SCIENTIFIC BRIEFING

HP TODAY

HYDROLOGICAL PROCESSES
Hydrol. Process. **28**, 5791–5803 (2014)
Published online 30 September 2014 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/hyp.10310

Dynamic, discontinuous stream networks: hydrologically driven variations in active drainage density, flowing channels and stream order

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Received 9 January 2014
Accepted 5 August 2014

Abstract

Despite decades of research on the ecological consequences of stream network expansion, contraction and fragmentation, surprisingly little is known about the hydrological mechanisms that shape these processes. Here, we present field surveys of the active drainage networks of four California headwater streams (4–27 km^2) spanning diverse topographic, geologic and climatic settings. We show that these stream networks dynamically expand, contract, disconnect and reconnect across all the sites we studied. Stream networks at all four sites contract and disconnect during seasonal flow recessions, with their total active network length, and thus their active drainage densities, decreasing by factors of two to three across the range of flows captured in our field surveys. The total flowing lengths of the active stream networks are approximate power-law functions of unit discharge, with scaling exponents averaging 0.27 ± 0.04 (range: 0.18–0.40). The number of points where surface flow originates obey similar power-law relationships, as do the lengths and origination points of flowing networks that are continuously connected to the outlet, with scaling exponents averaging 0.36–0.48. Even stream order shifts seasonally by up to two Strahler orders in our study catchments. Broadly, similar stream length scaling has been observed in catchments spanning widely varying geologic, topographic and climatic settings and spanning more than two orders of magnitude in size, suggesting that network extension/contraction is a general phenomenon that may have a general explanation. Points of emergence or disappearance of surface flow represent the balance between subsurface transmissivity in the hyporheic zone and the delivery of water from upstream. Thus the dynamics of stream network expansion and contraction, and connection and disconnection, may offer important clues to the spatial structure of the hyporheic zone, and to patterns and processes of runoff generation. Copyright © 2014 John Wiley & Sons, Ltd.

Key words drainage density; stream network; stream order; channel head; subsurface flow; catchment hydrology; headwater basins

Introduction

Anyone who spends sufficient time in a headwater catchment will observe that channel networks are rarely fixed features of the landscape. Instead, the actively flowing stream network extends and retracts as the catchment wets and dries, both seasonally and in response to individual precipitation events. The flowing stream network may also dynamically disconnect, as individual stream segments go dry. The dynamic character of stream channels is widely depicted on maps, with different lines used to represent permanent streams and their intermittent or ephemeral tributaries.

Despite the near ubiquity of this phenomenon, it has received surprisingly little attention from either hydrologists or geomorphologists. In the 1960s and 1970s, several observational studies documented the extension and retraction of flowing stream networks in response to individual storm events (Gregory and Walling, 1968; Tischendorf, 1969; Hewlett and Nutter, 1970; Morgan, 1972; Roberts and Klingeman, 1972; Blyth and Rodda, 1973; Anderson and Burt, 1978; Day, 1978; Roberts and Archibold, 1978; Gregory and Gardiner, 1979). Much of this work was motivated by the conjecture that drainage density should be a first-order control on hydrological response to precipitation (Carlston, 1963), because it determines the average travel distance for subsurface flow to reach the nearest channel (Dingman, 1978). When it became clear that drainage density was not, in fact, strongly correlated with measures of hydrological response (Dingman, 1978), this early work was largely abandoned. More recently, studies of stream and river network dynamics have been limited to observations of the seasonal drainage network expansion in an agricultural landscape (Wigington *et al.*, 2005), the peatland work of Goulsbra *et al.* (2014), and studies linking hydroecological responses in a dynamic section of a glacial outflow river (Ward *et al.*, 2001; Malard *et al.*, 2006; Doering *et al.*, 2007).

In our view, the virtual abandonment of this subject may have been premature. In 1973, Blyth and Rodda asked, 'Why has it largely been ignored that natural drainage networks are dynamic rather than static phenomena? What are the controls of the length of flowing channel?' Forty years later, these questions are equally germane. The original emphasis on drainage density as a control on hydrological response may have been misplaced, but nonetheless 'a stream is a dynamic expression of local groundwater conditions' (Bencala *et al.*, 2011), so the transient extension and retraction of the flowing stream network must reflect the local groundwater dynamics in the surrounding headwater basins. Thus, the dynamic extension/retraction and connection/disconnection of flowing stream networks are the visible expression of landscape-scale subsurface processes that would otherwise remain hidden. Therefore, the dynamic behaviour of the flowing network is likely to be scientifically informative, as a reflection of hydrological processes rather than a predictor of them.

By the flowing stream network, we mean the (possibly discontinuous) network of directed flow that is visible at the surface at any moment in time. This 'active drainage network' is distinct from the geomorphic channel network, the branching network of topographic features that are diagnostic of erosion and deposition by channelized flows of water. Depending on hydrological conditions, the active drainage network may occupy only part of – or potentially extend beyond – the geomorphic channel network.

Here, we do not address the geomorphological question of why the drainage density of the geomorphic channel network varies from place to place, or how it evolves over time. Instead, we ask the hydrological question of how the drainage density of the actively flowing network varies on seasonal and event time scales. The geomorphic channel network is a relatively persistent feature of the landscape on seasonal and event time scales, and much has been written about how it evolves in response to erosion thresholds and climate forcing (e.g. Montgomery and Dietrich, 1992; Rinaldo *et al.*, 1998; Tucker and Hancock, 2010; Rinaldo *et al.*, 2014). By contrast, the active drainage network and its temporal dynamics have received relatively little attention. This lack of scientific attention is particularly surprising in view of the ecological and biogeochemical significance of stream network dynamics in headwater catchments (Wharton, 1994; Stanley *et al.*, 1997; Peterson *et al.*, 2001; Fagan, 2002; Fisher *et al.*, 2004; Wigington *et al.*, 2005, 2006; Meyer *et al.*, 2007; Larned *et al.*, 2010; Zimmer *et al.*, 2013).

These stream network dynamics have important policy implications, with courts in multiple countries reviewing their definitions of 'stream' and 'river' (e.g. Hughes, 2005; Doyle and Bernhardt, 2011; Taylor *et al.*, 2011). In response to a recent US Supreme Court decision, Leibowitz *et al.* (2008) proposed several metrics of network connectivity, including the maximum duration of continuous flow in either the surface or hyporheic zone. Others have proposed analogous metrics (see review by Wharton, 1994). Many of these metrics have focused on arid and semi-arid riverscapes, with little attention paid to different hydroclimatic regimes (for an exception, see Buttle *et al.*, 2012).

Here, we present field data documenting the seasonal extension/retraction and disconnection/reconnection of active drainage networks in four mountainous headwater basins. These data show that drainage density and even stream order vary substantially in response to seasonal wetting and drying. We discuss potential controls on these seasonal changes in network configuration, and their implications for hydrologic responses to changes in climatic regimes.

