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WATER BUDGETS FOR NATURAL SYSTEMS

Lars Thörneby
Dept. of Technology, University of Kalmar, SE-391 82 Kalmar, Sweden

INTRODUCTION

Natural systems including constructed and natural wetlands as well as irrigated land areas, geofilters and ponds are capable of absorbing pollutant loadings, and in appropriate circumstances can provide a low cost alternative to traditional chemical and biological treatment. Many projects have shown reduction of nutrients, oxygen consuming substances but also more environmental hazardous compounds.
Natural systems seem to have a great potential for treatment of leachate. Some parts of these systems belongs to biological treatment and other parts to "filtration" and therefore these systems could be seen as a mix of transformation and filtration together with the volume reducing effect by evaporation and transpiration. Method used in Sweden are mainly Soil-Plant (SP) system there a large part of the treatment is removal of water by evapotranspiration. Irrigation of e.g. energy forest or land surfaces increases the possibility of natural evaporation. When an area of the landfill is irrigated the water balance will change. This paper focuses upon the water budget and water movement within the natural system.

Water balance

The inflow of water to a natural treatment system is the water to be treated (L) but also runoff, groundwater discharge and precipitation contributes to the inflow. Depending of type and construction, the system might lose water via streamflow, runoff, groundwater recharge, and evaporation/evapotranspiration.

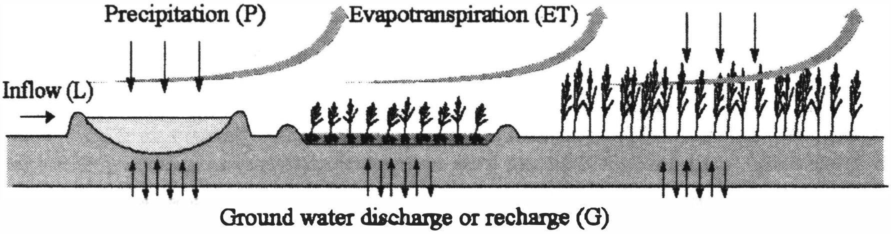

Figure 1. Water balance terms in natural systems

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Evapotranspiration (ET) is often an important factor in wetland and soil-plant (SP) system performance. Hence we can state the water balance as follows.

$$P + L_{IN} = ET + L_{OUT} + G + R + S$$

where P= Precipitation

L_{IN}= Inflow of water to be treated

ET= Evapotranspiration

L_{OUT} = Outflow of treated water

G= Ground water flow (positive when out of the system negative when into the system)

R= Runoff (positive when out of the system negative when into the system)

S= gain or loss of water in the system, a storage term

All terms have the dimensions of depth per unit time (for example, mm/ year or in/year). This shows the intensity of water flow, independent of total surface area. However, for a specific area it is possible to calculate the total quantity of water transported into or out of the area. from the intensity value. When applied to constructed wetlands and ponds with static water levels, the storage term S can be neglected. The storage term can also be neglected for variable levels and for irrigated land areas if the time span is sufficiently long, a year or more. Properly constructed ponds and wetlands should have no inflow or outflow of groundwater and ponds, wetlands or irrigated land should not gain or lose surface water from the surroundings. As there is no point outlet from irrigated land the outflow term L_{OUT} can be neglected in this case. The water balance equation then simplifies to

$P + L_{IN} = ET + L_{OUT}$ for wetlands and ponds and to

$P + L_{IN} = ET + G$ for irrigated land

Evapotranspiration

There are two main factors influencing evaporation from an open water surface. At first there must be sufficient heat supply to provide latent heat of vaporisation (the amount of heat given up or absorbed when a substance changes from one state to another) and second an ability to remove the vapour from the surface. The sun provides most of the energy needed. The ability to transport vapour away from the evaporative zone depends on factors as wind velocity over the surface and the specific humidity gradient. This gradient increases by increasing temperature as warm air holds more water than cold air does.

Considering evaporation from land surface there are two different conditions with and without vegetation. Without vegetation evaporation depends on the amount available surface water and by the rate water can be transported from underlying layers to surface, which in turn depend on the type of soil material. Available surface water may be either rainfall intercepted by vegetation, ponded water, and snowmelt or accumulated snow. With vegetation one must pay attention to both evaporation from the soil and plant foliage and transpiration by the plant. Hence, it is convenient to use the term evapotranspiration to cover the combined moisture loss from direct evaporation and the transpiration from plants.

The rate of evapotranspiration from a area is a function of solar radiation, temperature, humidity, wind velocity, vegetation type and growth stage, water retained on the surface, soil water content and soil characteristics. The rate of evapotranspiration slows down as moisture supply becomes depleted during dry periods because plants can control transpiration.

