetlands and age of trees were highly correlated with measurements of lake productivity, such as chlorophyll-a concentration, nutrients concentration, and water transparency in lakes in the Clatsop Plain on the north coast of Oregon.

Table 29. Pearson's product-moment coefficients for watershed characteristics in 200-m and 400-m bands and lake water quality (mean of all lake samples). Single underline indicates significance at alpha=0.1; double underline indicates significance at alpha=0.02. d.f.=1 for secchi and TSI secchi, d.f.=2 for all other coefficients. (Note: chlorophyll-a data in summer are missing).

		% of Watershed			
		Wetlands	High and Low Intensity Development	Large and Very Large Conifers	Population
TKN					
	200	-0.5447	0.1619	0.2721	-0.7786
	400	-0.9315	-0.2940	0.2630	-0.6480
TP					
	200	-0.0376	0.4964	-0.8724	0.2103
	400	-0.2192	0.3126	-0.8762	0.2552
Chla					
	200	-0.9949	0.8360	-0.0500	0.0787
	400	-0.7608	0.6319	-0.0561	0.2690
DOC					
	200	0.8404	-0.3407	-0.5647	0.3070
	400	0.6870	-0.1675	-0.5598	0.1606
Secchi					
	200	-0.9653	0.9023	0.1321	-0.2541
	400	-0.9339	0.5133	-0.3812	0.0020
TSI chl					
	200	-0.8839	0.6396	0.2102	0.1906
	400	-0.4799	0.6075	0.2074	0.3390
TSI TP					
	200	-0.0740	0.5680	-0.9187	0.3190
	400	-0.1832	0.4191	-0.9220	0.3678
TSI Secchi					
	200	0.8718	-0.7689	-0.3712	0.4835
	400	0.9931	-0.2872	0.1429	0.2433

From: Sytsma, et al. 2005. Chapter 3. Surface Water Chemistry and Watershed Characterization. Final Report Regional Lake Management Planning for TMDL Development.

A. Hydrologic Cycle

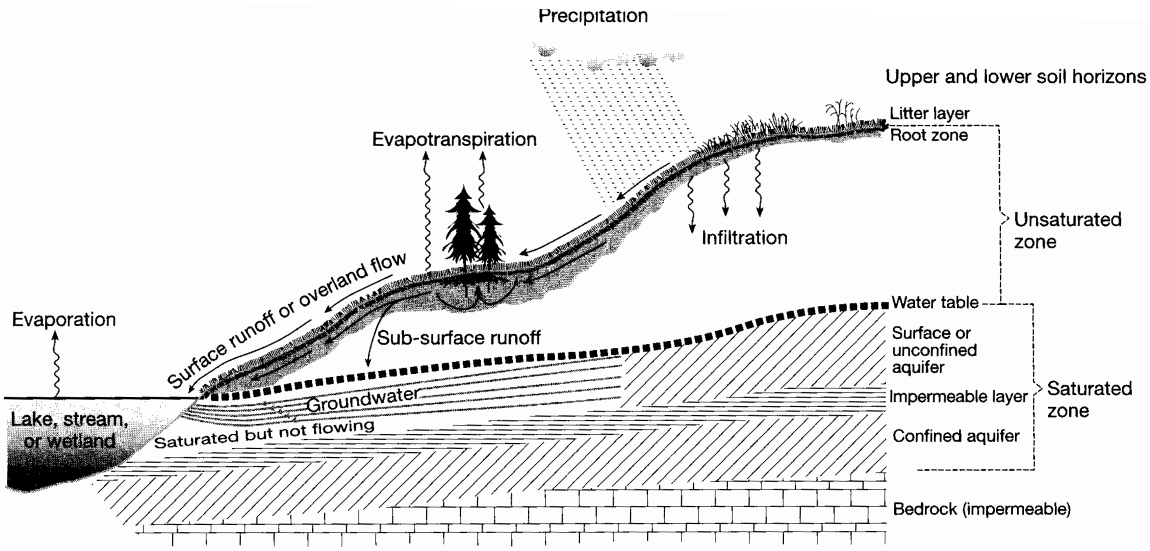


Figure 5–1 Schematic view of water movement in and on catchments, including the flow of groundwater into lakes, streams, or wetlands. Agriculture and other human activities contribute plant nutrients, organic matter, pesticides and other contaminants to runoff and groundwater. *(Greatly modified after Gibbs 1987.)*

Major reservoirs and exchanges See Tables 4-1 and 5-1 of Kalff.)

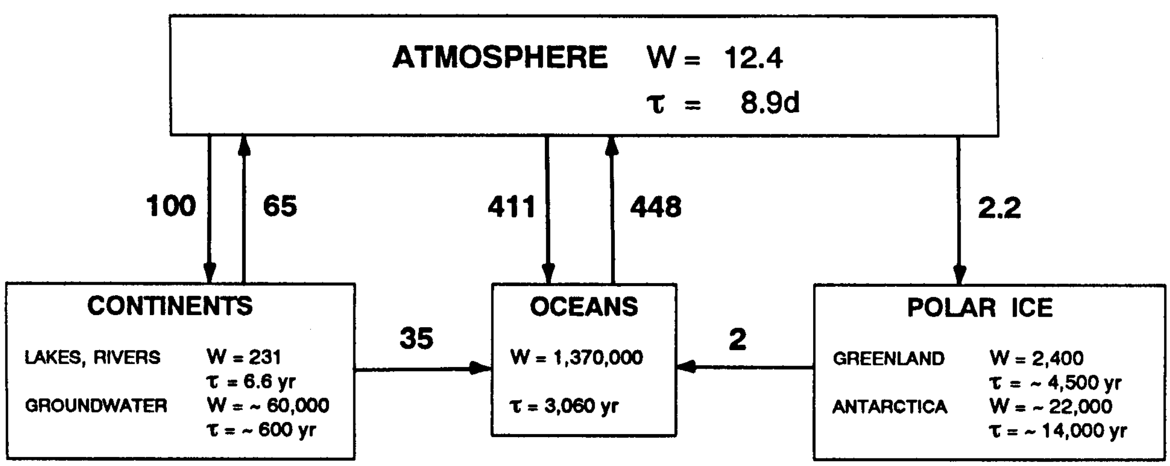


FIGURE 4-2 Global water balance. W = water content in 10^3 km^3, values on arrows = transport in 10^3 km^3 yr^{-1}, and τ = retention time. Estimate of ground water is to a depth of 5 km in the Earth's crust; much of this water is not actively exchanged. (Modified from Flohn, 1973, after L'vovich.)