Methods and site descriptions

Using on-the-ground field observations, we mapped the flowing stream network at four sites in California, representing a range of climatic, topographic and geologic conditions. Sagehen Creek is located in the northern Sierra Nevada mountains, just east of the Sierra crest. Providence and Duff Creeks (jointly referred to as Providence/Duff Creeks in this paper) and Bull Creek are collectively part of the Kings River Experimental Watershed and the Southern Sierra Critical Zone Observatory and comprise seven subcatchments in the southern Sierra Nevada mountains. All of the Sierra Nevada sites are snow dominated whereas our fourth site, Caspar Creek, is located in the rain-dominated Northern California Coast Range. All four sites have Mediterranean climates with wet winters and dry summers and are characterized by well-drained loamy soils. However, the four sites vary widely in the fraction of annual precipitation accounted for by snow (ranging from almost zero at Caspar Creek to over 80% at Sagehen Creek), as well as in their annual water yields (ranging from 33% to 66% of annual precipitation). Likewise, their dominant bedrock lithologies range from andesites and breccias at Sagehen Creek to weathered sandstone at Caspar Creek and granodiorite and granites at Providence/Duff and Bull Creeks. Further information about each site is summarized in Table I.

We mapped the flowing stream network at each site during field campaigns in Fall 2006, Spring and Fall 2007 and Spring 2008, walking the entire length of the geomorphic channel network each time. Based on Hansen's (2001) definitions, we focused on perennial and intermittent flow; some flowpaths observed during the snowmelt season may have weakly expressed channels and fall somewhere on the continuum between intermittent and ephemeral flow. To prevent pseudo-replication of seasonal channel dynamics, we avoided multiple sampling campaigns within the same season. We recorded each location at which surface flow disappeared or reappeared using a GPS receiver with typical accuracy of 10 m or better. We always kept the channel to our left to avoid inadvertently missing tributaries and completed each field survey within ~3–7 days to ensure that flows remained as steady as possible during the observation period. Depending on the field site and season, each field survey required ~10–60 km of overland travel on foot, often in difficult conditions. Flowing segments shorter than 10 m were not mapped; likewise gaps shorter than 10 m separating flowing segments were not mapped. For the spring surveys, snow occasionally persisted at the highest sites. When flow lines were visible on the surface or flow could be heard beneath the snow, flow was assumed to be continuous beneath the snow surface. The active drainage network may have been underestimated during the Fall 2006 surveys, due to difficulties in following faint traces of the geomorphic channel network when flow was absent.

We drew maps of the active drainage network by tracing flowing stream segments between the measured GPS points, following the geomorphic channel network (Figures 1a–4a). We determined the length of the total active drainage network by summing the lengths of these stream segments for each observation period and site. In

Table I. Site characteristics and observed scaling relationships

	Sagehen Creek	Providence/Duff	Bull Creek	Caspar Creek
Latitude/longitude	39.43 N, 120.24 W	37.06 N, 119.21 W	36.97 N, 119.06 W	39.34 N, 123.73 W
Drainage area (km^2)	27.2	4.01	3.58	8.48
Altitude range (m)	1930–2630	1500–2100	2145–2560	40–320
Dominant lithology	Andesites and breccias	Granodiorite and granite	Granodiorite and granite	Weathered sandstone
Mean precipitation (mm/yr)	1215	1000	1000	1200
Mean runoff (mm/yr)	398	347	656	645
Discharge record (years)	1954–2011	2004–2009	2004–2008	1963–2004
Discharge range (mm/d)	0.090–72	0.052–29	0.056–30	0.017–110
Number of network surveys	4	4	4	3
Discharge during surveys (mm/d)	0.1460–1.76	0.066–1.3	0.063–4.08	0.050–0.442
Flowing network length				
(km, min-max)	15.4–35.2	2.43–7.81	6.75–14	4.26–8.36
Dd (km/km^2, min-max)	0.565–1.294	0.605–1.947	1.883–3.909	0.502–0.985
Beta	0.312 ± 0.093(.)	0.401 ± 0.061(*)	0.182 ± 0.022(*)	0.310 ± 0.050(.)
Connected flowing network length				
(km, min-max)	12.4–32.5	0.822–6.15	4.58–14	1.29–5.37
Dd (km/km^2, min-max)	0.455–1.195	0.204–1.534	1.277–3.909	0.152–0.633
Beta	0.363 ± 0.115(.)	0.686 ± 0.195(.)	0.268 ± 0.010(**)	0.558 ± 0.241(n.s.)
Number of flowing sources				
(number, min-max)	9–42	9–31	9–27	16–39
(number/km^2)	0.331–1.544	2.244–7.731	2.512–7.536	1.887–4.599
Beta	0.561 ± 0.118(.)	0.425 ± 0.089(*)	0.235 ± 0.095(n.s.)	0.411 ± 0.064(.)
Number of connected flowing sources				
(number, min-max)	7–39	5–24	6–27	8–26
(number/km^2, min-max)	0.258–1.434	1.247–5.985	1.675–7.536	0.943–3.066
Beta	0.624 ± 0.212(.)	0.538 ± 0.084(*)	0.375 ± 0.071(*)	0.566 ± 0.054(.)

Dd = drainage density; Beta = scaling exponent with discharge. Scaling exponents reported as least squares estimates ± standard errors. Statistical significance is indicated for scaling exponents as follows: (.) = 0.1, (*) = 0.05, (**) = 0.01, (n.s.) = not significant at the $\alpha = 0.1$ level.

