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# Flow velocity and the hydrologic behavior of streams during baseflow

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[1] Diel variations in stream discharge have long been recognized, but are relatively little studied. Here we demonstrate that these diel fluctuations can be used to investigate both streamflow generation and network routing. We treat evapo-transpiration (ET) as a distributed impulse function in an advection model and analyze the effect of ET on diel fluctuations in discharge. We show that when flow velocity is high during high baseflow, discharge fluctuations tend to be in phase and constructive interference reinforces ET-generated signals resulting in strong diel fluctuations measured at a gauging station at the mouth of the watershed. As flow velocity slows with baseflow recession, ET-generated signals are increasingly out of phase so that fluctuations in discharge are masked by destructive interference. These results demonstrate that naturally produced fluctuations in discharge constitute discrete impulse functions that can be used to analyze eco-hydrologic behavior of whole-watersheds during baseflow periods. **Citation:** Wondzell, S. M., M. N. Gooseff, and B. L. McGlynn (2007), Flow velocity and the hydrologic behavior of streams during baseflow, *Geophys. Res. Lett.*, *34*, L24404, doi:10.1029/2007GL031256.

## 1. Introduction

[2] Traditionally, studies of stream flow generation and flow routing have focused on high flows, using rainfall impulses and a variety of natural or introduced tracers to characterize whole-watershed response [*Hewlett and Hibbert*, 1967; *Pilgrim*, 1976; *Pearce et al.*, 1986]. Recently, *Lundquist et al.* [2005] demonstrated that diel fluctuations during spring peak flows could also be used to examine stream flow generation and flow routing during snow-melt periods in mountainous basins of widely varying size. Diel fluctuations in discharge during baseflow periods, caused by evapo-transpiration (ET), occur in many streams during the summer [*Lundquist and Cayan*, 2002; *Czikowsky and Fitzjarrald*, 2004]. Studies that examined these fluctuations typically reported time lags of only a few hours between the time of daily maximum ET demand and daily minimum discharge [*Troxell*, 1936; *Wicht*, 1941; *Dunford and Fletcher*, 1947; *Bren*, 1997; *Czikowsky and Fitzjarrald*, 2004]. *Lundquist and Cayan* [2002, pp. 597–598] examined these fluctuations and concluded that "*because the travel distance between the location of the diurnal forcing and the river gauge is constant, and because this distance is short, variations in travel time due to changes in streamflow velocity are small. Hence, the hour of maximum flow tends to be consistent, with little shift in time as the season progresses.*" However, ET is widely distributed across watersheds, and we expect that ET from riparian forests would lead to substantial losses of stream water along the full extent of the stream network during summer baseflow. Also, geomorphic dispersion [*Rinaldo et al.*, 1991] resulting from the distribution of flow path lengths within a stream network affects both the timing and magnitude of discharge peaks measured at a stream gauge. Further, flow velocity decreases rapidly with decreasing discharge when discharge is low (Figure 1). Thus, we would expect that changes in streamflow velocity should have a large effect on the time lag between maximum ET and minimum discharge.

[3] Consider a hypothetical watershed in which stream flow velocity is infinitely fast. In such a watershed, a spatially distributed input signal from either precipitation or ET would be instantaneously transported to the stream gauge. Arrival times will be synchronous, irrespective of flow path length, so that the effect of geomorphic dispersion will be nullified. As flow velocity decreases, however, the effect of flow path length will increase, resulting in progressively greater and greater influence of geomorphic dispersion. Because the relation between velocity and discharge is highly non-linear (Figure 1), the effect of geomorphic dispersion should increase as flow velocity decreases over the period of baseflow recession. Consequently, the time lag between maximum ET demand and minimum discharge should increase, and the amplitude in diel fluctuations should decrease.

[4] In this paper we analyze diel fluctuations during baseflow recession (Figure 2) in WS1, a 100-ha watershed in the central western Cascade Mountains, Oregon, USA. Our work builds on previous work of *Bond et al.* [2002] who examined the effect of ET on temporal patterns of diel fluctuations during baseflow recession and showed that the time lag between maximum ET demand and minimum stream discharge increased and that the amplitude in diel fluctuations decreased. Here, we focus on the effect of changing streamflow velocity on the timing and amplitude of diel fluctuations during the period of baseflow recession. We suggest that stream flow velocity is a primary control on the propagation and attenuation of ET signals in WS1.

