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Catchment scale controls the temporal connection of transpiration and diel fluctuations in streamflow

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Abstract:

Diel fluctuations can comprise a significant portion of summer discharge in small to medium catchments. The source of these signals and the manner in which they are propagated to stream gauging sites is poorly understood. In this work, we analysed stream discharge from 15 subcatchments in Dry Creek, Idaho, Reynolds Creek, Idaho, and HJ Andrews, Oregon. We identified diel signals in summer low flow, determined the lag between diel signals and evapotranspiration demand and identified seasonal trends in the evolution of the lag at each site. The lag between vegetation water use and streamflow response increases throughout summer at each subcatchment, with the rate of increase as a function of catchment stream length and other catchment characteristics such as geology, vegetation and stream geomorphology. These findings support the hypothesis that variations in stream velocity are the key control on the seasonal evolution of the observed lags. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS streamflow; low flow; transpiration; connectivity; scale

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INTRODUCTION

Although hydrologists have traditionally focused their research on floods and other high discharge processes, low-flow processes have been identified as a significant area of concern in recent years, affecting fish habitat (Bradford and Heinonen, 2008; Mantua *et al*., 2010) and municipal water supply (Burn *et al*., 2008) and serving as an indicator of climate change (Arnell, 1999; Barnett *et al*., 2005). Diel fluctuations (sinusoidal variations in stream discharge with a 24-h period) have been observed in summer streamflow for more than 80 years (Blaney *et al*., 1930, 1933; White, 1932) and can reach up to 50% of mean measured discharge (Bond *et al*., 2002). These fluctuations, where summer streamflow generally reaches a daily maximum in the early morning and a minimum in the late day, are thought to be a consequence of diurnal patterns in evapotranspiration (Gribovszki *et al*., 2010), although the fluctuations in barometric pressure (Turk, 1975), the temperature-induced variability in the viscosity of water (Czikowsky and Fitzjarrald, 2004) and the thermal expansion of water (Czikowsky and Fitzjarrald, 2004) have been proposed as minor contributing factors.

Diel signals have been observed in streams ranging from 10 ha (Barnard *et al*., 2010) to tens of thousands of square kilometres (Lundquist and Cayan, 2002). In analyses of streamflow from 100 catchments in the Western United States (Lundquist and Cayan, 2002) and 151 streams in the Eastern United States (Czikowsky and Fitzjarrald, 2004), diel signals were shown to be widespread, existing independent of climate, geography, vegetation and geology. The characteristics of the diel signal have been used to estimate evaporation losses (Boronina *et al*., 2005; Reigner, 1966; Troxell, 1936; White, 1932), the contributing area of vegetative water use (Bond *et al*., 2002), the hydrologic connectivity between hillslopes and streams (Barnard *et al*., 2010; Goodrich *et al*., 2000) and the temperature and solute fluxes in the stream (Gribovszki *et al*., 2010).

The relative role of hillslope and riparian vegetation has been a key component of research on the diel signals. Past studies demonstrated that diel signals cease after a fire removed all hillslope, riparian and in-stream vegetation (Lawrence, 1990; O'Laughlin *et al*., 1982), suggesting that vegetation is the dominant source. At the Coweeta Experimental Forest in North Carolina, USA, all riparian and in-stream vegetation within 4.5 m elevation of the stream channel was removed from a 8.9-ha catchment (Dunford and Fletcher, 1947). Before removal, a strong diel signal was seen in the stream discharge, with an amplitude of approximately 10% of streamflow. After treatment, the timing of the diel signal remained constant, but the amplitude was greatly reduced. Fifty years later, Bren (1997) reported on another selective harvesting experiment, where all trees except those in a 60-m wide riparian strip were removed. After harvest, the observed diel signal amplitude increased, whereas the timing of peak streamflow appeared to remain constant. This

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observed increase in the strength of the diel signal, combined with numeric simulations, suggested that the bulk of the signal comes from the riparian and in-stream areas. Burt (1979) monitored spring discharge in a bracken covered moorland upslope of the riparian zone and found strong diel signals in lateral subsurface flow to the stream in the absence of riparian and in-stream vegetation. Barnard *et al*. (2010) monitored discharge from the base of a small, forested hillslope lacking a riparian zone at the H.J. Andrews Experimental Forest, Oregon, and observed a diel signal in lateral subsurface flow, demonstrating possible hillslope control of the signal. At a nearby site, Moore *et al*. (2011) found a tight correlation between streamflow and soil moisture on forested hillslopes. These studies suggest that the diel fluctuations are likely due to signals originating from a combination of hillslope, riparian and in-stream vegetation. What remains unclear is how the evapotranspiration signal in hillslopes, riparian and in-stream areas is transferred to the stream.

Over the last 30 years, three distinct hypotheses have been developed to explain signal transfer from vegetation to the streams, with an additional hypothesis addressing the in-stream propagation of the signal (Figure 1): the saturated wedge hypothesis (Burt, 1979), the riparian interception hypothesis (Bren, 1997) and the flow path migration hypothesis (Bond *et al*., 2002). The stream velocity hypothesis (Wondzell *et al*., 2007) addresses signal propagation in the stream channel. Although developed independently, these hypotheses do not appear to be mutually exclusive but rather exist on a continuum of hillslope–riparian hydrological processes.

Burt (1979) observed diel signals in both streamflow and lateral subsurface flow at Bicknoller Combe near Somerset, England. Diel fluctuations were also observed in measured specific conductance in the stream channel and in soil matric potential gradients, which were shown to point downhill during the night and towards the soil surface during the day, when vegetation water use peaks. Burt (1979) hypothesized

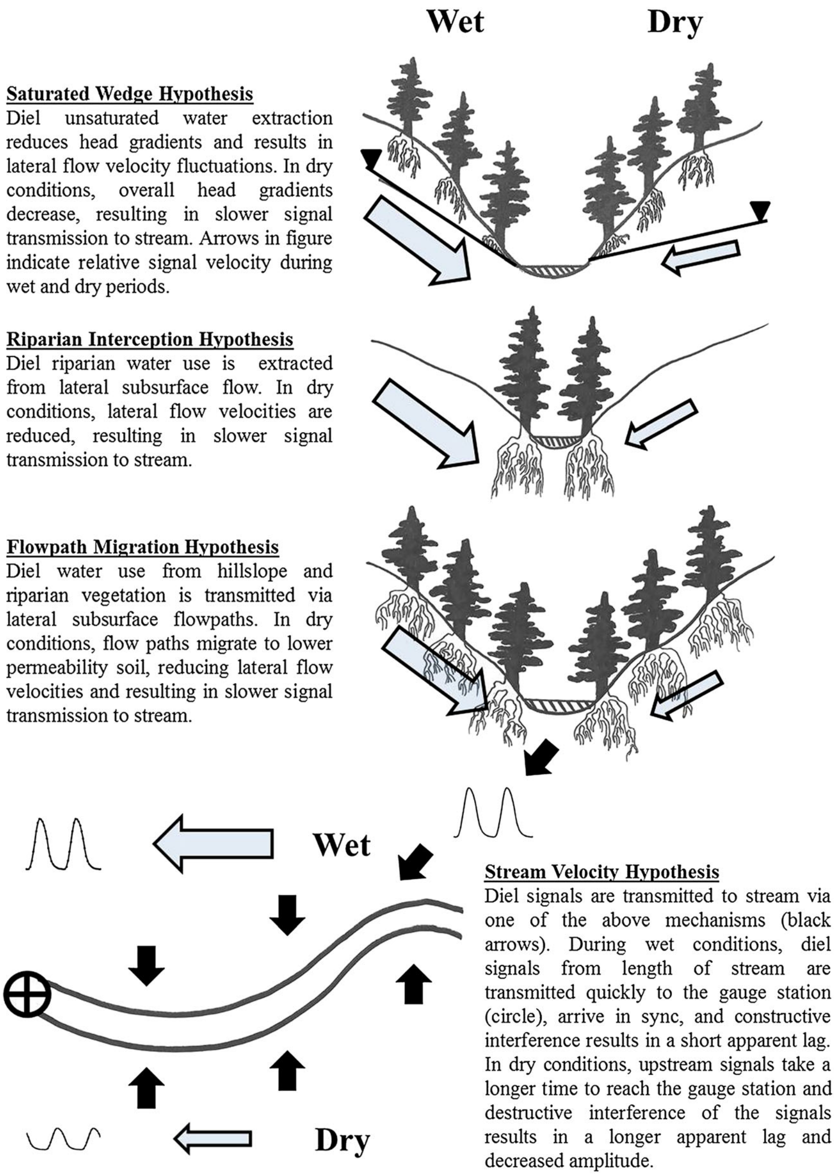

Figure 1. Schematic of vegetation signal transmission hypotheses

that these evaporation-driven matric potential gradients resulted in an upward flux of soil moisture and a shrinking of the saturated wedge during the day, resulting in lower hydraulic head gradients towards the stream, and a lower lateral subsurface flow from hillslopes to the stream. At night, the matric potential gradients move parallel to the hill slope, resulting in a recovery of the saturated wedge, increased head gradients and increased lateral subsurface flow. As summer progresses, the saturated wedge shrinks, resulting in smaller head gradients and smaller amplitude in the diel signal. We refer to this as the saturated wedge hypothesis.