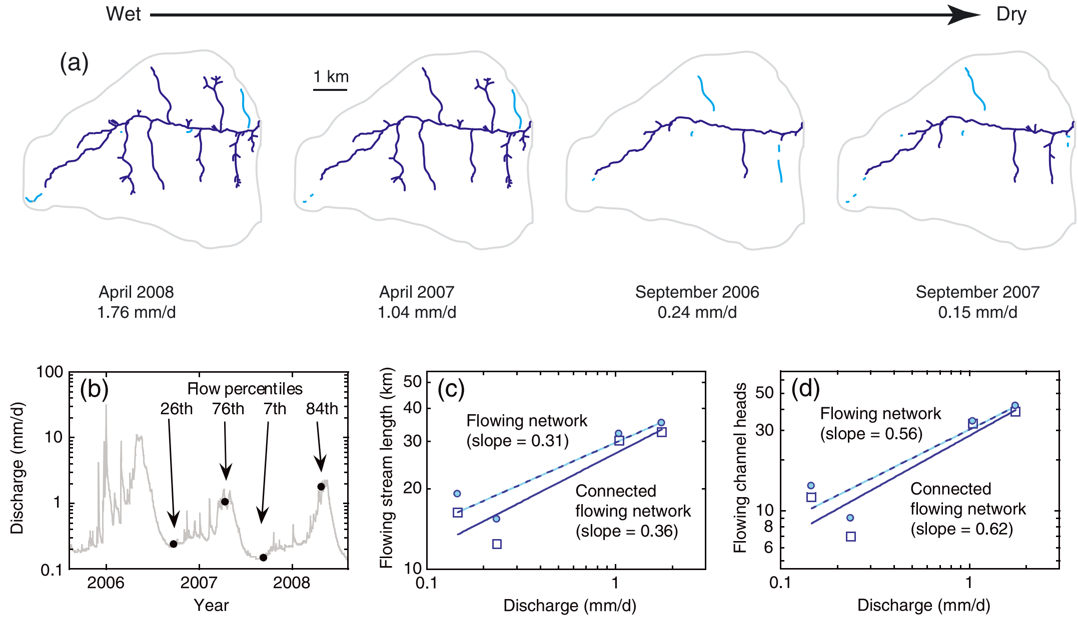

Figure 1. (a) Maps of the active drainage network at Sagehen Creek during four observation periods, ordered from high to low flow, with discharge at the outlet shown in mm per day. The active drainage network that is connected to the outlet is shown in dark blue, whereas channel segments that are actively flowing, but disconnected from the outlet, are shown in light blue. The watershed boundary is shown in grey. Note that maps are sorted in order of decreasing flow and not as a time sequence. (b) 5-day running mean hydrograph for water years 2005–2008. Observation periods are marked with black dots, with corresponding percentiles of the discharge distribution over the 57-year record (1954–2011) at Sagehen Creek. Mapped networks span the seventh to the 84th percentiles of the flow distribution. However, the mapped flows span only a factor of 12, whereas the flows on record span a factor of 800, suggesting that the active drainage network may have an even larger dynamic range than shown here. (c) Active drainage network length (circles) and connected drainage network length (squares) as functions of stream flow. (d) Number of flowing channel heads (circles) and connected channel heads (squares) in the drainage network, as functions of stream flow

addition, we determined the length of the connected drainage network by summing the lengths of all stream segments whose flow reaches the gauging station without crossing any mapped gaps. We tallied the number of flowing channel heads, defined as the farthest upstream points of surface flow along each tributary; points where surface flow resumed below gaps were not included in this tally. For sites that encompass multiple catchments (i.e. all sites except Sagehen), we summed the active drainage network lengths and numbers of channel heads across the catchments to obtain the site totals.

We compared the flowing network lengths and number of flowing channel heads to the 5-day average stream discharge measured at gauging stations at the catchment outlets. For sites that encompass multiple catchments, we summed the discharges across all catchments and divided by the combined drainage area to obtain an average water yield in mm/day. We used the 5-day average stream discharge because mapping the active drainage networks at each site usually required 3 to 7 days, due to the distances involved (Table I).

Results and discussion

At all four of our study sites, the flowing stream networks dynamically expanded and contracted in response to seasonal shifts in hydrologic conditions (Figures 1a–4a). For example, Figure 1a shows how the mainstem of Sagehen Creek contracted downstream (from the western end of the catchment towards the east), and the tributaries entering from the north and south shortened or disappeared entirely, as streamflow declined in response to seasonal drying. In April 2008, during the highest of the mapped flows, the network of Sagehen Creek encompassed roughly 35 km of flowing stream channels, compared with only 15 km of flowing channels in September 2006. Between these two mapping dates, the length of the active drainage network varied by more than twofold, as discharge measured at the gauging station varied by roughly sevenfold (Figure 1c). Similar dynamic network extension and retraction was observed at the other three study sites (Figures 2c–4c), with flowing network length varying by factors of two to three.

Active drainage networks at the four study sites were not only shorter during low-flow conditions, but also markedly less branched, with fewer flowing channel heads. At Sagehen Creek, for example, the number of flowing channel heads varied by nearly a factor of five, ranging from 42 in April 2008, during the highest of the mapped flows, to only nine in September 2006, when the flow was a factor of seven lower (Figure 1a and d). Similar dynamics in network complexity were observed

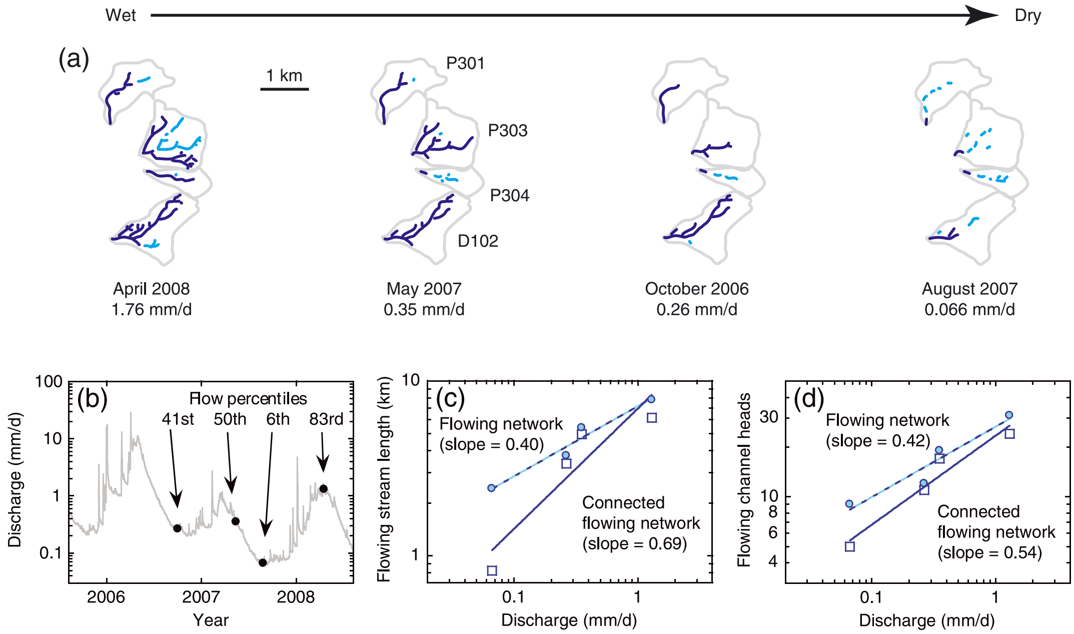

Figure 2. (a) Maps of active drainage networks at Providence/Duff Creeks during four observation periods, ordered from high to low flow, with combined discharge at the four outlets shown in mm per day. The active drainage network that is connected to each gauging station is shown in dark blue, whereas channel segments that are actively flowing but disconnected from the outlet are shown in light blue. Watershed boundaries are shown in grey. Note that maps are sorted in order of decreasing flow and not as a time sequence. (b) 5-day running mean hydrograph for water years 2006–2008, with the four observation periods marked with black dots. Mapped networks span the seventh to the 83rd percentiles of the flow distribution over the 6-year record (2004–2009) at Providence/Duff Creeks. However, the mapped flows span only a factor of 27, whereas the flows on record span a factor of 560, suggesting that the active drainage network may have an even larger dynamic range than shown here. (c) Active drainage network length (circles) and connected drainage network length (squares) as functions of stream flow. (d) Number of flowing channel heads (circles) and connected channel heads (squares) in the drainage network, as functions of stream flow

