https://doi.org/10.5194/esurf-2019-60
Preprint. Discussion started: 24 October 2019

Earth Surface Dynamics Discussions

Woody debris as a confounding factor in interpreting the width of spring-fed streams

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Abstract. Spring-fed streams throughout volcanic regions of the western United States exhibit larger widths than runoff-fed streams with similar discharge. Due to the distinctive damped hydrograph of spring-fed streams, large woody debris is less mobile in spring-fed than runoff-fed stream channels. The consequent long residence time of wood in spring-fed streams allows wood to potentially have long-term impacts on channel morphology. We used high-resolution satellite imagery in combination with discharge and climate data from published reports and publicly available databases to investigate the relationship between discharge, woody debris length, and channel width in 38 spring-fed and 20 runoff-fed streams. We identify an order of magnitude more logjams than single logs per unit length present in runoff-fed streams as compared to spring-fed streams. Histograms of log orientation in spring-fed streams additionally confirm that single logs are immobile in the channel so that the impact of single logs on channel morphology could be pronounced in spring-fed streams. Based on these observed differences, we hypothesize that there should be a difference in channel morphology. We find that spring-fed streams in our study are about 2 times wider than runoff-fed streams with similar mean discharge. Additionally, a model for stream width in spring-fed streams based solely on length of wood is a better model than one derived from discharge or including both discharge and wood length. This study provides insights into controls on stream width in spring-fed streams by identifying a strong correlation between wood length and stream width and confirming that spring-fed streams are significantly wider than runoff-fed streams.

1 Introduction

Leopold and Maddock (1953) first proposed a set of power laws to describe channel morphology based on discharge. Subsequent studies confirmed the existence of a relationship between discharge and width (e.g., Ferguson, 1986; Ackers, 1964; Stall and Fok, 1968), but the scatter in the relationship is large. There is a wealth of empirical correlations to describe width based on environmental conditions; however, the best relationships exhibit limited capacity to describe real channels (Gleason, 2015).

In certain cases, though, it may be possible to predict channel width more precisely. One example is that of spring-dominated or spring-fed streams. Spring-fed streams receive the bulk of their discharge from groundwater sources and thus exhibit relatively stable hydrographs (e.g., Whiting and Moog, 2001; Manga, 1996). Compared to runoff-fed streams, spring-fed streams

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transport a proportionally larger amount of sediment in everyday flows than high-flow events, leading to different channel responses to environmental variables

Previous studies have identified differences between runoff- and spring-fed channels (e.g., Whiting and Moog, 2001; Griffiths, Anderson, and Springer, 2008). Whiting and Moog (2001) studied streams in the western US, primarily in the Oregon Cascades, and found that the spring-fed streams in their study (0.005-8 m^3/s) are signficantly wider than their runoff-fed counterparts. Conversely, a study of spring-fed streams in Arizona (10^{-3} m^3/s) found that spring-fed streams exhibited lower width-to-depth ratios than runoff-fed streams (Griffiths, Anderson, and Springer, 2008). The streams studied by Whiting and Moog (2001) and Griffiths, Anderson, and Springer (2008) are comparable in every aspect save discharge and the presence of large woody debris (LWD). The streams studied by Whiting and Moog (2001) had high discharge and significant amounts of LWD, while the streams studied by Griffiths, Anderson, and Springer (2008) had very low discharge and essentially no LWD.

The presence of LWD increases variance in channel width, demonstrating the capacity to either constrict or widen (Montgomery et al., 2003). Channel widening associated with LWD is observed by Trotter (1990), Nakamura and Swanson (1993), Hart (2002), and Faustini and Jones (2003), for example. Manga and Kirchner (2000) found that the presence of wood increases mean water depth, implying lower mean velocities but local velocity increases. Zhang, Rutherfurd, and Ghisalberti (2016) demonstrated that single logs can increase bank erosion via those local velocity increases, providing a mechanism for channel widening with the presence of LWD. In contrast, removal of LWD has been observed to cause rapid changes to channel form, including rapid channel widening (Bilby, 1984; Smith et al., 1993; Brooks and Brierley, 2000). The mechanism for LWD constriction of channel width is streambank stabilization by LWD (Montgomery et al., 2003).

Despite evidence that LWD impacts channel dimensions, LWD was absent from early discussions of channel geometry (Gleason, 2015). We hypothesize that LWD widens spring-fed streams. In general, the stability of LWD in channels is related to flow characteristics of the stream and the size of LWD (Bilby, 1984, 1989; Berg et al., 1998; Gleason, 2015). Notably, Senter et al. (2017) show that peak annual discharge has a large impact on LWD mobility, and generally, hydrology is a good predicter of wood mobility (Kramer and Wohl, 2016). Thus, due to differing hydrograph behavior, peak events in runoff-fed streams may be able to mobilize wood, whereas the more stable hydrographs of spring-fed streams generally lie below the threshold for wood mobility, making LWD more likely to be immobile in spring-fed but not runoff-fed streams. In order to assess this hypothesis, Hygelund (2002) measured orientations and diameters of wood in Oregon streams to determine whether wood was oriented with respect to the thalweg. They found that wood in runoff-fed channels was generally more oriented with flow, demonstrating mobility, and wood in spring-fed channels was generally aligned randomly or more perpendicular with flow, implying immobility.

We hypothesize that this mobility behavior leads to the development of logjams in runoff-fed streams and explains the paucity of logjams in spring-fed streams, where single logs may dominate the population of LWD. We thus expect that the wood interaction mechanism explored by Zhang, Rutherfurd, and Ghisalberti (2016) for single logs in streams (i.e. an increase in bank erosion) may dominate, leading to channel widening associated with the presence of LWD. With sufficient logs immobile in a channel, the consequent bank erosion would increase the reach-averaged width-to-depth ratio. In contrast, logjams may produce more variable effects on channel morphology or locally stabilize banks, cause channel constriction.

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The purpose of this study is to examine the empirical relationship between LWD and the morphology of spring-fed streams in order to identify statistically significant relationships. We also respond to a recent call by Kramer and Wohl (2016) to employ remote sensing to study wood dynamics and to daylight unpublished data on wood dynamics. Specifically, we investigated (1) wood orientation and frequency of logjams, (2) discharge and width of stream channels, and (3) length of LWD and width of stream channels.

2 Field Area

In this study, we work with 36 spring-fed streams and 20 runoff-fed streams across the western United States in the Oregon Cascades, southwestern Montana, eastern Idaho, northern Arizona, northern California, and the Ozarks in Missouri, and 2 additional spring-fed streams in El Tatio Geyser Field in Chile (Table 1). Bankfull discharge ranges from the approximately 10^{-3} m^3/s discharge springs in Arizona (Griffiths, Anderson, and Springer, 2008) to Big Springs, MO at 13 m^3/s (USGS, 2018), with precipitation varying by only a factor of 4 in the North American examples. The streambeds generally consist of glacial outwash or alluvium.

The streams located in eastern Idaho and southwestern Montana are located in the easternmost part of the Columbia Plateau (Snake River Plain) and neighboring Middle Rocky Mountains physiographic provinces (Fenneman, 1931). The annual precipitation is 300-600 mm with about 150 mm snowfall (Arguez et al., 2010). Mean Annual temperatures range from 1-9°C (Arguez et al., 2010). The area is underlain by Quaternary rhyolite and basalt (Christiansen and Blank Jr, 1972). The streams in this region primarily run through oak/pine woodland.