On the basis of observations of an increase in the amplitude of the diel signal after the harvest of hillslope vegetation, Bren (1997) concluded that hillslopes did not contribute directly to the diel signal. Instead, riparian vegetation intercepted water from saturated and unsaturated lateral subsurface flow paths draining hillslope storage, resulting in a diel signal expressed at the stream channel. The removal of hillslope vegetation resulted in an increased hillslope soil moisture storage and subsequently an increased lateral subsurface flow. This increase in lateral subsurface flow resulted in an increased water for riparian vegetation and thus an increased riparian water use and diel signal amplitude. Increased lateral flow velocities would also result in more efficient signal transfer, leading to shorter lags between vegetation and stream signals. We refer to this as the riparian interception hypothesis.

On the basis of observations that the lag between transpiration and streamflow signals increased from 4 to 8 h over the course of the summer, in conjunction with decreased amplitude of the diel signal throughout summer, Bond *et al*. (2002) proposed a mechanism of increased disconnection of hillslope and riparian vegetation from the stream channel. This hypothesis was based on measurements made in Watershed 1 (WS1) of HJ Andrews, a humid, heavily vegetated catchment in Western Oregon. Previous work at a nearby site (WS10 at HJ Andrews) indicates that lateral flow between precipitation events is dominated by saturated flow, whereas unsaturated flow is generally vertical (Harr 1977). Bond *et al*. (2002) proposed that during wet conditions, the water table is high and saturated lateral flow is dominated by short, rapid flow paths, and diel signals originating from both riparian and hillslope vegetation are quickly translated to the stream. As the water table drops, subsurface lateral flow moves towards deeper, slower flow paths, both in the hyporheic zone and from the hillslopes, resulting in slower signal propagation to the stream. We refer to this as the flow path migration hypothesis.

The observation of Bond *et al*. (2002) of an increased lag between transpiration and streamflow signals over the course of the summer has emerged as a key characteristic of these diel signals. Increasing lags throughout summer have since been observed elsewhere (Lundquist and Cayan, 2002; Szeftel, 2010), although the rate of increase is variable and rarely quantified (Lundquist and Cayan, 2002). This increase in lag is not inconsistent with the three hypotheses outlined earlier. Although not specifically addressed by Burt (1979), a smaller saturated wedge later in summer and corresponding lower head gradients would result in slower water flux and an increase in the lag between vegetation water use and stream diel signal. Again, although not specifically addressed by Bren (1997), in the riparian interception hypothesis, as lateral subsurface flow rates decline throughout summer, lateral velocities would be expected to decrease, resulting in a slower signal from the riparian area to the stream channel. Bond *et al*. (2002) specifically addressed the increase in lag and theorized that as the water transitions to deeper, slower flow paths, the hydrological transport of the diel signal slows, resulting in an increased lag throughout summer.

In addition to the three hillslope scale lateral flow–based hypotheses listed earlier, Wondzell *et al*. (2007) proposed that declining stream velocities throughout the summer recession can account for the increase in lag between evapotranspiration and observed streamflow signal. In this hypothesis, hillslope and riparian vegetation create a diel signal, which is transferred to the stream along its entire length, more or less simultaneously. Signals are then transferred downstream. When the stream velocities are high, the signals from upstream locations reach the gauging station quickly and nearly simultaneously, and the constructive interference of the signals results in a strong diel signal in streamflow temporally synchronized with transpiration. When stream velocities are low, the transpiration signals from upstream take a longer time to reach the catchment weir, resulting in a destructive interference, which results in a larger apparent lag between transpiration and streamflow, and a weaker signal. Although this theory does not explain the source of the diel signals, or how they are transferred to the stream channel (i.e. lateral flow interception, saturate wedge decline, flow path migration or some other mechanism), it does offer a possible alternative explanation for the increase in lag throughout the summer recession.

As shown earlier, there are at least four possible explanations for the observed increase in lag between transpiration and streamflow diel signals throughout the summer dry down. A better understanding of the driver of this lag would improve our understanding of diel signals, the connectivity of hillslope and riparian vegetation with the streams and the low-flow hydrological processes in general. Previous studies, although valuable in demonstrating the phenomenon and developing site-specific process understanding, were ill-suited to fully test these hypotheses because of either their focus on individual catchments (Barnard *et al*., 2010; Bond *et al*., 2002; Bren, 1997; Burt, 1979; Wondzell *et al*., 2007) or their lack of explicit site intercomparison (Czikowsky and Fitzjarrald, 2004; Lundquist and Cayan, 2002). To better understand the causal mechanism for increased lags in summer streamflow, we need to thoroughly examine processes occurring at catchments with variable size, vegetation, geology and climate.

To test these hypotheses and to expand our understanding of diel fluctuations in summer streamflow beyond the idiosyncrasies of a few isolated watersheds, we analysed the effect of catchment area, geology and climate on the evolution of summer diel signal. Specifically, we determined patterns of diel fluctuations in summer streamflow at 15 subcatchments nested within three well-studied experimental watersheds: Dry Creek and Reynolds Creek in semiarid central Idaho and HJ Andrews in humid western Oregon. We analysed summer discharge by identifying periods where there is a strong diel signal and using the measured sap flow at Reynolds Creek HJ Andrews to determine lags between the transpiration signal and the streamflow. Seasonal patterns in the lags are then compared between subcatchments at each watershed and between the larger watersheds themselves. All analyses were performed with an eye towards evaluating the various hypotheses of diel fluctuation propagation in stream discharge. These analyses were facilitated by a public access to streamflow data via the Hydrological Information System (HIS) at Reynolds and Dry Creeks and the H. J. Andrews data server. The limitations of science using public data are addressed in the Discussion section.

SITE DESCRIPTIONS

Streamflow data from three distinct catchments were used in these analyses: Reynolds Creek and Dry Creek in central Idaho and HJ Andrews in western Oregon (Figure 2, Table I).

Dry Creek

Dry Creek is a 2693-ha catchment 5 km north of Boise, Idaho. Six nested subcatchments were used in this study ranging from 51 ha to the entire Dry Creek Experimental Watershed (2693 ha). Stream discharge has been monitored at the catchment outlet (Lower Gauge) since 1998, with subcatchments coming online between 1999 and 2007. Streamflow is monitored at permanent stations where stage–discharge relationships have been developed on the basis of manual measurements made across the range of discharge. Subcatchment outlet elevations within Dry Creek range from 1039 to 1677 m, and subcatchments are dominated by increasing snow with elevation in the winter. Soils are thin, high permeability sandy soils underlain by fractured grandiorite.

The vegetation is primarily Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) at higher elevations (>1500 m) and grasses and sagebrush (*Artemisia tridentata*) at lower elevations. The riparian areas are lush, with dense brush and stands of cottonwoods (*Populus fremontii*), water birch (*Betula occidentalis*), yellow willow (*Salix lutea*), mountain alder (*Alnus viridis*) and mountain Maple (*Acer spicatum*) for the entire extent of Dry Creek and its tributaries. In general, the trees and large shrubs are confined to the riparian areas and seeps at low elevations, and the hillslopes are vegetated with grasses that generally dry out midsummer. Further description of the catchments, soils and vegetation at Dry Creek can be found in the studies of Aishlin and McNamara (2011), Smith *et al.* (2011), Tesfa *et al.* (2009) and Williams *et al.* (2009).