The *residence time* (WRT of Kalff, p41) of a substance (here water) in a reservoir is obtained by dividing the amount of the substance in the reservoir by the flux of that substance into the reservoir. Thus the residence time in the ocean (From Wetzel):

$$\frac{1{,}370{,}000 \times 10^3 \text{ km}^3}{(35+2+411) \times 10^3 \text{ km}^3 \text{ yr}^{-1}} = 3058 \text{ years}$$

If the amount of the substance in a reservoir is not changing with time (i.e., the reservoir is in *steady state*), the residence time represents the average time a molecule of the substance spends in the reservoir between the time it arrives and the time it leaves. (Table 4-1, p42: Note that there are small discrepancies among various sources of similar information. Data are approximate, and the differences reflect slightly different assumptions about rates and reservoir volumes.)

Lake Water Budgets
A water budget, as the phrase suggests, is a quantification of all hydrologic inflows and outflows. If all hydrologic fluxes could be measured precisely, and if the lake surface elevation remains constant, the volume of water entering a lake would equal the volume leaving the lake.

Terms of a water budget include:
- Inflow
    - Precipitation
    - Streams/tributaries
    - Overland flow
    - Groundwater
- Outflow
    - Stream outlet
    - Groundwater
    - Evapotranspiration

Measurement of terms in water budget

Stream discharge

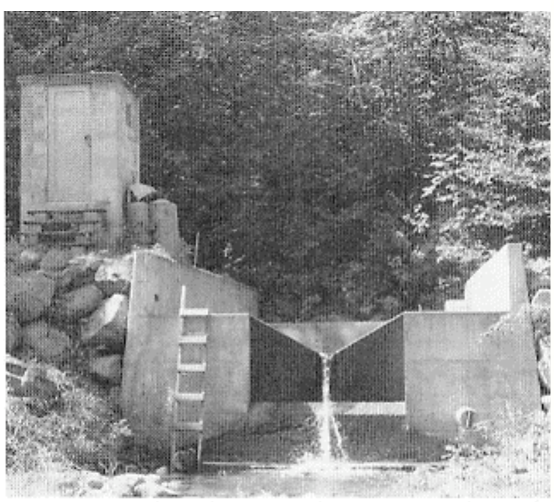
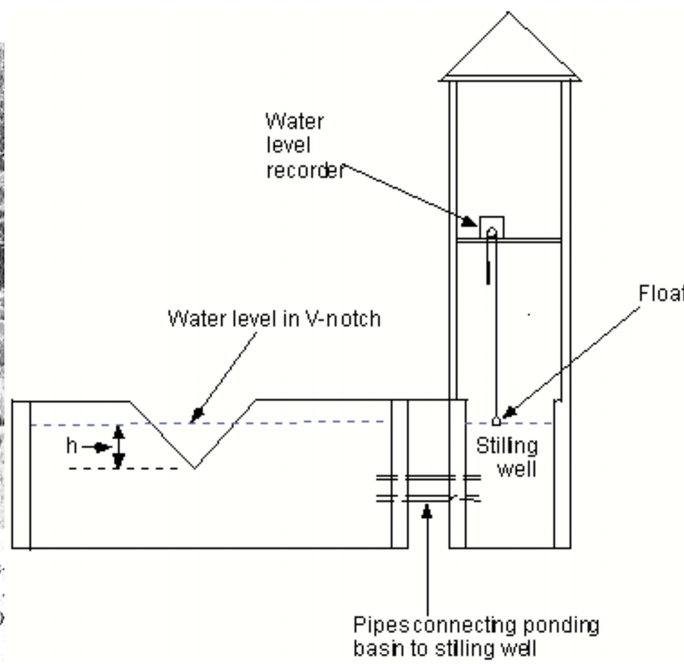


Figure 5–3 A calibrated weir used to determine stream discharge and housing for the water level recorder used to measure changes in discharge over time. *(Photo courtesy of J.D Cunningham, Visuals Unlimited.)*



The flow of water in a stream constantly changes in response to precipitation patterns. There is no "average" flow. As a consequence, a complete accounting of the water budget (inflows and outflows) of a lake is not easily obtained. A complete accounting would necessarily include detailed data collection of a representative sample of storm events and intervening dry periods for all seasons over a number of years.

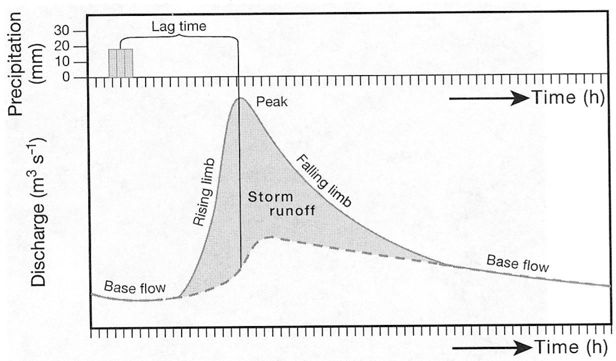


Figure 5–4 Diagrammatic stream hydrograph resulting from single storm event. *(After Beaumont 1975.)*

Note: Base flow = groundwater contribution to stream discharge

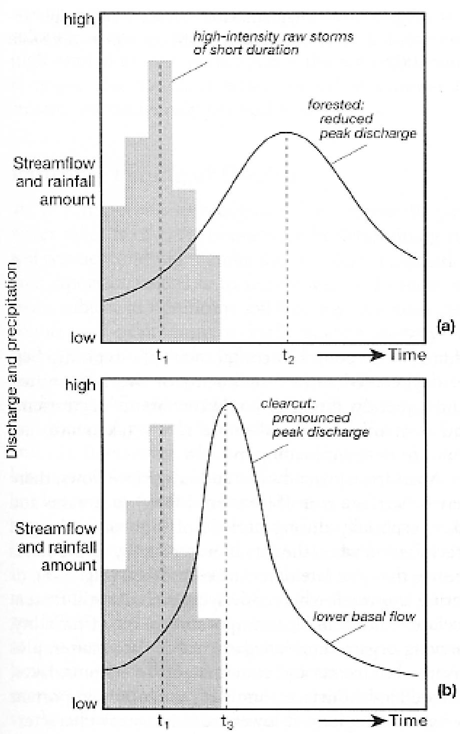


Figure 5–2 The effects of vegetation clearance on discharge. For equal rainfall, there is greater infiltration in the naturally vegetated catchment (a) than in the cleared catchment (b). The result is a larger but shorter flood, followed by a reduced base flow in the cleared catchment. However, high evapotranspiration by low latitude forests (in semi-arid regions) will reduce the annual net discharge as well as the base flow below that of clear-cut catchments during the season of lowest run-off. *(Modified from Whitlow 1983, in Allanson et al. 1990.)*

Evaporation/transpiration

Evaporation pan. These are at some weather stations. Typically automated.

