

THE ROLE OF STREAM NETWORK HYDROLOGIC TURNOVER IN MODIFYING
WATERSHED RUNOFF COMPOSITION

by

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ABSTRACT

Stream networks can attenuate and modify hydrological, biogeochemical, and ecological signals generated in the terrestrial and in-stream portions of watersheds. Stream networks can modify watershed signals through spatially variable stream gains and losses to and from groundwater, described herein as hydrologic turnover. We measured hydrologic gain and loss at the reach scale using conservative tracer experiments throughout the Bull Trout Watershed in the Sawtooth Mountains of central Idaho. These experiments allowed us to track water moving into and out of groundwater from and to stream water. We extended these measured reach scale water balance components to the stream network using observed empirical relationships between 1) accumulated watershed area and stream discharge, and 2) stream discharge and percent discharge lost from the stream. We developed a watershed and stream network-scale model to simulate hydrologic turnover across stream networks to quantify its effects across watershed of varying structure and stream networks of varying geometry. These analyses elucidated the influence of watershed inputs to streams on downstream stream water composition. We determined that the magnitude of contributions to discharge from any upstream watershed input depended on the magnitude of the initial input, but also on the amount of hydrologic turnover downstream along the stream network. Downstream hydrologic turnover was a function of the intersection of watershed structure and stream network geometry. Our results suggest that a distributed representation of hydrologic turnover at the stream network scale is requisite for understanding how the stream network filters and modifies watershed inputs signals observed in streams or watershed outlets.

CHAPTER 1 - INTRODUCTION

Introduction

Groundwater (GW) and surface water are commonly considered to be distinct and separate reservoirs and resources. Although this simplification may be a sufficient conceptualization for some studies, fully characterizing watershed-scale hydrologic processes requires the understanding that GW (and the terrestrial watershed feeding it) and surface water are parts of a single hydrologic system (Winter, 1995).

A common emphasis of GW – surface water exchange studies has been on exchanges between streams and adjacent GW water reservoirs (Winter, 1995). Stream networks should be seen as more than conveyances for watershed GW and associated solutes (Bencala, 1993): they interact with GW at a range of spatial and temporal scales (Cardenas, 2008; Woessner, 2000) from scales of centimeters and minutes to larger scales of thousands of meters and years (Harvey et al., 1996). Stream and stream networks, then, are integral components of an overall, downgradient watershed transport system (Bencala, 1993).

Considerable research on GW – stream water (SW) exchange has focused on hyporheic exchange. The hyporheic zone is the area of saturation that exists beneath and around the stream and contain some proportion of SW (White, 1993). Hyporheic exchange typically occurs over shorter spatial and temporal scales (Harvey and Bencala, 1993, Harvey et al., 1996). Increasingly, however, studies of GW – SW exchange are quantifying exchange at longer spatial and temporal scales (hundreds to thousands of

meters and hours to days)(Covino and McGlynn, 2007; Covino et al., 2011; Payn et al., 2009). Larger scale GW – SW exchanges have been recognized as important for understanding watershed water balances (Payn et al., 2009), influencing nutrient dynamics (Covino et al., 2010), and controlling SW solute chemistry (Covino and McGlynn, 2007).

These larger scale GW – SW exchange studies have additionally observed concurrent gross gains from and losses to GW across multiple stream reaches in mountainous, headwater watersheds (Covino and McGlynn, 2007; Covino et al., 2011; Payn et al., 2009). Simultaneous gains and losses were observed even in reaches that exhibited minimal or no net change in discharge. In the absence of a quantification of gross exchanges these reaches would appear to have little interaction with adjacent alluvial aquifers. These findings emphasize the crucial importance of understanding the full water balance at the stream reach scale and above, rather than simply net hydrologic dynamics (Covino et al., 2011).

Stream tracer experiments have been commonly used to quantify GW – stream water (SW) exchange and interaction. The Stream Solute Workshop (1990) provided general guidelines for using, interpreting, and modeling both biologically active (non-conservative) and inactive (conservative) tracers. Conservative tracers, which may include inert dyes or ionic tracers, can be used to isolate and measure physical hydrologic dynamics by “injecting” them in to a stream and measuring the timing of their movement (a break through curve, BTC) past a downstream location (Stream Solute Workshop, 1990). More recently, the use of empirical relationships between SW specific

conductance and concentrations of ionic tracers (Gooseff and McGlynn, 2005) have allowed more complete characterization of the BTC, especially at its leading and trailing ends. The sequential injection of conservative tracers at the base and head of a reach has facilitated the quantification of gross exchanges of SW with GW, rather than just net exchanges (Covino et al., 2011; Payn et al., 2009).

The physical exchange of water between GW and SW (i.e., hydrologic gain/loss) has been shown capable of setting/resetting stream solute signatures (Covino and McGlynn, 2007), controlling reach-scale water balances (Payn et al., 2009), and exerting a strong influence over stream network source water composition (Covino et al., 2011). However, these reach-scale exchanges remain poorly understood at larger scales and inadequately assessed for their combined influence on stream network source water compositions. These exchanges occur at larger scales than those typically documented in hyporheic zone studies (Harvey and Bencala, 1993). This process of simultaneously losing water with a unique solute signature from SW while gaining water from GW with a different signature is defined as hydrologic turnover. When compounded serially along a stream network, hydrologic turnover results in a continually shifting mixture of stream water sources (Covino et al., 2011).

This thesis research focuses on expanding the analyses presented in Covino et al. (2011) by applying the same modeling framework to six natural and seven synthetic watersheds. In doing so we seek to explore how unique watershed structures and stream network geometries can control 1) unique spatial patterns of hydrologic turnover and therefore 2) distinct evolutions of source water compositions in each watershed. In doing

so we seek to explore the implications of stream network scale hydrologic turnover for interpreting stream signals.

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CHAPTER 2 - THE ROLE OF STREAM NETWORK HYDROLOGIC TURNOVER IN MODIFYING WATERSHED RUNOFF COMPOSITION

Abstract

The role of stream networks in integrating, modifying, and transporting watershed signals is poorly understood. Stream networks can modify watershed signals through spatially variable stream gains and losses to and from groundwater, described herein as hydrologic turnover. We measured hydrologic gain and loss at the reach scale using tracer experiments throughout the Bull Trout Watershed in the Sawtooth Mountains of central Idaho. We extended these measured reach scale water balance components to stream network scales using observed empirical relationships between 1) accumulated watershed area and stream discharge, and 2) between stream discharge and percent hydrologic loss. We developed a network-scale model to simulate hydrologic turnover across stream networks and elucidate manifestations of these reach-scale processes at the watershed scale. This approach allowed us to estimate the proportional influence exerted by upstream reaches and local inflows on water sources expressed across the stream network. Analyses of six Sawtooth watersheds with varying topographic structure and stream network geometry indicated that the magnitude of contributions to discharge from any upstream source depends on the magnitude of the initial input, but also on the amount of turnover downstream along the stream network. Patterns of stream water source composition were distinct to each watershed due to unique intersections of watershed structure and stream network geometry. Our results suggest that a distributed

representation of hydrologic turnover at the stream network scale is requisite for understanding how the stream network can act as a filter to modify terrestrial watershed signals.

Introduction

Stream networks are integral components of watersheds. They integrate, transform, and transmit watershed physical (Rodríguez-Iturbe and Valdés, 1979), biogeochemical, and ecological (Vannote et al., 1980) process signatures. However, process signals and inputs to streams are often convoluted in watershed outlet observations (McGlynn et al., 2004), partly due to constructive interference arising from differential travel distances and flow velocity along networks (Bergstrom et al., in review; Wondzell et al., 2007). We have long realized that streams are not merely pipes that convey watershed signals (Bencala, 1993). Despite this realization, the in-stream hydrologic processes that modify watershed hydrologic, biogeochemical, and ecologic inputs have received little attention beyond the stream reach scale.

Much important research on surface water (SW) – groundwater (GW) exchange has focused on short temporal scale (minutes) and spatial scale (centimeters) exchange processes associated with transient storage and hyporheic zones (Harvey et al., 1996). However, longer duration and larger spatial scale exchange processes are being increasingly recognized. These studies document that streams do not only gain or lose water to GW across stream reaches on time scales greater than hours and days and spatial scales of tens to hundreds of meters, but that dynamic and simultaneous gains from and

losses to GW can occur across a broad range of flow states (Covino and McGlynn, 2007; Covino et al., 2010; Payn et al., 2009). This bidirectional movement of water into and out of streams can influence stream solute composition because streams can lose water of one signature and gain water of a different signature (Covino and McGlynn 2007).

Covino and McGlynn (2007), Payn et al. (2009), and Covino et al. (2010, 2011) all observed simultaneous gains and losses across a broad range of stream reach morphology, flow states, and sizes in Montana and Idaho. Because stream networks are serially organized flow systems, stream observations must be seen as the product of serial processing along the stream network. Therefore, dynamic and highly variable reach scale water balances have important implications for interpreting reach scale processes and how they compound to influence downstream source composition (Covino et al., 2011). Here, we define stream source composition as the quantitative distribution of upstream water sources observable at a given location in space and time.

The spatial distribution of dynamic stream gains and losses along a stream network can be influenced by watershed structure. Watershed structure is defined here as the arrangement of hillslope convergence and divergence and the resulting spatial pattern of upslope accumulated area (Jencso et al., 2009). It has long been recognized that the magnitude of water input to streams can be related to the amount of lateral watershed area or size of the adjacent hillslope (Anderson and Burt, 1978; Beven and Kirkby, 1979). Several studies have related watershed hydrological responses to the distributions of flowpaths within those watersheds (McDonnell et al., 1991; Kirchner et al., 2001; Nippen et al., 2011; Jencso and McGlynn, 2011). Studies have commonly focused on

relationships between moments of these distributions and watershed response (e.g., McGlynn et al. 2003; McGuire et al., 2005), however, recent work by Jensco et al. (2009; 2010) has expanded on these analyses to highlight the value of fully characterizing the spatial distributions of convergent and divergent hillslopes (watershed structure) in understanding watershed hydrology.