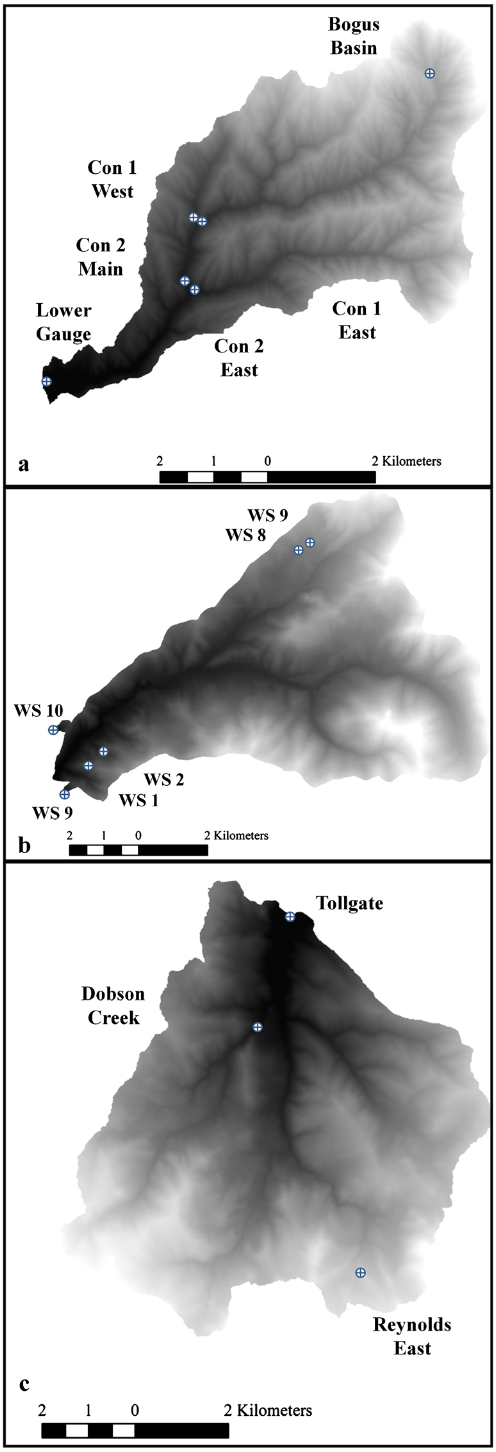

Figure 2. Study locations: (a) Dry Creek, (b) HJ Andrews and (c) Reynolds Creek. Circles indicate locations of gauging stations

Table I. Subcatchment area and lag characteristics

Subcatchment	Gauge elevation (m)	Area (ha)	Stream length (m)	Lag increase per day (min)	Time until lag increase of 1 h (days)	Years of record analysed	Years with observed diel signal
Dry Creek subcatchments							
Lower gauge	1036	2693.2	11 737	1.14	53	12	8
Confluence 2 Main	1146	2389.9	9 350	0.82	73	5	4
Confluence 2 East	1158	749.9	6 584	0.59	101	5	4
Confluence 1 East	1335	858.5	5 534	0.52	116	5	4
Confluence 1 West	1347	383.1	3 849	0.38	160	5	1
Bogus basin	1677	51.5	1 379	0.19	311	3	2
Reynolds Creek subcatchments							
Reynolds Tollgate	1395	5468	10 046	1.60	37	42	31
Dobson Creek	1474	1400	7 498	2.09	29	35	10
Reynolds East	2024	39	650	1.18	51	45	25
HJ Andrews subcatchments							
WS1	450	95.9	1 525	3.02	20	12	12
WS2	572	60.3	685	0.88	68	12	6
WS7	1102	15.4	313	0.20	298	12	6
WS8	1182	21.4	386	0.45	134	12	8
WS9	438	8.5	323	1.21	50	12	10
WS10	471	10.2	92	0.23	253	12	9

Reynolds Creek

Reynolds Creek is a 23 900-ha catchment 65 km southwest of Dry Creek. Of the 13 gauged catchments at Reynolds Creek, 3 catchments were chosen for this study because they are of similar size and elevation of the Dry Creek subcatchments and are unaffected by agricultural water use. The three analysed subcatchments, Tollgate, Dobson Creek and Reynolds Mountain East Basin, range from 40 to 5468 ha and were gauged with calibrated V-notch weirs (Tollgate and Reynolds Mountain East Basin) and a Parshall Flume (Dobson Creek). Streamflow at these three subcatchments has been monitored since 1966, 1973 and 1963, and subcatchment elevations are 1395, 1474 and 2024 m for Tollgate, Dobson and Reynolds Mountain East, respectively. Similar to Dry Creek, the annual water balance becomes more dominated by snow accumulation and melt at higher elevations. Although most of the higher elevations of the Reynolds Creek Experimental Watershed are underlain by basalt and latite, 25% of the Tollgate and 41% of the Dobson Creek catchment are underlain by granites, with small intrusions of alluvium and welded tuff. The soils derived from granitic parent material are loamy, shallow and rocky. Soils derived from basalt and latite tend to be deeper, with higher organic matter content and finer texture.

Similar to Dry Creek, lower elevations at Reynolds Creek are dominated by grasses and shrublands, whereas higher elevations are forested with ponderosa pine and Douglas-fir. Recently, juniper (*Juniperus occidentalis*) has encroached into much of the former grasslands in the catchments analysed in this study. Riparian areas are similar to those of Dry Creek, with alder, cottonwoods, maple and willow trees. Further description of the catchments, soils and vegetation at Reynolds Creek can be found in a 2001 special issue of *Water Resources Research* (Hanson *et al.*, 2001; Marks, 2001; Pierson *et al.*, 2001; Slaughter *et al.*, 2001).

HJ Andrews

The HJ Andrews Long-Term Ecological Research Site is a 6200-ha catchment where streamflow has been monitored for more than 60 years at 10 subcatchments. Streamflow at all subcatchments is monitored with stage recorders at concrete weirs, with low-flow collecting plates installed during summer. This study analysed data from six of the subcatchments, WS1, WS2, WS7, WS8, WS9 and WS10, which are 95.9, 60.3, 15.4, 21.4, 8.5 and 10.2 ha, respectively. Four catchments (WS1, WS2, WS9 and WS10) are low elevation (outlet elevations 400–500 m) and are rain dominated, whereas WS7 and WS8 are higher elevation, with a mixed snow and rain precipitation regime. All six subcatchments are underlain by highly weathered, deeply dissected andesites and basalts. Soils depths vary from 0 to 4 m, are rocky and highly permeable weakly developed andisols, generally with clay loam texture.

The hillslopes are dominated by mature Douglas-fir, whereas riparian areas include bigleaf maple (*Acer macrophyllum*) and red alder (*Alnus rubra*). WS1 was clear cut in 1962–1966, whereas WS10 was clear cut in 1975. WS7 was harvested in 1975, 1984 and 2001. WS2, WS8 and WS9 retain old-growth forests. None of the studied catchments have roads, except for a small access road at the top of WS10. The riparian areas of most catchments are heavily forested, whereas WS10 has been the site of numerous debris flows (most recently 1996) at the lower end of the stream channel, where the stream bed is mostly exposed bedrock. Further description of the catchments, soils and vegetation at the HJ Andrews can be found in the studies of Rothacher (1965), Jones and Grant (1996), Jones *et al.* (2000) and McGuire *et al.* (2005).

DATA ACCESS AND ANALYSES

Data access

All data from Dry Creek and Reynolds Creek were obtained from the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) Hydrologic Information System (HIS; icewater.boisestate.edu; Seyfried *et al.*, 2001, McNamara 2012). Stream discharge data from all of the gauged subcatchments (7 at Dry Creek and 13 at Reynolds Creek) are available from the start of gauging (1998 at Dry Creek, 1964 at Reynolds Creek) until 2009. New data are uploaded after interpolation and cleaning. Stream gauging at Dry Creek is recorded at 1-h intervals and uploaded directly to HIS. At Reynolds Creek, streamflow is recorded at breakpoints and then interpolated into hourly data, which are then uploaded once available.

Stream data from HJ Andrews were obtained from the online server (andrewsforest.oregonstate.edu; Johnson and Rothacher, 2009). Streamflow has been recorded at WS1 and WS2 since 1953, at WS7 and WS8 since 1964 and at WS9 and WS10 since 1969. As of 1999, a higher-angle plate has been installed in the weirs during summer to capture low-flow dynamics. Preliminary analyses showed that diel signals were not adequately captured at the sites before the summer plate installation; hence, data before 1999 were not included in this study.

Data from all gauging stations were downloaded onto a local machine, where MATLAB (2010; The MathWorks, Natick, MA) codes were used for analysis.

Sap flow

Sap flow was recorded for limited periods at Reynolds Mountain East, Reynolds Creek and WS1, HJ Andrews using heat dissipation sensors (Granier, 1987). Monitoring at Reynolds Mountain East was part of a study on the role of snowmelt in providing soil water to aspen stands. At Reynolds Creek, sap flow was recorded at 8 aspen (*Populus tremuloides*) within a 520-m^2 area from 28 June 2008 to 8 October 2008. At HJ Andrews, sap flow was measured at 40 Douglas-fir (*P. menziesii*) in four plots transecting WS1 during the summer of 2006 as part of a study on the controls on spatial variation in transpiration and the forest's role in carbon flux (Pypker *et al.*, 2009; Pypker *et al.*, 2008). At both locations, sap flow was monitored at a 15-min resolution.

A standard sap flow signal was derived from both the Reynolds Creek and the HJ Andrews stands, for use in comparing streamflow (Figure 3). For every 15 min of the day, the sap flow monitored from each tree, each day was averaged to get a yearly stand average sap flow at 00:00, 00:15, 00:30 h and so on throughout the day. In this way, we were able to derive an idealized sap flow signal without the daily variations due to cloud cover, variable shading, precipitation and other temporary climatic signals. Sap flow exhibited a strong diel pattern, with minimum transpiration at 0600 h for both sites and peak transpiration at 1300 h at Reynolds Creek and 1400 h at HJ Andrews (Figure 3). The idealized sap flow signal was then repeated twice to create a 3-day time series (the standard sap flow), which we used to test for lags between streamflow and sap flow. Separate standard sap flow time series were produced for Reynolds Creek and HJ Andrews.