Transpiration is typically modeled based upon empirical data from crops.

TABLE 4-3 Comparison of Water Loss from a Stand of the Emergent Aquatic Macrophyte *Phragmites communis* to That of Open Water, Berlin, Germany, 1950[a]

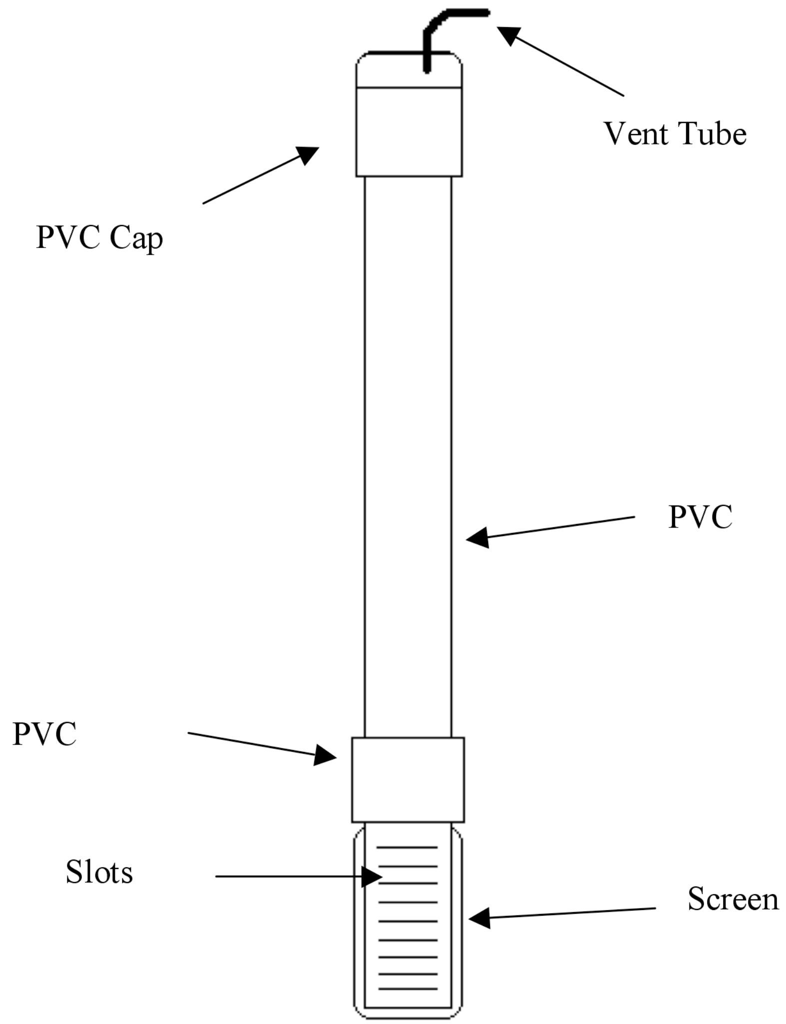
Date	*Evapotranspiration (kg m^{-2} day^{-1})*[b]	*Evaporation (kg m^{-2} day^{-1})*[b]	*Ratio of transpiration to evaporation*
11 May	3.20	3.24	1.0
25 May	2.50	1.44	1.6
27 July	9.82	2.24	4.4
22 August	16.01	2.29	7.0
17 October	2.79	0.79	3.9

[a] Modified from Gessner (1959), after Kiendl.
[b] mm day^{-1} or $\times$ 0.1 = g cm^{-2} day^{-1}.

Groundwater

Often difficult to measure and as a consequence often calculated by difference
Piezometers and seepage meters of various designs have been used to estimate groundwater input to lakes. See report on Clatsop Lakes by Neilson and Cummings.

Piezometer used to measure potentiometric surface of groundwater in the Clatsop Plains.