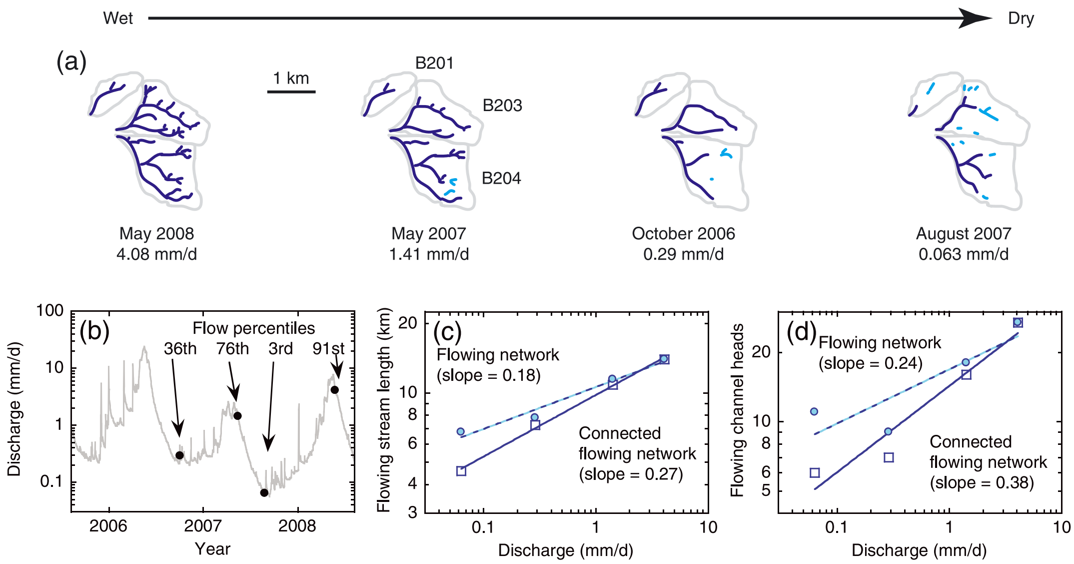

Figure 3. (a) Maps of active drainage networks at Bull Creek during four observation periods, ordered from high to low flow, with combined discharge at the three outlets shown in mm per day. The active drainage network that is connected to each gauging station is shown in dark blue, whereas channel segments that are actively flowing but disconnected from the outlet are shown in light blue. Watershed boundaries are shown in grey. Note that maps are sorted in order of decreasing flow and not as a time sequence. (b) 5-day running mean hydrograph for water years 2006–2008, with the four observation periods marked with black dots. Mapped networks span the third to the 91st percentiles of the flow distribution over the 5-year record (2004–2008) at Bull Creek. However, the mapped flows span only a factor of 65, whereas the flows on record span a factor of 570, suggesting that the active drainage network may have an even larger dynamic range than shown here. (c) Active drainage network length (circles) and connected drainage network length (squares) as functions of stream flow. (d) Number of flowing channel heads (circles) and connected channel heads (squares) in the drainage network, as functions of stream flow

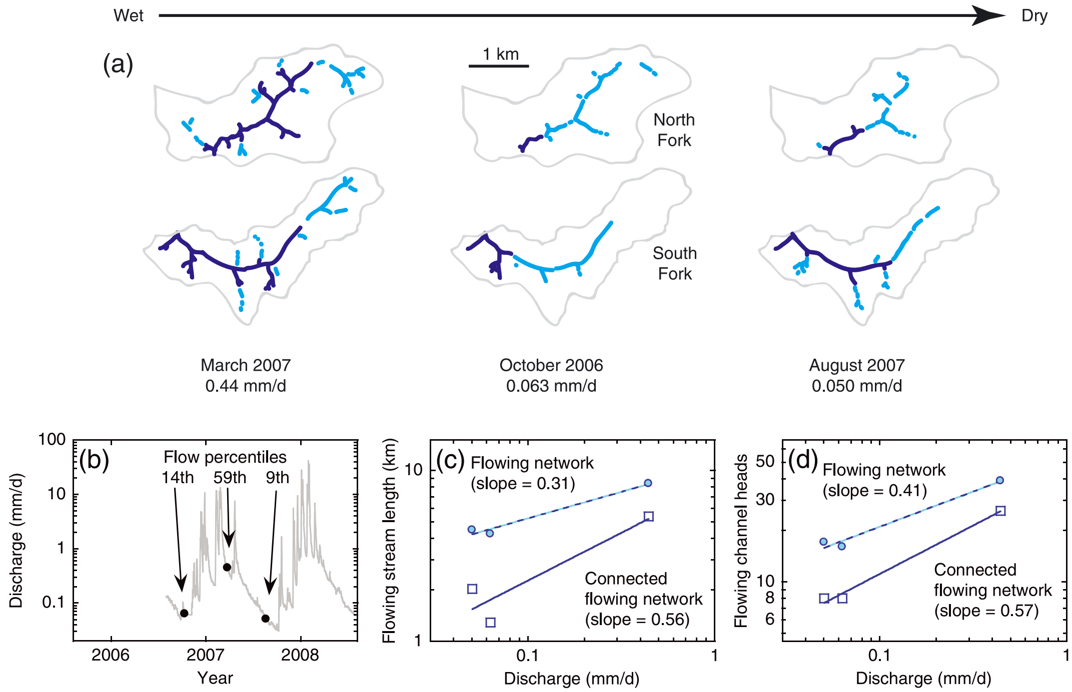

Figure 4. (a) Maps of active drainage networks at Caspar Creek during three observation periods, ordered from high to low flow, with combined discharge at the two outlets shown in mm per day. The active drainage network that is connected to each gauging station is shown in dark blue, whereas channel segments that are actively flowing but disconnected from the outlet are shown in light blue. Watershed boundaries are shown in grey. (b) 5-day running mean hydrograph for water years 2007–2008. Observation periods are marked with black dots. Mapped networks span the ninth to the 59th percentiles of the flow distribution over a 33-year record (1963–1995) at Caspar Creek. However, the mapped flows span only a factor of nine, whereas the flows on record span a factor of 2600, suggesting that the active drainage network may have a much larger dynamic range than shown here. (c) Active drainage network length (circles) and connected drainage network length (squares) as functions of stream flow. (d) Number of flowing channel heads (circles) and connected channel heads (squares) in the drainage network, as functions of stream flow

in the other three study sites (Figures 2d–4d), with the number of flowing channel heads varying by factors of 2.4 to 3.4 between high and low flows at each site.

Variations in network complexity in response to drying were also reflected in changes in the Strahler stream order of the mapped flowing stream networks. As mapped in April 2008, Sagehen Creek was a fourth-order stream, but as mapped in September 2006, it was only a second-order stream. Similarly, across the nine subcatchments shown in Figures 2–4, seasonal drying caused a reduction of two Strahler orders in two streams and one Strahler order in six streams; just one stream kept the same Strahler order throughout the study period. The observed malleability of Strahler stream order is problematic, given its widespread use as a diagnostic descriptor of streams and their drainage basins. Although Strahler orders are typically determined for published maps at a particular scale, our work suggests that the Strahler order is dynamic. Thus, we caution against the assumption that order is a fixed descriptor of a stream network.