The temporal stability of the sap flow signals at Reynolds Creek and HJ Andrews was tested to ensure that the standard sap flow time series was representative of the evapotranspiration (ET) demand through the growing season. For each time step in the measured sap flow record ($n = 14\,833$ and $27\,684$ for Reynolds Creek and HJ Andrews, respectively), the data for the following 72 h of measured sap flow were plotted against the standard sap flow, and the correlation coefficient was determined. For each day of the measured sap flow record, the value of the maximum correlation coefficient and the lag between the measured sap flow and the standard sap flow (defined as the time of maximum correlation) were recorded. A high correlation indicates that the shape of the measured sap flow signal matched that of the standard sap flow. A lag near 0 h indicates the measured sap flow timing matched that of the standard sap flow.

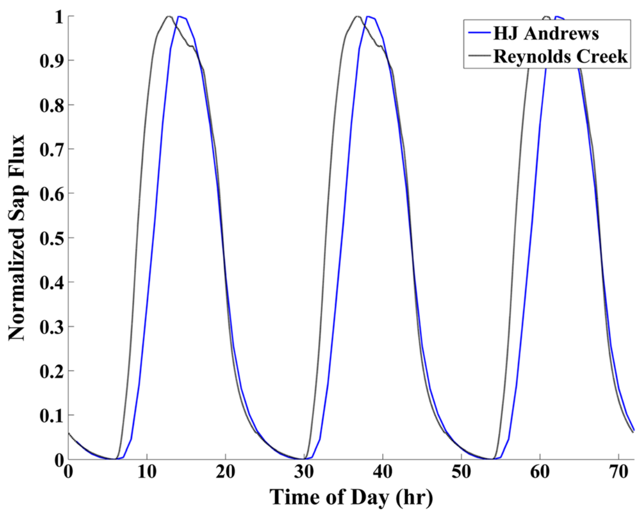

Figure 3. Sap flow standard time series for Reynolds Creek and HJ Andrews – seasonal hourly average sap flow from all instrumented trees, normalized to range from 0 to 1

These analyses showed that the temporal pattern of sap flow throughout the day was relatively constant throughout summer, with the lag between the standard and the measured sap flow occurring within a 1-h window for the duration of the summer growing season. Although the magnitude of measured sap flow varied through the year, peaking in mid-July and receding towards the end of monitoring, the daily maximum correlation coefficient was consistently higher than 0.9 for both Reynolds Creek and HJ Andrews, indicating little change in the shape of the sap flow signal. Isolated dips with a correlation coefficient of lower than 0.9 occurred during precipitation events and towards the end of monitoring.

Streamflow transformation and analyses

To isolate diel signals, we transformed the streamflow data to remove multiple day trends in streamflow due to seasonal patterns (fall wet-up and spring recession) and storm events. For each day, the median streamflow was determined, and an interpolated time series connecting the median streamflow values was developed (i.e. Figure 4). This time series was then subtracted from the original time series to create a detrended streamflow time series with the daily fluctuations isolated (i.e. Figure 5).

The detrended time series was then compared with the standard sap flow in the same manner that the standard sap flow was used to determine the temporal stationarity of the daily sap flow signal. For each time step, the bounding 3-day streamflow data were plotted against the hourly standard sap flow data ($3 \times 24 = 72$ time steps), and the Pearson correlation coefficient (r) was calculated (i.e. Figure 6). A 3-day window was chosen because it was sufficiently long as to not misidentify precipitation events and short enough that it did not require significant time between precipitation events. The correlation coefficient corresponded to the strength of the ET signal as seen in the streamflow. The time of day of the daily greatest negative correlation indicated the lag between sap flow signal and stream response because an increase in sap flow results in a reduction in streamflow. Although a lag was determined for all days, often the magnitude of the correlation coefficient was low. An r value less than -0.7 ($n = 72$, $P < 0.0001$) was chosen to represent a strong correlation between standard sap flow and streamflow. A sensitivity analysis showed that the results described in the next section did not vary using r values between -0.6 and -0.8. Because of the preprocessing described earlier (centering the daily discharge time series on the median daily value), using an r value between -0.38 ($P = 0.001$) and -0.6 resulted in a preponderance of days with no clear diel signal getting selected. At some years, at some watersheds, r values less than -0.8 were too stringent a standard, resulting in many days with clear diel signals not getting selected.

The lag between measured streamflow and standard sap flow was plotted against the day of year (i.e. Figure 7). The days when the correlation between streamflow and standard sap flow was high (r values less than -0.7) were used to determine the rate of increase in lag throughout the year. Two types of anomalous, non-ET-derived signals could match the appearance of the summer diel signals: precipitation events and snowmelt. To remove individual data points where storm events mimicked the diel sap flow signal, we used the largest continuous series of days with high correlation lags to determine the rate of increase in lag throughout the year (highlighted with grey background in Figure 7). Radiation-driven daily fluctuations in snowmelt were characterized by a diel fluctuation in the spring months with a negative lag, as water input was in phase with sap flow, rather than water extraction. To ensure that the continuous time series consisted of ET-derived signal rather than snowmelt, we limited our analyses to the period between May and August. Although this period could include some snowmelt in some years, especially in early to middle May, a visual inspection of the plots showed no instances where the snowmelt signal interfered with the summer diel signal in the catchments analysed. A regression line was fit to the continuous series of high correlation lags (grey line in Figure 7). Not all years produced a long

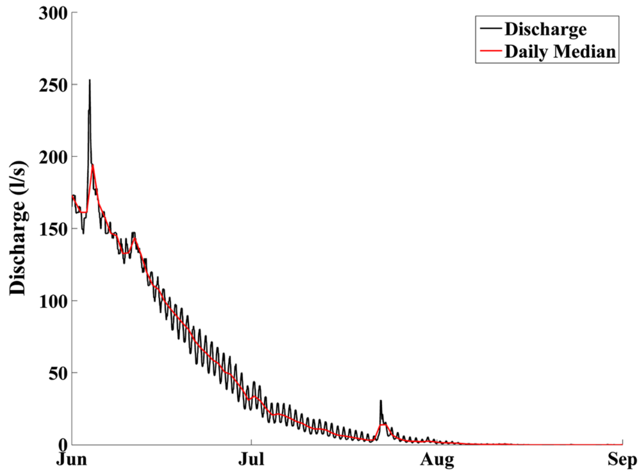

Figure 4. Summer recession at Lower Gauge, Dry Creek, 2008. Red line indicates interpolated daily median discharge

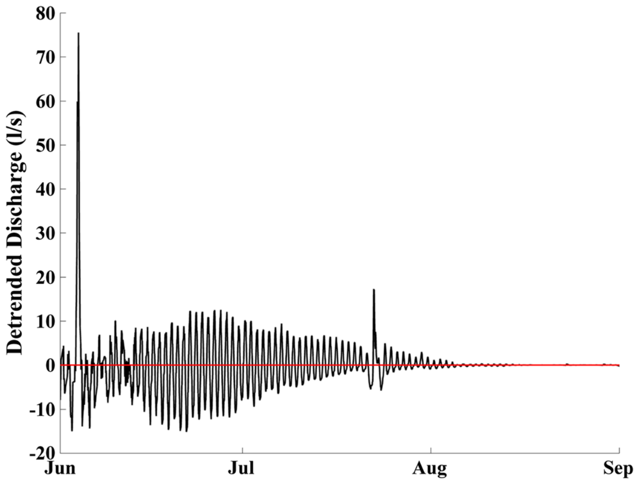

Figure 5. Detrended streamflow for summer recession, Lower Gauge, Dry Creek, 2008

continuous recession with clear diel signals because of summer precipitation events, gaps in the data record and streams completely drying up; hence, a visual inspection of all plots was undertaken to determine the set of years where a clear diel signal was observed, and the relationship between the lag and the day of year could be determined. This procedure was repeated for each subcatchment, for each year on record.

RESULTS

Streamflow at Reynolds Creek, Dry Creek and HJ Andrews

Streamflow at the 15 monitored catchments showed similar seasonal patterns of a fall wet-up and consistent high flows during the late winter and early spring fed by snowmelt (Reynolds and Dry Creeks, and upper HJ Andrews) and precipitation (lower HJ Andrews). During the spring recession, as inputs decline and ET increases, all subcatchments showed significant recession in streamflow, occasionally interrupted by spring and summer precipitation events. These recessions were characterized in most cases by a strong diel signal in streamflow, with the appearance of an approximate sine wave overlain on the master recession. The daily amplitude varied with stream level and catchment but often approached 50% of the median daily streamflow (Figure 4). These diel signals are even more obvious when the seasonal streamflow patterns are removed, by subtracting the daily median streamflow from the time series (Figure 5).