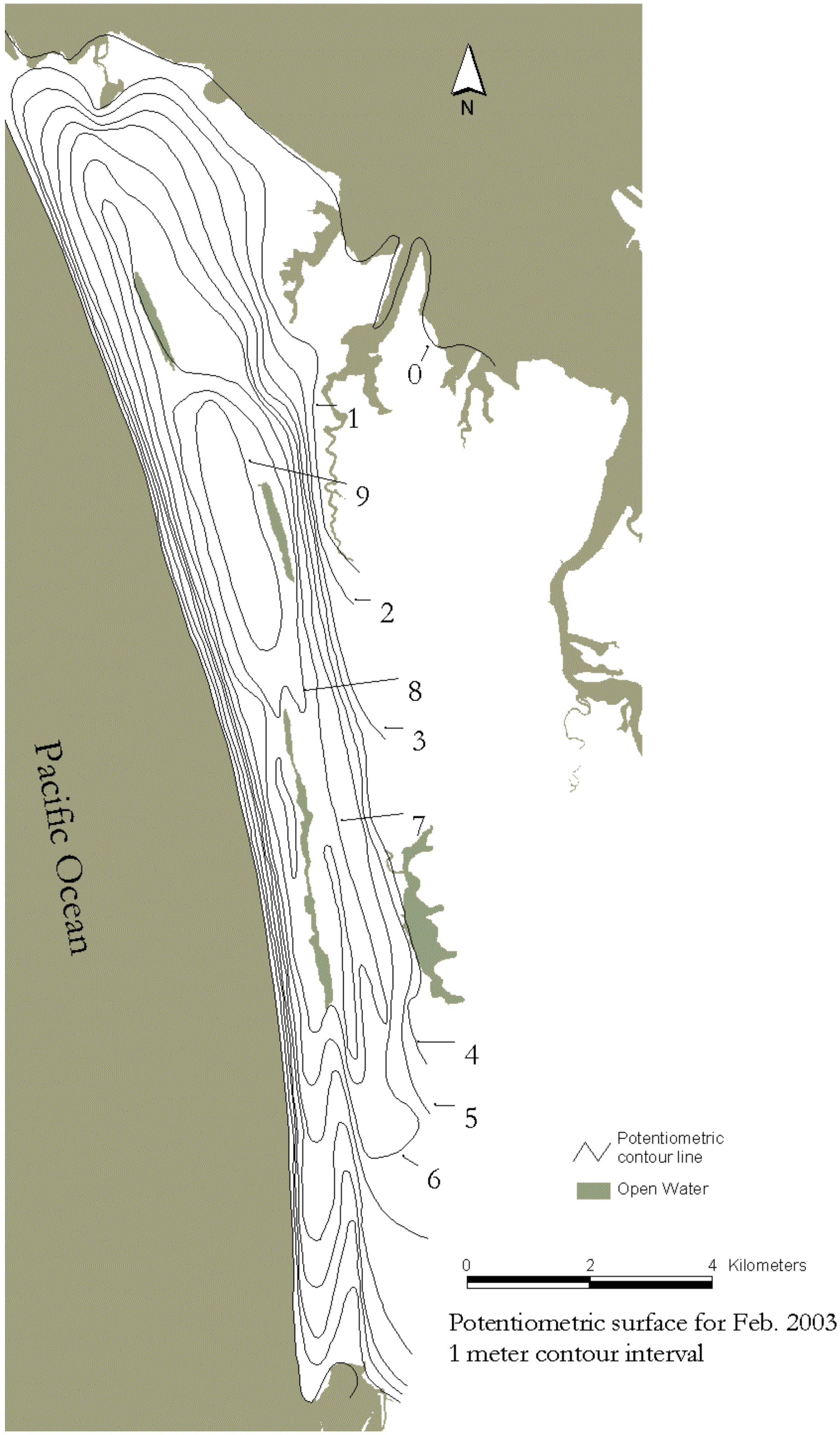
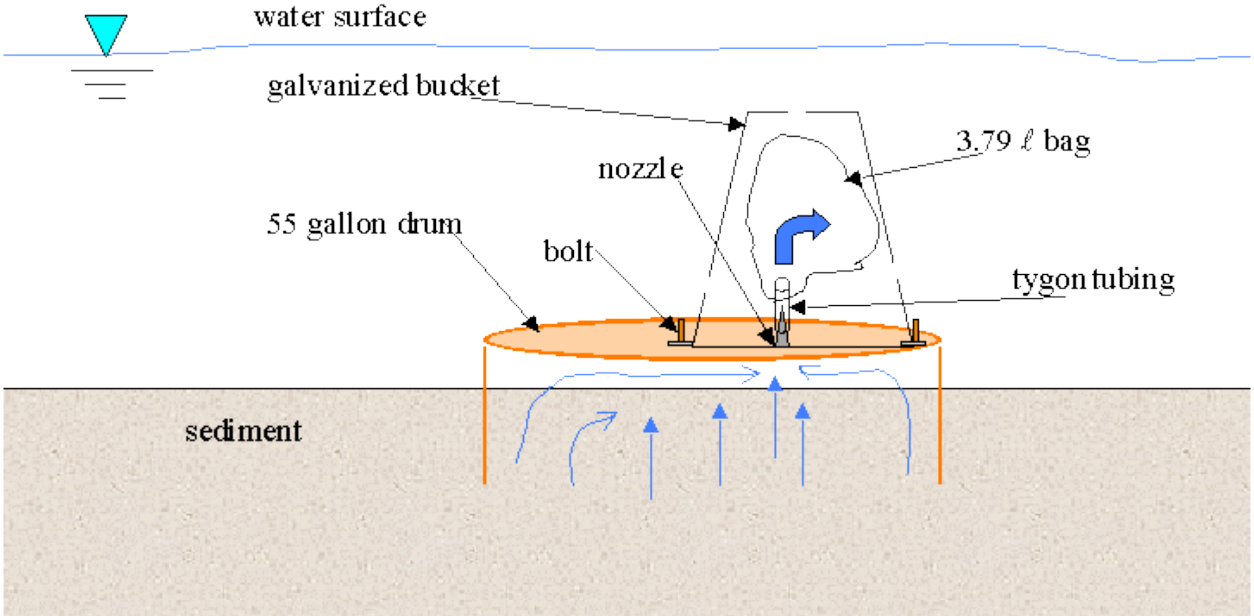


Figure 1: Potentiometric map for the Clatsop Plains aquifer February 2004.

Subsurface seepage meters are used to estimate groundwater flow into lakes.



