CATCHMENT WATER BALANCE, CLIMATE AND GROUNDWATER

Derek Eamus
Institute for Water and Environmental Resource Management, University of Technology, Sydney, Australia.

Keywords: Groundwater dependent ecosystems, vegetation water use, catchment water balance.

Contents

Summary

This article discusses the water balance of a catchment and shows how rainfall alone does not always represent the only significant input of water. The importance of solar radiation in determining evapotranspiration rates is highlighted and a simple leaf energy balance is presented. Daily and seasonal patterns of vegetation water use are discussed. The concept of groundwater dependent ecosystems is highlighted and discussed in detail. A case study of a catchment water balance and the catchment's associated groundwater dependent ecosystems is presented.

1. Introduction

Water is the key to all of life on earth. From sub-cellular processes (photosynthesis, enzymatic reactions) to continental-scale processes (erosion, sedimentation), water is central to ecosystem structure and function. This article deals with catchments, an intermediate scale between sub-cellular and continental, and examines catchments and groundwater from a vegetation and ecosystem perspective, not a physical hydrology perspective. In particular it discusses the interaction of vegetation with groundwater because this represents a new and developing topic and because this publication is concerned with Life Support Systems and thereby has a biophysical focus.

In particular, I shall address the following questions:

- What is a catchment water balance?
- How does climate influence water use by vegetation?
- How important is groundwater to catchment water balance and ecosystems?
- Is there a direct link between vegetation and groundwater?

2. Catchment water balance

In its simplest form, the water balance of a catchment is described by the equation:

$$I - O = \Delta S \qquad (1)$$

where I = input of water to the catchment; O = output from the catchment; and ΔS = change in storage within the catchment.

Input is most frequently thought of as rainfall, although mist, fog, snowmelt, surface flow (run-on), sub-surface lateral flow, stream/river flow and groundwater inflow can represent significant inputs of water in many locations and should not be neglected from consideration in ecohydrological investigations.

Not all rain that falls reaches the ground surface and a significant fraction of total rainfall is intercepted by vegetation and litter and evaporates to the atmosphere. Therefore net rainfall is defined as the difference between total rainfall and interception losses. Interception losses vary as a function of rainfall intensity and duration and are high during low intensity rain events and high for short duration rain events. Interception losses are also influenced by vegetation structure (for example, mature conifers intercept more rain than mature broadleaf canopies; closed canopies intercept more than open canopies) and season (winter deciduous canopies intercept less in winter than summer; hot and dry conditions favor rapid evaporation from wet canopies). Interception losses can vary between 100% (very short duration, very light rain onto a closed conifer canopy) and 5% (long duration, heavy rainfall). In a similar fashion, not all groundwater influx to a catchment is significant from an **ecosystem** perspective if it occurs at depths too large for it to interact with vegetation through the root zone.

Significant water outputs from a catchment are generally considered to be stream/river flow, surface evaporation, vegetation water use (transpiration), surface run-off, sub-surface flow and groundwater movement. The role of vegetation and climate in the discharge of a catchment's water is discussed in detail in section 3.

Storage of water can occur in soil, groundwater, lakes, rivers and in vegetation. Storage in vegetation is small in total volume (compared to that stored elsewhere) but can have a significant impact, in the short-term, on vegetation water use. Diurnal changes in stem storage of water in trees have a role to play in the diurnal patterns of water use by woodlands and forests. In the past, consideration of the interaction of vegetation and water has generally been confined to a consideration of rainfall only. However, in recent years it has become apparent that groundwater plays an important role in vegetation water use and ecosystem structure and function in many systems and this is discussed in the next section.

3. Discharge of water by vegetation

3.1. Radiation balance and evaporation

Evaporation of water occurs from wet surfaces due to the input of energy to the wet surface. Solar radiation is the principle input of energy driving evaporation, and solar radiation is shortwave radiation (wavelengths up to 1.0 µm). A surface (such as a leaf) can receive direct solar radiation (W_s; radiation that has not materially interacted with another mass) or diffuse solar radiation (w_s; radiation that has interacted with another mass, such as being reflected from a cloud or another leaf). Some of this radiation is absorbed by a leaf; some is reflected and some is transmitted through it. The albedo (α) of a surface is the fraction of total ($W_s + w_s$) solar radiation reflected from a surface. In addition to shortwave radiation, long-wave radiation (wavelengths longer than 1 µm) is also present, having been emitted by soil, vegetation and the atmosphere (but especially diatomic molecules such as CO_2 and H_2O). A leaf or canopy can both receive long-wave radiation (I_a) and emit long-wave radiation (I_g), but only receives incoming shortwave radiation (because leaves and canopies are too cool to emit shortwave radiation).

