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The zone of vegetation influence on baseflow revealed by diel patterns of streamflow and vegetation water use in a headwater basin

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Abstract

Water use by vegetation can be closely linked to streamflow patterns on a variety of time scales. However, many of the details of these linkages are poorly understood. We compared diel (24 h) patterns of transpirational water use with streamflow patterns in a small headwater basin that displays a marked diel variation during summer months. The study site was in western Oregon. Our objectives were to: (1) determine the phase shift, i.e. the time lag between maximum transpiration and minimum streamflow, and the strength of the correlation at that time lag; (2) determine the amount of streamflow that is 'missing' during each diel cycle (i.e. the difference between base flow, defined by the daily maxima, and actual flow) and use it to estimate the zone, or area, of vegetation that influences daily streamflow patterns; (3) test and refine a conceptual model of how the coupling between vegetation water use and streamflow changes over the period of summer drought in this basin. We found that vegetation water use in the summer is coupled to streamflow over time scales of 4 to 8 h, and water-use-related fluctuations accounted for 1 to 6% of summer base flow. Direct evaporation from the channel was an order of magnitude less than the diel streamflow decrease. Transpiration within only 0·1 to 0·3% of the basin area accounted for the diel variation in streamflow. As the basin drained further through the summer, the coupling between vegetation and streamflow was diminished and occurred at longer time scales, and the zone of vegetation influence became smaller. This pattern is in accordance with our conceptual model, which attributes the summer decline in the strength of the vegetation–streamflow coupling to the increasing depth of plant-available water in the soil profile. Although this study is preliminary, we believe it is an important first step in describing better the coupling of vegetation water use to streamflow. Copyright © 2002 John Wiley & Sons, Ltd.

Introduction

A central issue in hydrology today is to establish relationships between hydrological and biological processes in ecosystems (Rodriguez-Iturbe, 2000). To advance catchment-scale hydrological modelling, we need to couple key catchment areas to streamflow patterns and to identify and quantify components of the water balance (Beven and Freer, 2001; Seibert and McDonnell, in press). One approach has involved defining hydrologically similar sub-units of basins (Becker *et al*., 2000) or 'hydrologic response units' (Leavesley, 1983). Though these units are spatially explicit, they generally do not define how soil, sub-soil, and

vegetation interact within a unit or grid cell to influence water fluxes. The physical and biological details of these interactions are often beyond the realm of simple, conceptual model structures; however, Jones (2000) has proposed that some of these interactions may be identified from examination of the annual hydrograph. Though not spatially explicit, this approach has potential for revealing how vegetation, soil, and sub-soil interact in certain time periods that might ultimately inform how we should structure our models of soil–vegetation–streamflow relations.

In this short paper we extend Jones' approach, comparing temporal patterns of transpirational water use with streamflow patterns. Our study site was a small headwater basin in western Oregon, which displays a marked diel (24 h) cycle during summer drought periods. A diel cycle in streamflow can be interpreted to illuminate key characteristics of the hydrology of the catchment. We determined the amplitude and phase of diel cycles in streamflow (as advocated recently by Fleming *et al.*, (2001)) and related them to diel cycles of vegetation water use. Our objectives were to: (1) determine the phase shift, i.e. the time lag between maximum transpiration and minimum streamflow and the strength of the correlation at that time lag; (2) determine the amount of streamflow that is 'missing' during each diel cycle (i.e. the difference between base flow, defined by the daily maxima, and actual flow) and use it to estimate the zone, or area, of vegetation that influences daily streamflow patterns; (3) test and refine a conceptual model Figure 1 of how the coupling between vegetation water use and streamflow changes over the period of summer drought in this basin.

