CEGE 4501: Hydrologic Design

Chapter 1:
Hydrologic Cycle and Mass Balanace

University of Minnesota
Driven to Discover℠

Ardeshir Ebtehaj
Department of Civil, Environmental, and Geo-Engineering

September 10, 2018

Outline

Water and Human Societies

Water Resource Management

Water use purposes

Water use in the United States

Hydrologic Cycle

Hydrologic Mass Balance

Hydrologic Hazards

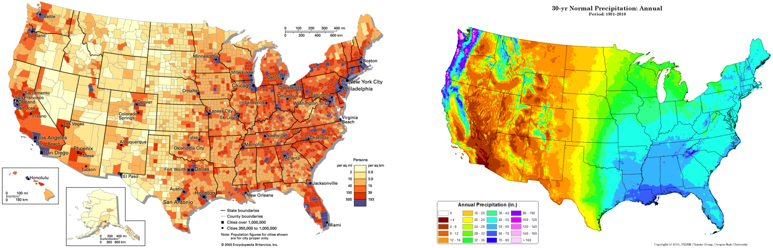
Hydrologic Sustainability

Water and Human Societies

Spread of human populations and formation of civilizations are correlated with the availability of fresh water. The **Mesopotamian civilization**, widely considered as the cradle of civilization, was in the the area between the **Tigris and Euphrates Rivers**. Contemporary distribution of human population in the United State is not an exemption. It is easy to see that the climatology of precipitation somewhat has dictated the density of human population in the US. Most of the biggest cities and economies of the country are in the vicinity of lakes, rivers and estuaries.

The explained correlation clearly does not come as a surprise because water is an essential element not only for survival of human populations but it is the most critical ingredient for food production, formation of central governance, and thus fundamental to human societies.

Hydrology is the study of water and its transport in all of its phases (i.e., solid, liquid, vapor) across different elements of **hydrosphere**, which is a region between 1 km deep in the lithosphere and 15 km high in the atmosphere. These days, *hydrology is a science* and largely focuses on **terrestrial water cycle** in continental and global scales under **natural condition**, without direct human control or intervention, which makes it distinct from classic *hydrologic and hydraulic engineering*.



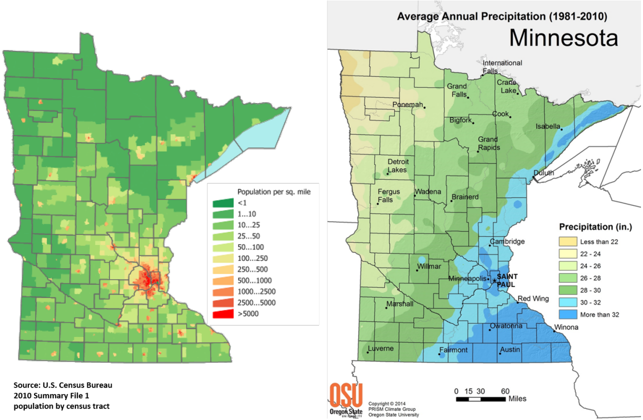
© 2003 Encyclopædia Britannica, Inc.

Copyright (c) 2015, PRISM Climate Group, Oregon State University

Figure 1: Left: U.S. population density. Right: U.S. mean annual precipitation [mm].

Water and Human Societies

In Minnesota it is easy to see that the population is centered around the metropolitan area of the Twin Cities, which, not surprisingly, is on the confluence of the Mississippi and Minnesota Rivers. Twin Cities are also located in the southeastern portion of the state that receives the most rainfall. These water resources are essential to the establishment of major populations and the study of hydrology plays a pivotal role in sustaining these populations.



Source: U.S. Census Bureau
2010 Summary File 1
population by census tract

Copyright © 2014
PRISM Climate Group
Oregon State University

Figure 2: Minnesota population density (left) and the mean annual precipitation [in] (right).

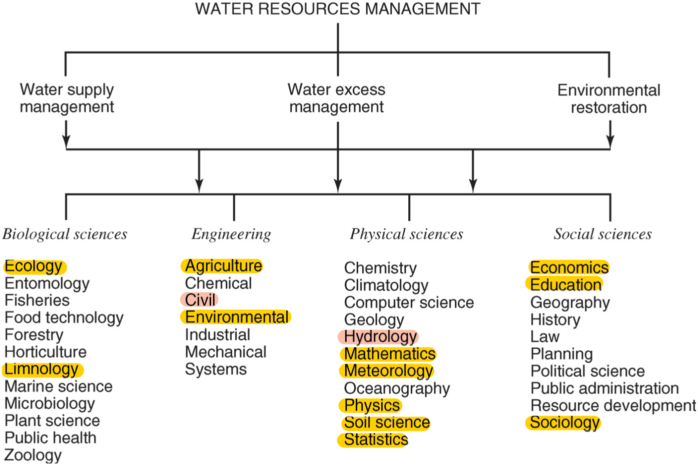
Applications of Hydrology

For engineers, hydrologic knowledge is applied to the use and control of water resources on the land areas of the Earth.