From the brief description above, we can see that the radiation balance of a surface such as a leaf is the net balance between incoming shortwave plus long-wave radiation and outgoing long-wave radiation. Thus:

$$R_n = (W_s + w_s)(1-\alpha) + I_a + I_g \qquad (2)$$

where R_n is net radiation.

Net radiation can be positive or negative. When positive, the leaf loses energy through several processes, but especially the evaporation of water. This water can be derived from three principle sources—soil water (water in the unsaturated, upper soil profile and derived from rainfall), river water (see below) and groundwater (see below).

As a leaf absorbs radiation, it is warmed and the leaf must lose energy. It does this through three paths. First, it loses long-wave radiation—all objects above a temperature of absolute zero (–273 degrees Kelvin) emit radiation. This is “black body radiation” and leaves lose long-wave radiation because of their relatively low temperature (compared to the sun). The amount of radiation emitted (B) increases with temperature and is described by the equation:

$$B = e\sigma T^4 \qquad (3)$$

where e is emissivity of the object (close to 1 for leaves); σ is the Stefan-Boltzmann constant; and T is temperature (in Kelvin). Clearly, small increases in the temperature of an object result in large increases in the amount of energy radiated from that object.

Leaves can also lose energy through diffusion of heat (H) from the leaf to the air (also known as the sensible heat flux density). Energy loss through sensible heat flux is increased by wind and is larger from small needle-shaped leaves than from large broad leaves.

Finally, leaves can lose energy through the evaporation of water since the conversion of 1 g of liquid water into 1 g of water vapor requires about 2.4 kJ of energy (supplied principally by solar radiation). This loss of energy is given the symbol λE, where λ is the heat required to evaporate water (latent heat of vaporization 2.4 kJ g^{-1}) and E is the rate of evaporation. It is important to note that the use of absorbed energy in photosynthesis is ignored as it is such a small fraction of the total incoming radiation. Similarly, over the short term or long-term (but not intermediate) the storage of energy (as an increase in temperature of vegetation) is small enough to be ignored.

Thus, the energy balance of a leaf is given by:

$$R_n = B + H + \lambda E \qquad (4)$$

Re-arranging equation 4, we get $\lambda E = R_n - B - H$. This is an important equation from an ecohydrological perspective as it describes how evaporation from a leaf (transpiration) is determined by the net radiation receipt of the leaf and the loss of energy through black body radiation from the leaf (which is determined by leaf temperature and hence radiation input) and sensible heat loss (which is influenced by leaf temperature).

When water is readily available to a canopy, most (up to 90%) of the available energy is used to evaporate water from leaves. By having maximum opening of stomata (and hence unregulated transpiration), carbon gain through photosynthesis is maximized. When water availability is limiting, however, partial and eventually, complete, stomatal closure occurs and the amount of water transpired, and hence the amount of energy lost from the leaf through this process, is greatly reduced and heating of the canopy and air increases. Stomatal closure also reduces photosynthetic carbon gain. Transpiration is the unavoidable consequence of opening stomata to allow photosynthetic carbon gain.

Canopies can receive significant inputs of energy as sensible heat from surrounding areas. The most obvious case is an oasis, where the moist, green, but isolated canopy, is surrounded by a hot dry desert. This input of energy is in addition to the net radiation received by the canopy, and can be a large proportion (10 to 30%) of the total energy budget of the canopy.

Radiation (energy) input to a leaf or canopy is thus the major determinant of transpiration (and evaporation from wet surfaces such as lakes and soil surfaces). The amount of radiation received by a canopy is very much determined by its location on the earth's surface, with tropical regions receiving far more radiation than temperate zones, which in turn receive far more radiation than polar regions. These differences in solar radiation input very much determine regional climate (along with differences in rainfall).

The amount of solar radiation incident on a flat horizontal surface on the earth's surface can be estimated from the following equation:

$$S = S_o * (D_m/D_a)^2 * (\sin\Phi\sin\delta + \cos\Phi\cos\delta\cos h) * \tau^{1/(\sin\Phi\sin\delta + \cos\Phi\cos\delta\cosh)} \quad (5)$$

where S_o is the solar constant; D_m is the mean distance of the earth from the sun; D_a is the actual distance of the earth from the sun; Φ is latitude of the site; δ is the angle of inclination of the sun; *h* is the solar hour (zero at solar noon and increasing 15^o per hour from solar noon); and τ is atmospheric transmissivity (typically 0.4 to 0.7 depending on cloud and atmospheric pollution levels).