The forest is a complex mosaic of land surface types varying from closed coniferous canopies, through sparsely vegetated cleared areas, to open lakes. Therefore the interaction of these different surface cover types with the incoming radiation and with the atmosphere is expected to be different. As a consequence of these different interactions, it is observed a substantial spatial variation in microclimate, as well as variations in surface fluxes of radiation, heat and water vapour. The components of the energy balance (*radiation flux* - solar and thermal; *sensible heat flux* -turbulent transfer or heat from the surface to the atmosphere; *latent heat flux* - evaporative cooling or warming upon condensation and soil heat flux) which determine the net energy supply to the canopy and the surface.

Before proceeding we recognize two different ways to define evaporation and evapotranspiration, respectively. First we have actual evaporation from a land surface without vegetation, which is the true value of loss of water from an area to the atmosphere. Second is potential evaporation representing the moisture losses under ideal conditions. One condition is that there is no water deficit in the soil. In the same way we recognize two ways for ET, actual ET and potential ET. The conditions for potential ET is that there should be no bare ground exposed through a fresh leaf cover whether the plants is trees, bushes or grasses. The leaf cover is also assumed to have uniform height. There should also be an adequate water supply, that is the soil field capacity (the quantity of water held in a soil by capillary action after gravitational water is removed) should be maintained all the time. This condition can be fulfilled by abundant and frequent precipitation or artificially by irrigation of land. Normally this condition is fulfilled in wetlands either they are natural or constructed. From now on we use the symbol ET_P for potential evapotranspiration and ET_A for actual evapotranspiration. Several methods have been devised for estimating E_P and ET_P. The models have often been named by the creator e.g. Penmans formula, Thornthwaits formula etc. Variables used in the models are temperature, altitude, humidity, wind velocity, type of vegetation, number of sun hours per day, sun radiation, precipitation, albedo and soil type. The basic rate is the reference crop evapotranspiration (ET_0) which for given climatic conditions is "the rate of evapotranspiration from an extensive surface of 8 cm to 15 cm tall green grass cover of uniform height, actively growing, completely shading the ground and not short of water."

Estimating evaporation can be done by an evaporation pan, which is a circular tank containing water, in which the rate of evaporation is measured by the fall of the water surface. There are different types of pans but for the most Class A pan is used, Pans often overestimate lake evaporation in the range of 10% to 60 %, due to the edge effect, i.e. energy is transported to the tank from the surroundings. The heat also increases convection, which enhance vapour transport from the tank.

For large wetlands evapotranspiration and lake evaporation are roughly equal. As it is difficult and also expensive to measure evapotranspiration very often ET is calculated from evaporation measurements by for example Class A pan and described as

$$ET = f * E_{\text{Class A pan}}$$

where f is a factor between 0.7 and 0.9

For small wetlands the factor (f) may be higher, sometimes above 1, due to the edge effect and also that heat may be drawn from the surroundings.

Often ET_A also is calculated from the precipitation data and the outflow data from a well defined watersheds or from relatively small (1-500 m^2) lysimeters.

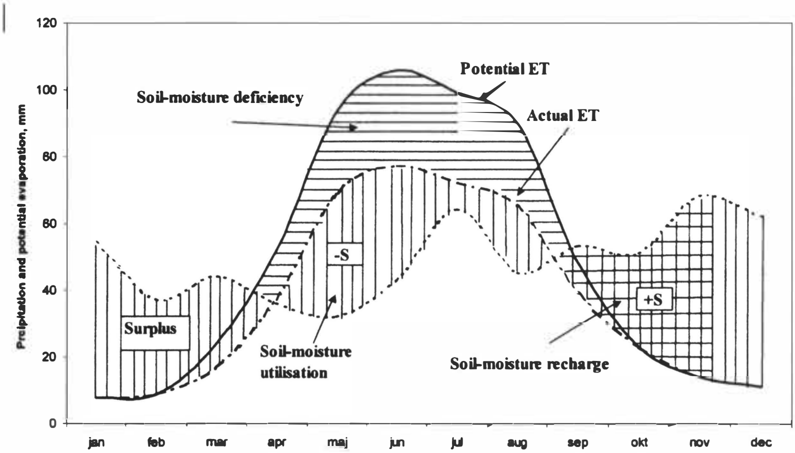

Figure 2. Mean values from ten years of precipitation, actual and potential evapotranspiration from southern Sweden.