Stream network geometry then defines how the stream network is spatially organized and therefore the distribution of distances over which dynamic gains and losses can occur and are propagated downstream to the watershed outlet. This distribution of stream network travel distances was introduced as the distribution of “width” by Kirkby (1976) and is commonly referred to as the width function. A predominant application of the width function is to characterize dispersion in watershed hydrologic response due to variability in the distance that inputs to the stream network travel to the outlet. This geomorphic dispersion is central to the geomorphic instantaneous unit hydrograph (GIUH, Rodríguez-Iturbe and Valdés, 1979). The use of the stream network in characterizing watershed hydrologic processes was expanded by Woods and Sivapalan (1999) to incorporate the connection between stream network geometry and the structure of the uplands which allowed the characterization of aggregated watershed structure from network geometry. However, they found that this connection existed only for catchments that were large relative to their hillslope scale.

Stream gains and losses to and from GW that occur dynamically along a stream network can lead to changes in stream source composition moving downstream. This process of simultaneous gains and losses is referred to here and in Covino et al. (2011) as

hydrologic turnover. Covino et al. (2011) introduced a method for extending reach-scale measurements of stream gains and losses to the network scale by utilizing a concise modeling framework based on empirical observations and relationships. Their proof of concept modeling results for a single watershed suggested that source water composition was dominated by local hillslope area in the headwaters but shifted to be more reflective of compounded hydrologic turnover moving in a downstream direction through the stream network. However, that study did not explicitly consider how source water compositions vary across a range of natural and synthetic end-member watersheds due to spatially variable, longitudinally compounded hydrologic turnover through each stream network.

Here, we focus on stream network-scale hydrologic dynamics and how they can manifest as distinct modifications of stream water source composition within unique stream networks. We expand the methods and analyses presented initially in Covino et al. [2011] to include seven synthetic watersheds and six natural watersheds within the Sawtooth Mountains of central Idaho. With these analyses, we seek to address the following questions:

- How does hydrologic turnover influence the evolution of stream water source composition?
- How do variable watershed structures and stream network geometries lead to spatial patterns of hydrologic turnover in synthetic and natural watersheds that manifest in variable stream source compositions?
- What are the implications of these results for interpreting stream network signals?

Methods

We performed conservative tracer (chloride, Cl⁻) injections on ten stream reaches within the Bull Trout Watershed in the Sawtooth Mountains of central Idaho to quantify net changes in Q and gross hydrologic exchanges between stream water (SW) and groundwater (GW) along each reach. Empirical relationships derived from these experiments became the basis of a network model that simulates hydrologic gains, losses, and turnover along a stream network.

Study Area

We selected six watersheds located within 70 km of one another in the Sawtooth National Forest of central Idaho for this study. Watersheds range in size from 11.4 km² to 62.8 km² and in elevation from 1957 m to 3256 m (Figure 1). Thirty year average annual precipitation is 108 cm, with 64% as of snowfall (Banner Summit snowpack telemetry, SNOTEL, #312, 2146 m elevation, located within 55 km of all watersheds). Land cover on hillslopes and at higher elevations is dominated by lodgepole pine (*Pinus contorta*) in the subalpine zone and grasses in the alpine zone; land cover in the valley bottoms is a mix of lodgepole pine (*Pinus contorta*), sedges (*Carex* spp.), grasses, and willows (*Salix* spp.). Parent lithology is biotite granodiorite of the Idaho Batholith, and valley fill is composed of Pleistocene till mixed with Holocene alluvium and colluvium (Kiilsgaard et al. 2003).

Field Hydrologic Measurements

Hydrologic data were collected in all watersheds to quantify annual, seasonal, and hourly discharge. In Bull Trout Watershed we additionally measured SW – GW exchange across a broad range of watershed positions and flow states. Field experiments were performed from May to September during 2006, 2007, and 2008. Measurements included salt dilution gauging (Covino et al., 2011; Kilpatrick and Cobb, 1985), tracer mass recovery experiments (Covino et al., 2011), and stream stage measurements.

Stream discharge was computed at the outlets of each watershed using continuous stage measurements (capacitance rods; TruTrack, Inc.; vertical resolution of 1 mm and temporal resolution of 10 min – 1 hr). Rating curves for each watershed outlet were calculated using periodic discharge measurements (velocity-area method and salt dilution gauging). Discharge was additionally measured in spatially distributed locations within Bull Trout using salt dilution gauging.

We performed conservative tracer mass recovery experiments (Covino et al., 2011) in ten separate reaches (191 – 3744 m) that spanned the range of flow states ($\sim 1 - 800 \text{ L s}^{-1}$) and stream types (1st order headwater to 3rd order valley bottom stream) for a total of 16 tracer experiments in Bull Trout Watershed to quantify changes in discharge across a reach as well as gross gains and losses of SW to and from GW. Slug additions of sodium chloride (NaCl) were injected first at the base (bottom) and then at the head (top) of each reach and used to measure discharge at each of those locations via salt dilution gauging (Covino et al., 2011; Kilpatrick and Cobb, 1985). The difference between these two discharge measurements was the net change in discharge ($Net\Delta Q$) along that reach.

We measured the mass of chloride (Cl-) injected at the head of the reach that was recovered at the base of the reach and calculated the percent of mass lost. We assumed full mixing of the stream water column and confirmed this with visual observation of rhodamine dye injections. Therefore, the calculated percent mass lost was approximately equivalent to the gross percentage of discharge lost. Gross loss of discharge (Q_{LOSS}) is the product of percent loss and local discharge. Gross gain of discharge (Q_{GAIN}) is calculated using mass balance:

$$\text{Eq. 1 } Q_{GAIN} = \Delta Q_{NET} + Q_{LOSS}$$

where over a given reach ΔQ_{NET} is the net change in discharge. We therefore quantified reach scale tracer dynamics and water balances using direct, experimental manipulations.

Terrain Analysis

We performed terrain analysis using digital elevation models (DEMs) derived from airborne laser swath mapping (ALSM) and USGS quadrangle maps. These DEMs were supplemented with GPS-surveyed streamlines, which were collected in four of the watersheds (Bull Trout, Pettit, Stanley, and Alturas). They were surveyed using a Trimble GeoXT GPS and differentially corrected using the Payette National Forest base station in McCall, ID (~120 km away). ALSM data were collected on September 2, 2009 by the National Center for Airborne Laser Mapping (NCALM). Instrument vertical and horizontal accuracy was 5 – 30 cm and 10 cm, respectively. Point cloud data were interpolated to a bare earth DEM with a resolution of 1 m and resampled to 10 m for this analysis. USGS quadrangles of 10 m resolution were downloaded from the USGS

seamless server; data available from the USGS, Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD.

Prior to delineating watershed boundaries, we applied a drainage-route deepening algorithm (Olaya, 2004) to each DEM to eliminate sinks in the relatively flat valley-bottoms. We chose to deepen drainage routes rather than fill sinks due to the loss of valley-bottom topography caused by sink-filling algorithms. After deepening drainage routes, we delineated the boundaries of each watershed using a single flow direction algorithm (D8, O'Callaghan and Mark 1984).

Upslope accumulated area (UAA) at each watershed cell was calculated using a triangular multiple flow-direction algorithm (MD_{∞}) (Seibert and McGlynn 2007) up to the field observation corroborated stream channel initiation threshold of 20 ha, after which area was routed downstream using a single-direction flow algorithm (D8, O'Callaghan and Mark 1984). Watershed cells downstream of cells where a channel was initiated were classified as stream cells. For these stream cells (i.e., 10 m stream reaches) we also calculated total watershed area and local input (LI) (Grabs et al. 2010; Jensco et al., 2009; McGlynn and Seibert, 2003). LI is the area that flows directly into a given reach and does not include area that flows into that reach through upstream reaches.

Stream networks generated from this process were visually checked against the GPS streamlines, the 1 m ALSM DEM and Digital Ortho Quarter Quads (digital aerial images) for agreement with observed stream networks. Minor, manual terrain modifications were made in some cases based on these auxiliary data to correct unrealistic flow paths along each stream network.

We used the outputs from these terrain analyses (stream networks, local inputs to those stream networks, and watershed area for each stream cell derived from upstream accumulated local inputs) to extend our measured hydrologic variables (Q_{GAIN} , Q_{LOSS} , and $Net\Delta Q$) from the reach scale at which they were measured to the stream network scale in all six natural and seven synthetic watersheds using the following empirical relationships.

Empirical Relationships

We quantified two empirical relationships between our measured hydrologic variables (Q_{GAIN} , Q_{LOSS} , and $Net\Delta Q$) and observed watershed terrain metrics (Figure 2).

First we quantified the relationship between area and discharge:.

$$\text{Eq. 2 } Net\Delta Q_i = \alpha * LI_i$$

Where $Net\Delta Q_i$ is net discharge gained across a reach, i ; LI_i is the local input at reach i .

Second we quantified the relationship between discharge and percent loss of discharge:

$$\text{Eq. 3 } \%Loss_i = \beta Q_i^\gamma$$

Where $\%Loss_i$ is the percent of discharge lost to GW in reach i ; and α , β , and γ are regression coefficients.

The relationship between discharge and area (Figure 2A, Eq. 2) is based on six measurements of discharge collected at six locations across three watersheds on July 24, 2006. Five of these measurements were based on stage measurements and rating curves at the outlets both Stanley and Alturas watersheds as well as the outlet and two upstream locations in Bull Trout watersheds. The sixth was taken using salt dilution gauging in the headwaters of Bull Trout watershed. These discharge measurement locations spanned the range of watershed area amongst all six watersheds (<1 km² to the largest at 66 km²).