## 2. Analyzing Changes in Diel Fluctuations Over Baseflow Recession

### 2.1. Hydrograph Analyses

[5] We used cross-correlation to investigate changes in time lags between the time of maximum ET demand (estimated as reference ET or $ET_0$ [*Allen et al.*, 1998]) and minimum stream discharge for the summers of 2000

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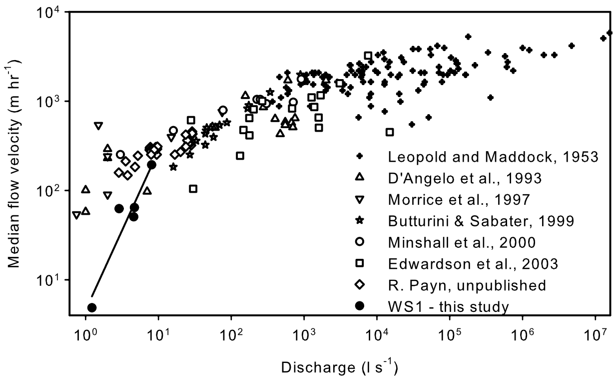


**Figure 1.** Discharge-velocity relations from a wide range of stream sizes and channel morphologies from gauging stations in a number of river basins and median flow velocities from stream tracer tests. Data and regression relation is also shown for flow velocities measured from tracer tests in the WS01 watershed ($u = 4.57Q^{1.78}$; $r^2 = 0.93$).

through 2004 (data available through the H. J. Andrews Experimental Forest data bank http://www.fsl.orst.edu/lter). Prior to analysis, days with missing data or with measurable precipitation were deleted from the dataset as were periods with high discharge in early summer or very low discharge in late summer (see Figure 2). For each day, hourly discharge was lagged behind hourly $ET_0$ by 0 to 23 hours and the correlation coefficient ($r$) between $ET_0$ and discharge was calculated for each time lag. The time lag with the minimum correlation was considered to be the time lag between the time of maximum $ET_0$ and minimum discharge. The amplitude of the diel fluctuation was calculated by subtracting the daily minimum from the daily maximum discharge and dividing by 2.0.

[6] Results from the period of baseflow recession in the summers of 2000 through 2004 showed that the changes in amplitude and time lag were highly related to flow velocity. The diel fluctuations in discharge had a maximum amplitude of 1.0 l $s^{-1}$ in early summer, and then decreased once flow velocity fell below 50 m $hr^{-1}$ (Figure 3a). Similarly, time lags between the time of daily maximum $ET_0$ and minimum discharge averaged between 5 and 6 hours in early summer, increased for flow velocities slower than 50 m $hr^{-1}$, and reached a maximum of 16 or more hours by late summer (Figure 3b). In some years, it was difficult to reliably identify the time lags in late summer when discharge was very low. Also, at very low flow velocities time lags exceeded 24 hours and overlapping daily cycles could not be reliably separated (e.g., 2 hr vs. 26 hr) (Figure 3b).