Particular applications include:

- Design of hydraulic structures
- Water supply
- Wastewater treatment
- Irrigation, drainage
- Hydropower, flood and drought control
- Navigation and erosion
- Fish and wildlife protection

Water Resource Management: An Interdicsiplinary Science



WATER RESOURCES MANAGEMENT

Water supply management

Water excess management

Environmental restoration

Biological sciences

- Ecology
- Entomology
- Fisheries
- Food technology
- Forestry
- Horticulture
- Limnology
- Marine science
- Microbiology
- Plant science
- Public health
- Zoology

Engineering

- Agriculture
- Chemical
- Civil
- Environmental
- Industrial
- Mechanical
- Systems

Physical sciences

- Chemistry
- Climatology
- Computer science
- Geology
- Hydrology
- Mathematics
- Meteorology
- Oceanography
- Physics
- Soil science
- Statistics

Social sciences

- Economics
- Education
- Geography
- History
- Law
- Planning
- Political science
- Public administration
- Resource development
- Sociology

Water use purpose

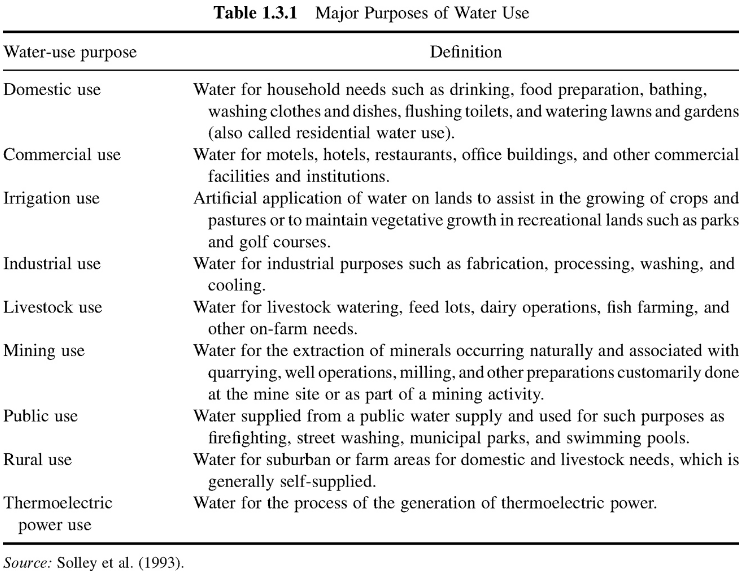


Table 1.3.1 Major Purposes of Water Use

Water-use purpose	Definition
Domestic use	Water for household needs such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and watering lawns and gardens (also called residential water use).
Commercial use	Water for motels, hotels, restaurants, office buildings, and other commercial facilities and institutions.
Irrigation use	Artificial application of water on lands to assist in the growing of crops and pastures or to maintain vegetative growth in recreational lands such as parks and golf courses.
Industrial use	Water for industrial purposes such as fabrication, processing, washing, and cooling.
Livestock use	Water for livestock watering, feed lots, dairy operations, fish farming, and other on-farm needs.
Mining use	Water for the extraction of minerals occurring naturally and associated with quarrying, well operations, milling, and other preparations customarily done at the mine site or as part of a mining activity.
Public use	Water supplied from a public water supply and used for such purposes as firefighting, street washing, municipal parks, and swimming pools.
Rural use	Water for suburban or farm areas for domestic and livestock needs, which is generally self-supplied.
Thermoelectric power use	Water for the process of the generation of thermoelectric power.

Source: Solley et al. (1993).

Figure 4: Water use purposes.

Water use in the United States

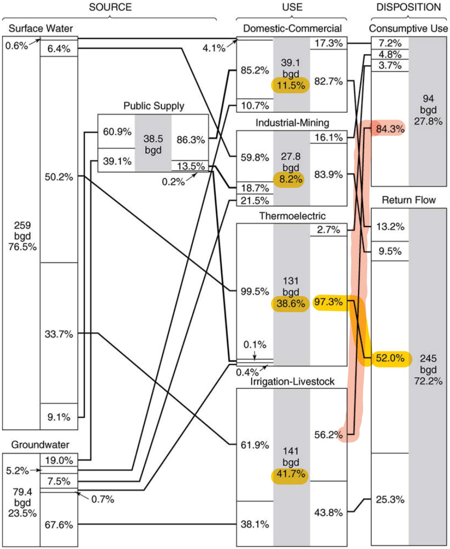


Figure 5: Water use in the United States in billion gallon per day (bgd). Irrigation and livestock are the largest consumptive users.

Hydrologic Cycle

Study of the circulation of water between the earth surface and its atmosphere, known as the **hydrologic cycle**, is central to hydrology. The hydrologic cycle explains **flux of water** across different **water reservoirs**.

Figure 6: A simple explanation of hydrologic cycle (Credit: NASA SVS).

