Geography 327
Hydrology

Evapotranspiration

"all the processes by which water in the liquid or solid phase at or near the earth's land surface becomes atmospheric water vapour" (evaporation, transpiration, sublimation)

Evaporation

- the change in state of water from a liquid to water vapour when the transfer of energy towards water increases the kinetic energy;
- hydrogen bonds are broken and water vapour is diffused from higher to lower vapour pressure, that is, from the evaporating surface into the surrounding air
- molecular diffusion occurs within about 1 mm of the surface, eddy diffusion is in response to air turbulence as opposed to the vapour pressure gradient
- water vapour consists entirely of free water molecules, while liquid water consists of both free and bonded molecules
- at the water surface, bonds between molecules are continuously being broken (evaporation) and re-established (condensation); net evaporation = 0, when RH = 100%
- most evaporation occurs over oceans and lakes, especially in dry and warm climates

Controls on evaporation rate

Universal factors

1. energy
    - evaporation requires the latent heat of vapourization, 540 cal/gm
    - the evaporation of 1 in of water from 1 acre of land represents a transfer of 6×10^{10} cal to the atmosphere
    - the sources of this latent heat are
        - solar energy is the major source of energy and control on evaporation, and thus distributions of insolation and evaporation tend to be strongly correlated: maximum evaporation (and usually cloudiness) in the tropics and during the warmest part of the day

        - sensible heat of air, soil and rock
        - kinetic energy of the water: internal energy and thus a self-limiting source of energy as the water cools to an equilibrium temperature and the overlying cooler air develops higher relative humidity

2. temperature

    - a measure of heat energy
    - but also the capacity of air to hold water vapour, the saturation vapour pressure (E), increases with increasing air temperature
    - E - e (actual vapour pressure) = saturation deficit, which is the amount additional water vapour that air can hold at a given temperature

3. humidity

    - with constant air temperature (*i.e.*, constant saturation vapour pressure), an increase in actual vapour pressure (e) causes a decrease in the in the rate of evaporation, as the saturation deficit (E-e) is reduced and relative humidity (e/E x 100) rises
    - changes in actual vapour changes are mostly result from a change in air mass with passing of a front

4. wind

    - causes eddy (turbulent diffusion) and thereby maintains the vapour pressure gradient between air and the evaporating surface
    - turbulence is function of wind speed and surface roughness; the latter factor is negligible over calm water
    - evaporation can rise dramatically with increasing turbulence but only up to a critical limit determined by humidity, temperature and especially energy (*i.e.*, the production and diffusion of free molecules)

Additional controls on evaporation from water bodies

1. water quality

    - 1% decrease in evaporation for a 1% increase in salinity, but a 2-3% decrease in evaporation from oceans is offset by the abundance of sea water turbidity decreases albedo

2. depth of the water body

    - influences the annual variation
    - given very high heat capacities and thermal conductivities of water, deep lakes maintain a lower surface temperature in summer than shallow lakes with less heat storage and closer to the surface
    - cool air next to the cool water surface inhibits diffusion, but in winter the relatively warm water surface and overlying air promote evaporation and diffusion of the water vapour
    - thus deep lakes have highest evaporation in winter, whereas shallow lakes loose heat rapidly in fall and freeze over, eliminating evaporation

- deep lakes (*e.g.*, the Great Lakes) are a source of winter precipitation (large snowfalls), as opposed to the dry winter climate of the arctic, subarctic and interior plains

3. area of water body

    - amount of evaporation with increasing lake area, but the rate of evaporation decreases exponentially from the upwind edge of the lake as the actual vapour pressure increases in the overlying air
    - the larger the lake the more the rate of evaporation is reduced away from the windward shore
    - thus maximum rates of evaporation are in dry air over small shallow lakes
    - a small evaporating surface has little influence on the humidity of overlying air; in all but calm conditions dry air is continuously delivered to the surface of small lakes
    - the degree to which rates of evaporation decrease with distance from the lake edge depends on the initial humidity of the air: humid air will be only slightly affected, while dry air induces initially high rates of evaporation which are then significantly reduced by the higher vapour pressure

Additional factors controlling the rate of evaporation from soil

1. soil moisture content

    - rate of evaporation decreases exponentially as soil dries out since further evaporation depends on rise of soil and ground water to the surface
    - thus maximum evaporation is from frequently wetted soil (*i.e.* irrigation or frequent precipitation)

2. soil texture

    - governs soil moisture content and capillarity, the rate of diffusion of capillary water
    - in fine soil, water is retained promoting initially high rates of evaporation, but once the top few cm dry out further evaporation rate depends on the capillarity of the soil:
    - clay: water can rise a meter or more but only very slowly
    - medium (silt): maximum capillarity, *i.e.* optimal combination of extent and rate of rise
    - coarse-texture: capillary rise of only a few cm, evaporation mostly from surface, thus drought susceptible

3. depth to water table

    - water table at the surface (a wetland) or shallow depth provides almost unlimited water
    - evaporation falls rapid with increasing depth to the water table to a critical depth below which groundwater is not involved in the evaporation process
    - this critical depth depends on capillarity and therefore soil texture:

coarse sand	35 cm
fine sand	70 cm
heavy loam	85 cm

4. soil colour

- much greater absorption of hear and thus evaporation in dark soils with lesser albedo

5. vegetation

    - reduces evaporation by shading soil, reducing wind speed at the ground surface and increasing vapour pressure by transpiring water vapour