Figures 1–4 illustrate not only the dynamic expansion and contraction of the mapped stream networks but also their disconnection and reconnection in response to seasonal wetting and drying. Many stream reaches that remained flowing during dry seasons nonetheless became isolated from the catchment outlet as individual reaches dried up within the mapped networks. This fragmentation of the stream habitat at low flows could have significant ecological consequences (Lake, 2003; Sponseller and Fisher, 2008). Aquatic organisms that rely on in-stream connectivity are affected by the length of the network and its longitudinal and network-wide lateral connections (e.g. Benda *et al.*, 2004; Campbell Grant *et al.*, 2007; Wipfli and Baxter, 2010). Disconnection forms gaps that can account for up to ~40% of the change in surface flow length, but with wide variation from site to site. For example, as seen in Figure 2a, gaps account for ~4% of the change in flowing stream length in the southernmost subcatchment, D102, whereas they account for ~40% of the stream length change in the subcatchment immediately to its north, P304, over a similar range of flow conditions (Figure 2). Both contraction and gap formation can shrink the flowing stream network, with the length of flowing channel that is connected to the downstream network decreasing by up to ~78% during dry periods (e.g. Figure 2a, middle subcatchment P303).

Across all four study sites, the networks of flowing channels that were connected to the outlet (shown in black in Figures 1a–4a) contracted markedly in response to seasonal drying, decreasing in total length by factors of 2.6–7.5, with the number of flowing channel heads decreasing by factors of 3.2–5.6. A comparison of the solid and open symbols in Figures 1c–4c and 1d–4d shows that as catchment wetness (and thus discharge) varied, these connected flowing networks changed by larger proportions, in both length and number of flowing channel heads, than the total flowing networks did. Even tributaries fed by springs, which one might expect to anchor the flowing network to fixed points on the landscape, may not flow continuously to the outlet, as observed in the persistent, but sometimes disconnected, tributary that enters Sagehen Creek from the north (Figure 1a).

All four network measures graphed in Figures 1–4 (flowing network length, connected network length, number of flowing channel heads and number of connected flowing channel heads) vary roughly as power functions of discharge, as shown in panels (c) and (d) of each figure. The individual log–log slopes rarely exhibit strong statistical significance, owing to the small numbers of points available to constrain each scaling exponent (Table I). Although the individual slopes are often only marginally significant, or non-significant, due to the small number of points, when they are pooled by analysis of covariance, they are clearly statistically significant (Figure 5, Table II). Total surface flow lengths scale as a power-law function of runoff with log–log slopes, β, between 0.18 and 0.40 (panel c in Figures 1–4). The power-law exponent β can be straightforwardly interpreted as the percentage change in total active drainage network length, per percentage change in discharge.

Although there are too few points to be sure that each scaling relationship in Figures 1–4 is truly linear in log–log space, clear power-law relationships have been observed in smaller catchments that have been more frequently surveyed (e.g. data of Gregory and Walling, 1968, redrawn in Figure 6). Furthermore, our scaling exponents are broadly consistent with a reanalysis of all published studies for which scaling exponents can be straightforwardly calculated (Table II). These previous studies mostly focused on much smaller catchments, and included several sites with much gentler topography and much weaker precipitation seasonality than ours. The fact that broadly similar scaling is found in catchments with widely varying geologic, topographic and climatic settings, and spanning more than two orders of magnitude in size, suggests that network extension/contraction is a general phenomenon that may have a general explanation.

The connected flowing network length (open symbols in Figures 1c–4c) scales less cleanly as a function of runoff than the total flowing network length does, illustrating the discontinuous effects of gaps in the flowing network. Single discontinuities due to stochastic processes, such as debris flow deposits or sediment collected behind tree falls, can drastically alter the connected stream length, even if these gaps are small and temporary. For example, two such gaps were mapped on the South Fork of Caspar Creek during the October 2006 survey but were not present in the subsequent survey in August 2007 (Figure 4a), leading to a substantial increase in the connected network length despite drier

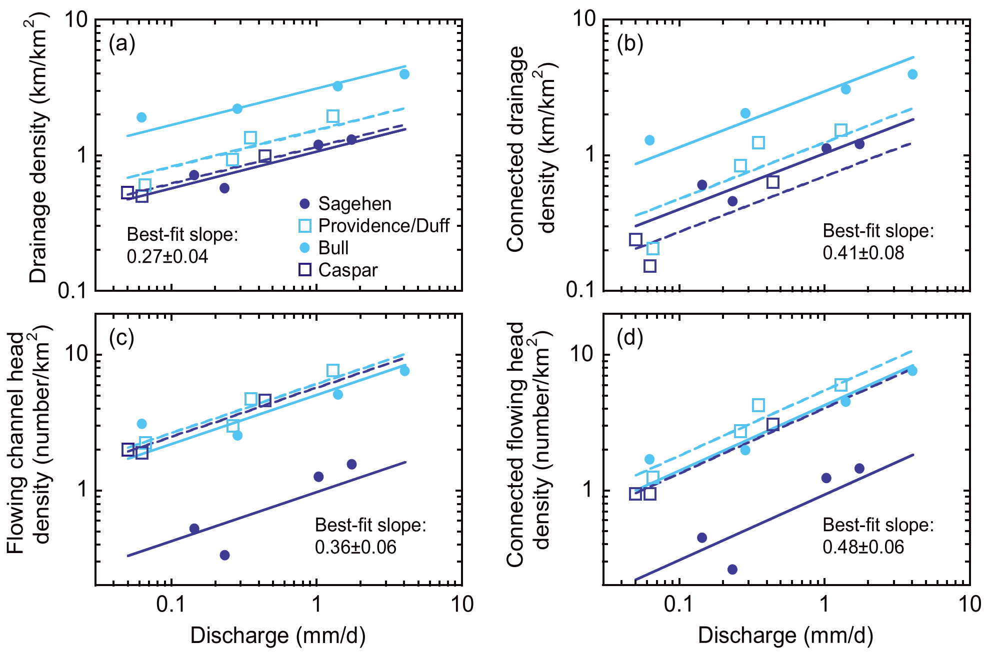

Figure 5. Discharge-dependence of (a) drainage density, (b) connected drainage density, (c) density of flowing channel heads and (d) density of connected flowing channel heads, at all four study sites. Best-fit lines are fitted by least squares, with a single slope for all four sites and an individual elevation for each site (i.e. analysis of covariance). When slopes were fitted individually to each site, their variability was not statistically significant, justifying the fit with one pooled slope for all four sites

Table II. Scaling of active flow network drainage density with discharge: summary of published surveys