Water Reservoirs on the Earth

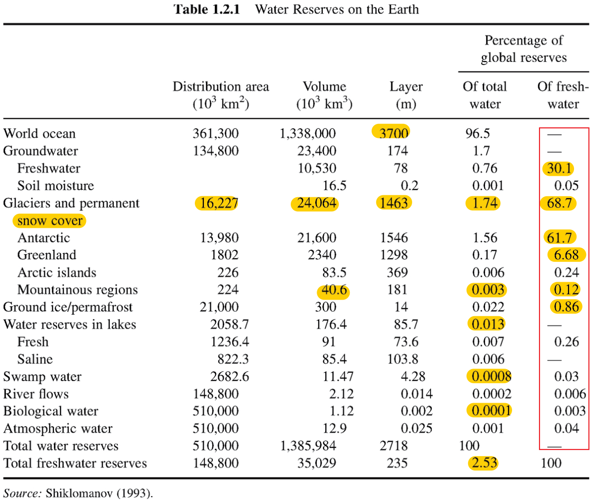


Table 1.2.1 Water Reserves on the Earth

	Distribution area (10^3 km^2)	Volume (10^3 km^3)	Layer (m)	Percentage of global reserves: Of total water	Percentage of global reserves: Of freshwater
World ocean	361,300	1,338,000	3700	96.5	—
Groundwater	134,800	23,400	174	1.7	—
Freshwater		10,530	78	0.76	30.1
Soil moisture		16.5	0.2	0.001	0.05
Glaciers and permanent snow cover	16,227	24,064	1463	1.74	68.7
Antarctic	13,980	21,600	1546	1.56	61.7
Greenland	1802	2340	1298	0.17	6.68
Arctic islands	226	83.5	369	0.006	0.24
Mountainous regions	224	40.6	181	0.003	0.12
Ground ice/permafrost	21,000	300	14	0.022	0.86
Water reserves in lakes	2058.7	176.4	85.7	0.013	—
Fresh	1236.4	91	73.6	0.007	0.26
Saline	822.3	85.4	103.8	0.006	—
Swamp water	2682.6	11.47	4.28	0.0008	0.03
River flows	148,800	2.12	0.014	0.0002	0.006
Biological water	510,000	1.12	0.002	0.0001	0.003
Atmospheric water	510,000	12.9	0.025	0.001	0.04
Total water reserves	510,000	1,385,984	2718	100	—
Total freshwater reserves	148,800	35,029	235	2.53	100

Source: Shiklomanov (1993).

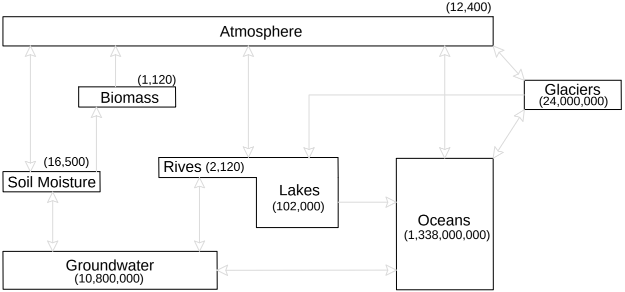
Continental access to freshwater resources: Europe (4-10%), North America (17-38%), Africa (5-30%), Asia (3-44.56%), South America (17-60%).

Hydrologic Cycle and Water Reservoirs

Oceans, glaciers, groundwater, soil moisture, lakes, rivers, and atmosphere are the earth's main water reservoirs.

Depending on the net outflow (Q, [$\mathrm{L^3T^{-1}}$]) and volume of these reservoirs ($\forall$, [$\mathrm{L^3}$]), each has a different **residence time** ($t_r = \forall/Q$, [T]).

Residence times of the main water reservoirs are – ocean (∼2500 yr), groundwater (∼8 yr), lakes and rivers (∼88 days), soil moisture (∼47 days), and atmosphere (∼9 days). Among these reservoirs, atmosphere shows the minimum residence time, an indication of its fast evolving dynamics. Groundwater residence time needs to be taken into consideration for sustainable developments in arid and semi-arid regions.



Note: Volumes are in cubic kilometers (km^3)

Figure 7: Hydrologic reservoirs and their approximate volumes [m^3] (right).

Hydrologic Cycle - Processes and Fluxes

Hydrologic cycle occurs through **water fluxes** across different water reservoirs. Water flux is the mass of water, per unit area and time (e.g., $\mathrm{kg\,m^{-2}\,T^{-1}}$), across the water reservoirs in the hydrosphere. The water fluxes can be in various phases such as vapor, liquid, and/or solid. A conceptual schematic of the fluxes between the Earth's water reservoirs is shown in the following figure.

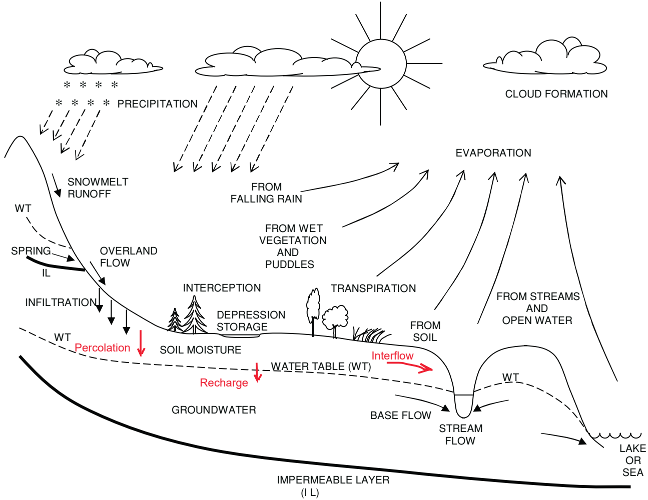


Figure 8: Hydrologic water cycle and fluxes.

Hydrologic Cycle - Processes and Fluxes

Precipitation: conversion of atmospheric water to liquid or solid water that reaches the earth's surface.

Interception: refers to precipitation that does not reach the soil, but is intercepted by the leaves, branches of plants and canopy.

Infiltration: downward flux of water at soil surface.

Overland flow: is the portion of rain, snow or irrigation water that is more than the surface infiltration capacity and flows across the land surface and enters into the channel flow.

Evapotranspiration: conversion of surface liquid water to water vapor through combination of direct "evaporation" from the soil/water surfaces and "transpiration" due to the vegetation metabolism.

Interflow: is the lateral flux of water in shallow depth, above the groundwater table, into the stream flows.

Percolation: downward flux of water between the soil surface and water table.

Recharge: downward flux of water at the water table.