Correlation with sap flow

The detrended streamflow was compared with the standard sap flow, derived from measured sap flow at Reynolds Creek and HJ Andrews. Because sap flow is not currently monitored at Dry Creek, the Reynolds Creek standard sap flow was used for the Dry Creek subcatchments. The proximity of the two catchments and the relative similarity between the Reynolds Creek and the HJ Andrews standard sap flows (Figure 3) support the assumption that the Reynolds Creek standard sap flow can be used to represent Dry Creek vegetation.

For each time step, the surrounding 3-day streamflow data were plotted against the 3-day standard sap flow for

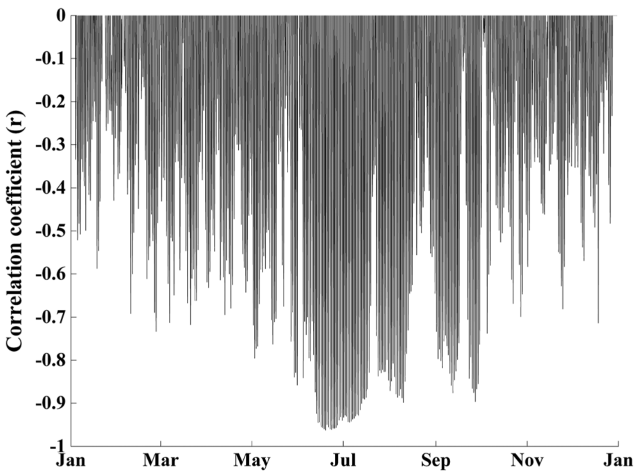

Figure 6. Correlation between standard sap flow and streamflow at Lower Gauge, Dry Creek, 2008. A large negative number indicates a strong sap flow signal observed in the streamflow. The extended period of strong signal in the summer months (May through September is broken up by precipitation events in May and June, which reduce the expression of the sap flow signal in the stream)

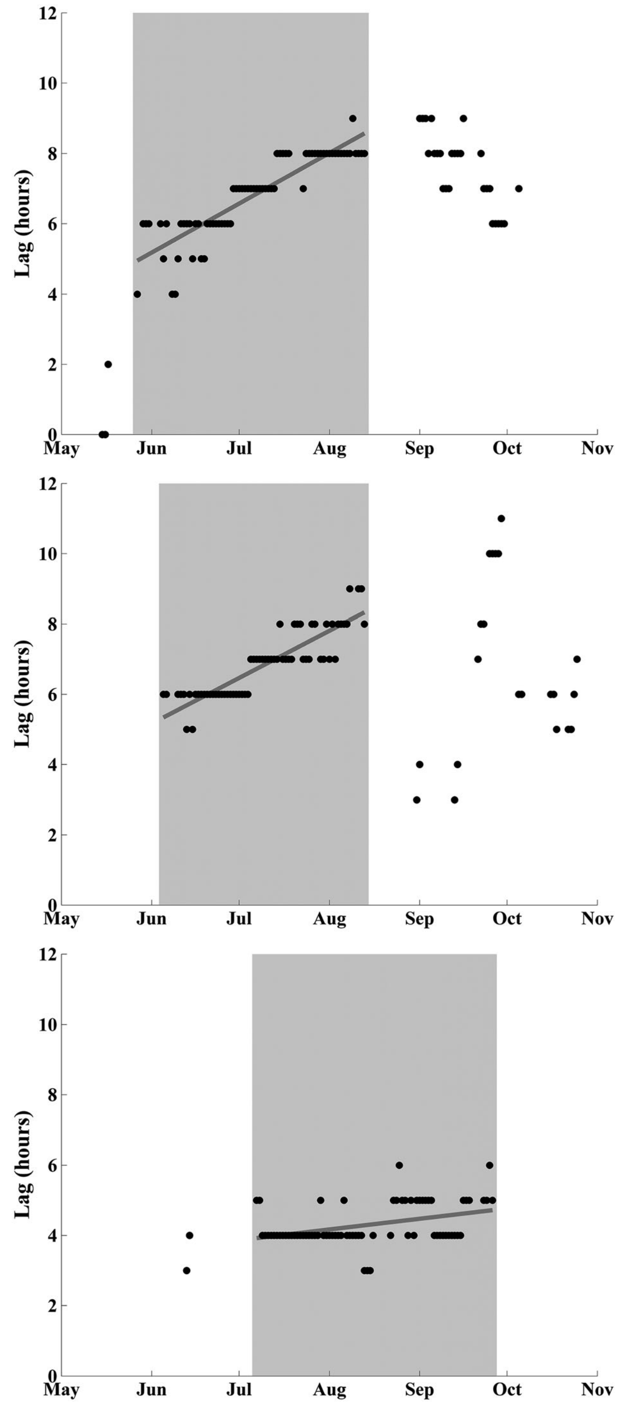

Figure 7. Lag between standard sap flow and streamflow at Lower Gauge, Dry Creek, Tollgate, Reynolds Creek and WS10, HJ Andrews, all for 2008. A lag of 0 h indicates that peak sap flow coincides with minimum daily streamflow. The grey band indicates summer continuous days of high correlation

the catchment, and the correlation coefficient was calculated. Figure 6 shows a representative plot of the correlation coefficients at the Lower Gauge of Dry Creek, 2008. Although there are other isolated periods with strong correlations, especially during the radiation driven spring snowmelt (outside the continuous lag time series analysed), the period of highest correlation occurs during the summer months. In Lower Gauge of Dry Creek, 2008, for example, the correlation between the streamflow and the standard sap flow is significant for half of May, all of June and most of August, with minimum daily r values less than -0.7 for most of this period. Precipitation events disrupted the string of high correlation in late May, and the streamflow cessation created a gap in data in late August. At other sites and at other years, similar patterns were seen, with the onset of strong correlations varying with the timing of spring snowmelt, and the presence and absence of spring and summer precipitation events.

Lags

A strong transpiration signal expressed in the streamflow would be characterized by a large negative correlation between sap flow and streamflow because an increase in transpiration would expect to cause a decrease in streamflow. For this reason, the lag between streamflow and transpiration was identified as the time of day with maximum negative correlation. Because the standard sap flow time series began at midnight, a high negative correlation occurring at midnight indicates zero lag between sap flow and discharge or, less likely, a 24-h lag, where the prior day's transpiration signal is being expressed. A high correlation at 0300 h indicates either a +3 or -21 h lag, whereas a high correlation at 2100 h indicates either a +21 h or -3 h lag.

Figure 7 shows an example plot of the lag versus day of year for a subcatchment in each site, in this case, Lower Gauge at Dry Creek, WS10 at HJ Andrews and Tollgate at Reynolds Creek for 2008. At Lower Gauge, before June and after mid-August, most days have a low correlation between transpiration and streamflow, as streamflow is controlled by precipitation and snowmelt and the transpiration signal is weak or nonexistent. Once the summer recession begins in late May, the correlation strength increases and a clear signal is observed. In the case of Lower Gauge, 2008, there is an increase in the lag throughout summer, with the lag increasing from approximately 5 h 1 June to more than 9 h by late August, after which fall precipitation events and low streamflow combined to mask the signal. Using just the days with high correlation between streamflow and standard sap flow in a continuous temporal group (marked in grey, Figure 7), a linear curve was fit to the lag data, and the increase in lag per day was determined. In the case of Lower Gauge, Dry Creek, 2008, the lag appeared to increase by 1.6 min/day throughout summer, which corresponds to an increase of 1 h every 37 days. Using similar analyses, we see a similar increase in lag at Tollgate and a small increase in lag at WS10.

The procedure of calculation of correlation coefficients, the identification of maximum daily correlation and lag and the calculation of slope of increase in lag per day were repeated for all years and all subcatchments (Table I). At the Lower Gauge, Dry Creek, the lag increased between 0.43 and 1.6 min/day, or 1 h every 38–141 days, with a mean value of 1.1 min/day, or 1 h every 53 days. At the other Dry Creek subcatchments, the average increase in lag per day was less than that observed at Lower Gauge, with Bogus Basin exhibiting the smallest increase in lag throughout summer (0.2 min/day, or 1 h in 311 days).

At Dry Creek, a linear relationship exists between the catchment area and the average daily increase in lag with slope 3.95E−4 $\frac{\text{min}/_{day}}{ha}$ ($r = 0.96$, $n = 6$, $P < 0.0001$; Figure 8). Similarly, stream length is linearly correlated with daily average increase in lag, with slope 0.11 $\frac{\text{min}/_{day}}{km}$ ($r = 0.92$, $n = 6$, $P = 0.0011$; Figure 9).

At Reynolds Creek, a similar increase in lag throughout summer was seen at all subcatchments, with Reynolds Mountain East Basin, Dobson Creek and Tollgate showing an increase of 1.2, 2.1 and 1.6 min/day (1 h per 51, 29 and 38 days) for catchments that were 39, 1400 and 5468 ha, respectively, on the order of the largest rates seen at Dry Creek. There was no apparent relationship between the subcatchment area and the rate of lag increase in summer ($r = 0.16$, $n = 3$, $P = 0.74$) nor between the stream length and rate of lag increase ($r = 0.67$, $n = 3$, $P = 0.22$).