Catchment	Area (km^2)	Duration of observations	Number of surveys	Dd range (km/km^2)	Beta ± S.E.	
Gregory and Walling, 1968 (Devon, England)						
A	0.21	1 year	32	0.7–3.6	0.320 ± 0.017	(***)
A	0.21	Summer	8	0.7–1.5	0.430 ± 0.039	(***)
A	0.21	Winter	24	0.7–3.6	0.323 ± 0.021	(***)
B	0.41	1 year	22	1.3–7.9	0.405 ± 0.029	(***)
B	0.41	Summer	6	1.3–5.4	0.502 ± 0.032	(***)
B	0.41	Winter	16	3.0–7.9	0.287 ± 0.013	(***)
Roberts and Klingeman, 1972 (Oak Creek, Oregon, USA)						
1	0.099	2 years	6	0.6–3.7	0.212 ± 0.045	(**)
2	0.005	2 years	6	1.2–10.1	0.538 ± 0.210	(.)
3	0.26	2 years	9	3.1–4.2	0.065 ± 0.009	(***)
4	0.232	2 years	7	1.7–3.6	0.123 ± 0.024	(**)
Blyth and Rodda, 1973 (River Ray at Grendon Underwood, Buckinghamshire, England)						
	18.56	1 year	35	0.55–2.76	0.200 ± 0.020	(***)
	18.56	June–September	15	0.55–2.36	0.271 ± 0.056	(***)
	18.56	November–March	22	1.49–2.76	0.101 ± 0.024	(***)
	18.56	October, April, May	8	1.08–2.16	0.092 ± 0.036	(*)
Day, 1978 (Armidale, New South Wales, Australia)						
	0.196	Two storms	21	0.7–5.3	0.365 ± 0.043	(***)
	0.196	Storm J	8	2.6–5.3	0.206 ± 0.041	(**)
	0.196	Storm K	13	0.7–0.9	0.042 ± 0.008	(***)
Day, 1983 (Armidale, New South Wales, Australia)						
D, Pipeclay Creek	0.086	150-mm storm over 5 days	17	4.8–8.3	0.095 ± 0.009	(***)
D, Pipeclay Creek	0.086	16-mo. period	77	3.8–9.2	0.092 ± 0.004	(***)
Roberts and Archibold, 1978 (Burnaby, British Columbia, Canada)						
	0.043	17 months	48	4.9–10.1	0.067 ± 0.017	(***)
	0.043	Nov–Dec 1970	19	4.9–8.6	0.197 ± 0.031	(***)
	0.043	Jan–Mar 1970	11	6.7–10.1	0.156 ± 0.021	(***)
	0.043	Jan–Mar 1971	19	7.7–8.0	0.019 ± 0.002	(***)
This study (California, USA: total flowing networks)						
Sagehen Creek	27.2	2006–2008	4	0.56–1.29	0.311 ± 0.093	(.)
Providence/Duff	4.01	2006–2008	4	0.61–1.95	0.401 ± 0.061	(*)
Bull Creek	3.58	2006–2008	4	1.88–3.91	0.182 ± 0.022	(*)
Caspar Creek	8.48	2006–2008	3	0.50–0.99	0.310 ± 0.050	(.)
All four sites (pooled estimate via analysis of covariance)					0.270 ± 0.037	(***)
This study (California, USA; connected flowing networks only)						
Sagehen Creek	27.2	2006–2008	4	0.46–1.20	0.363 ± 0.115	(.)
Providence/Duff	4.01	2006–2008	4	0.20–1.53	0.688 ± 0.195	(.)
Bull Creek	3.58	2006–2008	4	1.28–3.91	0.268 ± 0.010	(**)
Caspar Creek	8.48	2006–2008	3	0.15–0.63	0.558 ± 0.242	(n.s.)
All four sites (pooled estimate via analysis of covariance)					0.412 ± 0.076	(***)

Scaling relationships for prior studies recalculated using data digitized from plots in the cited sources. Drainage area in Gregory and Walling (1968) is assumed to be in square miles, not square kilometres, for consistency with their reported drainage densities. We further assume that scatterplots for individual sites are not offset in Figure 3 of Roberts and Klingeman (1972). Note that some time intervals are nested; e.g. summer and winter are subsets of the one-year interval reported in Gregory and Walling, 1968). Data from Day (1983) exclude points with drainage density less than 3.3 km/km^2, which deviate from the clear power-law relationship observed at higher drainage densities. This threshold was selected because the outlet location was high enough in the drainage to potentially bias the beta estimate at low flows and drainage densities. Beta = power-law scaling exponent; S.E. = standard error. Statistical significance is indicated as follows: (.) = 0.1, (*) = 0.05, (**) = 0.01, (***) = 0.001, (n.s.) = not significant at the $\alpha = 0.1$ level.

conditions. This example illustrates how rearrangement of bedload and debris can strongly impact the connected flowing stream network length.

It is important to keep in mind that in all studies of this kind, both discharge and network length are defined with reference to the location of the gauging station. Particularly in headwater catchments, gauging stations may be sited near the highest points in the network that still support perennial flow. This presents a definitional problem: if we define the outlet close to the point where the stream goes dry at low flows, the ratio of active channel lengths between dry and wet conditions (and thus the

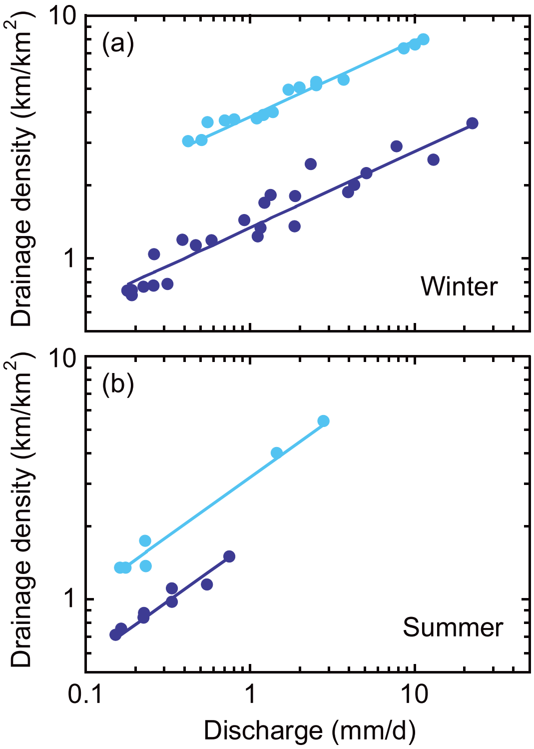

Figure 6. Power-law relationship between flowing stream network drainage density and discharge for catchments A and B (dark and light blue, respectively) of Gregory and Walling (1968). Slopes of 0.313 ± 0.015 and 0.486 ± 0.024 in winter and summer, respectively, fitted jointly to both catchments by least squares (slopes were not statistically different between the two catchments). Data digitized from Figure 1 of Gregory and Walling (1968)

network length scaling exponent) can become arbitrarily large. This issue may partly explain why network length (particularly connected network length) scales so steeply with discharge at Providence/Duff, for example (Figure 2c), because each subcatchment's weir is sited close to the uppermost limit of the connected network during low flows (Figure 2a).