Baseflow: lateral flow of groundwater into the stream flows.

Sublimation: direct phase change from ice to water vapor. Direct phase change of water vapor to ice is called **deposition**.

Throughfall: flux of intercepted precipitation water from plants' leaves and stems to the soil surface.

Exfiltration: the upward flux of water in soil layers, mainly due to capillary forces and suction heads in soil textures.

Hydrologic Cycle - Driver I

The question still remains–**what causes the hydrologic cycle?** The answer is simple, **solar radiation**. Although the earth is a closed thermodynamic system (no mass exchange with its environment), it is not an isolated system as it exchanges energy with the outer space. This exchange is a consequence of the average solar radiation flux of 342 $W\mathrm{m}^{-2}$ being delivered at the top of Earth's atmosphere. This energy is the driver of the hydrologic water cycle.

Due to the ellipsoidal shape and orbital geometry of earth, the equators receive more energy than polar regions. This differential energy budget eventually leads to a pressure gradient that circulates the earth atmosphere. The moving air masses transport water vapor from tropical oceans and precipitate them over lands. The precipitation water returns back to the atmosphere and oceans through the explained fluxes and processes such as infiltration, percolation, evapotranspiration, runoff and streamflow.

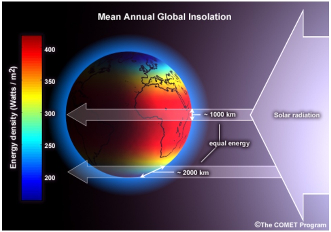


Figure 9: A schematic of the differential solar radiation that drives the water cycle (Credit: The COMET Program).

Hydrologic Cycle - Driver II

As explained, the convective motions of air and water masses, in atmosphere, are mainly because of an existing **pressure gradient**.

We will discuss in the next chapter that, as a general rule, when the temperature of an air parcel increases at a constant pressure, based on the ideal gas law, its density reduces and vice versa.

Therefore, in general, **a cold air mass is denser than a warm air mass** at constant pressure. Because the **air is compressible**, the density of cold air column decays faster than the density of a warm air column from earth surface to higher altitudes. Due to higher pressure of warm air column aloft than the cold air column, the air flows from warm to cold regions at high elevations (Figure 10, left).

As the air flows from warm to cold areas, the cold air column becomes heavier and its pressure increases at the surface. As a result, a surface air flow forms from cold to warm areas which eventually gives rise to a circulation pattern (Figure 10, right).

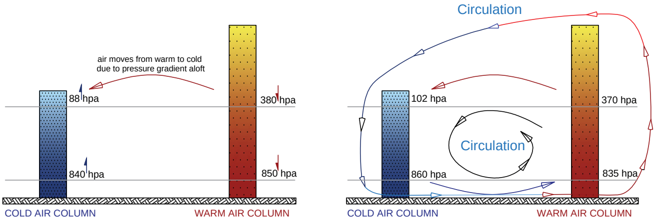


Figure 10: The circulation of the earth's atmosphere is due to formation of a pressure gradient from warm (tropics) to cold (polar regions) air masses.

Hydrologic Cycle - Driver III

According to the above simple conceptualization of the atmospheric circulation, one may think of the earth atmospheric circulation as shown below:

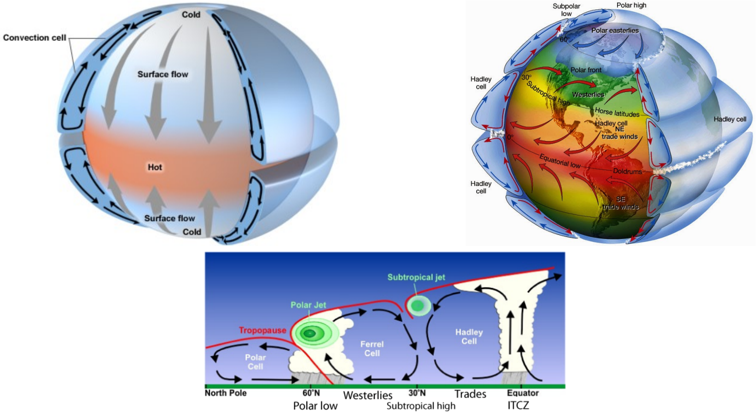


Figure 11: Schematic of a one (top left) and a three-cell model(top-right) for atmospheric circulation. The three-cell model represents the observed Earth's atmospheric circulation pattern.

However, the one-cell circulation model does not exist because these large eddies are unstable and more importantly there are other forces acting on air parcels that break these large hypothetical eddies apart. This force is the called the Coriolis force.

Hydrologic Cycle - Driver IV

In simple terms, with respect to the a rotating reference frame, it appears that the Coriolis force is deflecting an object that moves from the center to the perimeter and vice versa.

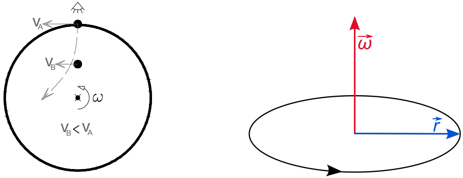


Figure 12: Coriolis force deflects an object thrown from point A to point B to the right of its path in a counter clockwise rotational system. This force is due to a combined effect of the angular ($\vec{\omega}$) and linear velocity ($\vec{v}$).