The spring-dominated streams in southwest Oregon and northern California are located along the border of the Cascade-Sierra Mountains and Basin and Range physiographic provinces (Fenneman, 1931). This area lies in the rain shadow of the Cascades to the west. Mean annual precipitation, dominated by snow, decreases from over 1 m to the west to about 0.5 m in the southern part of the study area (Arguez et al., 2010), and mean annual temperatures range from 8-12°C (Arguez et al., 2010). The area is underlain by Quaternary basalt and basaltic andesite. Typical land uses for the studied streams in this region are oak or pine woodland, grassland, shrubland, wetland, and some small farms.

The streams studied in northern Arizona are located along the Mogollon Rim (Pierce, Damon, and Shafiqullah, 1979). The high relief of the Mogollon rim at 2100 m induces a strong orographic effect (NRCS, 2005), yielding some of the highest precipitation in the state, an annual average of more than 800 mm (Arguez et al., 2010), and the mean annual temperature is 17°C (Arguez et al., 2010). The area is underlain by Tertiary basalts, Permian limestone (Kaibab Formation), and sandstone (Coconino Sandstone), with streambed material made up of valley fill alluvium (Moore, Wilson, and O'Hare, 1960). Watersheds included in this study run through oak/pine woodland and wetland meadows.

The streams in the Ozarks are located in the Potosi, Eminence Gasconade, and Roubidoux Formations (Panfil and Jacobson, 2001). The area is underlain by carbonate with interbedded chert and sandstone (Panfil and Jacobson, 2001). Mean annual temperatures range from 2-15°C, and precipitation is 0.5-1.2 m/yr (Arguez et al., 2010).

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The streams in El Tatio Geyser Basin, Chile are located on the San Pedro formation (Harrington, 1961). Located in the Atacama desert, precipitation is very low at 0.025 m/yr, but the high elevation means that the mean annual temperature is 3.6°C (Kull and Grosjean, 2000). This area is underlain by andesites, dacites, and rhyolites (Harrington, 1961), with the streambed material consisting of glacial outwash. The streams in this area run through desert landscapes above treeline.

Spring-fed streams occur in specifically defined geological settings in which a highly permeable material overlays an impermeable layer, such as in the volcanic regions explored in this study (Whiting and Stamm, 1995). The geologic setting is important for producing the conditions for spring-fed streams to exist and sustain. Due to these particular geological constraints, it is difficult to find a large, comparable set of runoff-fed streams. We selected a set of streams that are located as closely as possible to the spring-fed streams in this study to control for geology as much as possible. We can verify that the labeled runoff-fed and spring-fed streams display different hydrograph behavior by examining the mean and standard deviation of flow, when available. All spring-fed streams with available data exhibit standard deviations smaller than their mean, whereas the runoff-fed streams show standard deviations larger than their mean. When unavailable, we rely on the cited authors to correctly identify the flow source for the stream.

3 Methods

High-resolution satellite imagery has been shown to be effective in capturing quantitative data about stream morphology and LWD (e.g., Leckie et al., 2005; Senter et al., 2017). Using Google Earth Pro high-resolution imagery, we measured stream width along 10 stream cross-sections for 38 spring-fed and 20 runoff-fed streams including the GPS point in Table 1. This study is limited to exploring width as opposed to width:depth ratio due to the use of remote sensing for data collection. Spring-fed and runoff-fed streams are distinguished based on prior identification in research publications. The GPS points are located at or near the gauges cited. These measurements are compared to field measurements by Whiting and Moog (2001) and Hygelund (2002) for validation. By visual inspection of high-resolution satellite imagery, we determine whether a stream contains wood. Those with no visible wood and those without clear enough imagery are excluded from analyses about wood. In 2018, multiple attempts were made to contact managers of each spring-fed stream where no wood was observed, but we did not receive any responses.

For 25 spring-fed and 19 runoff-fed streams containing wood, we measured the length of 10 or more pieces of LWD found in or near the channel in this same reach (Table 1). Additional measurements were taken for streams exhibiting a high degree of variability in wood length. This measurement is meant to characterize the wood source to the streams, so wood found near the streams should be representative of the wood that enters the channel. If wood were only measured in the channel, then the results may be biased since we only measured wood for which we could confidently identify both ends. In the channel, this criteria rules out many pieces of wood, often excluding smaller pieces or pieces where one end is obscured by trees. Wood outside the channel is sometimes more clearly identifiable in aerial imagery. To verify the validity of this technique, we compare field measurements of wood length at one site to results from remotely sensed measurements. While fully submerged logs likely