Definitional biases such as these would be less pronounced if discharge and network length were measured with reference to gauging stations located lower down in the basin, well within the connected network of perennial flow (as at Sagehen Creek, for example). This would inevitably entail larger drainage areas and greater logistical challenges in field mapping, but would yield more stable and reliable scaling behaviour. Although network extension/retraction and connection/disconnection are phenomena of headwater catchments, headwaters account for most of the channel length of any stream network (Leopold *et al.*, 1964; Bishop *et al.*, 2008). Thus, the dynamics of headwater channels, such as those shown in Figures 1–5, are likely to determine the dynamic scaling behaviour of much larger networks as well.

The stream networks mapped in Figures 1–4 almost certainly underestimate the variability that would be observed at extreme high and low flows, because the historical ranges of flows were far wider than we could capture during our field mapping campaigns. For example, we mapped the Sagehen Creek network at flows spanning the 7th to the 84th percentiles of the flow distribution, but the mapped flows span only a factor of 12, whereas the flows on record span a factor of 800, suggesting that the active drainage network may have a much larger dynamic range than shown in Figure 1. Assuming the flowing network scales as the 0.31 power of discharge, as shown in Figure 1c, we would expect an 800-fold change in discharge to alter the length of the flowing stream network by nearly a factor of eight, rather than the roughly factor-of-two variation that was captured in our surveys. Similarly, at Caspar Creek, we would expect a roughly 11-fold change in flowing network length in response to the 2600-fold historical range of discharge, rather than the twofold change that we mapped over a ninefold range in discharge. These extrapolations are only rough estimates, because we do not know whether the scaling relationships observed amongst the mapped flows would also extend beyond them. Nonetheless, they indicate the range of network variability that could potentially be observed. This range of variability suggests that there are times when the actively flowing network extends beyond the geomorphic channel network, and other times when flowing streams occupy only a small fraction of it. This is consistent with field observations of overland, out-of-channel flow during snowmelt at the Sierra Nevada sites and the paucity of flow in the dry season at all sites.

Responses to similar changes in runoff can also be variable in space and time. For example, the northernmost catchment (P301) in Figure 2a shows the largest change in the spatial extent of the stream network between the two driest survey periods whereas the nearby P304 catchment shows the largest change in its flowing stream network between the two wettest survey periods. In contrast, the mainstem of the North Fork of Caspar Creek (Figure 4a) shows a gap ~800 m above the gauging station in Oct 2006 that does not persist in the drier conditions during the August 2007 survey. Sediment initially trapped behind a downed tree appeared to have been flushed downstream during the winter of 2006–2007, and the gap in flow dropped below our 10-m mapping threshold, illustrating how changes in the geomorphic channel network can influence the flowing stream network.

Mapped networks at both Sagehen and Caspar were markedly shorter in Fall 2006 than in Fall 2007, despite the fact that measured discharge was higher. This likely reflects both an improvement in mapping skill based on our increased knowledge of where the channels were flowing in Spring 2007, and the possibility that wetness conditions differed in a way that is not reflected in the runoff measurements themselves. This hypothesis could be tested by comparing the extent of the active flowing network to direct measurements of catchment wetness (such as soil moisture or groundwater levels).

Implications

Maps of flowing stream networks reveal useful information about subsurface hydrological characteristics at the points at which streams appear and disappear. These locations reveal the points where the total discharge can just be accommodated in the subsurface (Figure 7). Assuming that discharge at any point on the landscape scales with the upslope accumulated area, the discharge accommodated in the subsurface should equal A (P-E) where A = upslope accumulated area (L^2), P = precipitation (L/T) and E = evaporation (L/T), averaged over some appropriate time scale. If subsurface discharge occurs as diffuse flow in the hyporheic zone, then the discharge flux that can be accommodated in the subsurface can be expressed as asK, where a is the cross-sectional area (L^2) of the valley-bottom hyporheic zone, s is the downvalley slope (L/L), and K is the hydraulic conductivity of the subsurface material (L/T). Alternatively, we could express the flow in the hyporheic zone as wsT, where w (L) is the width of the valley-bottom hyporheic prism, and $T = Kb$ is the transmissivity of the subsurface cross-section at a given point (L^2/T), with b (L) denoting the depth of the hyporheic prism. (Although expressed here as a constant, the conductivity and the transmissivity can vary with depth, and a depth-integrated conductivity can easily be included in this simple model.) Thus, discharge at points where surface flow emerges can be expressed as

$$Q = A(P - E) = asK = wsT \quad (1)$$

Because flowing stream networks disconnect and reconnect, the aforementioned relation suggests that the transmissivity product ($asK = wsT$) does not vary smoothly downvalley. Instead, the flowing stream network can be expected to disconnect where Equation 1 holds, but the transmissivity product is increasing more rapidly than the contributing area A with distance downstream. Likewise, the flowing network will reconnect where Equation 1 is satisfied and the transmissivity product grows more slowly than the contributing area with distance downstream. This is consistent with the qualitative observation along the mainstem of North Fork Caspar Creek (Figure 4a) that the migration of a sediment plug in the stream valley permitted disconnection during the fall of 2006 that was not observed during the drier fall of 2007. At sites where flowing stream networks contract smoothly at their tips, we might expect that the transmissivity product increases smoothly downvalley.