At HJ Andrews, the pattern of lag increase throughout summer was similar to that of Dry Creek, with the largest catchment (WS1) having a greatest daily increase in lag observed in all subcatchments (3.0 min/day, or 1 h in 20 days) and the smaller subcatchments having subsequently smaller daily increases in lag (from 0.9 down to 0.2 min/day, or 1 h per 68 to 253 days, for WS2 and 10, respectively). WS9, the smallest catchment, did not fit this pattern, with a larger daily increase in lag (1.2 min/day, 1 h in 50 days) than all subcatchments at HJ Andrews except WS1. At HJ Andrews, there was a linear relationship between catchment area and daily lag increase, with slope 2.62E−2 $\frac{\text{min}/_{day}}{ha}$ ($r = 0.85$, $n = 6$, $P = 0.0069$). If WS9 is removed, the correlation is strengthened ($r = 0.94$, $n = 5$, $P = 0.0004$), and the slope increases to 3.10E−2 $\frac{\text{min}/_{day}}{ha}$ (Figure 8).

As with Dry Creek, there was an apparent linear relationship with stream length: the slope of the daily lag increase per kilometre stream length was 1.9 $\frac{\text{min}/_{day}}{km}$ ($r = 0.86$, $n = 6$, $P = 0.0061$). With WS9 removed, the correlation strength increases dramatically ($r = 0.99$, $n = 5$, $P < 0.0001$), and the slope increased to 2.5 $\frac{\text{min}/_{day}}{km}$ (Figure 9).

DISCUSSION

Propagation of transpiration signal to streams

Diel signals were observed at all subcatchments analysed, for all years when the streamflow monitoring equipment was functioning sufficiently to capture the sometimes small daily variability in stream discharge. Not all years had a sufficiently continuous period of diel signals for lag analysis because of complete stream dry up, summer precipitation events or other factors. However, the diel signal appears ubiquitous in the studied catchments. Furthermore, the lag between transpiration and streamflow signals increased throughout summer at all subcatchments, although the daily increase was quite small at some subcatchments (i.e. WS10, HJ Andrews).

We designed this project to test the alternative hypotheses of the origin and propagation of summer diel signals, as presented by Burt (1979), Bren (1997), Bond *et al.* (2002) and Wondzell *et al.* (2007). Briefly, the saturated wedge hypothesis (Burt, 1979) states that daily ET alters unsaturated matric potential gradients, resulting in lower contribution to the saturated wedge near the stream, lower head gradients and lower lateral flow towards the stream channel. The riparian interception hypothesis (Bren, 1997) states that riparian vegetation intercepts lateral subsurface flow, directly causing a reduction in the flux to the stream. The flow path migration hypothesis (Bond *et al.*, 2002) states that decreases in hillslope and riparian water tables result in deeper, slower flow paths slower hydrometric signal

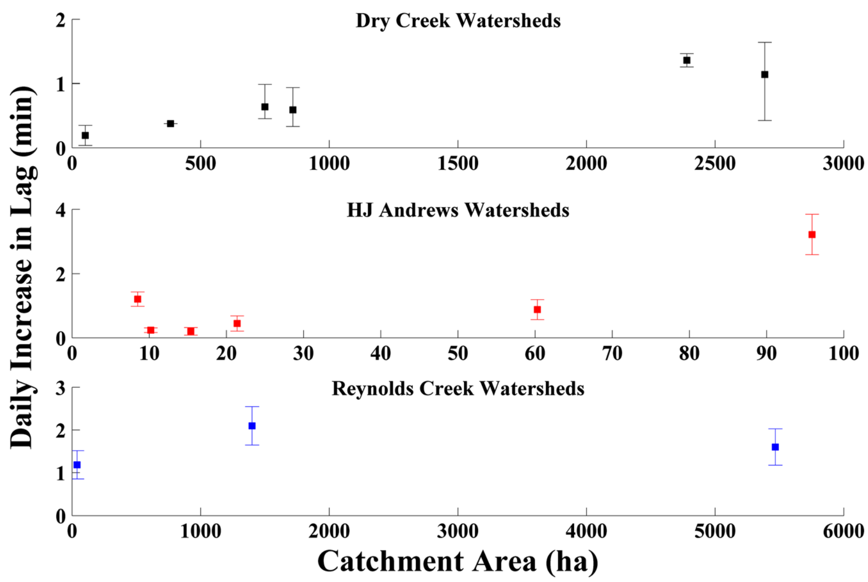

Figure 8. Rate of increase in lag through growing season at catchments of various area. Whisker indicates one standard deviation from mean. Note ranges of area and lag increase vary with each plot

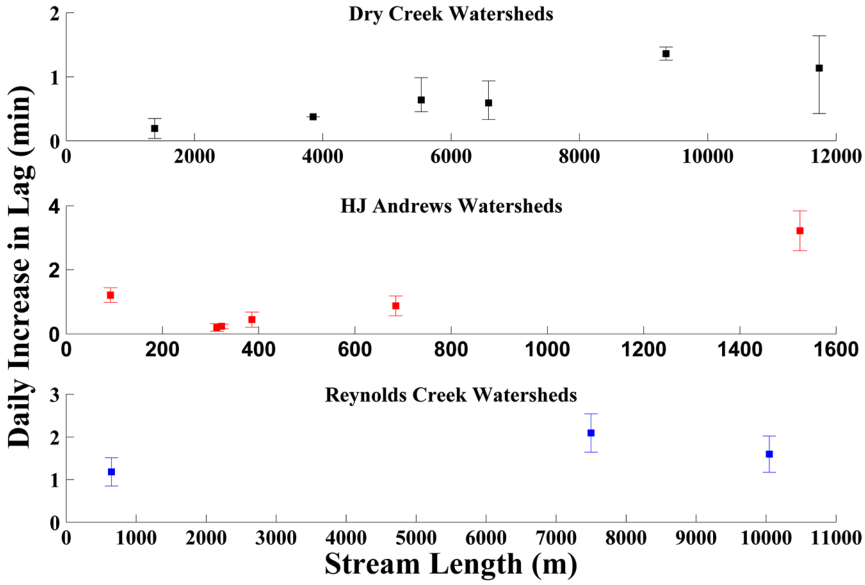

Figure 9. Rate of increase in lag through growing season plotted against main stem stream length. Whisker indicates one standard deviation from mean. Note ranges of area and lag increase vary with each plot

transfer and increased lags between transpiration and streamflow response. The stream velocity hypothesis (Wondzell *et al*., 2007) holds that the hydrometric signal from vegetation reaches the stream equally quickly throughout the year, but decreasing streamflow velocity throughout summer results in increased stream travel time, and destructive interference of transpiration signals leads to longer apparent lags (Figure 1).

Three findings of the streamflow analyses directly comment on the source and propagation of the diel signals in summer streamflow: the ubiquity of the signal, the correlation in daily lag increase with catchment area and stream length, and the behaviour of two sets of outliers, namely, WS9 at HJ Andrews and the subcatchments of Reynolds Creek.

Ubiquity of diel signals. One concern regarding the measurements of low-flow conditions is that diel fluctuations in air and stream temperature may result in errors in the stage measurements, causing an artificial signal in the streamflow, especially the small signals at very low flows. Cuevas *et al*. (2010) showed that temperature fluctuations could account for up to 19% of the diel signal in stage. These temperature-based artifacts in the stream discharge would be characterized by a constant lag through part or all of the season, where the lag is simply a measure of the temperature cycle. This contrasts with the consistent increase in lag observed at all catchments. Analysis at HJ Andrews WS10, which had the slowest increase in lag, indicated that the streamflow lag diverged from the temperature signal throughout summer (data not shown). This reduces concern that the observed signals are artifacts of the monitoring methods.

One limitation of the previous recent work on the driver of the diel signals in streamflow is that much of it has been performed in similarly wet, forested catchments, where there is considerable hillslope vegetation. Specifically, the studies of both Bond *et al*. (2002) and Wondzell *et al*. (2007) were performed at WS1 in HJ Andrews, where the hillslopes are heavily vegetated with 40-year-old Douglas-fir. In these analyses, we expanded analyses to five other subcatchments at HJ Andrews, where the dominant vegetation consists of stands of Douglas fir ranging from 40 to 450 years old and the climate varies from rain dominated to mixed, rain-snow precipitation as well as two semi-arid catchments where most of the contributing areas of the lower gauges are below lower tree line, and the hillslopes are covered by grass and isolated sage brush. At Dry Creek and Reynolds Creek, the riparian and in-stream areas, which remain wet throughout the year, are the only areas with significant woody vegetation at lower elevations and are thus presumed to be the dominant source of the diel signals. WS10 at HJ Andrews on the other hand has very little riparian or in-stream vegetation yet exhibits a strong diel signal.