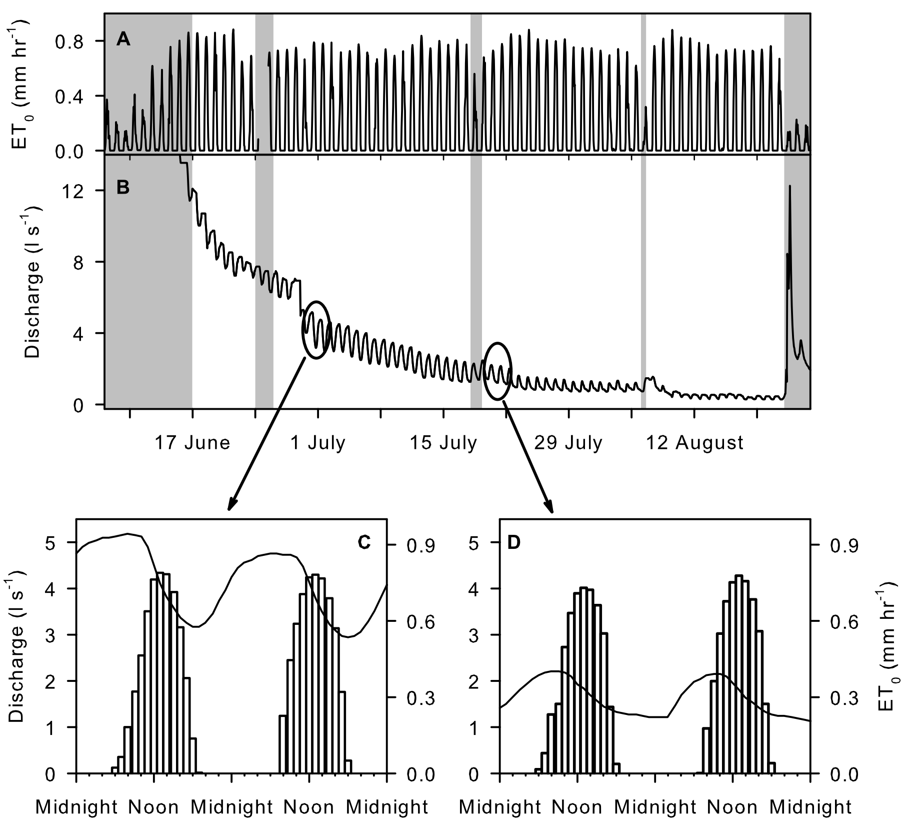


**Figure 2.** Temporal trends in (a) reference ET ($ET_0$) and (b) discharge over the period of baseflow recession in the WS1 watershed during the summer of 2004. Shaded zones denote time periods excluded from the analysis due to very high or very low discharge, rainstorms, or missing data. (Note: the abrupt decrease in discharge in late June was caused by the installation of V-notch wier plates on the flumes to improve measurement accuracy at low discharge.) Inset graphs are enlarged to show changes in the time lags between daily maximum $ET_0$ (bars) and minimum discharge (line) in (c) early- and (d) mid-summer.

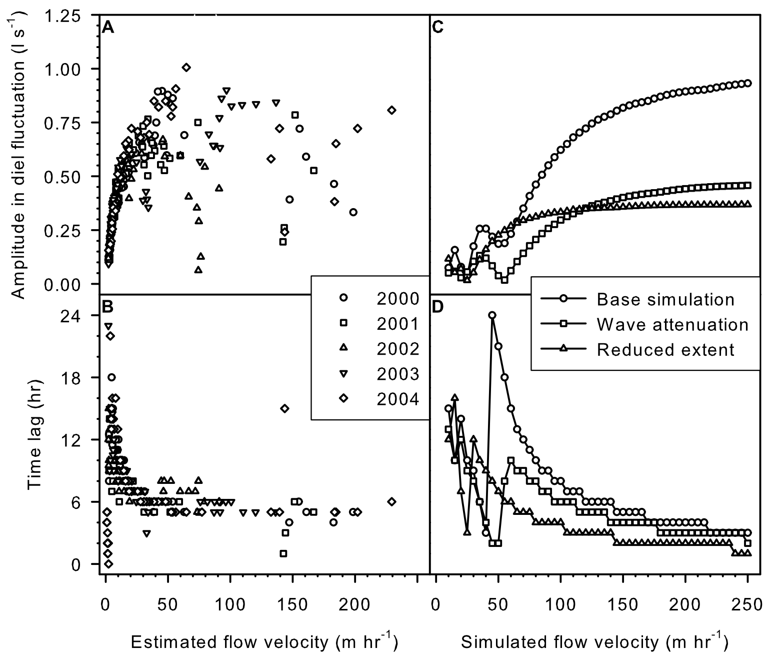


**Figure 3.** (a) The amplitude of diel fluctuations in stream discharge and (b) the change in time lag between the time of daily maximum $ET_0$ and the time of minimum stream discharge over the period of baseflow recession. Model simulations showing (c) the relation between stream flow velocity and the change in the amplitude of diel fluctuations in discharge, and (d) the change in the time lag between maximum ET demand and daily minimum stream flow.