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	Stream	Elevation (m)	GPS	Stream Width (m)	Wood Length (m)	Mean Discharge (m^3/s)	Bankfull Discharge (m3/s)	Watershed Area (km^3)
Oregon Cascades: Average Temperature[7]: 8-10 °C, Mean Annual Precipitation[7]: 0.3-1.3 m, Mean Annual Snowfall[7]: 0.5-0.7 m, Land use: pine woodland, grassland, wetland, small farms								
Spring-fed								
1	Blue Springs, OR [†]	1273	[42.69580, -122.07173]	4.3 ± 1.3	6.3 ± 1.7		0.089[1]	0.48[1]
2	Browns Creek, OR	1334	[43.72212, -121.80372]	15.4 ± 2.1	16.0 ± 3.2		1.22[1]	55.9[1]
3	Cultus River, OR [†,a]	1357	[43.88801, -121.76216]	30.0 ± 3.0	17.6 ± 4.0	1.8 ± 0.6[3]		42.7[3]
4	Deschutes River, OR [†,a]	1358	[43.81417, -121.77583]	11.1 ± 2.7	13.1 ± 3.6	4.2 ± 2.1[3]		342[3]
5	Fall River, OR[†,a]	1276	[43.79367, -121.52416]	15.4 ± 6.6	16.1 ± 3.4		4.39[2]	117 [10]
6	Lost Creek, OR[a]	520	[44.17542, -122.05447]	16.7 ± 5.2	18.22 ± 5.8	5.91[12]		197[12]
7	Quinn River, OR[a]	1354	[43.78417, -121.8351]	17.9 ± 5.2	13.6 ± 4.6	0.67[10]	1.06[3†]	undetermined
8	Reservation Spring, OR [†,a]	1274	[42.69984, -121.96478]	19.7 ± 3.2	22.2 ± 5.5		1.58[1]	0.12[1]
9	Snow Creek, OR [†,a]	1274	[43.87347, -121.76910]	16.3 ± 3.2	14.0 ± 2.0		1.82[1]	3.58[1]
10	Spring Creek A, OR [†,a]	1281	[42.67034, -121.88592]	36.1 ± 11.8	18.0 ± 3.4		2.01[1]	72.8[1]
11	Spring Creek B, OR	1282	[42.65413, -121.88043]	41.5 ± 3.8	16.8 ± 2.6		6.77[1]	33.8[1]
Runoff-fed								
12	Boulder Creek, OR [†,a]	521	[43.30361, -122.52917]	15.9 ± 3.5	11.4 ± 4.1	2.98 ± 4.32[3]	31.4[3†]	78.7[3]
13	Crystal Castle Cr C, OR	1393		0.96[1]	UNKNOWN		0.0491[1]	8.95[1]
14	Cultus Creek, OR [†,a]	1399	[43.82273, -121.82770]	6.9 ± 2.8	16.4 ± 4.6	0.62 ± 0.84[3]	3.02[3†]	86[3]
15	Deer Creek, OR [†]	1383	[43.80461, -121.83833]	4.3 ± 0.8	10.4 ± 2.3	0.2 ± 0.3[3]	0.463[1]	55.7[3]
16	Hills Creek, OR	494	[43.68056, -122.36944]	15.9 ± 2.3	12.0 ± 1.6	4.30 ± 5.84[3]	35.4[3†]	136.5[3]
17	Little Deschutes River, OR	1278	[43.68917, -121.50167]	12.5 ± 1.7	11.4 ± 4.8	5.83 ± 4.56[3]	10.6[3†]	2225[3]
18	South Fork McKenzie River, OR	521	[44.04722, -122.21667]	19.7 ± 2.3	17.7 ± 5.0	17.93 ± 16.64[3]	104.2[3†]	414[3]
Ozarks: Average Temperature: 2-15 °C, Mean Annual Precipitation: 0.5-1.2 m, Mean Annual Snowfall: 0.2 m, Land use[11]: oak/pine woodland								
Spring-Fed								
19	Big Springs, MO	131	[36.95000, -90.99000]	88.0 ± 18.0	N/A	12.8 ± 4.7[3]		undetermined
20	Maramec Springs, MO	239	[37.95000, -91.53000]	22.1 ± 3.1	N/A		0.044[6]	803[13]
21	Tucker Bay Spring, MO	119	[36.76576, -90.93988]	17.0 ± 2.4	14.3 ± 4.2		37.75[11]	undetermined
Runoff-fed								
22	Bourbeuse River, MO[a]	245	[38.14692, -91.58089]	16.9 ± 5.4	20.8 ± 1.9	4.01 ± 16.79[3]	249.8[3†]	350[3]
23	Current River, MO	272	[37.44833, -91.67111]	14.4 ± 3.7	17.8 ± 3.4	3.75 ± 4.88[3]	5.8[3†]	152[3]
24	Huzzah Creek, MO[†,a]	203	[37.97472, -91.20444]	23.1 ± 3.6	14.3 ± 4.6	8.08 ± 21.34[3]	101.9[3†]	671[3]
25	Little Piney Creek, MO[†,a]	211	[37.90953, -91.90333]	17.4 ± 4.4	18.3 ± 2.2	4.74 ± 11.76[3]	90.9[3†]	518[3]
26	Meramec River, MO[a]	208	[37.99847, -91.36094]	35.9 ± 9.2	24.1 ± 7.7	17.13 ± 42.33[3]	240.4[3†]	2023[3]
Eastern Idaho: Average Temperature[7]: 1-9 °C, Mean Annual Precipitation[7]: 0.2-0.6 m, Mean Annual Snowfall[7]: 0.7-1.6 m, Land use[11]: oak/pine woodland, farm								
Spring-Fed								
27	Big Springs, ID [†,a]	1947	[44.49892, -111.25711]	58.4 ± 8.9	12.5 ± 3.3		20.5[1]	0.15[1]
28	Billingsley Creek, ID	913	[42.81976, -114.87065]	11.3 ± 1.5	N/A			undetermined
29	Black Sands Creek, MT [†,a]	2023	[44.66017, -111.16191]	28.0 ± 7.4	15.8 ± 1.9		0.7 [1]	0.082[1]
30	Blue Heart Springs, ID	879	[42.71034, -114.83000]	24.8 ± 3.5	N/A		3.1[11]	0.01
31	Buffalo River, ID [†,a]	1938	[44.43844, -111.26001]	14.2 ± 1.8	11.4 ± 4.1		0.21[1]	0.8[1]
32	Chick Creek, ID [†]	1935	[44.42597, -111.21480]	4.5 ± 1.7	11.2 ± 2.7		1.08[1]	22.9[1]
33	Elk Springs Creek, ID	1977	[44.49468, -111.40109]	1.4 ± 0.4	6.7 ± 2.7		0.024[1]	0.28[1]
34	Lucky Dog Creek A, ID[a]	1951	[44.48591, -111.26705]	7.2 ± 0.6	11.1 ± 2.5		0.92[1]	0.15[1]
35	Lucky Dog Creek B, ID [†]	1947	[44.48822, -111.29158]	6.9 ± 0.7	12.5 ± 3.1		1.35[1]	5.75[1]
36	Mill Creek, ID	1939	[44.46311, -111.42967]	2.7 ± 0.7	7.2 ± 1.2		0.19[1]	1.88[1]
37	Silver Creek, ID	1478	[43.32336, -114.10835]	20.9 ± 1.8	N/A	4.0 ± 1.4[3]		181[3]
38	Toms Creek A, ID[†]	1932	[44.41647, -111.29339]	4.3 ± 0.6	9.7 ± 3.3		0.0872[1]	0.94[1]
39	Toms Creek D, ID	1914	[44.40137, -111.36421]	6.2 ± 1.3	9.0 ± 1.7		1.18[1]	14.4[1]
40	Tyler Creek,ID	2051	[44.50973, -111.39774]	1.2 ± 0.3	8.1 ± 1.9		0.2[1]	3.15[1]
Runoff-fed								
41	Fall River, ID[†,a]	1643	[44.05611, -111.35861]	40.1 ± 4.6	15.4 ± 3.4	23.78±20.39[3]	82.4[3†]	873[3]
42	Henry's Fork, ID [†,a]	1602	[44.113611, -111.333056]	62.2 ± 6.9	23.7 ± 2.8	28.14± 11.95[3]	54.4[3†]	1699[3]
43	Moose Creek, ID [†]	1950	[44.48355, -111.28622]	2.3 ± 0.3	9.9 ± 4.3		0.64[1]	39.7[1]
44	Robinson Creek, ID	1606	[44.11444, -111.32417]	14.5 ± 2.9	11.4 ± 3.4	3.59±3.80[3]	13.1[3†]	334[3]
El Tatio Geyser Basin, Chile: Average Temperature[8]: 3.6 °C, Mean Annual Precipitation[8]: 0.0025[8] m, Land use: desert, geyser basin								
Spring-fed								
45	Rio Salado, Chile	4300	[-22.33903, -68.01808]	8.53[9]	N/A		0.86[9]	undetermined
46	Stream 0, Chile	4300	[-22.33444, -68.03292]	3.0[9]	N/A		0.25[9]	undetermined
Northern California: Average Temperature[7]: 10-12 °C, Mean Annual Precipitation[7]: 1.2-1.6 m, Mean Annual Snowfall[7]: 0.1-1.3 m, Land use: oak/pine woodland, shrubland, grassland, farm								
Spring-fed								
47	Big Springs Creek, CA	789	[41.60115, -122.42650]	38.2 ± 8.3	N/A		1.7[4]	undetermined
48	Hat Creek, CA	1321	[40.68911, -121.42278]	7.6 ± 2.0	9.9 ± 2.5	4.0 ± 1.3[3]		421[3]
49	Lost Creek, CA	886	[39.57003, -121.16534]	8.7 ± 1.4	8.9 ± 3.4			undetermined
Runoff-fed								
50	McCloud River, CA [†]	335	[41.11083, -122.09534]	28.3 ± 7.2	10.3 ± 3.1	29.6 ± 41.4[3]	28.0[3†]	1564[3]
Mogollon Rim, Arizona: Average Temperature[7]: 17 °C, Mean Annual Precipitation[7]: 0.8 m, Mean Annual Snowfall[7]: 0.9 m, Land use[5]: oak/pine woodland, wetland meadow								
Spring-fed								
51	Unnamed Spring 1, AZ	2207	[34.47111, -111.28761]	0.4[5]	N/A		$1.1\times10_5^{-2}$	0.029[5]
52	Unnamed Spring 2, AZ	2313	[34.43378, -111.16097]	0.16 [5]	N/A		$2.2\times10_5^{-3}$	0.025[5]
53	Unnamed Spring 3, AZ	2313	[34.43528, -111.16036]	0.22[5]	N/A		$2.7\times10_5^{-3}$	0.0077[5]
54	West Pinchot Spring, AZ	2146	[34.50228, -111.19647]	0.29[5]	N/A		$3.4\times10_5^{-3}$	0.011[5]
55	Whistling Spring, AZ	2289	[34.44844, -111.19028]	0.29[5]	N/A		$2.6\times10_5^{-3}$	0.028[5]
Runoff-fed								
56	Buck Springs Canyon, AZ[†,a]	2286	[34.43972, -111.13972]	1.5 ± 0.5	1.5 ± 0.5		$6.1\times10_5^{-3}$	0.84[5]
57	Merritt Draw, AZ	2291	[34.44889, -111.19014]	0.9 ± 0.4	8.4 ± 3.8		$6.1\times10_5^{-3}$	0.51 [5]
58	Quaking Aspen Canyon, AZ	2267	[34.43919, -111.33889]	0.6[5]	UNKNOWN		$6.1\times10_5^{-3}$	0.94[5]