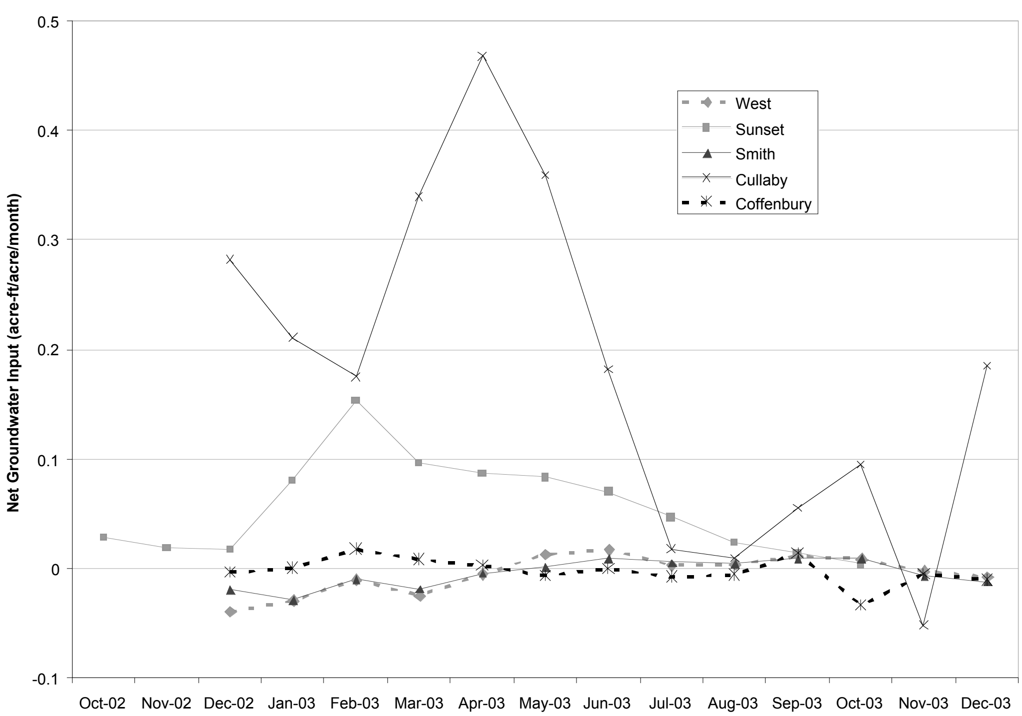
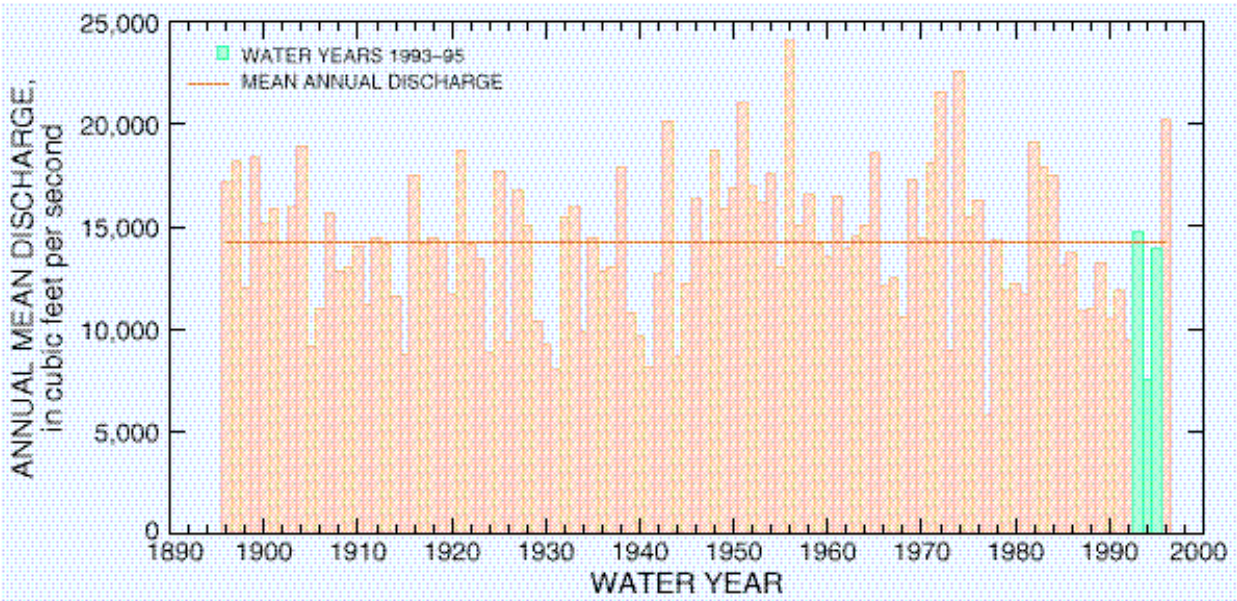


Figure 2: Comparison of net groundwater input for lakes on the Clatsop Plains, OR.

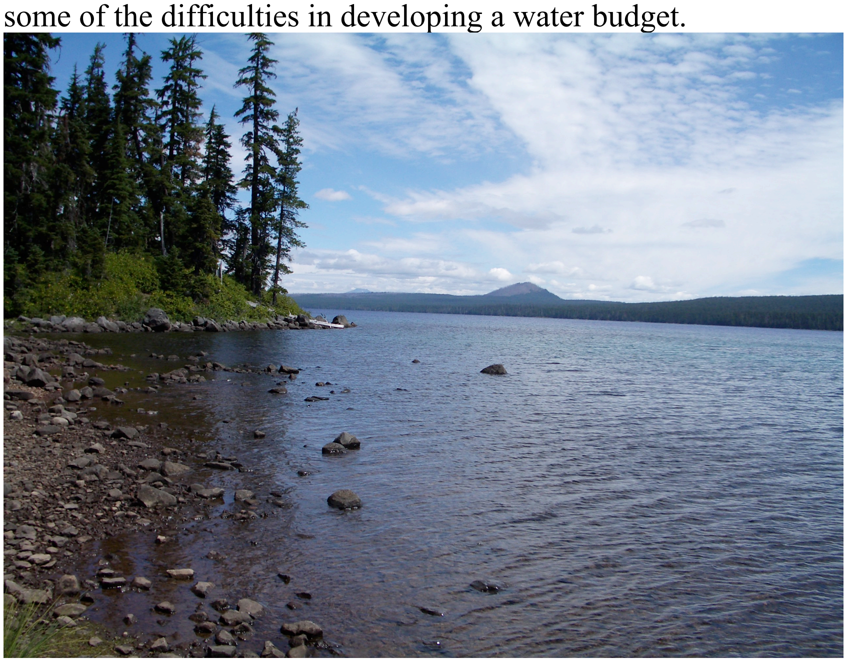
Substantial inter-annual variation in precipitation requires caution when constructing or reviewing a water budget.



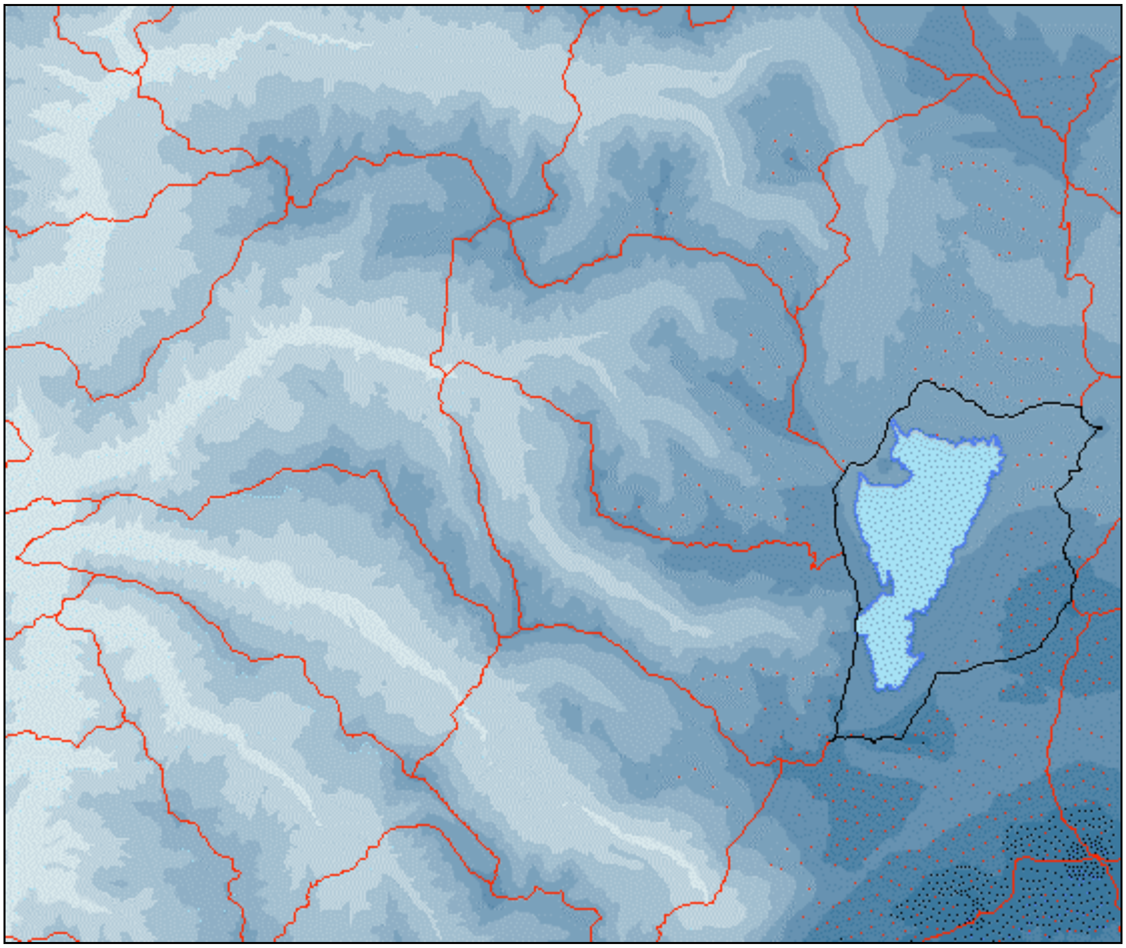
In addition to local variation in weather there are global climate patterns. Some of the variation is somewhat predictable or even cyclic, such as the ENSO (El Nino Southern Oscillation) cycles of the Pacific.