We used the conservative tracer tests described in section 2.2 to measure percent loss and discharge across a range of ten spatial locations and multiple flow states in Bull Trout watershed (n=16). We then used these measurements to characterize the relationship between discharge and % loss of discharge (Figure 2B, Eq. 3). These two relationships were leveraged to extend our field measurements beyond the reach scale.

Synthetic Watersheds

We generated seven synthetic watersheds for comparison against the six natural watersheds to understand how hydrologic turnover can propagate through simple watersheds and stream networks. The total watershed areas and network lengths of these watersheds were designed to lie within the range observed in the actual Sawtooth watersheds. Three of these networks varied in their stream network geometry while four varied in their watershed structure (the organization of convergent and divergent hillslopes). The networks that varied in network geometry ranged from 0 to 2 network bifurcations (Table 1). Those networks that varied in watershed structure varied in two ways: the shape of the distribution of local inputs and their organization (i.e., either skewed towards headwaters or towards the outlet; Table 1). Two watersheds had area distributed with a binary distribution and two with a gamma distribution. Each distribution was parameterized by the actual frequency distribution of LI in the six Sawtooth watersheds. Two of these watersheds (one binary and one gamma) were sorted with the highest LI in the headwaters and two were sorted with the highest LI closest to the watershed outlet (Table 1).

Conceptual Model of Stream Gains, Losses, and Hydrologic Turnover

In our conceptual model (Figure 3) water enters a stream reach either from an upstream reach or a lateral input from groundwater. Once in the reach, water from all sources is assumed to be fully mixed and therefore proportionally subject to loss from the stream reach to groundwater. The result of these simultaneous gains and losses is hydrologic turnover: the output from each reach is a constantly shifting mixture of water from all upstream sources (Figure 3a). If overall discharge magnitude is tracked moving in the downstream direction and separated into its source components, it is evident that even as discharge increases due to increasing inputs of area, both the absolute and relative magnitudes of contribution from any individual upstream source diminish due to compounding hydrologic turnover (Figure 3b).

Implementation of Conceptual Model

We implemented our concise, network-scale model that utilized the empirical relationships described above in conjunction with terrain analysis to scale the hydrologic variables measured at the reach scale (Q_{GAIN} , Q_{LOSS} , and $Net\Delta Q$) across the stream networks in each of the six watersheds. The water balance equation for each stream reach is a slight modification of Eq. 1:

$$\text{Eq. 4 } Q_i = Q_{i-1} + Q_{i,GAIN} - Q_{i,LOSS}$$

where Q_i is the discharge in a reach, i , and Q_{i-1} is the discharge in the reach(s) immediately upstream. $Q_{i,GAIN}$ and $Q_{i,LOSS}$ are the gain and loss in reach i and are calculated as functions of local input and stream discharge, respectively, using the

empirical relationships previously described. This equation is solved iteratively starting in the headwaters (where Q_{i-1} is set to zero as a boundary condition) and moving in a downstream direction across the entire stream network.

In order to determine source water mixtures at reach i , we calculated a stream water turnover factor, TF , as a measure of the proportion of stream water gained from groundwater in reach i relative to the discharge input from the upstream reach and the discharge lost from reach i .

$$\text{Eq. 5 } TF_i = 1 - \frac{Q_{i,GAIN}}{Q_{i-1} - Q_{i,LOSS} + Q_{i,GAIN}}$$

This turnover factor can be conceptualized as the influence that a given input has on the composition of stream water. The denominator of this relationship and therefore the overall ratio is effectively always positive because the loss is calculated as a percentage of stream discharge and discharge is never low enough to have a 100% or greater loss (Figure 2). Because $Q_{i,GAIN}$ occurs in both the numerator and denominator this relationship must always be less than one. We used TF to calculate the discharge added to the stream in reach i that remains in the immediate downstream reach, $i + 1$:

$$\text{Eq. 6 } Q_{i+1,i} = Q_{i,GAIN} * TF_{i+1}$$

where, $Q_{i+1,i}$ is the amount of discharge gained in reach i that remains in reach $i + 1$. This equation can be generalized to calculate the contribution from any upstream reach, j , by recognizing that it's turnover factor, TF_j , is the product of all TF_i between reach j and reach i :

$$\text{Eq. 7 } Q_{i,j} = Q_{j,GAIN} * \prod_{k=j}^i TF_k$$

The distribution of $Q_{i,j}$ across all j is the magnitude of all distinct spatial inputs to reach i .

Our model simulates hydrologic turnover at a 10 meter resolution across synthetic and natural stream networks by leveraging terrain characteristics to extend the results of stream tracer experiments beyond the reach scale. This model allows us to explore the influence of these compounded reach scale hydrologic dynamics on the evolution of source water compositions in seven synthetic and six natural watersheds.

Results

Empirical Relationships

We applied measured reach scale stream water (SW) – groundwater (GW) exchange across the network by using two empirical relationships. The linear relationship between watershed area and Q (Figure 2a) was derived from discharge measurements in Bull Trout, Stanley, and Alturas watersheds that span the range of watershed areas ($<1 \text{ km}^2 - 66 \text{ km}^2$) and flow states ($<10 \text{ L s}^{-1} - 900 \text{ L s}^{-1}$). The relationship is well characterized with a linear fit ($R^2 = 0.82$, Figure 2a). Tracer mass recovery experiments were performed to determine reach water balance components across a range of flow states and spatial locations in Bull Trout watershed. These experiments revealed a negative power law relationship between Q and % loss of Q ($R^2 = 0.94$, Figure 2b). Loss ranged between $\sim 40\%$ at flows of 2 L s^{-1} to $>1\%$ at flows approaching 900 L s^{-1} . These empirical relationships were used to extend our reach-scale measurements across multiple stream networks.

Hydrologic Turnover at the Stream Network Scale

Shifting Mixtures of Stream Source Compositions. We implemented our conceptual model in two ways across the entire Bull Trout Watershed (Figure 4): without the presence of hydrologic turnover (Figure 4A) and with hydrologic turnover as described mathematically in section 2.7 (Figure 4B). The thickness of a color band at any given network distance is the absolute magnitude of discharge contribution from the corresponding location on the color bar above each plot. The absence of turnover is illustrated by the horizontal stratification of each color band, and specifically indicated by the white dotted line (Figure 4A). These patterns represent that in the absence of hydrologic turnover, the amount of input from each network location stayed constant as it was transported downstream. Results from Bull Trout that include hydrologic turnover (Figure 4B), display the same shifts in source water mixtures as illustrated in our conceptual model (Figure 3): the relative and absolute contribution of a given input to the stream network diminished moving downstream through the stream network. This deterioration of each source's contribution due to hydrologic turnover is visibly evident (Figure 4B) as a pinching or narrowing of each color band moving downstream from the headwaters (left) to the outlet (right). The effect of turnover is highlighted by the pinching of the blue (distant) color band, outlined by the white, dotted line. The result of this reduction of each local input (LI) moving downstream is that the mixture of source waters at the outlet of the watershed is strongly skewed towards more proximal (red/orange) locations than more distant (blue), headwater locations. Therefore, in contrast to results in the absence of hydrologic turnover (Figure 4A), the mixture of

source waters at downstream locations is not evenly reflective of the comparative magnitudes of inputs from proximal and distant locations (Figure 4).

Synthetic Watersheds. Seven synthetic watersheds were generated and analyzed to bracket the range of natural network geometries and watershed structures. These watersheds were useful for understanding and providing context for our results from natural watersheds due to their radically simplified shapes. These shapes allow for simplified interpretation of model results. Three of these watersheds varied in their network geometries (Table 1, Figure 5), with two, one, or no bifurcations in their networks. Four varied in their upland shapes, resulting in spatial distributions of local inputs (LI) that either increased or decreased from the headwaters to the outlet, and did so with either a binary distribution of LI or a gamma distribution of LI following the sorted frequency distribution of LI in the actual Sawtooth watersheds (Table 1, Figure 6).

Results from these watersheds displayed the same shifts in source water mixtures as illustrated in our conceptual model (Figure 3): the relative and absolute contribution of a given input diminished moving downstream through the stream network. This deterioration of each source's contribution, due to hydrologic turnover, is visibly evident (Figure 5) as a pinching of each color band moving downstream from the headwaters (left) to the outlet (right). The result of this reduction of each local input (LI) moving downstream is that the mixture of source waters at the outlet of the watershed is strongly skewed towards more proximal (red/orange) locations than more distant (blue), headwater locations. Therefore, the mixture of source waters at downstream locations is

not evenly reflective of the comparative magnitudes of inputs from proximal and distant locations (Figure 5).

Moving along a gradient from no network bifurcation to two levels of bifurcation (Figure 5) it is evident that even with the same total stream network length, changing network geometry results in shifting discharge mixtures. Although the ultimate discharge magnitude in each network is the same, the discharge accumulates increasingly in the headwaters with more bifurcations as evidenced by the increasing convexity of the overall discharge accumulation from Figure 4A to Figure 4C.

This increasing influence of the headwaters with successive bifurcations is also evidenced in both the peak magnitude and final magnitude of the blue color band, which represents sources local inputs farthest from the network (Figure 5A-C). The most bifurcated network (Figure 5C) had a higher accumulation of discharge in locations farther from the outlet, and also a higher proportion of its final discharge from these locations. This network received 30% of its discharge at the outlet from these headwater sites, compared to 17% and 7% for the networks with one and no bifurcations, respectively (Figure 5). Another way to characterize the variability in source water compositions is the fraction of the network closest to the outlet that contributes $\frac{1}{2}$ of outlet Q ($Q_{1/2}$). In these synthetic watersheds, $Q_{1/2}$ varies (Table 1) from the lower 0.2 of the network (Figure 5A) to 0.42 in the twice-bifurcated network (Figure 5C).