Study Site

We analysed the relationships between patterns of streamflow and transpiration in a second-order basin (Watershed 1) in the H.J. Andrews Experimental Forest in western Oregon (Figure 1). The Andrews has a marine temperate climate, with >80% of precipitation occurring between November and April, and a protracted period of summer drought with a 4 month period of baseflow recession of the hydrograph. This study is part of a larger research effort at the Andrews Long-Term Ecological Research (LTER) program. Watershed 1, about 100 ha in size, has been part of a paired-basin experiment since 1952, and its climate,

soils, vegetation, land-use history, geomorphology, hyporheic zone, stream temperatures, streamflow, and other properties have been described in many publications (Dyrness, 1967, 1973; Halpern, 1989; Grant and Wolff, 1991; Jones and Grant, 1996; Perkins, 1997; Johnson and Jones, 2000; Jones, 2000). After logging of old-growth forest in Watershed 1 in the mid-1960s, vigorous stands of alder regenerated along the stream channel; hillslopes have variable-density stands of young Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and shrubs. A strong diel variation was apparent in streamflow of Watershed 1 during many of the summers from 1952 to the mid-1990s, stimulating the installation of a V-notch weir starting in 1999 to capture small variations in streamflow more accurately.

Methods

Measurements of transpiration

Transpiration was estimated from sapflow measurements and a vegetation survey, as part of a larger study to be reported separately. Sapflow was measured at 20 min intervals in a sample of trees, and tree-level measurements were converted to a ground-area basis using estimates of sapwood basal area of all woody vegetation from vegetation surveys (see below). Sapflow was measured using the thermal dissipation technique developed by Granier (1985, 1987), generally following the procedures described by Phillips *et al.* (2002). Radial variations in sapflow were measured in red alder (*Alnus rubra* Bong.) through the use of probes inserted to different depths in the sapwood (0–2, 2–4 and 4–6 cm). For Douglas fir we used radial profiles established previously for the trees of the same age at another location (Phillips *et al.*, 2002). In 1999, sapflow was measured from 1 July–8 September in seven Douglas fir and seven red alder selected to represent the typical range in size for this site along an ~ 60 m transect running upslope perpendicular to the stream. We found no significant differences based on slope position or tree size, so the mean values of sapflow per unit sapwood area were used as predictors for all trees in each class (softwoods versus hardwoods). In 2000, sapflow was measured from 17 June through to the end of September in only the seven Douglas fir trees, and water use by hardwoods in 2000 was estimated from relationships between the two species in 1999. We used
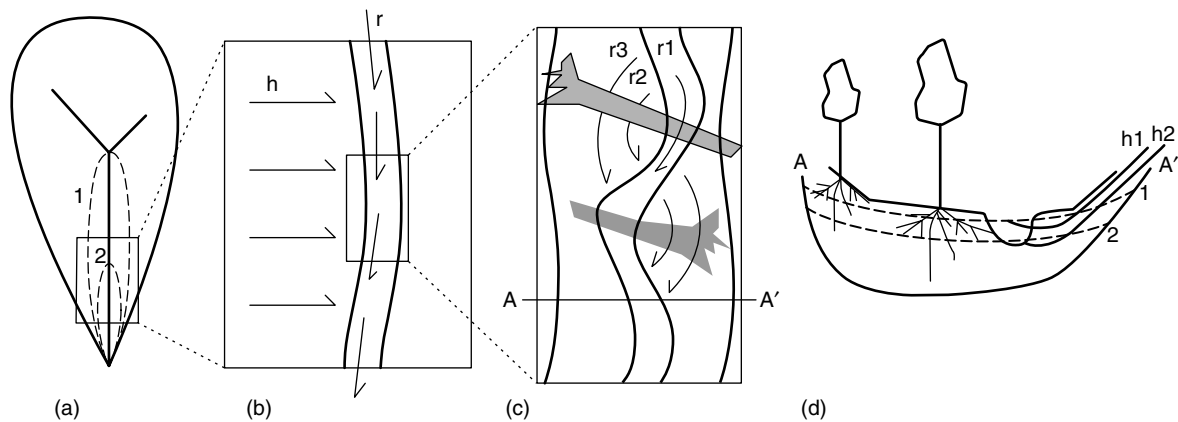
Figure 1. Conceptual model of vegetation–hydrology coupling at diel time scales over the summer baseflow recession period in a headwater basin (Watershed 1) in the H.J. Andrews Forest. (a) The basin consists of hillslopes and the valley floor, including the stream channel and floodplain/terraces, the groundwater system and the riparian system. (b) Hydrologic flowpaths operate on hillslopes (h) and in the riparian zone (r). (c) Riparian zone plowpaths include in-streamflow (r1), near-stream, fast, hyporheic exchange flowpaths (r2), and far-from-stream, slow, hyporheic exchange flowpaths (r3), created by sediment and large wood stored in the valley floor. (d) A cross-section of the valley floor shows shallow flowpaths (h1) and deep flowpaths on hillslopes (h2) contributing lateral flow to the valley floor and stream, and the changing positions of a water table or near-saturated zone in early summer (time 1) and late summer (time 2). The vegetation zone of influence on the diel cycles in streamflow can be envisioned as an area of lower hillslopes and the riparian zone (a) with a water table at a given height (1 or 2 in (d)). In early summer, when the water table is high (time 1), the stream channel has surface flow (r1) and is exchanging flow actively with the hyporheic zone through near-streamflowpaths (r2, part (c)). At time 1, the water table, or some near-saturated zone, is within the reach of most roots of riparian and lower hillslope vegetation (d). Thus, water use by lower hillslope and riparian vegetation produces a local depletion of moisture at the time of maximum sapflow, which is measured as a daily minimum in streamflow at some later time that day. The time lag between maximum sapflow and minimum streamflow is relatively short, because water routing through the flowpaths involved (h1, r1 and r2, parts (c) and (d)) is relatively fast. Later in the summer (time 2), when the water table has fallen, the stream channel has less surface flow and less active exchange along short hyporheic flowpaths, so the contributions of h1, r1 and r2 to streamflow are diminished relative to h2 and r3 (parts (c) and (d)). At time 2, the water table and near-saturated zone fall below the reach of most roots of riparian and lower hillslope vegetation (d). As in the early summer, local depletion is transmitted to the stream gauge through predominantly slower flowpaths (such as r3, part (c)), lengthening the time lag between maximum sapflow and minimum streamflow. Also, because deep flowpaths beyond the reach of tree roots are relatively more important to streamflow in late summer, the strength of the relationship between maximum sapflow and minimum streamflow declines at time 2 relative to time 1. By very late summer, the increasing dominance of deep hillslope and long hyporheic flowpath contributions to streamflow obscure the connection between sapflow and streamflow, almost eliminating the diel cycle in streamflow. These changes may be associated with a contraction of the area of vegetation influence from time 1 to time 2 (part (a))