Waldo Lake

Waldo Lake precipitation and water budget illustrate the inter-annual variation in hydrology and some of the difficulties in developing a water budget.



Waldo Lake

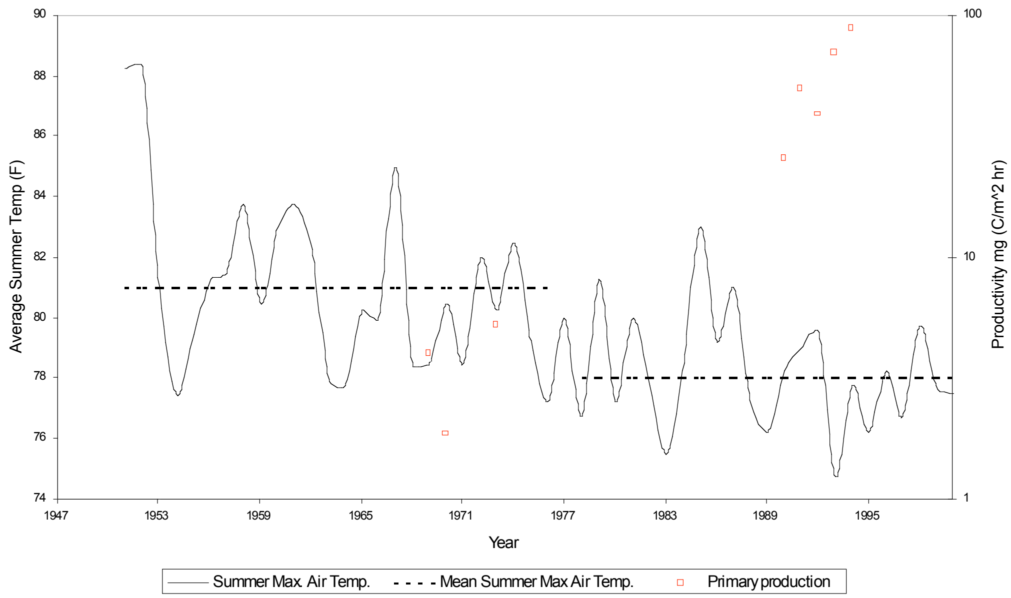


Interpolated precipitation field for water year 2000 for the Waldo Lake watershed and vicinity. Darker shading indicated higher amounts of precipitation. The Waldo Lake watershed is outlined in black. Other drainage basins are outlined in red.

It was possible to estimate the total amount of water that left the Waldo Lake basin as a combination of evapotranspiration and groundwater recharge. The calculation could only be computed for the time period from 1981 through 1994 based on streamflow data availability. The results indicated that, <u>of the average annual precipitation of 73.6 inches, 56.6 inches of water leave the basin as either ET or groundwater recharge. That is, an annual average of 81% of the streamflow entering the lake, the vast majority of water entering the lake, does not exit as outflow from the lake.</u>

For Waldo Lake, surface climate and streamflow were related to Pacific Decadal Oscillation (PDO) in a manner that was consistent with other locations in the Pacific Northwest. Both precipitation and streamflow have statistically significantly higher values during the cool phase of the PDO and lower values during the warm phase. In addition, summer maximum temperatures have been higher during the cool phase of the PDO than during the warm phase.

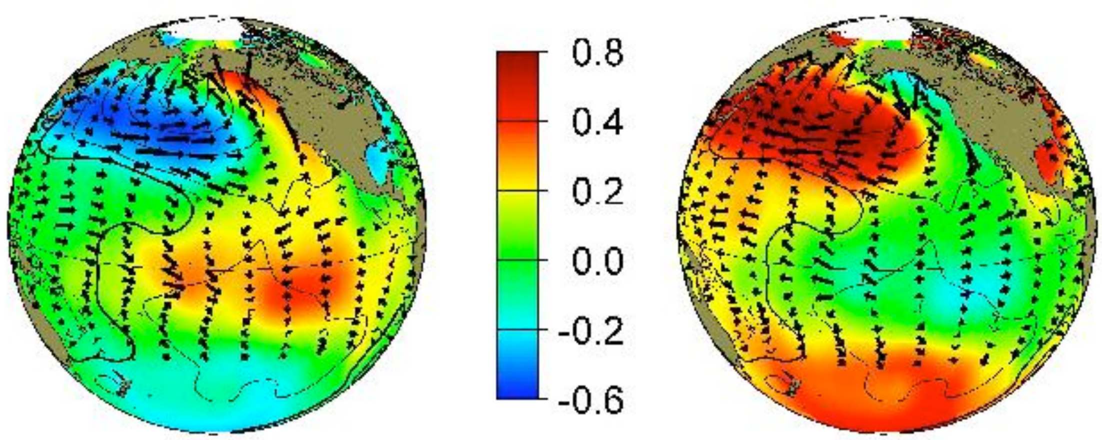
There is some indication that primary productivity is correlated with periods of lower temperatures and lower precipitation.