Similar behavior to that described above is evident in synthetic watersheds whose network geometries remain constant as a non-bifurcated channel, but whose watershed shapes vary. In these watersheds the relative and absolute magnitude of an individual

input, as represented by a unique color band, diminishes as it moves downstream with more distant inputs being markedly more diminished in magnitude than closer ones. While these watersheds all have the same area, the spatial distribution of that area varies between them (Figure 6, Table 1). The discharge accumulation pattern in watersheds whose area is distributed with the majority in the headwaters is convex (Figure 6B, D) similar to the bifurcated networks mentioned previously (Figure 5B,C). In contrast, the watersheds with more area accumulated towards the outlet manifest this distribution as a concave discharge accumulation (Figure 6A, C). Figures 6A and 6B represent extreme examples of sorted LI, with one receiving the majority of its area inputs in the headwaters and another near the outlet. This results in distinct mixtures of source waters at the outlet of each watershed. $Q_{1/2}$ at the watershed outlets of these four watersheds varies (Table 1) from 0.7 (Figure 6A) to 0.27 (Figure 6B). Despite these differences, it is important to note that although the area of the watershed in figure 6B is accumulated almost entirely in the headwaters, these locations (represented as blue in figure 6B) contribute only ~10% of total discharge at the outlet due to compounded hydrologic through the stream network.

Natural Watersheds. Model results from the six Sawtooth watersheds display patterns broadly reminiscent of the synthetic watersheds described above but with greater complexity (Figure 7). Overall discharge accumulates steadily in each watershed moving downstream, but with variable rates of accumulation depending on how the watershed LI is distributed along the stream network. These variable rates of area and Q accumulation are visibly evident as small convexities and concavities inset in the overall increasing

trend in Q . The contributions of each spatial source of stream water decay as they move downstream towards the outlet due to hydrologic turnover as illustrated in our conceptual model (Figure 3). However, because each watershed has a unique distribution of LI and stream network geometry, the source mixture changes through the network and creates distinct patterns in the pinching and slope of the color bands in each plot (Figure 7). At a given network distance, steeper positive slopes in overall discharge accumulation or steeper negative slopes between color bands represent a higher degree of hydrologic turnover due to either greater gains or losses at that location, respectively. $Q_{1/2}$ in these watersheds varies from a low of 0.2 in Hellroaring to a high of 0.3 in Bull Trout (Table 1). Therefore, because Hellroaring and Bull Trout have the shortest network lengths and smallest watershed areas, variability in $Q_{1/2}$ amongst the natural watersheds cannot be easily explained by general watershed characteristics (Table 1).

A vertical slice through each panel in Figure 7 at each watershed outlet (right side of each plot) is the distribution of absolute contributions to discharge from each upstream location. When these distributions are normalized to total discharge in each watershed (Figure 8, grey bars) they can be compared across watersheds. The corresponding distributions of LI at each upstream location (Figure 8, black lines) represent the spatial inputs of water to the network. When compared in this way it is evident that although large local inputs do indeed correspond in location along the x-axis to peaks in relative contribution to the outlet from that location, they correspond less in magnitude as we move further away from the outlet (further to the left on the x-axis). The distributions of LI in each watershed range from generally flat to slightly decreasing moving towards the

outlet; all distributions additionally display noticeable heterogeneity corresponding to locations with relatively higher or lower areal contributions to the network. In contrast, the distributions of contributions to discharge for each of the upstream locations (Figure 8, grey bars) reveal a trend in five of the watersheds (Figure 8A-E) of increasing contribution with proximity to the outlet, an observation similar to that exhibited in figures 4-7. The distribution in Alturas increases initially but starts to flatten and even decreases at ~7000 m downstream from the headwaters. Although this runs counter to the trend observed in the other watersheds, it can be partially accounted for by observing that the downward trend in the distribution of LI moving towards the outlet is much steeper in Alturas than in the other watersheds (Figure 8E).

The cumulative distribution of percent contribution to discharge (Figure 9) illustrates the different distance scales that contribute discharge to the outlet of watersheds. The local slope of each distribution corresponds to the magnitude of contribution from that distance, with steeper slopes indicating higher contributions from those locations. Therefore, each watershed displays a general trend of increasing slope moving downstream (from left to right). The distance below which all discharge has been contributed (i.e., the outlet) is set by the overall length of the stream network, with the watersheds sorted by network length at the 100th percentile. However, the relative sorting of the watersheds changes moving through percentiles of discharge contribution. At the 50th percentile of discharge contribution the order of Alturas, Stanley, and Pettit is reversed from the order at the 100th percentile. The distance at which each watershed's distribution crosses the dotted line marking the 50th percentile is the distance that divides

the network into two portions that each contribute half of the discharge at the outlet. The size of the downstream portion relative to the overall network corresponds to the $Q_{1/2}$ (Table 1). This downstream portion is shorter than the upstream portion in each watershed due to hydrologic turnover weighting the parts of the network closer to the outlet more heavily.

Discussion

How Does Hydrologic Turnover Influence the Evolution of Stream Source Compositions?

Our results illustrate the connection between hydrologic turnover (the simultaneous or sequential loss and gain of water to and from groundwater) and the ultimate source water composition of stream water (SW) at the watershed outlet. The source composition at a watershed outlet is a representation of the relative and actual magnitudes of contributions of water and associated solutes from each distance upstream of the outlet. It illustrates the influence of spatially distinct watershed locations on stream water signatures moving through a stream network. In the absence of hydrologic turnover the source composition at a watershed outlet would be an exact reflection of the magnitudes of local inputs (LI) from throughout the watershed (i.e., Figure 7, black lines). Regardless of distance traveled, the contribution from a given spatial location would retain the same magnitude because water is not exchanged with groundwater, only gained (Figure 4).

Our model demonstrates that hydrologic turnover at the stream network scale can strongly modify SW source composition as exemplified in both synthetic and actual

watersheds. Hydrologic turnover results in the variable diminishment in the influence of more distant sources on outlet water composition (Figures 3-7) when it is compounded longitudinally through the stream network. The magnitude of this diminishment varies with the spatial pattern of hydrologic turnover, which in turn is a function of watershed structure and stream network geometry. Hydrologic turnover modifies source compositions in two ways: by diminishing the magnitude of spatial inputs to the stream network through losses to groundwater and by further diluting all inputs with gains from groundwater. The degree to which it modifies source compositions in each reach, i , is calculated as a turnover factor (TF_i , Eq. 5). This hydrologic turnover causes the diminishment of each source's contribution, which is evident in the pinching of color bands moving downstream through watersheds (Figures 3-7) relative to the increasing discharge. In the absence of hydrologic turnover the color bands in Figures 3-7 would be distributed horizontally across each plot (Figure 4A).

We measured hydrologic turnover at the reach scale using tracer tests to characterize both changes in discharge and gross hydrologic losses across reaches. We were then able to extend measured turnover to the stream network scale by leveraging empirical relationships between 1) watershed area and discharge, 2) and discharge and percent hydrologic loss (Figure 2). These relationships could be widely applicable in a variety of watersheds; however, other watersheds may exhibit relationships between hydrologic turnover and stream slope, bed materials, hydraulic radius, stream velocity, or other watershed or hydrologic characteristics.

How do Variable Watershed Structures and Stream Network Geometries Lead to Spatial Patterns of Hydrologic Turnover in Synthetic and Natural Watersheds that Manifest in Variable Stream Source Compositions?

The magnitude of an individual LI contribution to the source composition at a specific downstream location in a watershed is the result of compounded hydrologic turnover as described in equation 7. This compounded hydrologic turnover results in diminishment in contribution to overall discharge as an input moves downstream. As the distance between reach i and reach k increases in equation 7 (i.e., k becomes larger), the magnitude of an input decreases. However, the magnitude of hydrologic turnover is controlled by the magnitudes of discharge gained from and lost to groundwater. Since gross hydrologic gains and losses vary spatially in conjunction with watershed LI and stream discharge, respectively, and because each watershed has a unique network geometry the spatial pattern of hydrologic turnover is specific to each watershed. The patterns in the color bands of Figures 4-7 illustrate how source compositions vary with distinct patterns in synthetic and natural watersheds due to the “finger prints” of each watershed.

The synthetic watersheds all vary in their ultimate source compositions (Figures 5 and 6) due to the variability in how their area is accumulated through the stream network. Convex shapes in the overall accumulation of discharge (Figures 5B,C and 6B,D) indicate greater accumulation in the headwaters while the reverse is true for concave shapes (Figures 5A and 6A,C). Watersheds that accumulate area predominately in their headwaters (upper 1/3 of the stream network, blue on color ramp; Figures 5B,C and

6B,D) show source compositions with a greater contribution from those further locations than either non-bifurcated watersheds or those that accumulate more area closer to the outlet (Figures 5A and 6A,C). Although this general observation is intuitive and expected, it is important to realize that the actual magnitude of the contribution from headwater locations in these watersheds is strongly modified by hydrologic turnover moving through the network. Because percent discharge loss is smaller in reaches with higher discharge, larger gains in the headwaters induce some stability in the contribution of these headwater locations due to lower percent losses of discharge. This relative stability is evident in a comparison between Figure 6C and D: the diminishment of discharge from headwater sources is within an order of magnitude in Figure 6D but more than an order of magnitude in Figure 6C.

The watersheds in Figures 6A and 6B are end members on a spectrum of watershed shapes (tear drop shapes of opposite orientation). Results from these watersheds can be used to bracket expected results from natural watersheds. The magnitude of contributions from headwater sources at the outlet is higher in Figure 6B than 6A but it is still only a fraction of the initial inputs from those headwater locations. The watershed depicted in Figure 6B exhibits contributions from its headwaters that reach a maximum of 10 L s^{-1} but only 2 L s^{-1} at the watershed outlet. These results suggest that even in watersheds with most of their area in the headwaters, the source composition at the outlet is strongly weighted towards more proximal locations; however, the degree depends on how LIs are distributed along the stream network.