Table 1. Summary of data collected for spring-fed and runoff-fed streams. Elevation, GPS, bankfull Stream Width, and Wood Length were collected from Google Earth Pro. Streams marked with † were included in histogram analysis, and those marked with an a were used to examine whether wood placement changed over time. Stream Width, Wood Length, and Mean Discharge are reported as Mean±SD when statistics are available. (1) Whiting and Moog (2001), (2) Hygelund (2002), (3) USGS (2018), (4) Deas (2006), (5) Griffiths, Anderson, and Springer (2008), (6) Maramec Spring Park, (7) Arguez et al. (2010), (8) Kull and Grosjean (2000), (9) Munoz-Saez, Manga, and Hurwitz (2018), (10) Manga (1996), (11) Wilkerson (2003), (12) Jefferson et al. (2010), and (13) Vandike (1996). Bankfull discharge values attributed to 3† are estimated as the 1.25 year flood from USGS data.

have an impact on stream morphology as well, they are largely not included in this study due to unreliable identification via satellite imagery. For the remainder of the paper, the term "wood length" refers to the average wood length.

To test the precision of our technique of measuring length in Google Earth Pro, we measured the length of a single log 10 times in a row to yield a length of 17.6±0.2 m with 90% confidence. The small size of the confidence interval (1.2%) suggests relatively high precision for the technique.

For streams marked by a † in Table 1, we also took histograms of log orientation for single logs in each stream. Histograms were taken using Google Earth Pro imagery. Ideally, we could measure wood orientation on a scale from 0° (directly in line with flow) to 180° (directly opposite to flow). This is possible in the field, but due to limitations in imagery resolution, we were unable to reliably distinguish the bottom and top of LWD in this study. As a result, we noted orientation of LWD on a scale from 0° (parallel to flow) to 90° (perpendicular to flow), unable to note orientation (± 90°).

More detailed geomorphic and sedimentologic data were collected by Whiting and Moog (2001), Hygelund (2002), and Griffiths, Anderson, and Springer (2008). Discharge data reported are separated between bankfull and mean discharge in Table 1 for clarity, although for spring-fed streams, since discharge is fairly constant, bankfull discharge and mean discharge are nearly the same (e.g., Whiting and Moog, 2001; Manga, 1996; Whiting and Stamm, 1995). For streams with adequately clear satellite imagery, histograms of wood orientation were made by using Google Earth Pro to measure the angle between wood orientation and the adjacent streambank for all wood outside of logjams (approximately 100 pieces) in a stream segment containing the GPS coordinate in Table 1. We additionally observed, for streams with multiple dates of clear imagery, whether there was any detectable change in wood placement for 20+ observed logs between dates. Dates were typically from about 2005 to about 2018 with variation in the specific years and time periods when imagery were available. Regional precipitation records do not indicate persistent drought through the entire time period at any site (Arguez et al., 2010), although local conditions may deviate from regional averages. We primarily observed single pieces of LWD with few or no logjams in the studied spring-fed streams. We quantified this observation by measuring the density of single logs and the density of logjams over a reach about 500 m in length for streams with adequately clear imagery. We found all best fit parameters using the Marquardt-Levenberg algorithm.

Discharge data are obtained from a range of sources. When available, mean and standard deviation are reported. For spring-fed streams, mean is similar to bankfull discharge (e.g., Whiting and Moog, 2001; Manga, 1996; Whiting and Stamm, 1995), so when bankfull discharge is not available, mean discharge is used for analyses. For runoff-fed streams, if bankfull discharge is unavailable, 1.25-year return period is used as an estimate for bankfull discharge. Statistics are repeated with and without estimated bankfull discharge.

Data are modeled to determine which physical factors are most statistically related to stream width. We begin from the historical convention of $w = aQ^b$, where w is width, Q discharge, and a, b, and c are constants, which are fit separately for each model and data set. Additional tested models incorporate wood length l in a few different ways. The proposed models we test are:

1. $w = aQ^b$

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2. $w = al^b$
3. $w = alQ^b$
4. $w = lQ^b$
5. $w = al^cQ^b$

where w is stream width, l wood length, Q discharge, and c and b are constants. Models 3 and 4 appear nearly the same, but we fit them separately since model 4 requires fewer fit parameters. These formulae align with the body of research that confirms a power law relationship between stream width and discharge, while taking into account a power law or linear relationship between wood length and stream width for spring-fed streams. We assess the value of candidate models using adjusted R^2 (Miles, 2014), which accounts for the number of predictive variables included in the model, and Akaike's Information Criterion (AIC), which measures the amount of information lost when data are approximated by a given model as compared to other candidate models also accounting for the number of predictive variables (Akaike, 1974). An adjustment for small sample sizes (AICc) is presented by Hurvich and Tsai (1989), which we use in this study. If the set of AICc values is $\{AICc_i\}$, then the probability that model i is the best of a set of candidate models is given by $e^{(min(\{AICc_i\})-AICc_i)/2}$.

4 Results

4.1 Wood Dynamics

We begin with a description of the observed wood dynamics within the studied streams. In order for single logs to drive changes in morphology, we assume that logs must be immobile in the channel. In order to confirm that this is the case in spring-fed, but not runoff-fed, streams, we examined histograms of wood orientation.

In order to examine the validity of orientation data taken remotely, we compared our orientation results to those of Hygelund (2002) for Cultus River and Cultus Creek, shown in Figure 1. These sites were chosen from the data available in Hygelund (2002) due to their close proximity to one another and differing flow regime. Using a Kolmogorov-Smirnov Two-Sample Test, we find that for the measurements in Cultus River (Figure 1 (a)), there is an 80% chance that the measurements are from the same distribution and a 15% chance for the measurements on Cultus Creek (Figure 1 (b)). The latter low confidence could be due to the fact that the measurements were taken in different years and possibly in different stream segments, and we argue that the qualitative behavior of the histograms is similar enough to draw the same conclusions about wood orientation. Generally, we find that there is relatively good agreement, at least qualitatively, between the in-field results obtained by Hygelund (2002) and those we obtained via satellite imagery.