Time series of summer (June-Sep) maximum temperature, average summer maximum temperature for the two PDO periods (cool between 1947 and 76 and warm between 1977and 1994). Also shown are the primary productivity measurements presented by Larson (2000).

The Pacific Decadal Oscillation (PDO)

Typical wintertime Sea Surface Temperature (colors), Sea Level Pressure (contours) and surface windstress (arrows) anomaly patterns during warm and cool phases of PDO



warm phase cool phase

The "Pacific Decadal Oscillation" (PDO) is a long-lived El Niño-like pattern of Pacific climate variability. While the two climate oscillations have similar spatial climate fingerprints, they have very different behavior in time. Fisheries scientist Steven Hare coined the term "Pacific Decadal Oscillation" (PDO) in 1996 while researching connections between Alaska salmon production cycles and Pacific climate. Two main characteristics distinguish PDO from El Niño/Southern Oscillation (ENSO): first, 20th century PDO "events" persisted for 20-to-30 years, while typical ENSO events persisted for 6 to 18 months; second, the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signatures exist in the tropics - the opposite is true for ENSO. Several independent studies find evidence for just two full PDO cycles in the past century: "cool" PDO regimes prevailed from 1890-1924 and again from 1947-1976, while "warm" PDO regimes dominated from 1925-1946 and from 1977 through (at least) the mid-1990's. Shoshiro Minobe has shown that 20th century PDO fluctuations were most energetic in two general periodicities, one from 15-to-25 years, and the other from 50-to-70 years.
http://ingrid.ldeo.columbia.edu/%28/home/alexeyk/mydata/TSsvd.in%29readfile/.SST/.PDO/

Major changes in northeast Pacific marine ecosystems have been correlated with phase changes in the PDO; warm eras have seen enhanced coastal ocean biological productivity in Alaska and inhibited productivity off the west coast of the contiguous United States, while cold PDO eras have seen the opposite north-south pattern of marine ecosystem productivity.

Causes for the PDO are not currently known. Likewise, the potential predictability for this climate oscillation are not known. Some climate simulation models produce PDO-like oscillations, although often for different reasons. The mechanisms giving rise to PDO will determine whether skillful decades-long PDO climate predictions are possible. For example, if PDO arises from air-sea interactions that require 10-year ocean adjustment times, then aspects of the phenomenon will (in theory) be predictable at lead times of up to 10 years. Even in the absence of a theoretical understanding, PDO climate information improves season-to-season and year-to-year climate forecasts for North America because of its strong tendency for multi-season and multi-year persistence. From a societal impacts perspective, recognition of PDO is important because it shows that "normal" climate conditions can vary over time periods comparable to the length of a human's lifetime

From: http://jisao.washington.edu/pdo/

Here is an example of a “typical” water budgets for two lakes that shows the common terms

TABLE 4-2 Annual Water Budget for Lawrence Lake, Michigan, and Mirror Lake, New Hampshire

Source/loss	*10^3 m^3*	*Percentage of total*
Lawrence Lake:[a]		
Inputs		
Inlet 1	146.6	32.1
Inlet 2	87.5	19.1
Ground water	178.1	39.0
Precipitation	44.6	9.8
Total inputs	456.8	100.0
Outputs		
Outlet	436.5	90.4
Evapotranspiration	46.2	9.6
Seepage losses[b]	0.0	0.0
Total outputs	482.7	100.0
Mirror Lake[c]:		
Inputs		
Runoff	663.1	78.1
Precipitation	182.3	21.9
Total inputs	845.4	100.0
Outputs		
Outlet	409.8	48.5
Evapotranspiration	76.0	9.0
Seepage losses	360.0	42.5
Total outputs	845.8	100.0

[a] After Wetzel and Otsuki (1974).
[b] Indirect evidence indicated that seepage losses were negligible. Subsequent direct measurements have shown that seepage losses are negligible (< 0.1 liter m^{-2} day^{-1}) in Lawrence Lake (Wetzel, unpublished data).
[c] After Likens *et al.* (1985).

Pathways of water to a lake.

The water which arrives in a lake may follow a variety of pathways from the atmosphere to the lake. As a consequence, the water arriving in the lake may have spent very little time in contact with the rock, soil and terrestrial vegetation of the watershed, and thus mostly reflect the chemistry of rainwater, or it may have spent much more time in contact with the soil and reflect a variety of weathering processes. The chemical makeup of the water entering a stream or lake is the result of a mix of different biogeochemical processes.

Climatic regions (See Kalff p46, p59, and especially, p64)

The amount of precipitation varies substantially from one area to another. Hutchinson (1957) identified 3 basic climatic regions:

> *exorheic regions*: rivers originate and flow to the sea. (Temperate and tropical humid regions)
>
> *endorheic regions*: rivers originate but fail to reach the sea. (Between the subtropical

deserts and the temperate and tropical humid regions.)

arheic regions: no rivers arise (although rivers may flow through these regions: e.g., the lower Nile.

Lakes located in exorheic regions are typically relatively fresh. Lakes located in endorheic regions are typically salty because of evaporation. (Lakes may shift between these zones with climate change.) There are no lakes in the arheic regions.

Note Kalff discussion in section 4.4: "A look at 'Typical' Lakes and Streams." Kalff notes that there has been considerable historical bias in the lakes and streams limnologists have chosen to study. Disproportionally, limnologists have studied small, dimictic, oligotrophic temperate zone lakes. Not surprisingly, the result of the bias is that…"theories based on small nutrient-poor temperate systems dominate limnology and its textbooks." p50

Watershed processes (see figure 5-1, p54; 5-2, p55)

Geomorphology

Since water contact with soils and rocks in passing through a drainage system is a fundamental determinant of the chemistry of water, the position of a lake in a watershed can influence its chemistry and consequently its biology.

Soils development in a watershed is a function of 5 factors:

Parent material. Few soils weather directly from the underlying rocks. These "residual" soils have the same general chemistry as the original rocks. More commonly, soils form in materials that have moved in from elsewhere. Materials may have moved many miles or only a few feet. Windblown "loess" is common in the Midwest. It buries "glacial till" in many areas. Glacial till is material ground up and moved by a glacier. The material in which soils form is called "parent material." In the lower part of the soils, these materials may be relatively unchanged from when they were deposited by moving water, ice, or wind.