sapflow measurements in red alder to represent all hardwood species, and measurements of Douglas fir to represent all softwood species.

Measurement of vegetation cover

In 1999, species and sapwood basal area of trees >1 cm diameter at breast height were determined in 100 m^2 plots arranged systematically along seven, 50 m transects perpendicular to the stream—each transect included five contiguous plots. The catchment has a pronounced triangular shape—whereas the transect closest to the weir reached nearly one-third of the way up the slope, transects more distal from the weir covered only about one-eight of the slope. There are no distinct 'upslope' and 'lower slope' vegetation zones in this basin due to its steep sides, which

form a V-shape. Douglas fir accounted for about 66% of the total sapwood basal area and nearly 100% of coniferous basal area in within the 100 m-wide corridor. Most of the remaining 34% of the sapwood basal area is hardwoods; bigleaf maple (*Acer macrophyllum*) and red alder (*Alnus rubra* Bong.) are the dominant hardwoods.

Measurements of streamflow and lag correlations with sapflow

Streamflow was measured at 15 min intervals at temporary V-notch weirs installed on the trapezoidal flume at Watershed 1. Streamflow data from summer, 2000, were interpolated to 20 min resolution to match sapflow data for statistical analyses. Five, 7 day periods were identified for analysis, spanning from wet to increasingly dry conditions: 24–30 June, 8–14

July, 22–28 July, 5–11 August, and 19–25 August. For each period, the correlation between sapflow and streamflow was calculated for each 20 min lag (relating streamflow to sapflow at an earlier time period) from 0 to 16 h, following methods in Post and Jones (2001). Data were plotted as a correlogram, showing the correlation (Y axis) as a function of time lag (X axis).