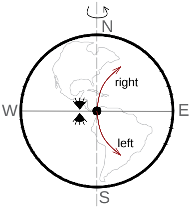
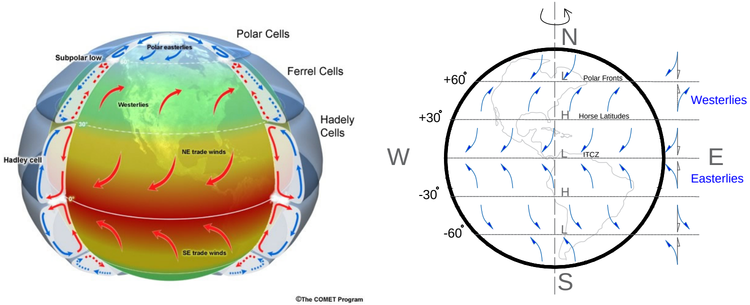


Figure 13: The Coriolis force deflects air parcels to the right and left of the their moving direction in the Northern and Southern Hemisphere, respectively, for the shown view points.

Hydrologic Cycle - Driver V

As a result of the Coriolis and pressure gradient forces, those large hypothetical circulation cells (Figure 11, left) breaks into three smaller cells as shown below. As we know how the Coriolis force deflects air parcel movements, it is easy to conclude that the "surface" air flows from mid-latitudes high-pressure areas towards the tropical low-pressure convergence zones are deflected towards east. These surface airflows are called easterlies or trade winds. On the other hand, surface airflows from high-pressure horse latitudes towards polar fronts are deflected to the west and create the westerlies.



©The COMET Program

Figure 14: Schematic of a three-cell atmospheric circulation model and deflection of airflows in northern and southern hemisphere.

Hydrologic Cycle - Driver VI

In regions within ±5-20 latitudes, the Coriolis force is strong enough to creates cyclonic activities around the high and low pressure areas. Based on the explained Coriolis effect, it is easy to understand that the air flows counter clockwise around lows and clockwise around highs in northern hemisphere.

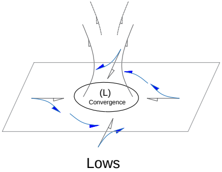


Figure 15: A schematic of airflow in a low pressure cell, convergence at the surface and divergence aloft. A satellite footage of the Hurricane Irma shows its counter clock-wise rotation around a strong low-pressure system.

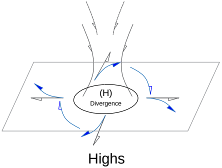
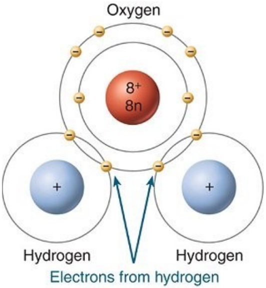


Figure 16: A schematic of airflow in a high pressure cell, divergence at the surface and convergence aloft.

Water Physical Properties

The unique physical properties of water characterize the hydrologic processes. Unlike other planets in our solar system, the pressure and temperature found on Earth allow water to occur naturally in all three phases, as shown in the phase diagram below. This is obvious, especially in areas like Minnesota, where we have rainstorms in summer and snowstorms in the winter.

Due to unique polar structure of water molecules, water has a very high values **specific heat capacity** (c_p=4186 J kg^{-1} K^{-1} at T=15°C) and **latent heat of vaporization** ($L_V = 2.5 \times 10^6$ J kg^{-1} at T=15°C) which have significant effects on our weather and climate systems.



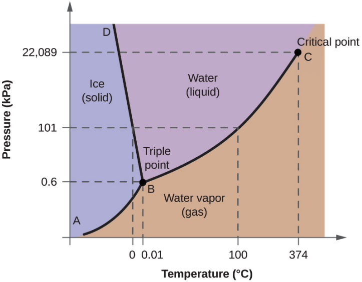
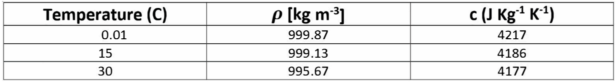


Figure 17: Polar structure of a water molecule (left). The water phase diagram showing that water occurs naturally in all three phases on earth (right). At the triple point, all three phases of water exist.

Water Properties

- **Water density:** $\rho_w = 1000$ [kg m^{-3}]
- **Ice density:** $\rho_c = 917$ [kg m^{-3}]
- **Specific heat capacity:** is the heat Q [J] required to raise the temperature T of the unit mass of a given substance by one degree of Kelvin, which is $c = Q/(m\,\Delta T)$ [Joule Kg^{-1} K^{-1}] . Depending on the temperature $5^\circ \leq T \leq 100^\circ C$, the specific heat capacity of water varies between 4180 to 4220 [Joule Kg^{-1} K^{-1}].



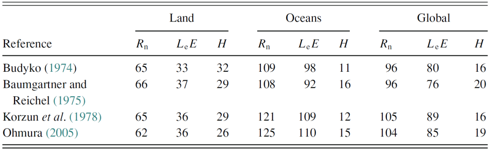
Temperature (C)	ρ [kg m^{-3}]	c (J Kg^{-1} K^{-1})
0.01	999.87	4217
15	999.13	4186
30	995.67	4177

- **Latent heat capacity ($\mathcal{L}$):** is the heat Q required for phase change of unit mass of a substance, that is $\mathcal{L} = Q/m$. During the phase change, the temperature of the substance remains unchanged.