Following Hygelund (2002), we note that from the histogram of aggregated data for spring-fed streams in Figure 2 (a), it appears that wood is preferentially oriented around 50-90° (see supplement for individual stream histograms). If wood were mobile in streams, we would expect to see preferential orientation at 0-20° (Braudrick and Grant, 2000). We compare the histogram for spring-fed streams to that for runoff-fed streams in this study, where wood is preferentially oriented around

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0-20°. While the aggregate histograms exhibit clear results, many individual histograms demonstrate differences from these trends (see supplement). For instance, Chick Creek, ID (a spring-fed stream), contains wood mostly oriented around 0° or 50°, while Moose Creek, Deer Creek, and Buck Springs Canyon (runoff-fed streams) show random orientation, and Boulder Creek (runoff-fed) is preferentially oriented around 30-50°. In Chick Creek, LWD is significantly longer than the width of the stream, so the flow regime in the channel may have little impact on the orientation of wood. In the runoff-fed streams, the deviations from the trend are likely due to other aspects of wood dynamics noted during data collection. First, most wood observed in runoff-fed streams was found in logjams, and identifying single logs to measure the orientation was difficult. In runoff-fed streams in this study, there were on average 37 pieces of single wood per km as opposed to the 130 pieces of single wood per km found in spring-fed streams, as shown in Figure 3. This disparity also prevented us from collecting as much data in certain streams due to a dearth of single logs. We noticed about 5 logjams per km in runoff-fed streams compared to about 1 per km in spring-fed streams. This indicates that there may be a bias toward new wood when measuring single pieces in some runoff-fed channels since older wood may be moved to logjams already.

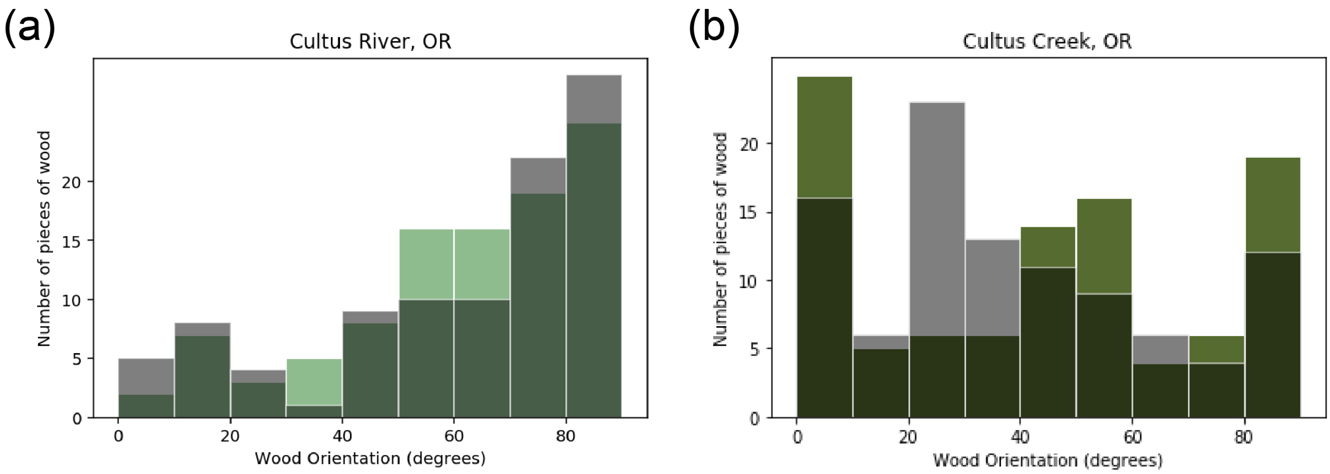

Figure 1. Orientation of woody debris was measured from adjacent bank for approximately 100 pieces of woody debris using Google Earth Pro (green). Hygelund (2002) measured orientation of woody debris in the field (transparent black). Data are shown together for (a) Cultus River and (b) Cultus Creek. The distributions align very well for Cultus River and are have the same qualitative shape for Cultus Creek, although the center peak is displaced between the two sets of measurements.

We verify conclusions about residence of LWD by examining imagery from multiple dates on the streams marked by an a in Table 1. Imagery data were clear for a period of 3-10 years, depending on the site, and we examined at least 20 pieces of LWD at each site. In each spring-fed stream, we were unable to detect any changes in wood placement at any site. In all of the runoff-fed streams except for Buck Springs Canyon, AZ, we observed a change in orientation or location for at least one observed piece of LWD. We suggest that no large run-off events occurred during the 3-year period for which clear imagery are

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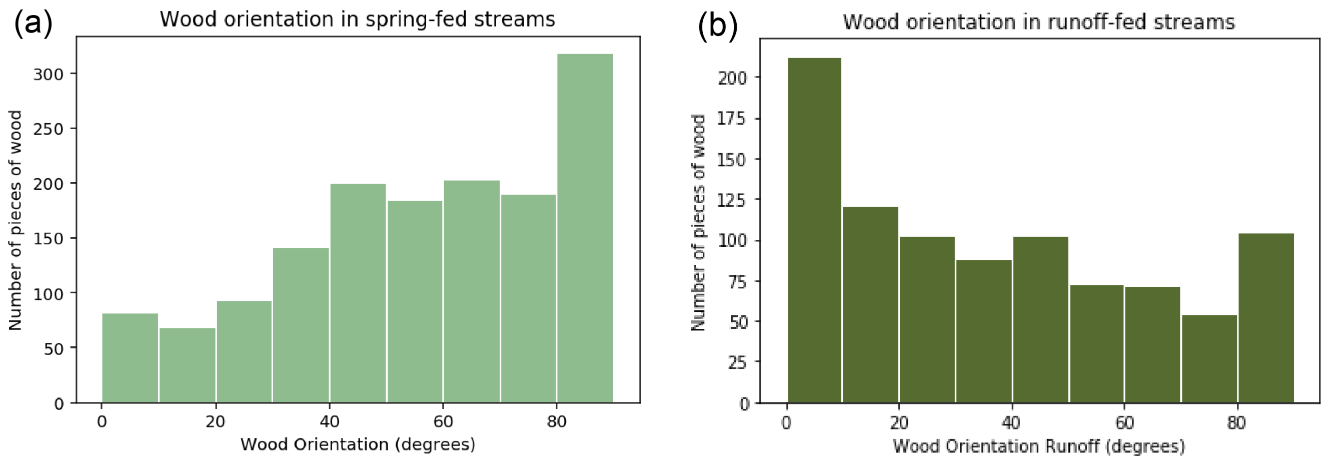

Figure 2. Using google Earth Pro, orientation of woody debris was measured from adjacent bank for approximately 100 pieces of woody debris in each stream which had clear enough imagery to reliably identify LWD (marked by a † in Table 1). Histogram data are aggregated for (a) spring-fed and (b) runoff-fed streams. Wood in spring-fed streams is preferentially oriented from 50-90°, whereas wood in runoff-red streams is more randomly oriented with a significant portion of wood oriented 0-20°.

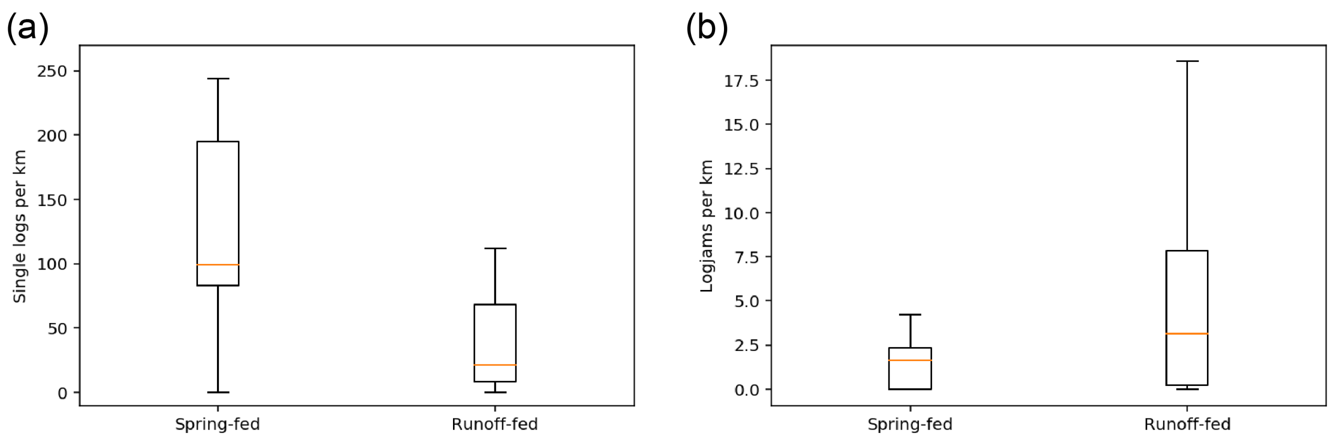

Figure 3. Boxplot representing the number of (a) single logs and (b) logjams identified per km via satellite imagery on spring-fed and runoff-fed streams.

available at Buck Springs Canyon. We thus confirm that there is little mobility of wood in the spring-fed streams in this study, distinct from the motion observed in runoff-fed streams.