The synthetic watersheds shown in Figure 5A-C have uniform local inputs along the stream network, but display variability in the evolution of their source compositions moving through each stream network. This variability is due to differences in stream network geometry (increasing bifurcation) rather than distinct watershed structures (i.e., distributions of local inputs). Increasing bifurcation can have an effect on evolving source water compositions similar to that of watersheds that are increasingly round in their headwaters (Figure 6A,B): discharge increases with a convex rather than concave shape moving downstream. In these examples, more water from headwater sources remains part of the source composition at the outlet, although less significant than would be expected based on the initial magnitudes of those inputs. Although ~35% of the discharge in Figure 5C was accumulated in the headwaters these sources contribute only ~13% of the stream source composition at the outlet. Bifurcation can have an additional effect on turnover: it can separate local inputs to the stream network, and therefore discharge, into smaller amounts resulting in higher percent losses in each reach (Figure 2B).

Watershed structure and stream network geometry can both lead to variability in the evolution of stream source compositions (Figures 5,6). In natural watersheds the specific evolution of source compositions as well as the accumulation of discharge is influenced by the combination of watershed structure and stream network geometry. Discharge accumulation patterns in each watershed studied here (Figure 7) consist of nested convex and concave shapes similar to those exemplified in Figures 5 and 6. However, natural watersheds exhibit more intricate patterns reflective of the more complex shapes of these real watersheds. These nested convexities and concavities

(Figure 7) mirror the nested patterns in the distributions of local inputs (Figure 8, black lines) along each stream network. Convexities at any scale suggest increasing accumulation of area moving downstream, a trend which is indicative of either more convergent hillslopes or a higher density of stream reaches at those network distances.

Source compositions in each of these watersheds evolve with distinct patterns that are complex combinations of the simpler ones exhibited by synthetic examples (Figures 5,6). Steeper slopes between color bands at a given network distance represent higher losses and therefore higher hydrologic turnover. Synthetic watersheds (Figures 5, 6) exhibit either progressive trends (Figures 5A, 6A-B) or distinct breaks (Figures 5B, 6C-D) in hydrologic turnover moving from upstream to downstream. These general trends are evident in natural watersheds, as well, but with specific patterns influenced by the watershed structure and network geometry of the watershed.

Source compositions at the outlet of each watershed (gray bars, Figure 8) are in part a reflection of the magnitudes of the inputs along the network. The degree is a function additionally of distance travelled. Inputs are modified by spatially variable hydrologic turnover at each reach. Therefore, inputs that have travelled through more reaches are increasingly diminished relative to the corresponding distribution of LI (black lines, Figure 8). As one moves further upstream from the outlet, the distributions of LI remain similar to those of source composition. However, the relative magnitudes of the two distributions become increasingly decoupled with large but distant inputs such as those in Alturas and Stanley (Figure 8D,F) noticeably diminished relative to other, more proximal inputs. This decoupling indicates that more proximal sources are relatively

magnified in their contribution to source compositions at the outlet, where small local inputs correspond to disproportionately larger contributions to source composition as exemplified near the outlets of Yellowbelly and Pettit (Figure 8C,E). All of the watersheds' source compositions at the outlet and throughout the network are unique reflections of the combination of watershed structure and stream network geometry under the influence of hydrologic turnover at the network scale.

Despite the noticeable differences in the patterns and evolution of source compositions and their relationship to the unique morphologies of each watershed, it is important to note similarities in these patterns amongst watersheds. Each watershed exhibits a power law decline based on field observations and the form of Equation 8. Although the shape of the decline varies with the magnitude of each LI, the general shape remains the same. This results in similar weighting of watershed outlet source compositions towards sources closer to watershed outlets (Figures 4B, 5-7). This weighting is illustrated further in the relative magnification of the contribution to outlet source compositions from more proximal locations (Figure 8). Therefore, closer locations can exert an outsized influence on outlet source compositions while more distant inputs are diminished and therefore exert much less influence than the magnitude of the input alone might suggest.

Although these similarities between watersheds can facilitate a general understanding of how stream networks can modify watershed signals, there was no discernable trend in any of these patterns related to simple or aggregated watershed metrics. This lack of trend emphasizes the importance of characterizing the distributed

structure and geometry of the watershed in order to understand how stream source compositions evolve moving through watersheds with variable watershed structures and stream network geometries. We suggest that our modeling approach is a valuable and potentially currently the only method of quantifying watershed signal modification due to hydrologic turnover.

What are the Implications of Stream Network Scale Hydrologic Turnover for Interpreting Watershed Processes in Stream Signals?

In the absence of hydrologic turnover the spatial distribution of local inputs could serve as a surrogate for source compositions and therefore the relative influence that each location has on watershed outlet signals. In this case, stream network locations with highly convergent hillslopes or with a higher density of stream reaches would therefore have a larger influence on watershed outlet source compositions regardless of distance from the outlet. However, hydrologic turnover at the network scale modifies these signals such that the spatial location of a LI also influences its impact on downstream source compositions. Because of longitudinally compounded hydrologic turnover, its influence downstream depends on the magnitude of the input that is weighted by the distance traveled in the stream network. Because of this stream network influence on stream source compositions, it is requisite to understand spatial distributions of hydrologic turnover for interpreting observed stream signals as the convolution of terrestrial watershed processes and complex stream network processes.

The interaction of stream water with groundwater results in the mixing of solutes between hydrologic reservoirs with distinct biogeochemical settings. Therefore, solutes

can behave differently within the stream network than in the groundwater system (Bencala, 1993). Understanding the spatial distribution of hydrologic turnover is valuable in understanding spatial patterns of solute and stream water signatures. Hydrologic turnover can influence the concentrations of nutrients or other solutes that are endogenous to the watershed, but can also exert an attenuating effect on solutes (i.e., pollutants) that are introduced to the watershed. Interaction between GW and SW can act to retain water and associated solutes from the stream and dilute the remaining with endogenous GW. When considering hydrologic turnover and its implications for pollutant transport through a stream network one can consider the TF (Equation 5) as an impact factor. At each stream reach the turnover factor reflects the impact that groundwater exchange exerts on in-stream solute concentrations or signatures. With extension to multiple reaches, it is the serial combination of these impact factors which influences the retention, transport, and concentration of solutes introduced to the watershed from exogenous sources.

To date, our modeling framework has treated GW – SW exchange as occurring between two distinct reservoirs and have not considered how SW lost to GW could return to SW as a gain at a later time or farther location downstream. While this is the most likely scenario it currently remains beyond our ability to measure. Therefore, we have implemented a concise set of equations to highlight the importance of understanding how this basic turnover process propagates through stream networks. Implementing the return of previously lost SW and associated (potentially modified) solutes is a logical next step.

The stream network is positioned between terrestrial biological, chemical, or ecological signals at the watershed scale and their influence on some integrated stream signal at a downstream sampling location. As such, whether inferring terrestrial watershed processes from stream signals or predicting the effect of observed terrestrial processes on stream signals, it is paramount to understand the degree to which each source influences the stream water composition observed at a given spatial location. Our results suggest hydrologic turnover is an important physical process that can exert a strong influence on the evolution of source compositions moving downstream through the stream network. Therefore, in order to interpret stream signals as reflections of watershed terrestrial processes or to predict the effects of terrestrial processes on streams it is critical to characterize the spatial distribution of hydrologic turnover and the resulting source compositions. This becomes imperative in the almost universal situation where the terrestrial processes of interest are distributed heterogeneously across watersheds. Heterogeneous terrestrial processes result in variable stream network loading that is subsequently modified by the stream network in a manner unique to each watershed and stream network. Thus, the stream network can be conceptualized as a filter through which compounded but spatially heterogeneous watershed signals are propagated, resulting in modified downstream signals. We suggest that the deconvolution of these stream signals to understand watershed processes may be intractable in the absence of a characterization of the modifying hydrologic processes (gains and losses from and to groundwater: hydrologic turnover) that occur along stream networks.

Conclusion














We presented a method for understanding how stream networks can modify watershed signals through hydrologic turnover (the simultaneous or sequential gain and loss of stream water from and to groundwater, respectively). We measured hydrologic turnover (gross gains and losses) at the stream reach scale and related these observed hydrologic dynamics to hydrologic (stream discharge, Q) and watershed (local input area, LI) characteristics that could be used to scale from reaches to watersheds. We then simulated hydrologic turnover across seven synthetic (11 – 14 km²) and six natural (11 – 63 km²) watersheds to elucidate how stream network geometry and watershed structure modify source compositions observed across stream networks.

We observed that the contribution to discharge from any one upstream source was initially controlled by the local hillslope size (i.e., the size of the input). However, this contribution diminished as it moved downstream due to compounded hydrologic turnover. The result of this compounded turnover was that stream source compositions were variably weighted towards proximal inputs rather than towards larger inputs. We documented the decoupling of watershed outlet source composition from the distribution of local inputs that progressively increased upstream from the outlet. The evolution of source compositions in each watershed is distinct, illustrating the importance of watershed structure and stream network geometry in controlling specific spatial patterns of evolution of source compositions. Our results suggest that the influence of a given local input on stream signals is dependent on 1) the magnitude of the initial input and 2) the distance it has traveled, with the latter becoming increasingly important as a function

of hydrologic turnover. These results emphasized the role of the stream network in modifying watershed signals from hillslopes.