  Latent heat of vaporization: $\mathcal{L}_{\ell v} = 2.5 \times 10^6$ [J Kg^{-1}]

  Latent heat of melting (fusion): $\mathcal{L}_{s\ell} = 3.34 \times 10^5$ [J Kg^{-1}]

  Latent heat of sublimation: $\mathcal{L}_{sv} = 2.86 \times 10^6$ [J Kg^{-1}] and thus $\mathcal{L}_{sv} = \mathcal{L}_{s\ell} + \mathcal{L}_{\ell v}$



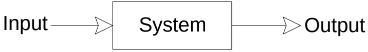
	Land			Oceans			Global		
Reference	R_n	L_eE	H	R_n	L_eE	H	R_n	L_eE	H
Budyko (1974)	65	33	32	109	98	11	96	80	16
Baumgartner and Reichel (1975)	66	37	29	108	92	16	96	76	20
Korzun *et al*. (1978)	65	36	29	121	109	12	105	89	16
Ohmura (2005)	62	36	26	125	110	15	104	85	19

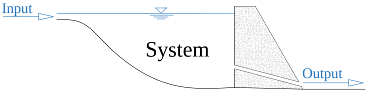
Figure 18: mean global heat budget at the earth surface in [W m^{-2}]

Water Budget and Mass Balance

Water budget analysis is extremely important for sustainability of water resources management. Water mass balance analysis in hydrologic systems assesses storage of water in natural or man-made reservoirs and evaluates continuity of water flow across those reservoirs.

We often use a system approach to explain hydrologic processes. Mass of water parcels is considered as a conserved quantity and a simple mass balance over a system of water storage can be cast as follows:





$$\text{accumulation}\,(\Delta S) = \text{Input}\,(I) - \text{Output}(O) \quad [\mathrm{L}^3].$$

We naturally evaluate the above mass balance equation over a certain of period time Δt as:

$$\frac{\Delta S}{\Delta t} = \frac{I}{\Delta t} - \frac{O}{\Delta t} \qquad [L^3\,T^{-1}],$$

where for small time intervals, we have $\lim_{\Delta t \to 0} \frac{I}{\Delta t} = Q_{in}$, $\lim_{\Delta t \to 0} \frac{O}{\Delta t} = Q_{out}$, $\lim_{\Delta t \to 0} \frac{\Delta S}{\Delta t} = \frac{ds}{dt}$ and thus,

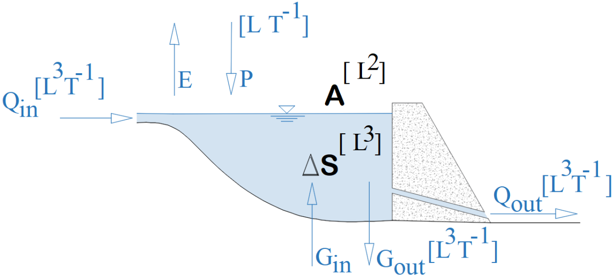
$$\frac{ds}{dt} = Q_{in} - Q_{out} \qquad [L^3\,T^{-1}].$$

In a steady state condition the mass balance reduces to $Q_{in} = Q_{out}$ as $\frac{ds}{dt} \to 0$. Note that we often express hydrologic flow/fluxes per unit area such as $[\mathrm{m}^3\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}]$=$\mathbf{[m\,s^{-1}]}$ or $\mathbf{[mm\,hr^{-1}]}$ or $\mathbf{[mm\,day^{-1}]}$, which is common for representation of the precipitation or evapotranspiration fluxes.

Reservoir Water Budget

Review of some important units:

- **Length:** 1 [inch] = 2.54 [cm], 12 [inches] = 1 [ft]
- **Area:** 1 [acre]= $\frac{1}{640}$ [miles^2] = 43,560 [ft^2] = 4,047 [m^2]
- **Volume:** [ac.ft] = 43,560 [ft^3] = 1233.5 [m^3]
- **Discharge:** [m^3 s^{-1}] or [cfs], where 100 [cfs] = 2.83 [m^3 s^{-1}]



$$P\,A + Q_{in} + G_{in} - E\,A - Q_{out} - G_{out} = \frac{\Delta S}{\Delta t} \quad [\mathrm{L}^3\ \mathrm{T}^{-1}]$$

$$P + \frac{Q_{in}}{A} + \frac{G_{in}}{A} - E - \frac{Q_{out}}{A} - \frac{G_{out}}{A} = \frac{\Delta S}{A\Delta t} \quad [\mathrm{L}\ \mathrm{T}^{-1}]$$

Watershed Water Budget

One crucial step in hydrologic mass balance analysis is defining the boundary or control volume of the system such as a small pond, a large dam or a watershed.

A watershed is defined as a locus of all points (pixels of a digital elevation model) on the earth's surface that drain precipitation water to a single point called the "**watershed outlet**". The boundary of a watershed is called the "**divide**". Watersheds can be delineated either manually or automatically using digital elevation models (DEM) and computational algorithms. The size of a watershed can range from a few acres to millions of square miles (Amazon River Basin) depending on the geomorphologic characteristics of land surfaces and location of the outlet.

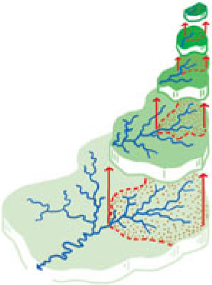


Figure 19: A schematic of a watershed and its divide (left, credit: Alice Ferguson Foundation). A schematic of how watersheds are nested (right, credit: Marsh, 1998, p. 170

Watershed Water Budget

At a global scale, as earth is a close thermodynamic system, water mass balance at the earth's surface is $\frac{dS}{dt} = P - ET$. in a steady state condition this mass balance leads to $P = ET$.