A visual representation of the differences between spring-fed and runoff-fed wood dynamics is shown in Figure 4 (a) for Cultus River, OR (spring-fed) and Figure 4 (b) for Cultus Creek, OR (runoff-fed), which both feed into Crane Prairie Reservoir. As shown in Table 1, the measured lengths of LWD at both streams are about 17 m long. The mean discharge of Cultus Creek from 1923-1991 was 0.55 m^3/s with the 95th percentile of flow $q_{95} = 2.3$ m^3/s, while mean discharge in the Cultus River was

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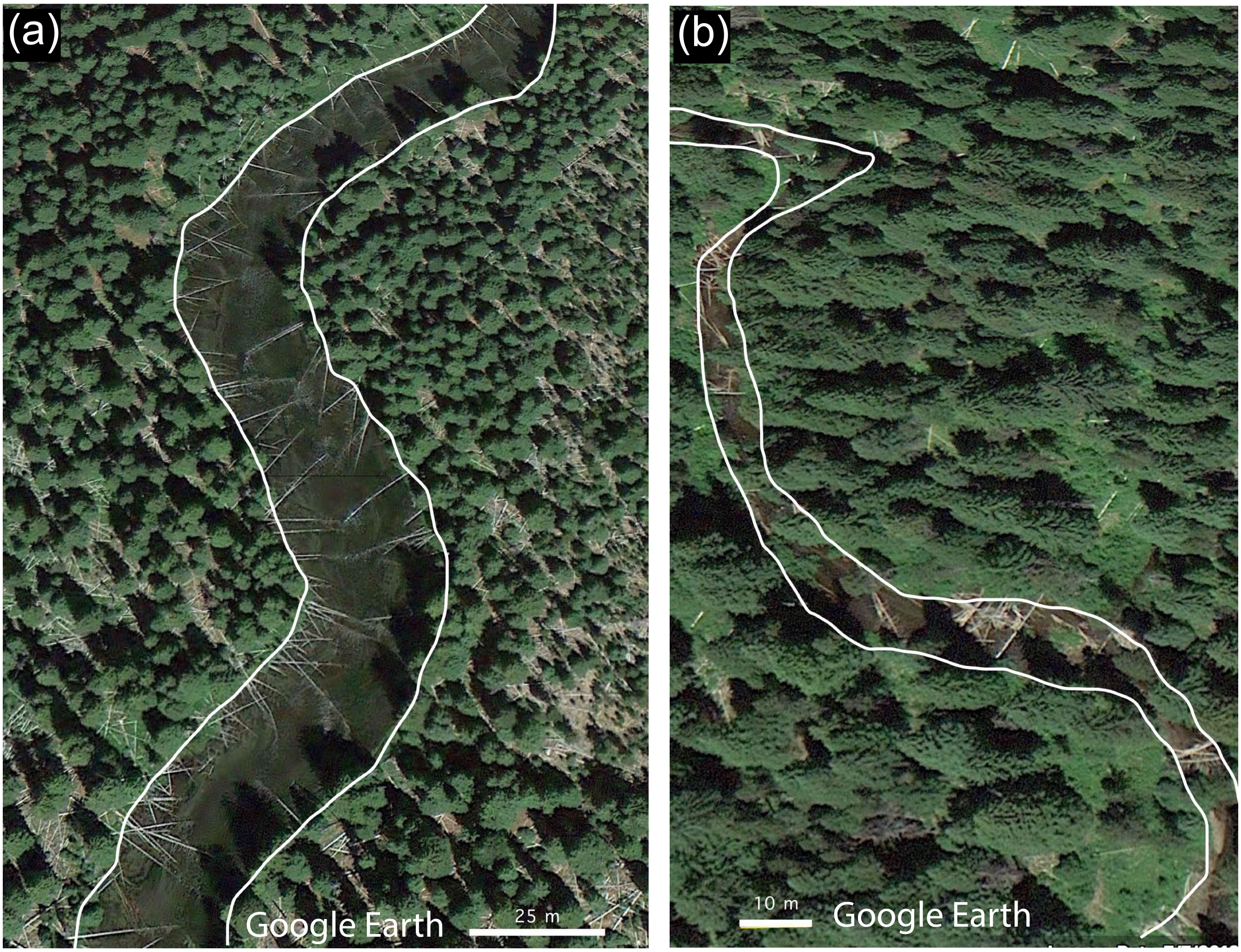

Figure 4. © Google Earth Pro high-resolution imagery showing (a) Cultus River and (b) Cultus Creek. Stream channels are outlined in white, and flow direction is down from the top of the image in both panels. These images are representative of the general wood dynamics in the two streams, where most of the wood in (a) is single logs, and most of the wood in (b) is in logjams, so little of the wood in panel (b) would contribute to the histogram shown in Figure 2 (b).

1.5 m^3/s with $q_{95} = 2.8$ m^3/s (USGS, 2018). Despite the similar peak flows, Cultus River (30.0±3.0 m) is nearly five times wider than Cultus Creek (6.9± 2.8 m). In Figure 4 (b), there are also numerous large logjams visible in Cultus Creek, whereas very few are visible in Cultus River (Figure 4 (a)), and those present are small. This comparison is representative of the types of reaches found in spring-fed versus runoff-fed streams included in this study.

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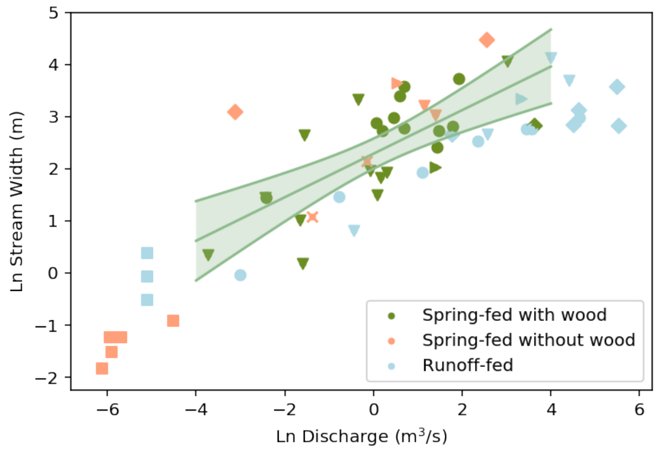

Figure 5. Relationship between bankfull discharge or 1.25 year flow and stream width plotted on a ln-ln plot for spring-fed streams with wood (dark green), spring-fed streams without wood (orange), and runoff-fed streams (light blue). The line of best fit for streams containing wood is shown ($w = aQ^b$, $b = 0.42 \pm 0.09$, $a = 9.9 \pm 1.2$); 95% confidence interval for the fit is shaded. Location symbols are the same as in Figure 6, with the addition of x's for the El Tatio Geyser Field streams. Runoff-fed streams are fit by a statistically significant different value of $a = 5.1 \pm 1.1$, indicating that runoff-fed streams are narrower than spring-fed streams at the same bankfull discharge. All runoff-fed streams contain wood, and no runoff-fed streams without wood were available for comparison.