In summary: 1) hydrologic turnover is the result of variable gains and losses across stream networks; 2) hydrologic turnover varies spatially due to heterogeneous local inputs throughout the network, which are organized by both watershed structure and stream network geometry; 3) network-scale turnover cannot be characterized by a single, aggregated watershed metric, but rather we must use a distributed method that accounts for internal watershed organization; 4) distributed modeling of hydrologic turnover reveals the variability in source compositions that can result from distinct watershed structures and network geometries. Because the stream network can act as a filter to modify watershed signals, understanding network-scale hydrologic turnover is important for either predicting how watershed signals are manifested in their stream networks or for interpreting stream signals as convolutions of stream and watershed processes.

Table 1. Basic watershed characteristics for all six natural and all seven synthetic watersheds analyzed in this study including Horton's (1932) form factor. $Q_{1/2}$ is the proportion of the overall stream network closest to the outlet that contributes $\frac{1}{2}$ of overall discharge at the outlet.

Watershed	Map	Main stem length (km)	Watershed Area (km ²)	Horton's Form Factor (Area/Length ²)	$Q_{1/2}$
Bull Trout		6.4	11	0.27	0.30
Hellroaring		5.2	15	0.55	0.20
Pettit		8.3	23	0.33	0.24
Yellowbelly		10.3	27	0.25	0.24
Stanley		8.6	33	0.45	0.27
Alturas		10.3	63	0.59	0.21
One bifurcation		14	15	0.08	0.20
Two bifurcations		11	15	0.12	0.30
Three bifurcations		7	15	0.31	0.42
Binary - high to low		14	11	0.06	0.22
Binary - low to high		14	11	0.06	0.15
Gamma - high to low		14	11	0.06	0.27
Gamma - low to high		14	11	0.06	0.07

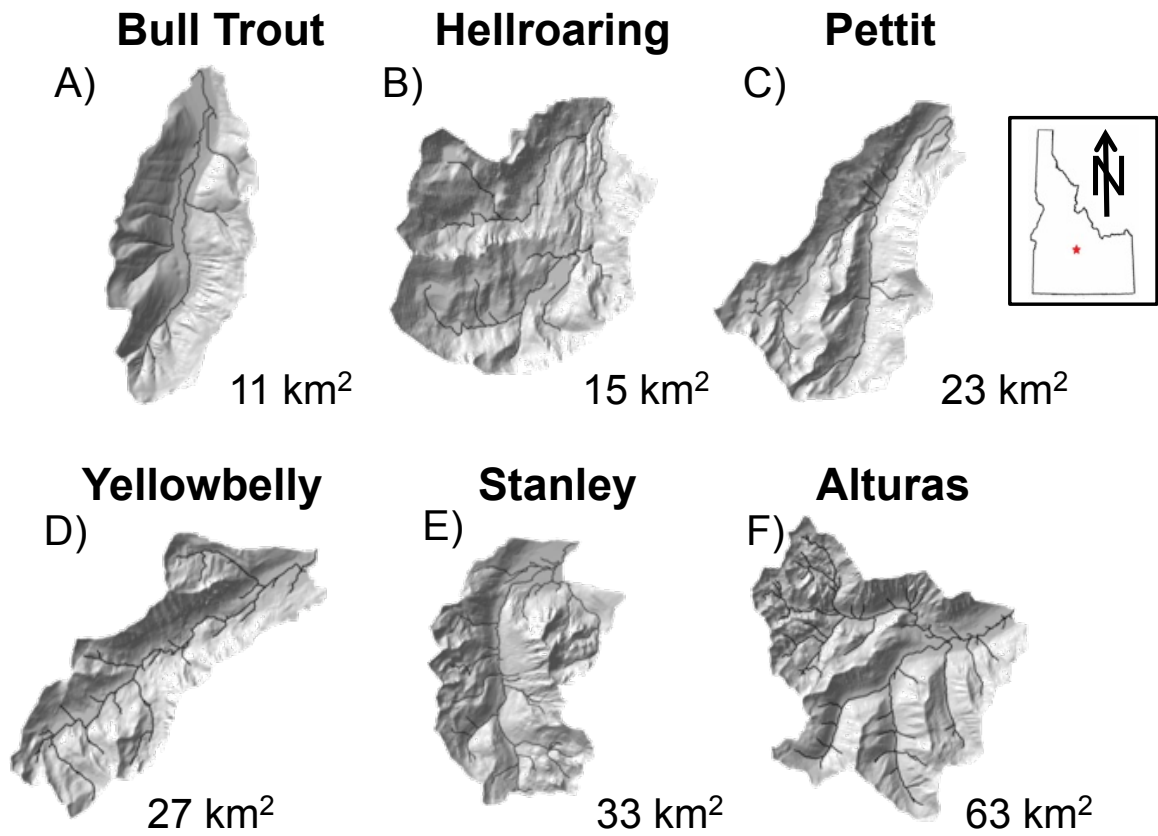


Figure 1. (A-F) Detailed hillshade, stream network, and area six watersheds considered in this study. Watersheds are arranged in order of increasing watershed size. Stream networks were delineated based on watershed DEMs using an area accumulation threshold of 20 ha for channel initiation. (Inset) Location of the six watersheds within the Sawtooth Mountains of central Idaho.

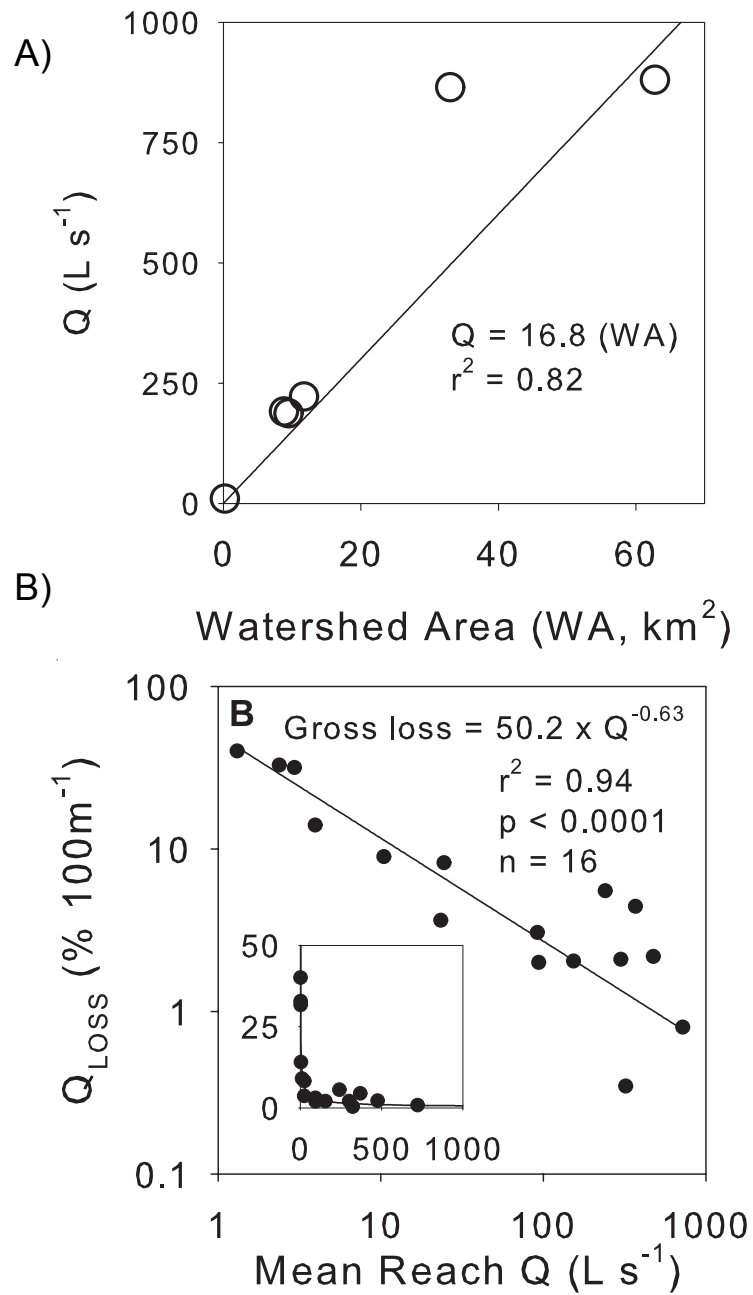


Figure 2. Empirical relationships between (A) watershed area and discharge across all six watersheds with linear regression; and (B) discharge and % loss of discharge per 100 m of channel length with negative power law regression (modified from Covino et al., 2011).

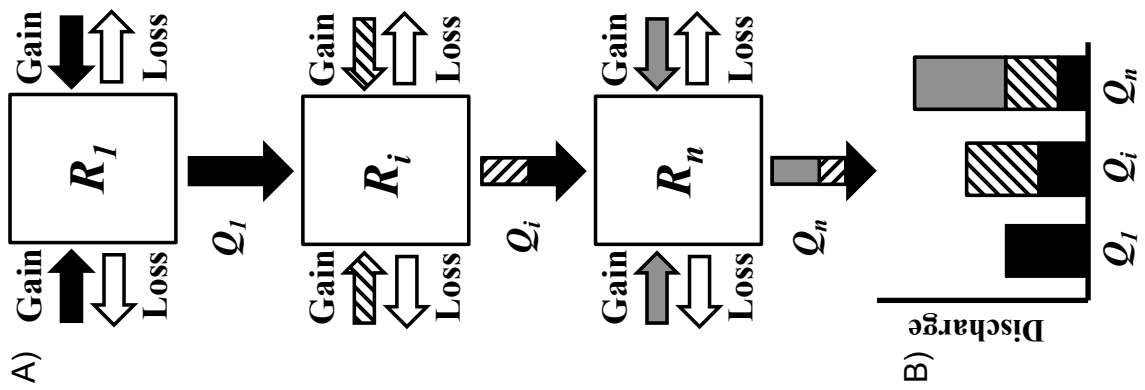


Figure 3. (A) Conceptual model of simultaneous gross gains and losses, hydrologic turnover and shifting source compositions of discharge output from each reach. (B) Discharge output from each reach with height of overall and individual bars corresponding to total discharge and discharge contribution from each specific reach, respectively.