## 2.2. Whole Network Simulation

[7] We used a one-dimensional advection model to test further the effect of changing flow velocity on ET-caused fluctuations in stream discharge. Previous research has shown that diel fluctuations in discharge are caused by ET from riparian vegetation [*Dunford and Fletcher*, 1947; *O'Loughlin et al.*, 1982; *Bren*, 1997] along gaining reaches, where water tables are shallow, so that ET from riparian forests reduces water flux from hillslopes to streams [*Bren*, 1997]. Such gaining reaches are likely to occur at the base of hillslope hollows because topographic convergence controls accumulated upslope area [*Freeze*, 1972; *Anderson and Burt*, 1978; *Beven*, 1978], and thus both the location and amount of lateral hillslope inputs to riparian zones [*Beven*, 1978]. Consequently, our model used the WS1 watershed topography such that the modelled stream network simulated the actual channel distances to the stream gauge. We assumed that the location and magnitude of lateral inputs were proportional to the actual location and size of upslope contributing areas at each point along the stream network. We used topographic analysis of WS1, using a 10-m digital elevation model (DEM) to quantify the shape of the stream network and the location and size of upslope inputs to the stream network.

[8] A network-scale advection model was constructed in which the stream and valley floor was denoted as a linear sequence of $10 \times 10$ m cells, each with a known hillslope contributing area that was used as a surrogate for the lateral inflow of water. The model simulated the effect of ET on lateral inputs with a sine function so that hillslope inputs oscillated smoothly over a 24-hr period, reaching a minimum at 14:00 hrs and a maximum at 02:00 hrs. Diel fluctuations in hillslope inputs were held constant in all model runs so that simulation results would not be confounded by changes in the magnitude or timing of the ET-generated signal. Hillslope inputs were routed down the simulated stream network using spatially constant flow velocity to generate instantaneous stream discharge at the watershed outlet. Wave attenuation (equivalent to dispersion in solute transport) of ET-induced signals generated in each stream cell was simulated as an exponential function of channel distance from the gauging station, so that amplitude of waves moving down the channel decreased. Because the actual lateral inputs to each cell were unknown, lateral inputs to each stream cell were proportional to the upslope contributing area draining into each cell, with the summed inputs equalling 4 l $s^{-1}$ at the watershed outlet with a diel amplitude of 1 l $s^{-1}$. This discharge approximates the whole watershed discharge measured at high baseflow [*Wondzell*, 2006].

[9] The relation between stream flow velocity and both the diel amplitude and time lags observed in WS1 (Figures 3a and 3b) did not exactly match the model simulations (Figures 3c and 3d). The model was not calibrated to the WS1 stream network, however. Data were not available on the changes in the extent of the wetted stream network with baseflow recession or on the location and size of lateral groundwater inputs. Nor were data available to parameterize the effect of wave attenuation. Additionally, the model used a uniform flow velocity over the entire stream network. The WS1 stream velocities (Figures 3a and 3b) were estimated from a regression equation based on stream tracer data (Figure 1). At very low discharge, median travel velocity appeared to be influenced by transient storage that retarded movement of the solute pulse thereby underestimating the true flow velocity. Additionally, tracer-based velocity meas-

ures likely underestimate wave celerity. Despite the lack of calibration, the observed data and the simulation results both show increasing time lag and decreasing amplitude in diel fluctuations with baseflow recession.

[10] Estimated stream-network transit times differed greatly over the range of simulated flow velocities (10 to 250 m $hr^{-1}$). Water entering the channel at the most distal point in the stream network would reach the stream gauge in only seven hours at high baseflow in early summer, whereas it would take several days at low baseflow in mid- through late-summer. Simulations showed that ET signals generated along the stream network reached the stream gauge with relatively short time lags and sufficiently "in phase" so that constructive interference resulted in a strong diel signal at high flow velocity (Figures 3c and 3d). As flow velocities decreased, time lags increased and ET signals became progressively more and more out of phase so that destructive interference resulted in very small diel fluctuations. Amplitude and time lag changed little with changes in flow velocities higher than 150 m $hr^{-1}$ (Figures 3c and 3d). A threshold was apparent at velocities resulting in network transit times less than $\sim$12 hours ($\sim$100 m $hr^{-1}$ for the full channel network in this watershed). At velocities below this threshold, amplitude and time lag changed markedly with changes in velocity. A second threshold was apparent at velocities with corresponding transit times of $\sim$24 hours ($\sim$50 m $hr^{-1}$ for the full network). At velocities slower than this, diel cycles from different days began to overlap so that changes in amplitude and time lag began to oscillate with changes in flow velocity.