Note that the steady state assumption is a function of the time-scale. The above global steady state assumption is valid for sufficiently long period of time such as a year, because evapotranspiration and precipitation are highly dynamic processes that vary significantly in a shorter time scale. However, based on the law of conservation of mass it is easy to conclude that on an annual basis the steady state assumption is reasonable and precipitation and ET are equal. As the time scale increase the accuracy of this mass balance also increase. Observational evidence suggests that the annual rate of both precipitation and ET is approximately 1000 [mm yr^{-1}].

At a watershed scale, each basin may exchange water mass with its surrounding basins through the underlying groundwater systems. A watershed mass balance can be written as follows:

$$\frac{dS}{Adt} = P + \frac{G_{in}}{A} - \left(ET + \frac{Q}{A} + \frac{G_{out}}{A}\right) \quad [\mathrm{L\,T^{-1}}].$$

After averaging over sufficiently long period of time, for a steady state condition, we have

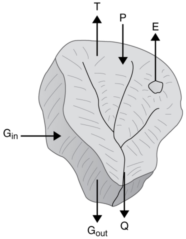
$$P + G_{in}/A = ET + Q/A + G_{out}/A.$$

Long resident time of groundwater implies $G_{in} \approx G_{out} \rightarrow 0$:

$$P \approx Q/A + ET \Rightarrow ET \approx P - Q/A.$$

When a storm is occurring, the air humidity is relatively high, which reduces the ET significantly. Assuming ($\overline{ET} \approx 0$), the watershed mass balance can be reduced to

$$P \approx Q/A.$$



Hydrologic Cycle and Satellites

Remote sensing has provided new insights for deeper understanding of hydrologic cycle in the past few decades. Satellites, including those launched by NASA, have provided invaluable information about global land and sea surface temperatures (e.g., Advanced Very High Resolution Radiometer, AVHRR), atmospheric moisture (e.g., Atmospheric Infrared Sounder, AIRS), precipitation (e.g., Global Precipitation Measuring, GPM), snow (e.g., Special Sensor Microwave Imager/Sounder, SSMI/S), soil moisture (e.g., Soil Moisture Active Passive satellite, SMAP), vegetation coverage (e.g., Moderate-Resolution Imaging Spectroradiometer, MODIS), and even changes in ground water elevation (e.g., Gravity Recovery and Climate Experiment, GRACE).

Figure 20: A sophisticated explanation of hydrologic water cycle: insights from space-based remote sensing (credit: NASA Goddard).

Hydrologic Hazards

Floods: Flood prediction and management is an important topic in hydrologic engineering. A flood is an overflow of water that submerges land that is usually dry. A flood happens when lands that are normally dry are covered by water. Flooding may occur as an overflow of water from water bodies, such as rivers, lakes, or oceans.

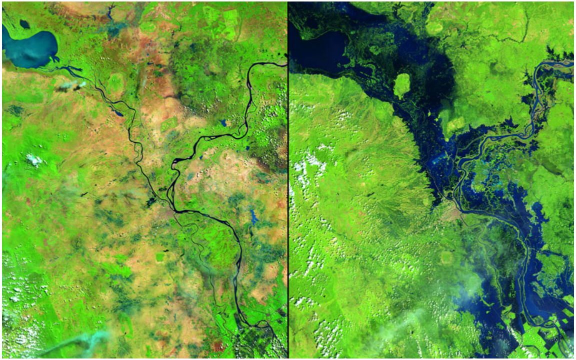


Figure 21: These images, from 17 May and 24 October 2013, show the impact of Typhoon Nari and heavy seasonal rainfall on Cambodia's Mekong and Tonle Sap Rivers. More than half a million people were affected by the flood and more than 300,000 hectares of rice fields are believed to have been destroyed.

Floods in U.S.

- California Flooding - February 2017: Heavy, persistent rainfall across northern and central California created substantial property and infrastructure damage from flooding, landslides and erosion. Notable impacts include severe damage to the Oroville Dam spillway, which caused a multi-day evacuation of 188,000 residents downstream. Excessive rainfall also caused flood damage in the city of San Jose, as Coyote Creek overflowed its banks and inundated neighborhoods forcing 14,000 residents to evacuate. Total Estimated Costs: $1.5 Billion; 5 Deaths
- Louisiana Flooding - August 2016: A historic flood devastated a large area of southern Louisiana resulting from 20 to 30 inches of rainfall over several days. Watson, Louisiana received an astounding 31.39 inches of rain from the storm. Two-day rainfall totals in the hardest hit areas have a 0.2% chance of occurring in any given year: a 1 in 500 year event. More than 30,000 people were rescued from the floodwaters that damaged or destroyed over 50,000 homes, 100,000 vehicles and 20,000 businesses. This is the most damaging U.S. flood event since Superstorm Sandy impacted the Northeast in 2012. Total Estimated Costs: $10.0 ($10.3) Billion; 13 Deaths
- Texas and Oklahoma Flooding and Severe Weather - May 2015: A slow-moving system caused tremendous rainfall and subsequent flooding to occur in Texas and Oklahoma. The Blanco river in Texas swelled from 5 feet to a crest of more than 40 feet over several hours causing considerable property damage and loss of life. The city of Houston also experienced flooding which resulted in hundreds of high-water rescues. The damage in Texas alone exceeded 1.0 (1.1) billion. There was also damage in other states (KS, CO, AR, OH, LA, GA, SC) from associated severe storms. Total Estimated Costs: $2.5 ($2.6) Billion; 31 Deaths
- Northern Plains Flooding - Spring 1997: Severe flooding in North Dakota, South Dakota and Minnesota due to heavy spring snow melt. This flooding caused widespread damage to agriculture, infrastructure, homes and businesses. Total Estimated Costs: $3.7 ($5.7) Billion; 11 Deaths

  source: https://www.ncdc.noaa.gov/billions/events.pdf

Hydrologic Hazards

Droughts: Droughts continue to be one of the most severe weather-related problems in the world.