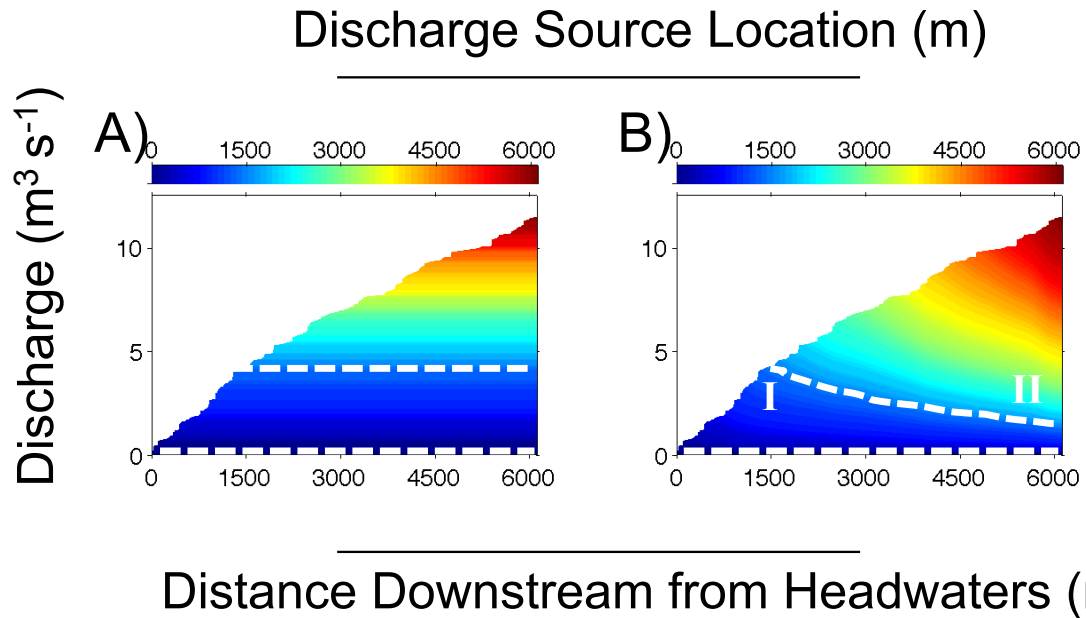


Figure 4. Overall discharge magnitude and source composition moving downstream in Bull Trout watershed with (A) no turnover and (B) showing the effects of hydrologic turnover. The overall height of the trend at any distance corresponds to the total discharge at that distance downstream from the headwaters. The vertical thickness of each color band represents the magnitude of the contribution to total discharge from the corresponding distance on the color bar at the top of each plot as it evolves through the stream network. Note the pinching of the blue color band (water from headwater locations) moving from (I) to (II) as indicated by the dotted line in (B) contrasted to the lack of pinching in (A). This narrowing is indicative of the effects of hydrologic turnover in (B) that is absent in (A).

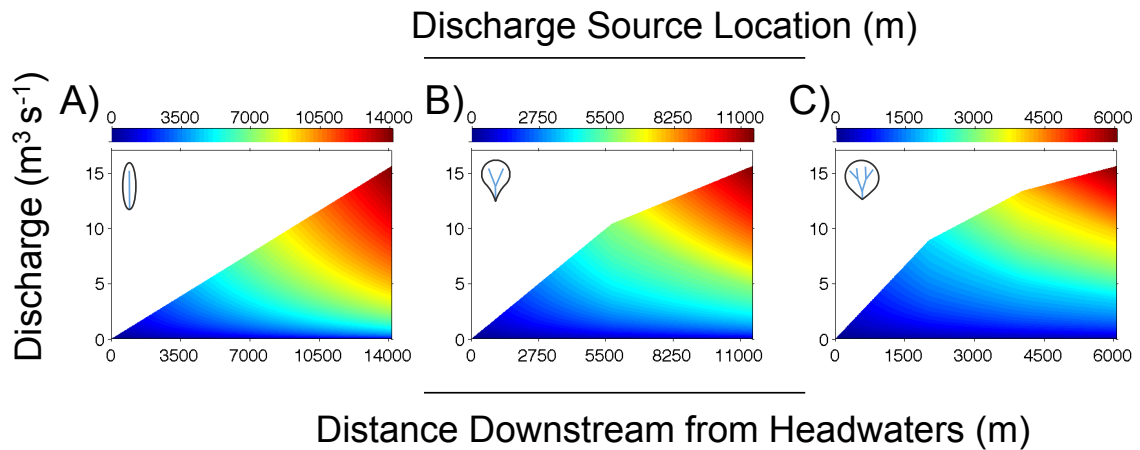


Figure 5. Overall discharge magnitude and shifting source compositions moving downstream in three synthetic watersheds with (A) no, (B) one, and (C) two levels of bifurcation. The overall height of the trend at any distance corresponds to the total discharge at that distance downstream from the headwaters. The vertical thickness of each color band represents the magnitude of the contribution to total discharge from the corresponding distance on the color bar at the top of each plot as it evolves through the stream network.

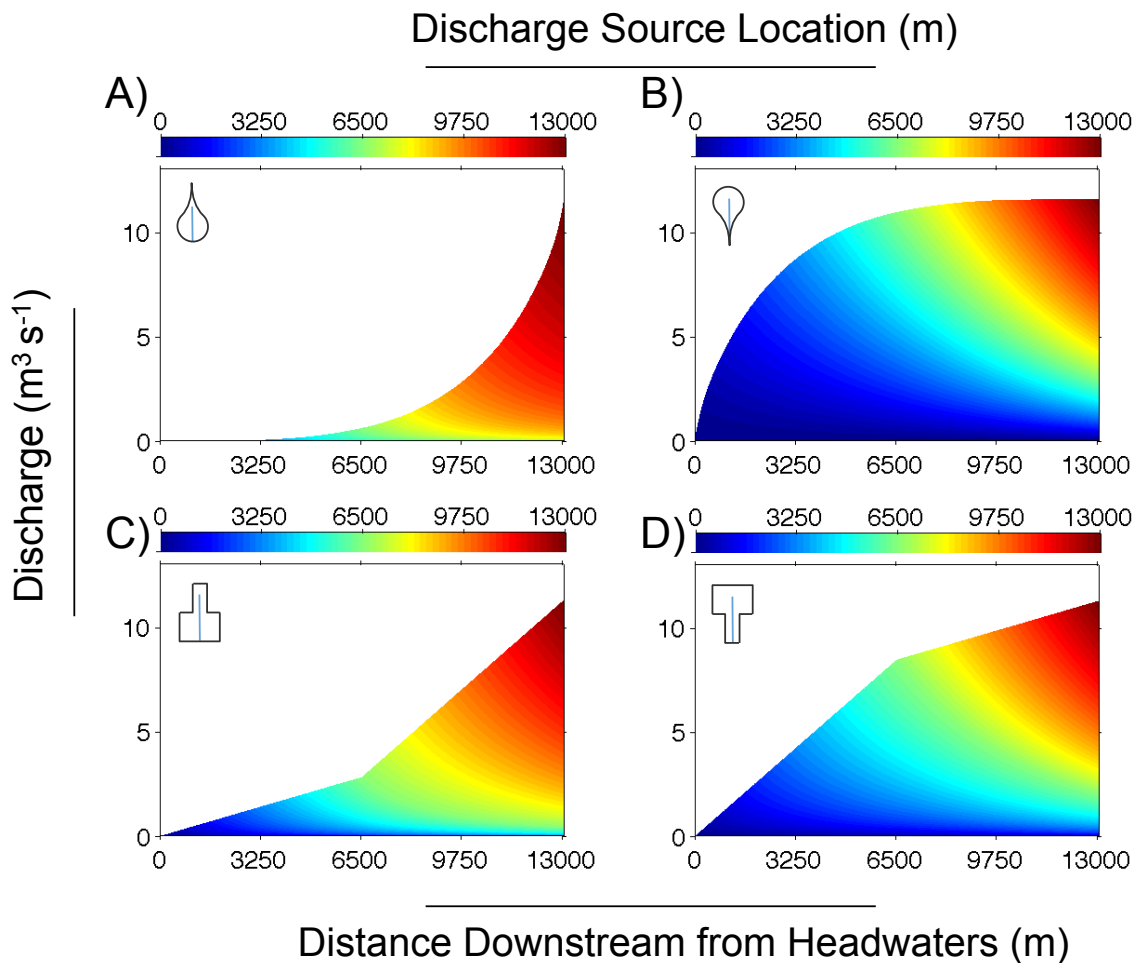


Figure 6. Overall discharge magnitude and shifting source compositions moving downstream in four synthetic watersheds with varying distributions of local inputs to stream networks. The overall height of the trend at any distance corresponds to the total discharge at that distance downstream from the headwaters. The vertical thickness of each color band represents the magnitude of the contribution to total discharge from the corresponding distance on the color bar at the top of each plot as it evolves through the stream network. Local inputs are distributed using either a gamma distribution fit to actual Sawtooth Mountain local input distributions (A and B) or a binary distribution (C and D). Distributions are sorted either from small inputs in the headwaters to large inputs towards the outlet (A and C) or the reverse (B and D).