[11] Additional simulations explored the sensitivity of the diel fluctuations to attenuation of the ET-generated signals and to changes in the spatial extent of the wetted stream network. Attenuation of diel fluctuations as they moved down the stream channel decreased the simulated amplitude of the fluctuations. Attenuation also changed the time lags because ET-induced fluctuations in discharge generated lower in the watershed had relatively greater effect on whole watershed behavior (Figures 3c and 3d). Similarly, changing the extent of the wetted stream network dramatically changed the network topology and resulted in strong feedbacks with flow velocity so that the overall pattern in the amplitude and time lag of diel fluctuations changed substantially.

## 3. Discussion

[12] Diel variations in stream flow have long been recognized [*Troxell*, 1936; *Wicht*, 1941; *Dunford and Fletcher*, 1947], but the simple question of how ET, distributed widely across a watershed, can generate cyclical fluctuation in discharge at the mouth of the watershed remains unanswered. Studies consistently report time lags of only a few hours between the time of daily maximum ET demand and daily minimum discharge [*Troxell*, 1936; *Wicht*, 1941; *Dunford and Fletcher*, 1947; *Bren*, 1997; *Czikowsky and Fitzjarrald*, 2004] despite a large range in the sizes of the watersheds studied. Because time lags tend to be short and relatively constant, none of these studies considered the effects of flow velocity and network routing. As we have demonstrated, however, velocity and network routing must have a substantial effect on the timing and amplitude of diel fluctuations measured at any stream gauge, particularly at low flows. However, this relation is generally not described in the literature.

[13] The explanation given by *Lundquist and Cayan* [2002], quoted earlier, is at odds with the expected whole watershed response resulting from routing synchronously fluctuating inflows down a stream network. For their explanation to hold, some factor would need to eliminate diel fluctuations generated high in the watershed so that the gauge records only reflect fluctuations generated at relatively short distances from the stream gauge. It may be possible that wave attenuation in many watersheds is sufficient to damp the amplitude of diel fluctuation generated long distances from the stream gauge so that the gauge is only sensitive to fluctuations generated at short distances. Alternatively, we have shown that diel fluctuations have greatest amplitude when flow velocities are high so that fluctuations in the amount of water input to the channel can be transported to the stream gauge more or less "in phase." Under these conditions, time lags are expected to be short. Perhaps, diel fluctuations are mostly documented under these conditions. At lower discharges, geomorphic dispersion may so damp the amplitude of diel fluctuations and time lags may become so long that these are not readily apparent at most stream gauges and therefore not widely reported in the literature.

[14] A number of other stream attributes are known to show diel fluctuations, including specific conductivity [*Kobayashi et al.*, 1990], $O_2$ and inorganic carbon ($CO_2$, alkalinity, pH) [*Dawson et al.*, 2001] whose concentrations in stream water are strongly affected by stream respiration and cause diel fluctuations in the concentrations of nitrogen, greenhouse gasses [*Harrison et al.*, 2005], and trace metals [*Nimick et al.*, 2003]. In all of these cases, diel fluctuations of solute concentrations are caused by widely distributed but temporally synchronous processes, and the resulting changes in water chemistry must be transported down the stream network to the monitoring site. Thus flow velocity is likely to interact with biogeochemical processes to influence concentration of solutes. This finding has significant implications for potential mitigation measures in response to total maximum daily load exceedence.

[15] The overall results of both the direct observations and the model simulations suggest a general property of stream networks in which network topology and flow velocity strongly influence watershed response to widely distributed inputs during baseflow periods. We suggest that diel fluctuations warrant further research. The wide number of solutes that also show diel fluctuations suggests that a coupled analysis of both discharge and solutes may prove useful in elucidating both the physical and biogeochemical controls on whole-watershed responses during baseflow periods.

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