Figure 2 shows mean values for ten year from a local in southern Sweden. ET_A is calculated from the difference between precipitation and the outflow from the area and ET_P is calculate from local meteorological data by Penman. During the winter period when P is greater than ET_P there is a surplus of water. This surplus will runoff the area. When ET_P exceeds P, the water must be drawn from the soil by the plants that limit the available soil water causing a drop in ET. During this period deplete the soil moisture below field capacity. Again, in autumn, when P exceeds ET the soil moisture is recharged and when this is completed the surplus runoff. The differences between ET_P and ET_A during the summer period is the quantity of water that have to be supplied by irrigation to sustain the full value of ET_P. Thus, it also is the quantity of water that can be removed from the natural system if the surplus of water under the winter season can be discharged either to surface water or ground water. Considerable less water can be treated if the precipitation during the winter has to be stored and/or treated. In Sweden it is especially the southeast part, which have the greatest water deficit (D+) during the vegetation period (Fig 3). The east coast in northern Sweden, the middle part and southern Sweden has less deficit (D) of water during growing season. The rest of Sweden has surplus of water (S) and the mountain region and also an area south of the lake Vänern has great surplus. This means that if the purpose is to remove water during growing season it can only be done in regions marked D and D+ on the map.

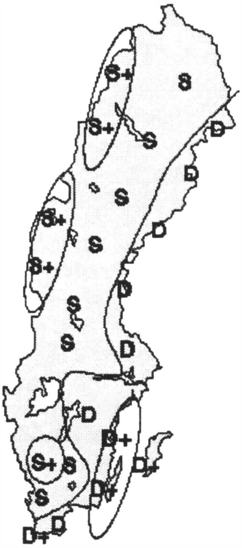

Figure 3.

The peak summer daily loss ranges from about 6 mm/d in subtropical climates to 3.5 mm/din the north temperate region. However, this loss occurs during the daytime hours, and peaks at an instantaneous loss rate that may be double or triple the daily average Fig. 4.

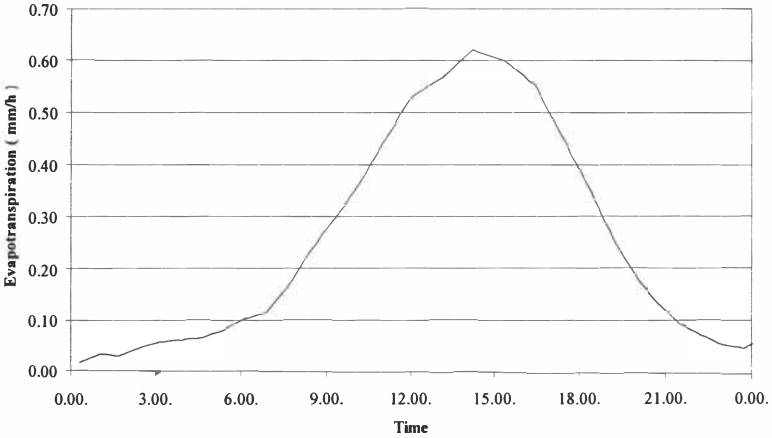

Figure 4. Evaporation rate from a small wetland area in southern Sweden under a warm summer day (Tmax =30 C)

Natural systems

Wetlands are a general term used to describe areas, which are neither fully terrestrial nor fully aquatic. Wetlands are inundated or saturated by surface or groundwater at a frequency and duration to support and that, under normal circumstances, do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Coastal wetlands extend back from estuaries and include salt marshes, tidal basins, marshes, and mangrove swamps. Inland freshwater wetlands consist of swamps, marshes, and bogs. These areas range in character from majestic swamps to shallow, unimpressive depressions, which hold water at most only a few weeks out of the year. Wetlands are important for many reasons. Some provide critical habitats for migratory waterfowls, while others check flooding and siltation on our waterways. Some acts as filters- removing and sequestering contaminants that might otherwise find their way into our drinking water while others provide us with recreational opportunities such as fishing and boating.

In humid climates with a large annual surplus in the water budget and with generally high water tables, the various event of geologic history, such as erosion and deposition by wind and by ice sheets of the most recent glacial stage, have created natural depressions with floors at or below the water table elevation. Seepage of ground water, as well as direct runoff of precipitation, maintains these free water surfaces permanently throughout the year. Examples are found widely distributed in Europe and North America where plains of glacial sand and gravel contain natural pits and hollows left by melting of stagnant ice masses. Many former fresh-water water-table ponds have, since they were formed by glacial ice, become partially or entirely filled by the organic matter from growth and decay of water-loving plants. The result is a bog whose surface lies close to the water table. In many cases there is no surface outflow or inflow to these lakes of glacial origin and the organic matter produced will accumulate to such thickness that the open water is replaced by organic mass called peat. A water budget might in this case be expressed as

$$P - ET = G_{IN} + G_{OUT}$$

where

P is actual precipitation,

G is ground water movement to and from the bog,

ET evapotranspiration.

During dry periods with high evapotranspiration there is supply of water from the ground water and a certain drying up of the highest part of the bog. Next rain will initially therefore be delayed before it can recharge ground water. Using this type of wetlands for treatment of heavily polluted waters will sooner or later contaminate the groundwater, as all of the added water will become groundwater.