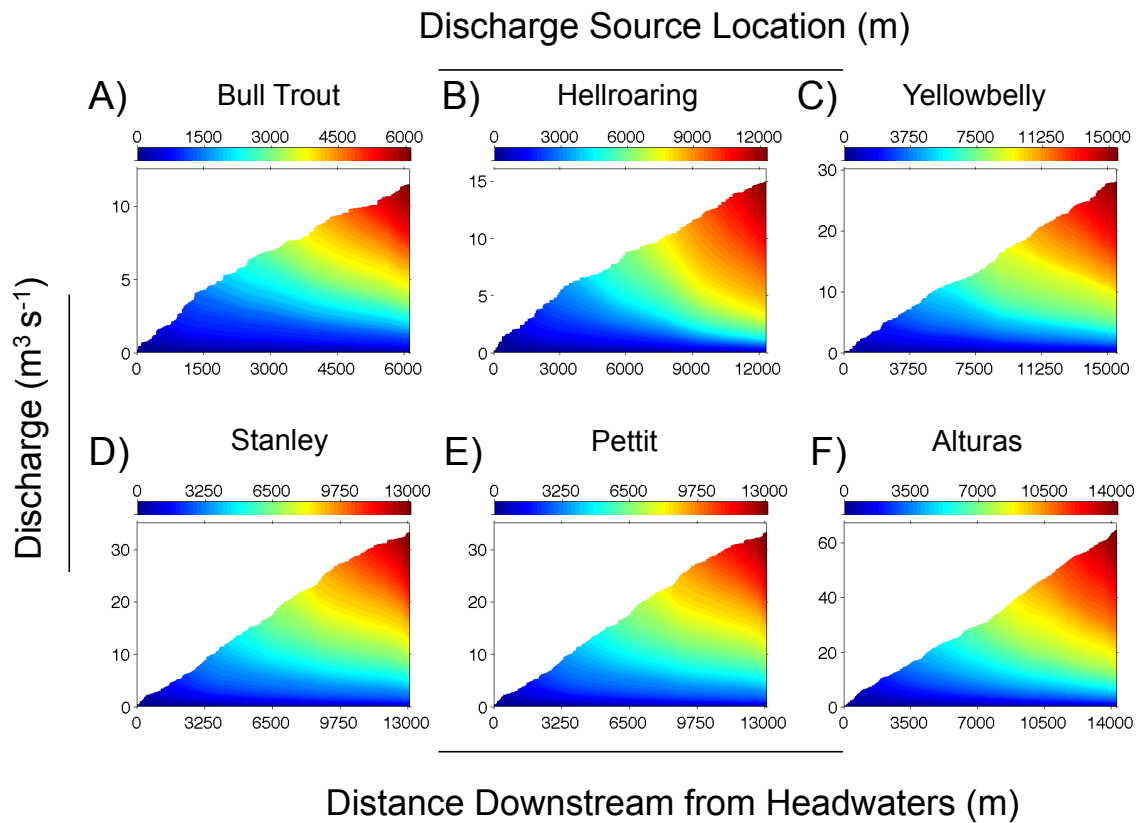


Figure 7. Overall discharge magnitude and shifting source compositions moving downstream through each of the six watersheds. The overall height of the trend at any distance corresponds to the total discharge at that distance downstream from the headwaters. The vertical thickness of each color band represents the magnitude of the contribution to total discharge from the corresponding distance on the color bar at the top of each plot as it evolves through the stream network. Watersheds are arranged from the smallest (A) to largest (F) watershed areas.

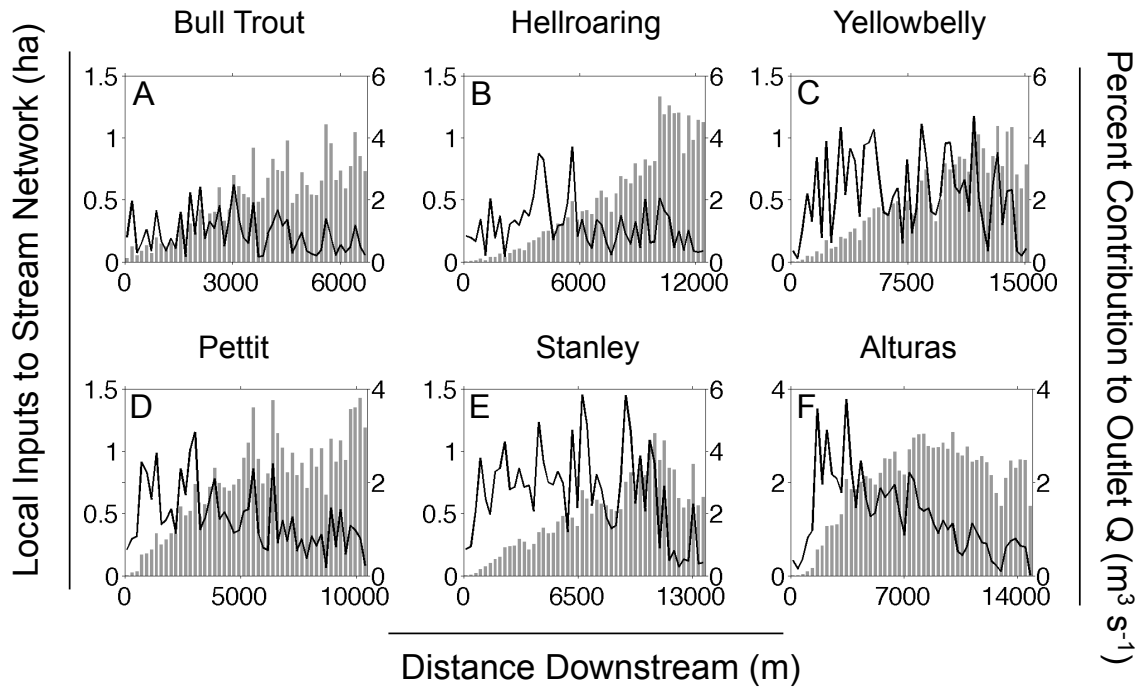


Figure 8. Distribution of local inputs with distance downstream from headwaters for each watershed (black lines) with headwaters at zero and outlet at far right of each plot. Overlain on distribution of percent contribution to discharge at outlet from each network distance (gray bars). Magnitudes of both bars and lines are summed magnitudes across all network positions that share the same distance class.

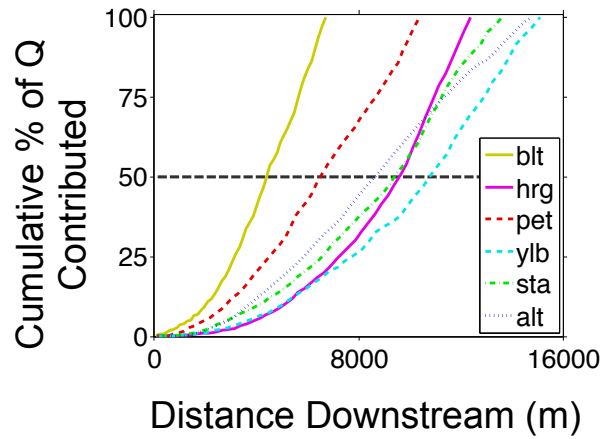


Figure 9. Cumulative spatial distributions of percent contribution to discharge at the watershed outlet moving downstream through each stream network. The distance where the dashed line (50% of discharge) intersects each function divides the upstream and downstream portions of the watershed that each contribute half of discharge at the outlet.

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CHAPTER 3 - SUMMARY

Summary

In this thesis research we sought to examine and illustrate the influence of simultaneous stream gains from and losses to groundwater (hydrologic turnover) at the stream network scale on the evolution of stream source water composition across six natural and seven synthetic watersheds. Additionally we elucidated the potential for stream networks to modify rather than simply transmit watershed signals. We found that hydrologic turnover exerts a strong influence on stream source compositions by diminishing the contributions of local inputs (LI) to the stream network the farther they move downstream through the stream network. The evolution of stream source composition in each watershed exhibited unique patterns of discharge accumulation and hydrologic turnover that were reflections of each watershed's structure and stream network geometry. We concluded that in order to understand how a stream network can modify watershed signals it is requisite to characterize the spatial distribution of hydrologic turnover in that watershed, which is a function of the distributed watershed structure and stream network geometry.

We measured gross stream gains from and losses to groundwater at the stream reach scale using stream tracer experiments across a range of watershed positions and flow states. We determined two empirical relationships from these measurements and simple, distributed terrain analysis: between 1) discharge, Q , and watershed area and 2) percent loss of Q and Q . These experimentally determined empirical relationships

allowed us to extend our hydrologic observations from the reach scale to the watershed scale.

We then used a concise, network-scale model to simulate hydrologic turnover across seven synthetic and six natural watersheds. We observed that the contribution to discharge from any one upstream source was initially controlled by the local hillslope size (i.e., the size of the input). However, this contribution diminished as it moved downstream due to compounded hydrologic turnover. The result of this compounded turnover was that stream source compositions were weighted towards proximal inputs rather than towards larger inputs. The evolution of source compositions in each watershed was distinct, illustrating the importance of watershed structure and stream network geometry in controlling specific spatial patterns of evolution of source compositions. Our results suggest that the influence of a given local input on stream signals is dependent on 1) the magnitude of the initial input and 2) the distance it has traveled, with the latter becoming increasingly important as a function of hydrologic turnover. These results emphasize the role of the stream network in modifying watershed biogeochemical or ecological signals.

The stream water – groundwater exchange induced by hydrologic turnover has important implications for stream biogeochemistry due to mixing between reservoirs with potentially different biogeochemical settings. This mixing could strongly influence the in-stream concentrations of endogenous solutes or attenuate that of exogenous pollutants. Therefore, understanding the organization and magnitudes of these exchange processes is required for interpreting or predicting stream network biogeochemical signals.

Understanding the degree to which each local input influences stream composition as they propagate downstream is vital for interpreting these signals as reflections of terrestrial processes or for predicting the influence that observed terrestrial processes will have on stream signatures. This connection between spatial watershed locations and stream signals becomes even more important to elucidate in the near-universal situation where these processes are spatially heterogeneous and therefore loading to the stream network is spatially variable. Without an understanding of how unique watersheds can modify watershed signals it may be intractable to interpret stream signals as the convolution of spatially variable watershed processes.

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