Locations closer to the equator (tropical zones) receive more solar radiation (daily and annually) than those closer to the poles (northern Europe, northern America) because of the increase in inclination of the surface of the earth to the sun. In addition to latitude, slope and aspect (a north facing slope in the northern hemisphere receives less radiation than a southern facing slope) influence the amount of radiation received. Cloud cover and pollution affect the transmissivity of the atmosphere and therefore the amount of radiation reaching the ground.

Having established the central role of net radiation and climate in driving evaporation from vegetation, it is important to consider the sources of water used by vegetation.

-
-
-

Bibliography

Cook P.G., Hatton T.J., Pidsley D., Herczeg A.L., Held A., O'Grady A.O. and Eamus D. 1998. Water balance of a tropical woodland ecosystem, north Australia: a combination of micro-meteorological, soil physical and groundwater chemical approaches. *Journal of Hydrology* 210, 161-177. [This paper gives details of methods, philosophy and the results of an application to determine a catchment water balance].

Dawson T.E. and Ehleringer J.R. 1991. Streamside trees that do not use stream water. *Nature* 350, 335-37. [This paper gives the results of a study using stable isotopes to establish which source of water is being used by trees.]

Eamus D., O'Grady A.P. and Hutley L.B. 2000. Dry season conditions determine wet season water use in the wet-dry tropical savannas of northern Australia? *Tree Physiology* 20, 1219-1226. [This paper provides details of the methods and results of a study of tree transpiration in a highly seasonal environment.]

Hatton T.J. and Evans R. 1997. Dependence of ecosystems on groundwater and its significance to Australia. Sinclair Knight Mertz, Australia. Pp109. [This is one of best reviews of groundwater dependent ecosystems, providing details of definitions and extent and importance of groundwater dependent ecosystems.]

Humphreys W.F. 1999. Relict sytogofauna living in sea salt, karst and calcrete habitats in arid north western Australia contain many ancient lineages. In W Ponder and D Lunney (Eds). The other 99%. The conservation and biodiversity of invertebrates. Transactions of the Royal Zoological Society of New South Wales. [An important paper providing details of fauna found in groundwater systems.]

Hutley L.B., Doley D., Yates D.J. and Boonsaner A. 1997. Water balance of an Australian subtropical rainforest at altitude: the ecological and physiological significance of intercepted cloud and fog. *Australian Journal of Botany* 45, 211-329. [An unusual paper showing how cloud and fog water can contribute to tree and ecosystem water balance.]

Hutley L.B., O'Grady A.P. and Eamus D. 2001. Monsoonal influences on evapotranspiration of savanna vegetation of Northern Australia. *Oecologia* 126, 434-443. [Provides details of methods and results of a study using eddy covariation techniques to examine daily and seasonal patterns of water use of a savanna.]

Mensforth L.J., Thorburn P.J., Tyerman S.D. and Walker G.R. 1994. Sources of water used by riparian *Eucalyptus camaldulensis* overlying highly saline groundwater. *Oecologia* 100, 21-28. [An important paper highlighting the use of stable isotopes and the impact of saline groundwater on vegetation water use.]

O'Grady, A.P., Eamus, D. and Hutley, L.B. 1999. Transpiration increases during the dry season: patterns of tree water use in eucalypt open-forests of northern Australia. *Tree Physiology 19:* 591-598. [Provides details of methods and results of a study investigating tree water use in a highly seasonal environment, using sapflow technology.]

Biographical Sketch

Derek Eamus is Professor of Environmental Sciences and Director of the Institute for Water and Environmental Resource Management at the University of Technology, Sydney, Australia. He has undertaken research into the interaction of water, vegetation and climate for the past 13 years and has recently focused on groundwater dependent ecosystems. He has supervised a large number of research students and postdoctoral research scientists on projects that have applied a range of techniques in plant ecophysiology, including stable isotope, eddy covariance and sapflow methodologies. His three major current research projects are first, to examine mechanisms linking catchment water status and net primary productivity; second, mechanisms underlying stomatal responses to vapor pressure deficit and third, groundwater-vegetation interactions in saline affected landscapes.