The saturated wedge hypothesis states that a saturated area near the stream channel is the primary source of lateral subsurface flow. This hypothesis posits that transpiration temporarily reduces the water table gradient, thus reducing lateral subsurface flow. Hillslope vegetation, especially on the upslope edge of the saturated wedge, would be required to be the dominant source of the signal to sufficiently reduce the overall hydraulic gradient and thus lateral flow at a daily timescale. Riparian vegetation, on the other hand, would be expected to reduce soil moisture near the base of the wedge, resulting in steeper overall hydraulic gradients (though smaller saturated area) and thus possibly resulting in an increase in downslope water flux during periods of high transpiration. In the case of Dry and Reynolds Creek, where vegetation is primarily in the riparian area and grasses that appear inactive through most of the summer cover the hillslopes, we would not expect to see the diel signal according to the saturated wedge hypothesis.

In the riparian interception hypothesis, near stream vegetation interception of lateral subsurface flow is the dominant source of the diel streamflow signal. According to the riparian interception hypothesis, we would not expect to see a signal in catchments with little or no riparian vegetation, such as WS10 at HJ Andrews, where the riparian vegetation has been periodically removed because of debris flows, most recently in 1996. A site visit to WS10 confirms that there is little woody vegetation near the stream channel, whereas the hillslopes are densely forested with Douglas-firs 30 years and older. Again, the ubiquity of the signal, including at WS10, suggests that riparian interception is not the sole source of the diel signal. This is also supported by the observations of Barnard *et al.* (2010), who documented a strong diel signal in lateral subsurface flow at the base of a hillslope 100 m upstream of the gauging station at WS10.

The flow path migration hypothesis allows for both riparian and hillslope vegetation connectivity to the streamflow and thus does not appear to conflict with the observed ubiquity of the diel signal observed. However, measurements by Wondzell *et al.* (2010) show that the water table at WS1 in HJ Andrews does not vary by more than a few centimetres within any 24 h, suggesting that flow paths likely do not migrate very far vertically. A small vertical migration would not be expected to be sufficient to explain the large observed changes in lag. Measurements of subsurface flow path locations or water table depths near the stream are unavailable for Dry Creek and Reynolds Creek.

The stream velocity hypothesis does not comment on the source of the diel signals, only their propagation to the catchment outlet, and thus would be expected to function independently of the hillslope and riparian vegetation.

Correlation of daily increase in lag with catchment area and stream length. At Dry Creek and HJ Andrews, there appeared to be a strong correlation between daily lag increase and both catchment area and stream length. This relationship is consistent with that seen at nested subcatchments in Yosemite, CA, by Lundquist *et al.* (2005), where there was a larger daily increase in summer lag as catchments increased from 25 to 775 km^2. At HJ Andrews, WS9 appears to not fit this pattern, whereas at Reynolds Creek, the pattern does not appear to exist at all. These outliers are discussed in the Outliers: HJ Andrews WS9 and Reynolds Creek section.

Because the saturated wedge, riparian interception and flow path migration hypotheses primarily describe water flux from hillslopes to the stream, it is unclear how they explain the observed correlation between the catchment area and the evolution of the lag. An increase in hillslope length or a change in local slope could affect the evolution of the lag by affecting upslope contributing area or hydraulic gradients, but there is no evidence of a relationship between catchment area and near gauge hillslope characteristics. At Dry Creek, where the correlation between daily lag increase and catchment area was the greatest, the average length of the hillslopes directly adjacent to the gauge stations at the six subcatchments showed no correlation with catchment area ($r = -0.30$, $n = 6$, $P = 0.56$) or slope ($r = -0.06$, $n = 6$, $P = 0.90$). In addition, there was not a significant relationship between daily increase in lag and hillslope length ($r = -0.48$, $n = 6$, $P = 0.33$) or slope ($r = 0.07$, $n = 6$, $P = 0.89$).

Increased catchment area could be expected to increase near-stream wetness, especially in the dry season (Beven and Kirkby, 1979). Increased wetness could result in a delayed transition from fast to slow downslope water flux under any of the three hypotheses and would affect the seasonal evolution of the lags. However, an analysis of wet and dry years, which could serve as a proxy for wet and dry stream areas, showed little difference in lag evolution. For instance, at WS10, HJ Andrews, the average spring (May through June) discharge was more than 5.7 liters per second for 3 years and less than 4.3 liters per second for the other 7 seven years. For the wet years, the daily increase in lag was 0.27 ± 0.09 min/day, whereas the increase for wet years was 0.22 ± 0.17 min/day. For Tollgate at Reynolds Creek, the wettest 10 years had a daily increase in lag of 1.19 ± 0.86 min/day and the driest 10 years had an increase of 1.59 ± 0.51 min/day. Among all the monitored catchments, the wet and dry years were never statistically different, and the daily increase in lag for wet years was not consistently greater or less than the dry years. This suggests that wetness, and thus catchment area, should have little effect on the evolution of the lags according to the saturated wedge, the riparian interception and the flow path migration hypotheses. The observed catchment area correlation with lag evolution again contradicts these hypotheses.

The stream velocity hypothesis suggests that as catchment size increases, and streams get longer, the daily increase in lag should increase. For a given increase in stream length, the opportunity for destructive interference increases because water from the most distant stream reaches has a longer path to the gauging station. For a very short stream, the in-stream transit time of upstream diel signals may be insufficient to get significantly out of sync with downstream signals, no matter the stream velocity. For a long stream, a small decrease in stream velocity could result in a large increase in total stream transit.

Another way in which catchment area could affect lags in the stream velocity hypothesis is in the seasonal reduction in stream discharge. Analyses of the catchment records used in this study show that the absolute stream discharge decreases more throughout summer in the larger catchments compared with the smaller catchments. At a given gauging station, there is a relationship between velocity and discharge, generally thought to be of the form $V = aQ^b$, with $b < 1$ (Leopold *et al.*, 1964). The greater decrease in discharge for the larger catchments results in a larger decrease in velocity, which would then result in a larger decrease in lag than the smaller catchments. For example, WS1 and WS10 are 2 km apart and similar in geology, elevation and vegetation;

however, WS1 is 101 ha, whereas WS10 is 10 ha. Discharge at WS1 was 1.399 cfs on 1 June and 0.044 cfs on 1 September, a decline of 1.355 cfs. During the same period, WS10 declined from 0.167 to 0.004 cfs, a decline of 0.163. Assuming a *b* value of 0.5, the anticipated decline in stream velocity for WS1 would be 280% greater than that of WS10. Smaller values of the *b* parameter will reduce the difference in velocity decline between the two watersheds, but the decline is always greater in the larger watersheds.

Because of uncertainties in the discharge–velocity relationship and the velocity–daily increase in lag relationship, predicting the relationship between catchment area and daily increase in lag would be difficult at this time. Despite this uncertainty, the observed increase in daily increase in lag with catchment area remains a support of the stream velocity hypothesis.

Outliers: HJ Andrews WS9 and Reynolds Creek. Dry Creek and most of the subcatchments at HJ Andrews fit a clear pattern of increased daily lag with greater catchment area and stream length. However, Reynolds Creek and WS9 of HJ Andrews did not fit this pattern. At Reynolds Creek, the middle catchment, Dobson Creek, had a greater daily increase in lag compared with the smaller and larger catchments. WS9 exhibited the second greatest daily increase in lag at HJ Andrews, although it had the smallest catchment area and shortest stream length.

At Reynolds Creek, there was no apparent relationship between catchment area and stream length and daily lag increase. The daily increase in lag at Tollgate gauge was intermediate between the two subcatchments of Dobson Creek and Reynolds Mountain East. Although Dobson Creek encompasses a much larger proportion of Tollgate than Reynolds Mountain East (26% vs 0.7%), Reynolds Mountain East is similar to much of the high elevation catchments that drive late summer streamflow, especially in the main stem of Reynolds Creek. Directly upstream of the Tollgate weir, two large subcatchments merge, one being Dobson Creek and the other being the main stem of Reynolds Creek, which encompasses Reynolds Mountain East. It is possible that there is a significantly different relationship between catchment area and daily increase in lag in the two subcatchments draining into Tollgate because of differences in geology, snow melt patterns and/or ecology, resulting in different lags. If we assume that the discharge from the two subcatchments can be modelled as sine waves and the stream discharge roughly equal for the two, then the combination of the two at the confluence directly upstream of the Tollgate weir should approach the formula for the sum of sine waves:

$$Q\sin(t+\mathrm{lag_a})+Q\sin(t+\mathrm{lag_b}) = 2Q\cos\frac{\mathrm{lag_a}-\mathrm{lag_b}}{2}\sin\left(t+\frac{\mathrm{lag_a}+\mathrm{lag_b}}{2}\right)$$

where $Q\sin(t+\mathrm{lag_a})$ is the discharge from the main stem of Reynolds Creek and $Q\sin(t+lag_b)$is the discharge from Dobson Creek. If the discharge from the two subcatchments is roughly equal, the combined flow would exhibit a sine wave with a lag that was the average of the lag of the two subcatchments. If the discharge from the two subcatchments was unequal, numeric analyses suggest that the lag at the confluence would be bounded between the simple average and the lag of the larger stream. In either case, this would result in Tollgate exhibiting a lag intermediate between the two subcatchments, as seen in Figure 8, supporting the stream velocity hypothesis.