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Determining evaporation

theoretical (physically-based) approaches

1. turbulent (mass) transfer

    - turbulent diffusion as a function of wind speed and vapour pressure gradient
    - evaporation = $k\ u_z\ (e_w - e_z)$, where

        - k is a constant
        - u is wind velocity
        - e is the vapour pressure
        - w is the water surface
        - z is a reference height about the evaporating surface

    - this approach assumes that heat and vapour move away from the water surface in response to decreasing air temperature and water vapour pressure; thus it does not apply to surface temperature inversions or condensation (dew or frost)
    - precise measurements of temperature and humidity over short vertical distances restrict the use of this approach to experimental situations

2. energy balance approach

    - net radiation = sensible heat +/- soil or water heat +/- latent heat
    - measurement of the first three terms permits the calculation of latent heat, the portion of the net radiation used for evaporation

direct measurement

1. lake water balance:

    - measuring inputs and outputs of water, including changes in storage (lake level) caused by evaporation
    - precipitation + groundwater + surface inflow = evaporation -surface outflow - seepage +/- changes in storage
    - seepage through the lake floor is difficult to measure and there may be a large cumulative error in the measurement of all the variables

    - evaporation pans
    - water loss from a shallow pan, the simplest and most common method
    - in Canada, evaporation is measured from shallow pans (1.2 m in diameter, 25 cm deep) at hundreds of climate stations during the frost free season
    - evaporation = change in water level - precipitation
    - pan data reflect, but always exceed, water loss from lakes and reservoirs
    - empirical correction factors (typically 0.6 -0.8) are applied to account for the excess water loss resulting from

        - radiation striking the sides of the pan is and extra source of energy; pans have been embedded in the ground, but then this increases the heat flux from the ground and the possibility of shading by plants and splash from the soil
        - size and depth

            - lakes store heat at depth keeping the surface cooler
            - the small amount of pan water does not influence the humidity of the overlying air and thus a constantly higher rate of evaporation is maintained
            - pans have been floated on lakes but then they are less accessible and more costly to maintain

        - turbulence as water passes around the pan and over the rim; the water level is always below the rim causing turbulence to develop inside the rim
        - use of the pan by birds and other animals

2. atmometer

    - filter paper or a porous plate supplied with water from a graduated cylinder
    - more controlled than an evaporation pan, but does not simulate evaporation from water bodies
    - thus mostly used experimentally for monitoring variation in rates of evaporation among sites and with changes in humidity, temperature, net radiation and wind

3. lysimeter

    - measuring evaporation from soil
    - impervious chamber (*e.g.*, sheet metal box) installed in the ground such that changes in the measured weight of soil in the lysimeter represent changes in the soil water balance = precipitation - evporation
    - output by seepage cannot occur or occurs through a hole where it is measured

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Transpiration

"evaporation ... from the vascular system of plants"

- pure evaporative water loss occurs only where vegetation is absent: ice and snow fields, bare soil and rock surfaces, and open water

- otherwise water loss from land consists of evaporation from soil, evaporation of intercepted water, and transpiration of water by plants
- water is absorbed by the roots, rises by capillary action to stomatal cavities in the leaves where it evaporates and is diffused through stomata (Gr. stomatos: mouth, stomatology: diseases of the mouth)
- plants with deep root systems that extend below the groundwater table, typically in dry environments, are called phreatophytes (Gr. Phreatos: well, phyton: plant)
- these trees (*e.g.*, cottonwood and aspen) also will penetrate water mains to access water
- transpiration maintains the turgor of non-woody plants, delivers mineral nutrients to plant tissue and is a cools mechanism
- the vapour pressure gradient between the leaf tissue (and bark, to a lesser extent) and the surrounding air draws water from soil into the roots and up the plant through the xylem

- as water evaporates within the leave tissue, salt can precipitate and further attract water if the soil is saline, the salt concentration gradient is reversed and water can be drawn out of the plant
- thus saline soils tend to be sparsely vegetated with salt-tolerant (halophytic) plants

- under dry, windy and/or hot, sunny conditions, transpiration can exceed the rate at which water can be supplied from the soil; closing of the stomates prevents water loss but also access to atmospheric CO_2 for photosynthesis
- plants in dry environments (xeriphytes) can sore radiant energy during the day and photosynthesis (open their stomates) at nights, when lower temperatures and high relative humidity results in lower rates of transpiration
- conversely, under cool humid conditions, where there is ample soil water supply and slow transpiration, liquid water will drip from the stomates

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Potential evapotranspiration

- wet surface evaporation: "rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation which has unlimited supply of water without advection [wind] and heat-storage effects"
- an index of "drying power", first introduced for climatic classification
- precipitation / PET is a simple but powerful index of surface water balance
- since evapotranspiration depends on type of vegetation, short grass is assumed
- PET is estimated from various climatic parameters: temperature, day length, net radiation, wind speed, relative humidity
- actual ET is controlled mainly by plant and soil properties (especially water retention and capillarity)

Relative importance of evapotranspiration

- by one estimate, 62% of continental precipitation evapotranspires, about 97% of this is from land and 3% from open water bodies
- evapotranspiration represents nearly all the soil and surface water loss from dry environments, where runoff is minimal

- on a global scale, evapotranspiration consists mostly of evporation from soil, because a large proportion of the continents is occupied by desert grassland and tundra
- with a continuous vegetation cover, evaporation from soil is least important (about 10% of ET from forests) and transpiration and evaporation of intercepted water account for most of the ET
- there vegetation has a profound impact on the hydrological cycle, such that streamflow can be augmented by managing vegetation (*e.g.*, thinning forests to reduce transpiration and interception loss)