Estimates of 'missing streamflow' and zone of vegetation influence

The 'missing streamflow' associated with the diel signal was calculated for each day of the measurement period as the difference in volume between assumed baseflow (defined by successive daily maximum flows) and actual flow. In this case, which is the inverse of the concept of baseflow/quickflow separation, we assumed that transpiration diverts (i.e. competes for) water from the stream. A straight line was interpolated between successive daily maximum flows, which were spaced at 20–26 h intervals, and the missing streamflow discharge between this straight line and the observed discharge was estimated at 15 min intervals and summed for each day, producing an estimate of missing streamflow discharge for each day. We analysed meteorological data from a nearby site to calculate the potential evaporation loss from the channel as a possible control on daily streamflow depression. We found that this could account for a maximum of 0.025 1 s^{-1}, centred around solar noon. This was an order of magnitude less than streamflow depression in the June and July periods and much of the August period.

The effective zone of influence of vegetation was calculated as the ground surface area required for daily transpiration to equal the missing streamflow. This approach assumes that transpiration is the only cause of diel variation in streamflow, and it ignores
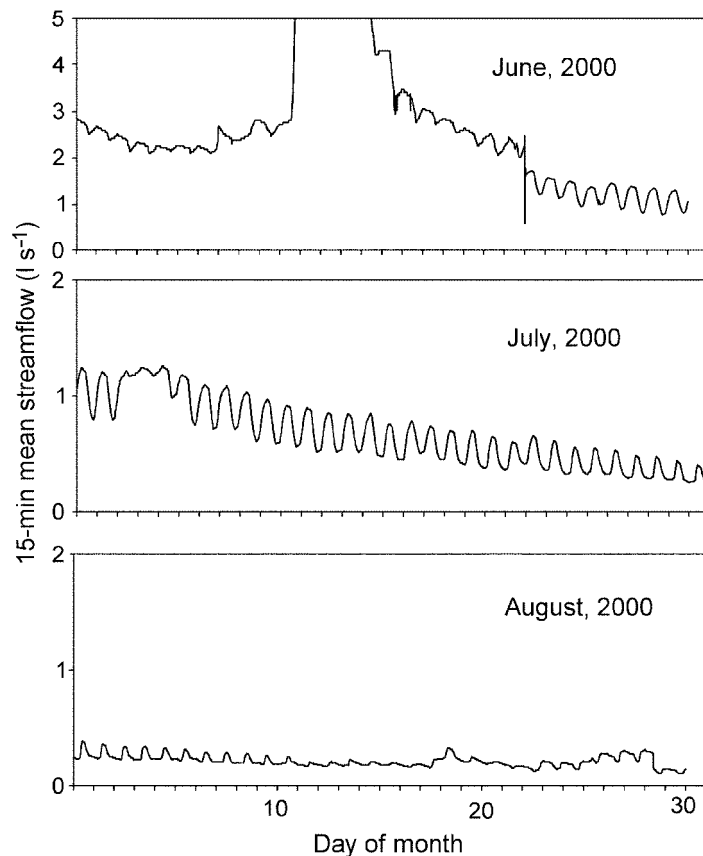

Figure 2. Streamflow through the V-notch weir of WS1 at 15 min intervals for June, July and August, 2000

possible confounding influences in the diel signal, such as inflow of water from upslope with a different phase and amplitude and the minor channel component. Therefore, the calculated area should be considered only an estimate, and probably an upper limit.

Results

Distinct diel patterns in streamflow in 2000 at Watershed 1 were first apparent in May (data not shown), then became pronounced in late June and persisted through early September with decreasing amplitude (Figure 2). Transpiration rates were highest in June and early July, peaking at a little less than 3 mm day^{-1} and declined to a little over 1 mm day^{-1} by the end of the summer. Likewise, 'missing streamflow' was greatest in the early summer and declined through the summer, as indicated by the change in amplitude of the diel cycle in Figure 2.