Marshes and swamps, where the water stands at or close to the ground surface over a broad area represent the appearance of the water table at the surface. Such areas with poor surface drainage have a variety of origins. They might be created by shifting river channels on floodplains or emerged from the sea. These types of wetlands have high importance for the society as they prevent flooding; purify surface and groundwater hence preventing excessive nutrients from discharge into lakes and seas. It is also a home and breeding place for many economical important species. Also, they act as a water reservoir during drought as the water is slowly drained when the water level decrease in the flow channel making it possible to maintain a certain basic flow in the stream for long periods of drought.

Another type of "wetland" is land with overland flow meaning lands with runoff that flows down slopes in more or less broadly distributed films, sheets or rills. There is a distinction between overland flow and channel flow or stream flow, as in the latter the water occupies narrow trough confined by lateral banks. This type of " wetland" might be grass-covered slopes or heavily forested slopes bearing a thick mat of decaying leaves. If such hillside has been thoroughly drained of moisture in a period of drought then is subjected to a period of rain the rain will initially been held in droplets on the leaves (interception). This water may be returned to the atmosphere by evaporation, so that if the rainfall is brief, little water reaches the ground. The ground surface is capable of absorbing by infiltration even a heavy rain in the early stages of a rain period and might, if the duration of the rain is relatively short, one hour or less, be able to prevent any overland flow. At longer rain periods the soil passages is sealed or obstructed and the infiltration rate is dropped to a low steady level. The excessive precipitation will be accumulating in small pools and the surface flow is held back until most natural hollows are filled sk surface detention. Further increase or continued rain cause the water overflow from hollow to hollow giving a true overland flow. The depth of the flowing layer increase as farther down slope we measure. The flow is proportional to the length of the total flow. But as the water proceed downhill, the flow velocity increase and therefore the depth will be less than expected. Overland flow Q_{OF} is measured in millimetres of water per unit time, as for precipitation P and infiltration G and a water budget after a sufficient time of raining might be expressed with a simple formula.

$$Q_{OF} = P - ET_{P} - G$$

Overland flow can be used for treatment of leachate on site or outside as polishing steps for water with low concentration of nutrients.

Constructed wetlands for treatment of leachate can be of different types and they can either be localized on the landfill site or outside the landfill. For the purpose of water removal it is better localizing the wetland on-site as it decrease the quantity of leachate. Outside the landfill the whole leachate production plus the annual precipitation will flow through the wetland. The irrigated area in soil plant (SP)-system can be compared to vertical flow "wetlands" or intermittent gravel filters, which have demonstrated advantages for oxygen transfer and nitrogen control. SP- system are capable of absorbing pollutant loadings, and in appropriate circumstances can provide a low cost alternative to chemical and biological treatment as well as more engineered systems. The irrigated land can either be an area planted with grass, bushes or trees or it can be a natural grassland or forest. However concerning water removal on-site localization removes more water than offsite localization do. The water budget as mentioned before can be described as follows

$$P + L_{IN} = ET_P + G \text{ or}$$

$$G = (P + L_{IN}) - ET_P \text{ outside the landfill and}$$

$$G = (P + L_{IN}) - ET_P - P^*a \quad \text{on-site}$$

where

a = the ratio between irrigated and non irrigated land area

Natural systems that provide wildlife habitat also may receive various kinds of environmental contaminants through the water supplied to them. Chemicals that bioaccumulate in the foodchain (such as mercury, selenium, or organochlorine pesticides) are typically the chemicals of greatest concern for possible effects in wildlife. Certain other chemicals (such as copper, zinc, or ammonia) that may occur in wastewaters may limit the habitat values of the area by reducing the availability of aquatic foodchain organisms for wildlife, but they are less likely to affect birds or mammals directly.

Consequences of ET and rainfall

Losses of water by ET serve to slow the water, and increase detention time, precipitation has the opposite effect. This gain and loss of water have impact on detention time. As detention time is important design and operational factor some attention must be given these gains and losses.

In constructed lateral flow systems as sub surface flow (SSF) wetlands, hydraulic load is often in the range of 20 to 50 mm per day or 0.9 to 2 mm per hour. Thus an ET rate of about 0.5 mm per hour at noon, considerably slowing downs the flow at that time of the day. A rainfall of an intensity of 0.5 mm per hour will correspondingly increase the flow of water. For vertical flow systems as irrigated land or vertical flow wetlands ET has more dramatically impact on the flow. The hydraulic load at SP system is commonly about 5 mm per day distributed 3 to 4 times at daytime, which means an average daily flow rate of about 0.2 mm per hour. Due to the relatively low hydraulic load at SP-system ET has a great influence on the detention time. At long dry and hot periods almost no water percolate through the root-zone and the detention time increase.

Large fluctuations in daily flow pattern can during daytime, in SSF wetlands, cause dryness at the inflow end. Compensation of this by increasing the flow might, in turn, cause overflow at the outflow end, under periods with low ET.