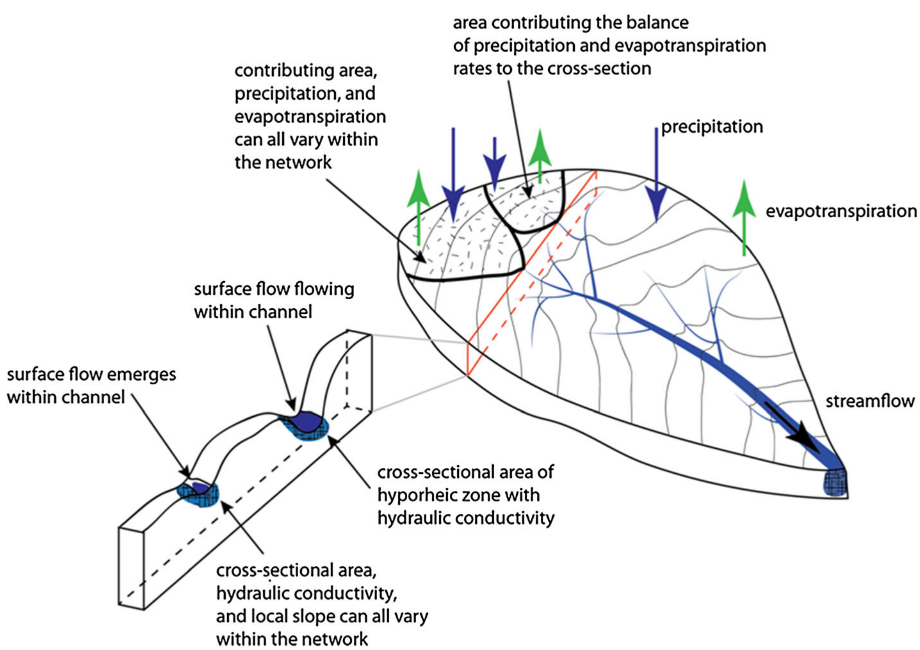

Figure 7. Conceptual diagram for flow connection and disconnection, as controlled by the balance between hyporheic transmissivity and water delivery from upstream. Total flow (surface and subsurface) scales as the contributing area times the balance between the spatially averaged precipitation and evapotranspiration rates. Where this accumulated flow can be accommodated in the subsurface, surface flow will not occur. Surface flow will emerge at points where the flow from upslope can no longer be accommodated in the subsurface. Conversely, the flowing stream will disappear again at points where the capacity of the subsurface to conduct hyporheic flow increases faster in the downvalley direction than the accumulated drainage area does. Although groundwater flow occurs at all scales, this simple conceptual model invokes the simplification that regional scale flows are small relative to smaller scales. A more complete understanding requires quantification of those fluxes, which is currently difficult

Variations in flow will shift the points of connection and disconnection along the geomorphic channel network, revealing subsurface information along this network of points. This information could be combined with geophysical measurements of the subsurface prism along the geomorphic channel network. By coupling discharge measurements with flowing stream network mapping, one could then map subsurface hydraulic conductivity or transmissivity along the channel network. Patterns in hydraulic conductivity along the stream network could then be validated using distributed temperature sensing techniques that identify gaining and losing reaches. These reaches may shift in time due to changing groundwater-surface water interactions. Understanding the subsurface hydraulic conductivity field can help in interpreting gains and losses of streamflow due to hyporheic exchange, especially with complementary distributed temperature sensing studies (Selker *et al.*, 2006).

Gains and losses of streamflow in the flowing stream network will reflect groundwater flows at different scales. In headwater basins, such as the ones mapped in Figures 1–4, most groundwater flow is likely to be roughly parallel to the surface topography. Indeed Equation 1 relies on a conceptual model in which streamflow is generated from water that flows roughly parallel to the surface topography, in a relatively shallow subsurface layer that has an impermeable boundary below. If, instead, the subsurface is conductive to depths that are on the same order as the topography, or greater, then the water table surface can become decoupled from the topography and presumably different scaling relationships would apply (in particular, the headwater drainage area would no longer be defined by the topographic surface).

The dynamic character of stream networks has important implications for hydrologic modelling. In many hydrologic models, a time-varying groundwater system feeds a channel network of fixed dimensions. By contrast, our observations and the decades-old studies reported in Table II show that the active drainage network is not fixed but instead extends and retracts substantially in response to variations in groundwater inflows. Stream discharge can be expressed as the average seepage rate per unit channel length, times length of active drainage network. The open question is: as stream discharge changes, how much does the active network change and how much does seepage flux per unit length change? Our observations, and those reported in Table II, demonstrate that active network length increases as roughly the 0.2–0.4 power of discharge, implying that the average seepage flux per unit length must scale as roughly the 0.6–0.8 power of discharge. Therefore, whilst changes in network length are significant (and thus assumptions of fixed network dimensions in many hydrological models should be revisited), changes in average seepage flux per unit channel length are still the dominant term in discharge variations. Our observations contradict the recent suggestion by Biswal and Marani (2010) that seepage inflows per unit length are constant in time, and thus that changes in discharge are proportional to changes in active network length. Moreover, by arguing that discharge decreases *because* the network contracts, Biswal and Marani (2010) seem to us to be inverting cause and effect. Our observations are more consistent with the view that stream network extension and contraction are the result, not the cause, of hydrologic changes in headwater catchments. The idea that the network controls the hydrograph is a superficially appealing notion (as it was 50 years ago when the initial studies of network extension/contraction began), but in our view, it is a distraction from the important task of understanding how hydrological processes control stream network expansion and contraction.

Concluding remarks and future directions

Maps showing how the flowing stream network evolves over time can help focus efforts to learn more about subsurface hydrology at the transition points between surface and subsurface flow. These transition points are as numerous as the number of heads of the flowing stream network. They also migrate up and down the channel network in response to variations in hydrologic conditions, tracing out a dynamic map of the balance between downvalley seepage rates and subsurface transmissivity.

Our work shows that flowing stream networks are dynamic and discontinuous across a wide range of topographic, geologic and climatic settings. Furthermore, the scaling relationships relating stream discharge to active network length and the number of flowing channel heads exhibit clear central tendencies amongst many diverse sites (Table II). Controls on the sensitivity of the flowing stream network to changes in runoff should be better understood, especially because a substantial fraction of every stream network is made up of its headwater channels.

We expect that other topographic attributes (e.g. average drainage area at flow heads, average altitude of flow heads and channel slope at flow heads) will also exhibit systematic relationships with catchment wetness, as measured by stream discharge. The analysis of these variables will be presented in a future paper.

Mapping the dynamics of flowing networks across a wider range of hydroclimates and at more frequent intervals would help in evaluating process controls. Confluences of tributaries may be critical zones worthy of additional study because of potential step changes in slope, discharge and sediment load that can affect surface flow. However, mapping stream networks by hand, as we have done, presents significant logistical challenges, particularly in steep forested terrain. Some approaches to collect the high-resolution spatiotemporal information needed to map dynamic stream networks include spatially distributed state loggers (e.g. Bhamjee and Lindsay, 2011), temperature loggers and electrical conductivity sensors (e.g. Goulsbra *et al*., 2009; Peirce and Lindsay, 2014), as well as fibre-optic distributed temperature sensing systems and thermal cameras mounted on low-altitude drones. Permafrost-dominated catchments offer the intriguing possibility of mapping changes in surface and subsurface flow where the subsurface boundary layer conditions are evolving over time. In addition, observations in disturbed catchments could help determine how land use change affects the sensitivity of the flowing stream network to changes in hydrologic conditions.

Acknowledgements

We thank Evan Kha, Roger Davis, Madeline Solomon, Steve Dunn, David Swenson, Terry Smith and Michael Cotton for assistance with field work, Trey Apel for GPS processing advice and Andrea Rinaldo and Caitlin Rushlow for helpful discussions. The University of California's Sagehen Creek Field Station, CalFIRE and the US Forest Service (USFS) provided logistical support, especially during the winter and spring surveys. Flow data were provided by the US Geological Survey (USGS) long-term monitoring station at Sagehen Creek and by the USFS at Caspar, Providence and Bull Creeks. This work was partly supported by a Berkeley Water Center grant to J. W. K., by a National Science Foundation graduate research fellowship to S. E. G., and by the NSF Idaho EPSCoR Program under award number EPS-0814387 to S. E. G.

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