Climate. Soils vary, depending on the climate. Temperature and moisture amounts cause different patterns of weathering and leaching. Wind redistributes sand and other particles especially in arid regions. The amount, intensity, timing, and kind of precipitation influence soil formation. Seasonal and daily changes in temperature affect moisture effectiveness, biological activity, rates of chemical reactions, and kinds of vegetation.

Topography. Slope and aspect affect the moisture and temperature of soil. Steep slopes facing the sun are warmer, just like the south-facing side of a house. Steep soils may be eroded and lose their topsoil as they form. Thus, they may be thinner than the more nearly level soils that receive deposits from areas upslope. Deeper, darker colored soils may be expected on the bottom land.

Biology. Plants, animals, micro-organisms, and humans affect soil formation. Animals and micro-organisms mix soils and form burrows and pores. Plant roots open channels in the soils. Different types of roots have different effects on soils. Grass roots are "fibrous" near the soil surface and easily decompose, adding organic matter. Taproots open pathways through dense layers. Micro-organisms affect chemical exchanges between roots and soil. Humans can mix the soil so extensively that the soil material is again considered parent material.

The native vegetation depends on climate, topography, and biological factors plus many soil factors such as soil density, depth, chemistry, temperature, and moisture. Leaves from plants fall to the surface and decompose on the soil. Organisms decompose these leaves and mix them with the upper part of the soil. Trees and shrubs have large roots that may grow to considerable depths.

Time. Time for all these factors to interact with the soil is also a factor. Over time, soils exhibit features that reflect the other forming factors. Soil formation processes are continuous. Recently deposited material, such as the deposition from a flood, exhibits no features from soil development activities. The previous soil surface and underlying horizons become buried. The time clock resets for these soils. Terraces above the active floodplain, while genetically similar to the floodplain, are older land surfaces and exhibit more development features.

Vegetation

Vegetation cover varies widely in response to climatic and historical influences. The two most pronounced influences of vegetation cover are temperature and precipitation. There are many different climatic patterns of variation of temperature and precipitation, each of which produces a characteristic type of vegetation. Microclimate influences are also important. In turn, vegetation has a profound influence on the output of water and other materials from watersheds.

Many different processes influence the pattern of output of water and materials from a watershed. Work in the Hubbard Brook watershed provides an example of the nature of these processes.

This data illustrates the effect of clearcutting on P export from a watershed (Hobbie and Likens, 1973)

Table 3. Input of phosphorus in precipitation and output in streams from watersheds 2 (deforested) and 6 from 1 June 1968 to 31 May 1969 (in g P ha^{-1} yr^{-1}). The output is given as the sum of the total dissolved phosphorus (TDP) plus fine particulate phosphorus (FPP) (Table 1) and as large particulate phosphorus (LPP) (Table 2) which is the sum of the phosphorus in inorganic particles plus that in organic particles > 1 mm

	W-2	W-6
Input	99*	108*
Output		
TDP + FPP	20	9
LPP	183	12
Net gain or loss	-104	+87

*Estimated on the basis of precipitation analyses during 1971-1972, when the weighted concentration was 8 µg P $liter^{-1}$.

Annual vegetation cycles

There are 2 principal annual driving forces: rainfall patterns and retention (or exclusion) by the vegetation.

Many ions are conservative and track runoff. Vegetation nevertheless influences weathering by hydrogen ion inputs to weathering, retention of particles by vegetation cover, and an "inflexible" appetite for water for evapotranspiration. Examples of relatively conservative ions are Ca, Mg, and Na. These ions are in low demand by vegetation, compared to supply, and mainly follow hydrological cycles.

Some ions are essential for plants, and may be "limiting" (in Liebig sense.) Examples are N (NH_4 and NO_3), P, and K. Retention by growing vegetation is an important process.

Long-term cycles

There is often a long-term pattern of catastrophe and succession in terrestrial vegetation. After catastrophic fire or windstorm, there may be a loss of biotic control or influence over mineral element budget of a watershed. As a result, there may be a dramatic increase in the export of some ions, which were sequestered in the vegetation, e.g., species of N, P, K, etc.

The watershed may be described as a final steady state if it is recognized that the forest is composed of a mosaic of patches in various stages of succession. Individual small watersheds can be expected to move repeatedly through a recurring cycle of events driven by catastrophe and succession.

Some literature for your reading enjoyment

Yin and Nicholson (1998) used **satellite data** to develop new calculations of Lake Victoria's water balance. They were able to document differences in the amount of cloudiness over the lake (less cloudy) than over the shore stations where ground data were collected (more cloudy). Correcting for the increased amount of evaporation (over that predicted from shore stations) gave a calculated water budget more in agreement with observed changes in lake level. (Yin and Nicholson, 1998 Hydrological Sciences Journal **43**:789-811.

Yanni et al. (2000) applied a **forest hydrology model** (ForHyM2) to simulate monthly rates of stream discharge in the Mersey River Basin. Simulations were in good agreement with the historical records once contributions from **fog and mist** were included. (Yanni et al., 2000 Hydrological Processes **14**:195-214.)

Harvey et al. (2000) used **piezometers** to measure the flow of groundwater into Hamilton Harbor. Their estimates emphasized the **importance of ground water**. For example, their estimate of ground water flow exceeded yearly precipitation input. (Harvey et al., 2000, Ground Water **38**:550-565.)

A homework problem.
In ionic solutions it is often easier to work in "equivalent weights" than in "mass weights". Working in "equivalent units" takes into account the combining or equivalent weights of ions (ionic weight/ionic charge), which permits examination of the "ion balance" to determine whether there is an error in the chemical analyses. The equivalent sum of the anions should equal the equivalent sum of the cations. From general chemistry you know that the milliequivalent concentration of an ion in solution is its mass concentration (mg/L) divided by its equivalent weight. The equivalent weight is the atomic or molecular weight of the ion divided by its valence or charge.

Some homework

The following data are for the Columbia River, just below The Dalles Dam, for December 1, 1958. Convert the data to milliequivalents and compare the concentrations of anions and cations for ion balance. Are they about equal? If so, you can be somewhat certain that the sample analysis was done correctly.

In case you have forgotten and no longer have your general chemistry text book here is a hint. The equivalent concentration of 23 mg Ca/L =23/(40.08/2)=1.1477meq/L. That is the mass/(atomic weight/valence).

Ion	Conc (mg/L)
HCO_3^{-1}	108
SO_4^{-2}	19
F^{-1}	0.5
Cl^{-1}	4.9
NO_3^{-1}	0.3
Ca^{+2}	23
Mg^{+2}	6.2
Na^{+1}	16
K^{+1}	0