Correlations between sapflow and streamflow were highest and the time lag between maximum sapflow and minimum streamflow was shortest in the early summer (Figure 3). From 24–30 June, sapflow explained nearly 80% of the daily variation in streamflow ($r^2 = 0.76$), and the time lag between maximum sapflow and minimum streamflow was about 4 h. The estimated effective zone of influence of vegetation on daily streamflow was only about 0.3 ha (i.e. 0.3% of the total basin) in the early summer (Figure 4). As the basin dried out in July and August, the relationship between maximum vegetation water use and minimum streamflow diminished, the time lag increased, and the estimated size of the vegetation zone of influence declined from 0.3 to 0.1% of basin area (Figure 4). By 5–11 August, maximum sapflow accounted for only 50% of the variation in minimum streamflow, and the lag had increased to 8 h (Figure 3). By the end of August, maximum sapflow was not significantly related to streamflow at any lag (Figure 3). The period from 12–18 August was a time of particularly muted diel streamflow variations—here, direct evaporation from the channel could account for approximately 25% of diel stream depression.

Discussion

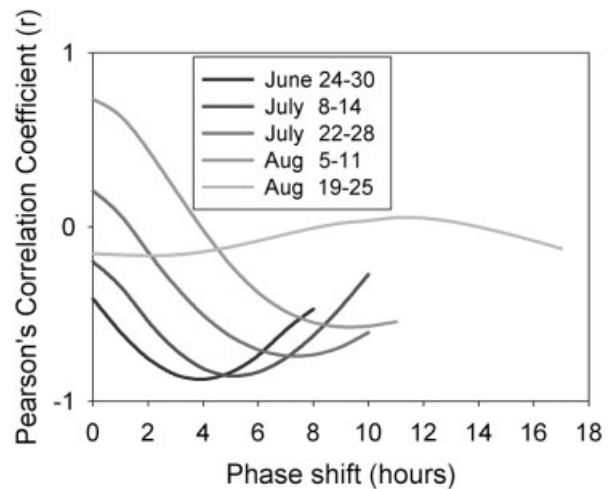Diel variations in streamflow are observed in many small basins, and have been attributed to snowmelt

Figure 3. Phase relationships between transpiration and streamflow over 7 day periods during the summer of 2000. The point of the minimum value of *r* for each curve indicates the phase shift between daily maximum transpiration and daily minimum streamflow
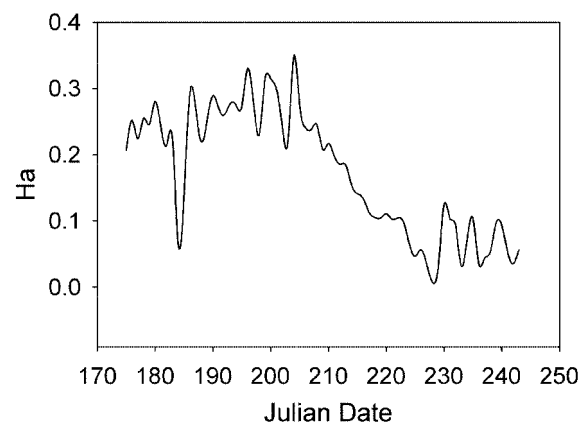

Figure 4. Surface area of transpiring vegetation (on a horizontal plane) that accounts for the daily 'missing streamflow' in WS1 from late June–early September, 2000

and freeze–thaw cycles (Jordon, 1983; Caine, 1992; Hardy *et al*., 1999; Williams *et al*., 1999), temperature influences on viscosity and water fluxes in the hyporheic zone (Constantz *et al*., 1994; Bencala, 2000), and vegetation water use (Troxell, 1936; Meyboom, 1965). The various causal factors restrict diel cycles in streamflow to characteristic times of year or certain basin conditions, which helps to discriminate their proximal cause. For example, diel cycles during periods of frozen ground (e.g. Shanley and Chalmers, 1999) may be attributed to freeze–thaw

cycles, whereas those occurring during periods of extreme drought (e.g. Burt, 1979) are more likely to be due to vegetation water use. The Andrews provides an ideal test case for examining these patterns, since the summer period is characterized by an extended drought with no rainfall inputs.