- Meteorological droughts – lack of precipitation
- Agricultural droughts – lack of soil moisture
- Hydrological droughts – reduced stream flow and groundwater levels

Figure 22: California Drought: left image is on Jan 2014 and right image is on Jan 2017

Hydrologic Hazards

Droughts: Droughts continue to be one of the most severe weather-related problem around the world.

- Meteorological droughts – lack of precipitation
- Agricultural droughts – lack of soil moisture
- Hydrological droughts – reduced stream flow and groundwater levels

Figure 23: California Drought in 2014—a closer look.

Droughts in U.S.

- Western Drought - 2014: Historic drought conditions affected the majority of California for all of 2014 making it the worst drought on record for the state. Surrounding states and parts of Texas, Oklahoma and Kansas also experienced continued severe drought conditions. This is a continuation of drought conditions that have persisted for several years. Total Estimated Costs: \$4.0 (\$4.2) Billion; 0 Deaths
- U.S. Drought/Heatwave - 2012: The 2012 drought is the most extensive drought to affect the U.S. since the 1930s. Moderate to extreme drought conditions affected more than half the country for a majority of 2012. The following states were affected: CA, NV, ID, MT, WY, UT, CO, AZ, NM, TX, ND, SD, NE, KS, OK, AR, MO, IA, MN, IL, IN, GA. Costly drought impacts occurred across the central agriculture states resulting in widespread harvest failure for corn, sorghum and soybean crops, among others. The associated summer heatwave also caused 123 direct deaths, but an estimate of the excess mortality due to heat stress is still unknown. Total Estimated Costs: \$30.0 (\$32.4) Billion; 123 Deaths
- Southern Plains/Southwest Drought & Heat Wave - Spring-Summer 2011: Drought and heat wave conditions created major impacts across Texas, Oklahoma, New Mexico, Arizona, southern Kansas, and western Louisiana. In Texas and Oklahoma, a majority of range and pastures were classified in "very poor" condition for much of the 2011 crop growing season. Total Estimated Costs: \$12.0 (\$13.3) Billion; 95 Deaths

  source: `https://www.ncdc.noaa.gov/billions/events.pdf`

  `http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx`

Hydrologic Sustainability

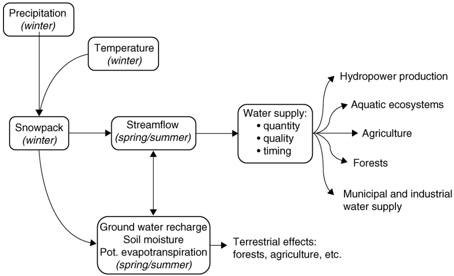
Sustainable development is the development that can meet the needs for the present generation without compromising the ability of future generation to meet their own needs.

Hydrologic sustainability refers to engineering and management practices that enable us and ecosystem to have access to water in sufficient quantity and quality at present without compromising the ability of future generation to meet their own needs to freshwater resources.

Challenges to sustainability:

Urbanization: By 2050 more than 9 billion people will live on the Earth. Now we have more than 22 cities with more than 10 million inhabitants. The challenges are related to water supply, drainage, waste and storm water collection and treatment. The excessive demand exerts immense pressure on our natural water resources systems.

Climate Change: A change in the state of climate that can be identified by changes in the mean and/or variability of its properties that can persist for an extended period of time – typically decades or longer (IPCC). The climate system consists of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface, and the biosphere. These subsystems are influenced largely by the human activity and extraterrestrial sources such as the Sun. https://www.esrl.noaa.gov/gmd/ccgg/trends/full.html



Precipitation *(winter)*

Temperature *(winter)*

Snowpack *(winter)*

Streamflow *(spring/summer)*

Water supply:
- quantity
- quality
- timing

Hydropower production

Aquatic ecosystems

Agriculture

Forests

Municipal and industrial water supply

Ground water recharge
Soil moisture
Pot. evapotranspiration
(spring/summer)

Terrestrial effects: forests, agriculture, etc.

Sustainability of hydrologic systems can be quantified in terms of their water mass balance.

Lack of the Hydrologic Mass Balance

Lake Urmia is a prime example of a water body with an imbalanced water budget. The Urmia lake, once was the sixth largest saltwater lake on earth has shrunk to 10% of its original size in mid 80s, mainly due to damming (less inflow) and excessive groundwater withdrawals (more outflow). The following animation shows shrinkage of the lake surface from 1984-2014. We can see that how a simple mass balance problem can have significant unforeseen ramifications for regional ecology and human population.

Figure 24: Lake Urmia (area: 5200 km^2) in north west of Iran diminishes from 1984-2014. A simple mass balance miscalculation or ignorance! (credit: NASA).

Lack of the Hydrologic Mass Balance

Formerly one of the four largest lakes in the world with an area of 68,000 km2 (26,300 sq mi), the Aral Sea has been steadily shrinking since the 1960s after the rivers that fed it were diverted by Soviet irrigation projects. By 1997, it had declined to 10% of its original size.

Figure 25: Aral Sea: Man-made environmental disaster - BBC News