At HJ Andrews, WS9 has similar geology to the other subcatchments, similar climatic patterns to the nearby WS1, WS2 and WS10 and similarly aged forest cover to WS2 and WS8, yet the daily increase in lag did not fit the relationship with catchment area and stream length. The seasonal increase in lag at WS9 appears to represent a much larger catchment, with a longer stream. A site visit to HJ Andrews in August 2011 showed that the stream channel in WS9 was significantly different than those of WS1, WS2, WS7, WS8 and WS10. The stream channels in the rest of the gauged subcatchments were generally rocky, with stream water quickly moving downstream through few impediments, whereas stream water at WS9 moved much more slowly, in and out of gravel bars and around large woody debris clogging the channel. It appeared that as the stream flow increased and the free water surface rose above these impediments, the influence of the gravel bars and woody debris would be greatly reduced. We hypothesize that the discharge–velocity relationship is considerably different at WS9 than at the other subcatchments in HJ Andrews, resulting in a greater decrease in stream velocity with a reduction in discharge than seen at other catchments. This would result in a greater daily increase in lag with decreased catchment discharge, supporting the stream velocity hypothesis. The hillslopes and riparian vegetation at WS9 did not appear significantly different from the other low elevation, old-growth subcatchment at HJ Andrews (WS2), leaving it unclear how the other hypotheses could account for the anomalous behaviour at WS9.

A perceptual model of diel fluctuations in summer streamflow

Although most our evidence seems to support the stream velocity hypothesis as the dominant control of lag timing at HJ Andrews and Dry Creek, the degree in which diel signals from the hillslopes influence streamflow remains unclear. Although it appears that the riparian vegetation is sufficient to create the diel signals (as seen at Dry Creek), the hillslope signals seen at HJ Andrews by Barnard *et al.* (2010) as well as the behaviour of WS10 in this analysis suggest hillslopes contribute to the observed stream signal as well. The observation of ubiquitous diel signals indicate that the diel signals are a combination of the three source hypotheses, solely the flow path migration hypothesis or some other explanation not yet identified.

Although the riparian interception and flow path migration hypotheses can explain the observed relationship between daily lag increase and catchment area and stream length, the relationship seems best explained by the stream velocity hypothesis because of the increased possibility of destructive interference in longer streams.

The anomalous behaviour exhibited by Reynolds Creek and WS9 at HJ Andrews can be best explained by the stream velocity hypothesis. At Reynolds Creek, the Tollgate subcatchment was intermediate of the two smaller subcatchments, whose lower stream reaches combine directly above the Tollgate weir. Similarly, the behaviour of WS9 at HJ Andrews could be due to its unique stream structure (slow, highly restrictive stream channel), which could lead to a different velocity–discharge relationship than that seen at the other local catchments.

From these observations (the ubiquitous signals, the relationship between the seasonal increase in lag and catchment area and the behaviour of the outliers), we have developed the following perceptual model of diel fluctuations in summer streamflow:

Between subcatchments: Within a given subcatchment, the diel signal can be explained by a combination of the saturated wedge, riparian interception or flow path migration hypotheses, although none are sufficient to explain all observations. The dominant control on the rate that the lag increases appears to be a function of both stream length and the velocity–discharge relationship. At Dry Creek, where stream channel characteristics are rather uniform for all catchments, there is a strong correlation between the catchment area and the daily lag increase, as increased catchment area leads to longer streams, which lead to longer stream travel times, more destructive interference from upstream diel signals and more rapid increase in lag. A similar pattern is seen at HJ Andrews, where increased catchment area leads to increased daily lag. WS9 appears to be an outlier, as the stream channel is much less rocky, and the velocity appears to drop more radically with decreased discharge. At Reynolds Creek, there appears to be a complex interaction between catchment area, stream length and stream velocity, resulting in no apparent correlation between daily lag increase and catchment area. This could be due to the mixture of signals from subcatchments with heterogeneity in geology, vegetation and stream characteristics resulting in different subcatchment behaviour at Reynolds Creek.

Between catchments: The relationship between catchment area (stream length) and daily increase in lag did not appear to be consistent between the three larger research subcatchments. At HJ Andrews, the slope of the relationship between daily lag increase and catchment area is two orders of magnitude greater than that seen at Dry Creek. Reynolds Creek, although not showing the clear relationship between daily lag increase and catchment area, does appear to have greater daily increases in lags at all catchments than those of Dry Creek, a catchment with similar climate and vegetation. These differences suggest that local controls such as average stream slope, channel composition or other characteristics influencing local stream discharge–velocity relationships dominate the daily increase in lags. Further research is required to determine the precise controls on the lags and lag–area–stream length relationships.

On the use of hydrometric databases

Data availability is a recent point of emphasis with the National Science Foundation, with increased enforcement of effective data management procedures. Dry Creek, Reynolds Creek and HJ Andrews have been pioneers in presenting free, easy access to the data collected by the primary investigators. Dry Creek has published its data on the Icewater Server using CUAHSI HIS since 2009, with data from climate stations, stream gauging sites and soil moisture stations all available. Reynolds Creek preceded Dry Creek by 8 years, having begun publishing data sets via an open ftp site as a data note in *Water Resources Research* (2001). The Reynolds Creek data are currently being moved to the Icewater CUAHSI HIS server, where all of the data for this study were stored. The HJ Andrews has housed its data on its own server since 1995, where 170 data time series, including the work of hundreds of researchers, are now available.

One of the primary goals of this project was to assess whether this readily available data would be sufficient to develop new basic understanding of hydrological processes. Although the authors were well aware of these three field sites, having spent considerable time in all three, running experiments at the HJ Andrews, leading the gauging of Dry Creek and monitoring sap flow at the HJ Andrews and Reynolds Creek, we attempted to look at these data with fresh eyes. We identified three primary deficiencies of using these universally accessible data independent of site visits and personal knowledge of the sites: measurement uncertainty, metadata and difficulties interpreting outliers.

Data uncertainty was a significant consideration. There is uncertainty in all measurements, and there have been recent calls to make a better effort to quantify uncertainty in hydrologic studies (Beven, 2006; Graham *et al*., 2010). In all three databases, we were unable to find, and there appeared to be no location to record uncertainties in the measurements. These uncertainties could include estimates of measurement error (instrument precision, calibration ranges and precision of rating curves, etc.), times when the data needed cleaning, transitions between measurement techniques, and others.

A second difficulty lay in gaps in the metadata. The metadata for these sites did not and likely could not include all of the information to thoroughly analyse results. The timing of the measurements was a critical component of this study. It makes a significant difference whether the hourly data presented online were the average or median flow rate over the previous hour, the measurement taken at the beginning, end or some time in the middle of the time step. In the case of this study, it only really mattered that the readings were always taken at the same time, but this was information that should be kept in the metadata. Additional information that should be easily accessed would be uncertainty in the rating curves (as mentioned earlier), the instrument type, model and make, and others.

The final difficulty in using readily available data lies in interpreting outliers. One of the key differences between the WS9 and the rest of the analysed catchments at HJ Andrews is the structure of riparian areas in the stream channel. Although there are some qualitative descriptions of the stream channel at the other subcatchments and mention of the frequent debris flows at WS10, it would be difficult to express in metadata how much different the riparian area in WS9 was from the rest of the HJ Andrews catchments. It took a site visit and a visual inspection of the stream channels of all the catchments to sufficiently gauge the differences in the stream beds. Further, although the meta-analysis identified catchment area as a control on the daily lag increase, it took a site visit to determine that it was likely the mean stream travel time (stream length and stream velocity) that was the actual driver.

CONCLUSIONS

Summer low-flow hydrological processes have been identified as an increasingly important area of interest in catchment hydrology, and diel signals in later summer discharge remain a poorly understood phenomenon that can dramatically reduce late season flow rates. This study analysed diel fluctuations in summer low flow at 15 subcatchments in three distinct research watersheds, Dry Creek, Reynolds Creek and HJ Andrews. The goal of this study was to compare four hypotheses on the source and propagation of diel signals from vegetation to the stream. We found diel signals at all monitored subcatchments, for all years on record. The lag between these signals and transpiration was shown to exhibit consistent patterns of increased lag with time at all subcatchments. The rate of this increase appeared to be a function of catchment area and stream length at Dry Creek and HJ Andrews. The source of the diel signals remains unclear and appears to be a result of a combination of hypothesized sources (hillslope, riparian and in-stream vegetation, transferred to the stream via unknown mechanisms). However, the stream velocity hypothesis of Wondzell *et al.* (2007) appears to best explain the patterns of lag increase at the different catchments. We found the availability of data from the three catchments invaluable in this study, although site visits and personal knowledge of the sites were necessary for increased understanding of the observed patterns.

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