The diel streamflow patterns at our site are similar to those reported recently by others working in a similar Pacific Rim environment (e.g. Kobayashi and Tanaka, 2001). The signal in our study site appeared in late June and disappeared by mid-September. Snowmelt was complete by mid-May at Watershed 1 and its neighbours (Perkins, 1997). In 1997 the maximum daily range in stream temperatures in Watershed 1 was $1-2\,°C$ (Johnson and Jones, 2000); continuing measurements through 2001 show no change in this maximum range (Sherri L. Johnson, personal communication). Thus, we conclude that the diel cycle at Watershed 1 is most likely caused by vegetation water use, rather than by snowmelt or temperature effects on water viscosity.

According to our conceptual model Figure 1 the strongest coupling and the shortest lag between maximum water use by vegetation and minimum streamflow each day should occur during the early summer, when vegetation is using the water forming stream baseflow. In the spring, the diel signal may often be obscured by precipitation-induced fluctuations in streamflow and cloud-cover-induced reductions in transpiration. Temporal patterns of upslope lateral flow during the wet spring and early summer may also obscure diel signals in streamflow that would otherwise occur. In the early to mid summer, the combination of high evaporative demand, relatively high soil moisture content and very heavy vegetation cover result in very high rates of transpiration, which corresponds well with the period of maximum amplitude in the diel streamflow signal in Watershed 1. (During this time, missing streamflow as a percent of total streamflow was greatest.) As the summer progressed, our conceptualization is that that streamflow fluctuations should become less sensitive to transpiration rates as vegetation increasingly taps deeper water. The progressive weakening and delayed relationship between maximum sapflow and minimum streamflow appear to support this.

In our conceptual model Figure 1 the increased lag may be attributable to increasing amounts of flow at the gauge originating from deep flowpaths, where water fluxes are slower than the near-surface or near-channel flowpaths that transmit the diel signal. For example, a 4 h lag in the early summer may imply a 0·3 ha zone of vegetation influence on diurnal streamflow that occupies a 500 m long, 6 m wide stretch of valley floor. In this case most of the water involved is in near-surface flowpaths with flow rates of $\sim$0·04 m s^{-1} (500 m/4 h) to 0·0005 m s^{-1} (6 m/ 4 h). An 8 h lag later in the summer may imply a 0·1 ha zone of vegetation influence that occupies a 250 m long, 4 m wide stretch of stream. In this case the water involved is in below-surface flowpaths with flow rates of 0·01 m s^{-1} (250 m/8 h) to 0·0001 m s^{-1} (4 m /8 h). The lack of any significant relationship between temporal patterns of sapflow and streamflow by the end of August implies: (1) that vegetation may be using water from flowpaths with rates too slow to transmit a diel signal to streamflow; (2) that evaporation from the open water surface (now about 25% of this flow suppression) may be combined with other soil evaporation effects; (3) that the flowpaths sustaining baseflow are below the root zone. One or all of these explanations may be at work. More research is needed to shed additional light on these processes.

Conclusions

We report some of the first measurements of vegetation hydrologic function in the portion of the catchment in which diel sapflow is coupled to diurnal variations in streamflow, for a small, headwater basin. Although preliminary we believe that this is a first step in describing better the coupling of vegetation water use with streamflow, and inferring the changes in water flow paths controlling stream baseflow recession at the daily time step over the course of a summer drought period. Of course, vegetation water use is coupled to streamflow at other time scales that have geophysical or ecological significance. For example, our vegetation water-use measurements at the diel time scale accounted for at most 6% of summer streamflow, but at the annual time scale (evapo)transpiration accounts for 45% of precipitation, hence 80% of streamflow. This work represents a first step in decomposing/deconvolving the mechanisms and associated contributing areas that control streamflow, which may improve our ability to discretize key catchment features for conceptual model

construction. Future work will extend these measurements and analyses to other headwater basins, and to examination of vegetation–streamflow coupling at seasonal and inter-annual time scales.

Acknowledgements

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