4.2 Discharge and Width

A common relationship used to describe stream width is the Leopold power law relating width w and discharge Q by constants a and b (Leopold and Maddock, 1953): $w = aQ^b$. Typically, the value of b is close to 0.5, but b can vary depending on the streams being analyzed (Gleason, 2015). Whiting and Moog (2001) found $b = 0.57$ for the spring-fed streams in their study. The finding of Whiting and Moog (2001) suggests that discharge impacts the width of streams in their study to a similar degree as for most channels. We verify the result of Whiting and Moog (2001) for the streams in their study by finding $b = 0.55 \pm 0.1$.

For the full set of spring-fed streams in this study containing wood, we find that $a = 9.9 \pm 1.2$ and $b = 0.42 \pm 0.09$ with a Pearson correlation coefficient of 0.52. Spring-fed streams without wood are fit by a statistically different trendline given by $a = 14.4 \pm 1.4$ and $b = 0.67 \pm 0.08$ with a Pearson correlation coefficient of 0.87. Runoff-fed streams are significantly different from spring-fed streams containing wood only in the coefficient a, with $a = 5.1 \pm 1.1$ and $b = 0.36 \pm 0.03$ with a Pearson correlation coefficient of 0.89 (When repeated without estimated bankfull discharges, the results are statistically indistinguishable except an increase in R^2 to 0.99). The value of a is significantly smaller for the runoff-fed streams than the spring-fed streams included in this study. This corresponds to much narrower widths for the runoff-fed streams, confirming the results of Whiting and Moog (2001). It is also noteworthy that the correlation coefficient for spring-fed streams with wood is much lower than for the other two groups, indicating that there is another very important factor needed to describe width adequately.

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4.3 LWD and Width

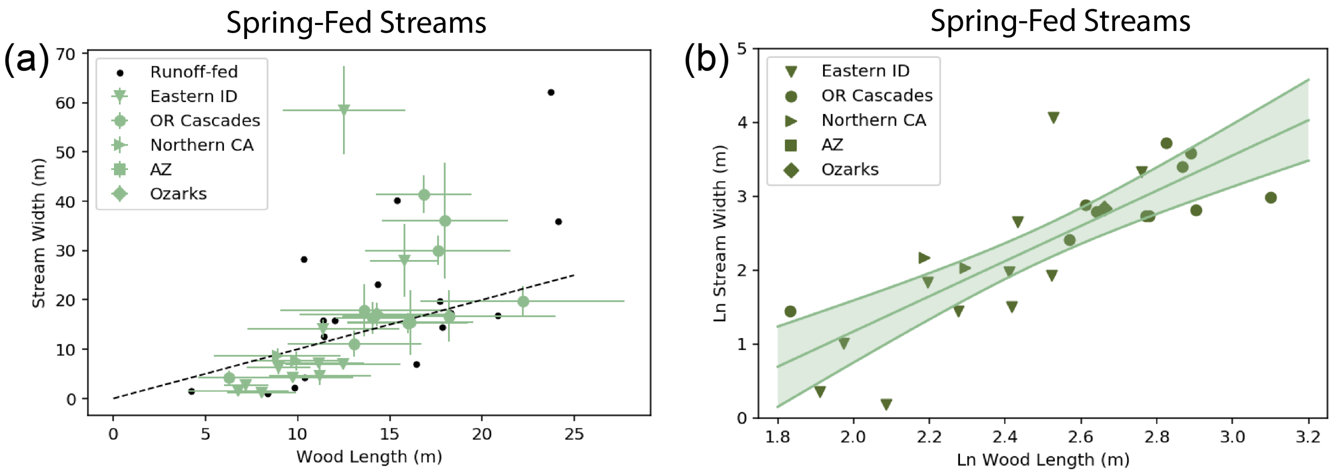

Figure 6. Wood length and stream width were measured using Google Earth Pro satellite imagery. The relationship between wood length and stream width for spring-fed streams is shown (a) on a plot with $width = length$ shown as a dashed line and error bars showing the standard deviation and runoff-fed streams marked with black dots (error bars left off for clarity of viewing) and (b) on a ln-ln plot with the line of best fit ($w = al^b$ with $b = 2.4 \pm 0.4$ and $a = 0.04 \pm 0.03$), error bars and runoff-fed streams left out for clarity. The 95% confidence intervals for the line of best fit is shaded. In both panels, the data symbols represent the geographic locations of the streams. There is no apparent significant clustering by location. In panel (a), streams that fall above the dotted line are wider than the wood load entering the streams, whereas the streams falling below the line are narrower than the wood load.

We compare the stream widths we measured to those measured by Whiting and Moog (2001) for the subset of streams included in both studies. For all of the streams contained in both studies, the widths measured by Whiting and Moog (2001) fall within the confidence interval for the widths measured in this study via remote sensing.

We additionally compare field measurements of wood length of 10 pieces of LWD at Cultus River, OR ([43.82381, -121.79687]) to remotely sensed wood length data for 10 pieces of LWD at the same location. In the field, we find that the wood length was 18.5±5.0 m, and via remote sensing, we measured 17.4±3.9 m. The confidence intervals for these measurements overlap, so we conclude that it is accurate to measure wood length via Google Earth high-resolution satellite imagery.

For the 25 spring-fed streams containing wood, we find that there is a power law relationship between LWD length and stream width, as shown in Figure 6 (b), with a Pearson correlation coefficient of 0.66. For streams lying below the dashed $width = length$ line in Figure 6 (a), wood found in and around the streams is typically longer than the streams are wide, while streams above the dashed line are wider than the LWD found in the system. Most streams in the study are clustered near the dashed line, so wood length is comparable to stream width. There is variation in the length of LWD between streams. This variation is generally geographically explicable, with streams located near one another having similar LWD sizes. Also note that in Figure 6 (a), the standard deviation for wood length generally increases with increasing stream width. We speculate that

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	Function	a	b	c	Adjusted R^2	AICc	AICc Probability	a	b	c	Adjusted R^2	AICc	AICc Probability
		All Spring-fed						Spring-fed $\leq$ 30 m					
1	$w = aQ^b$	14.00	0.27		0.25	118.0	0.36	11.65	0.16		0.16	84.7	0.00
2	$w = al^b$	0.45	1.39		0.29	118.9	0.23	0.24	1.53		0.62	68.0	0.99
3	$w = alQ^b$	1.07	0.22		0.39	116.0	0.99	0.97	0.06		0.54	73.1	0.08
4	$w = lQ^b$		0.25		0.44	116.2	0.91		0.05		0.54	73.1	0.08
5	$w = al^cQ^b$	0.93	0.22	1.06	0.39	117.0	0.60	0.24	0.00	1.53	0.60	71.0	0.22
		All Runoff-fed						Runoff-fed $\leq$ 30 m					
1	$w = aQ^b$	9.53	0.23		0.39	89.8	0.39	8.10	0.19		0.67	47.2	0.11
2	$w = al^b$	0.19	1.68		0.45	87.9	0.99	1.71	0.80		0.24	60.9	0.0
3	$w = alQ^b$	0.92	0.11		0.44	89.1	0.55	0.72	0.10		0.28	60.0	0.0
4	$w = lQ^b$		0.09		0.43	89.2	0.53		0.03		0.16	61.1	0.0
5	$w = al^cQ^b$	0.62	0.09	1.16	0.44	90.0	0.34	90.96	0.34	-1.11	0.78	43.0	0.99

Table 2. Fit statistics for candidate models for spring-fed and runoff-fed streams. Adjusted R^2 and Akaike's Information Criterion (AICc) account for the number of predictive variables. A larger R^2 value indicates better fit, while a smaller AICc value indicates that less information is lost. The AICc Probability is the likelihood that a given model is the best model based on the criterion of lost information as measured by AICc. The results from Adjusted R^2 match very well with the AICc results in ranking. For both runoff-fed and spring-fed streams, we note that models 3, 4, and 5 are essentially identical when fit for all streams since parameters a and c in model 5 are indistinguishable from 1.

larger streams may contain wood that has traveled further and thus exhibits larger variation in size, but we do not have data to confirm this hypothesis. Runoff-fed streams are marked in Figure 6 by black dots.

The relationship between LWD length and stream width is displayed on a ln-ln plot in Figure 6 (b) with the line of best fit for $w = al^b$, where w is stream width, l is wood length, and a and b are constants. The 95% confidence interval is shaded for $a = 0.04 \pm 0.03$ and $b = 2.4 \pm 0.4$. The Pearson correlation coefficient for this relationship is 0.66, indicating that wood is strongly correlated to the width of spring-fed streams. We see from Figure 6 (b) that the fit parameters encompass well the variability in the data. The best fit for the runoff-fed streams is not significantly different from that for the spring-fed streams, with a Pearson correlation coefficient of 0.56.

4.4 Using LWD and Discharge to Describe Stream Width

There are comparably large Pearson correlation coefficients for the relationships between wood and width as well as discharge and width for spring-fed streams, implying both are important descriptive factors for stream width. There is, however, a ln-ln correlation between discharge and wood length with Pearson correlation coefficient of 0.44, indicating that the two parameters do not contain totally unique information but do contain a significant amount of unique information. Since discharge and wood length are both significant descriptors for stream width and contain unique information, we examine a model for stream width incorporating both parameters. Full results for all tested models are shown in Table 2. For all cases, model ranking is very similar for AICc and Adjusted R^2.

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For all spring-fed streams, model fittings of parameter a in model three and a and c in model 5 are indistinguishable from 1, making models 3, 4, and 5 nearly identical, so we discuss only models 1, 2, and 4. Model 4 performs significantly better than models 1 and 2, as demonstrated by a high adjusted R^2 and a low AICc value in Table 2, although there is still a significant probability that model 1 or 2 could be the most effective model (36% and 24% respectively). This is unsurprising given that models 1 and 2 resemble model 5 very closely. For spring-fed streams with an average width less than 30 m (the group of streams which are close to or narrower than available LWD), models 3 and 4 are indistinguishable and models 2 and 5 are indistinguishable, so we discuss only models 1, 2, and 3. Model 1 (based only on discharge), drops in significance from an adjusted R^2 of 0.25 to 0.16 while all other models rise in significance, most notably model 2 which rises from adjusted R^2 of 0.29 to 0.62. This trend is preserved in AICc values, which indicate that model 2 (based only on LWD length) is the highest-performing model for spring-fed streams narrower than 30 m.

For all runoff-fed streams with available discharge and wood length data, models 3, 4, and 5 are indistinguishable, so we evaluate only models 1, 2, and 4. The highest-performing model is model 2 (based only on LWD length), although models 1 and especially 4 receive high AICc probabilities (39% and 53% respectively). When we restrict analysis to runoff-fed streams narrower than 30 m wide, the adjusted R^2 for models 2, 3, and 4 drop significantly, while significance of models 1 and 5 increase. For model 5, though, the fit parameter ($c = -1.1 \pm 0.4$) is negative, completely opposite from that for all runoff-fed streams ($c = 1.2 \pm 0.6$). Due to the small sample size and unexpected sign, we find it unlikely that this model is appropriate in general. If we remove model 5 from consideration, then model 1 is clearly the best remaining model. (When repeated without estimated discharges, R^2 values were 0.98 for all models, likely due to the small number of points, allowing for over-fitting. The values of a and c are still indistinguishable from 1.)

The fit for all of the proposed models is plotted onto graphs for spring-fed (a) and runoff-fed (b) streams in Figure A3.

5 Discussion

5.1 Wood dynamics

We found that there is a significant difference between wood loading in spring-fed and runoff-fed streams. This difference is demonstrated by the different frequencies of single logs versus logjams in runoff-fed and spring-fed streams as well as the orientation histograms for spring-fed and runoff-fed streams. The orientation histogram and historical satellite imagery for spring-fed streams indicate immobile wood, while the histogram and historical satellite imagery for runoff-fed streams indicates frequent log mobility. While it may be more complicated to interpret orientation data in small streams (Kramer and Wohl, 2016), the historical satellite imagery confirm the conclusion that LWD is stable in spring-fed streams and often mobile in runoff-fed streams in this study. The clear differences in wood dynamics suggest a different impact of wood on morphology of spring-fed and runoff-fed streams, in which the impact of single logs may be dominant in the former.

In particular, we note that the wood dynamics observed in spring-fed streams in this study differ from the logjams that would be typically expected for streams in which wood length is similar to or smaller than channel width (Kramer and Wohl, 2016). The preponderance of single logs matches better with the category of small streams, where stream width is less than wood

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length (Kramer and Wohl, 2016). This difference suggests that adding a criterion for hydrograph variability may be useful in classifying streams by LWD. Such a criterion may allow for the classification of spring-fed streams as small due to their low peak discharge relative to the mean.

5.2 Discharge and width

Figure 5 shows a distinction between spring-fed streams with and without wood in the relationship between discharge and width. There is, however, only a small set of data points available to identify the relationship for spring-fed streams without wood, and 5 of the 12 streams in this group are unusually narrow for the study group. The remaining points are not visually distinct from the pointcloud for spring-fed streams with wood. For the streams in the Ozarks and Eastern Idaho, we speculate that these streams may once have had significant amounts of wood due to their size, location in wooded areas, and a history of ”management” that may have included wood removal (Willis et al., 2017; Schaper, 2001; Maramec Spring Park; Silver Creek, 2006). If this is the case, then the presence of wood may have had a lasting impact on the channel morphology that is still measurable despite the present lack of wood, explaining why those streams lie in the point cloud for streams containing wood. While many, if not all, streams in the study may have been subject to wood removal at some point, we take the current wood load as representative of the type of wood dynamics that would have existed prior to wood removal. Additional management is not expected to have had much impact on results since geomorphic restoration efforts are typically not attempted over large reaches such as those used in this study (Boyer, Berg, and Gregory, 2003).

In contrast to the U.S. streams the El Tatio streams, are above the treeline so would not have had wood in the past. It is possible that the channels were shaped by a different hydrological regime, but the streams run through glacial outwash, so the shape of the channel is dynamic and is probably controlled by the contemporary, spring-fed fluvial regime. Including all spring-fed streams in calculating the relationship between stream width and discharge does not significantly change the relationship parameters. This finding indicates that we are unable to reliably distinguish between spring-fed streams with wood and those without, an analysis which may be confounded by the minimal availability of spring-fed streams without wood for data collection.

There is, however, a robust distinction between spring-fed and runoff-fed streams in terms of the relationship between discharge and stream width, demonstrated in the fitted parameter a. This parameter indicates that for streams larger than those measured by Griffiths, Anderson, and Springer (2008), it is generally the case that spring-fed streams are wider than runoff-fed streams.

5.3 LWD and width

We expect wood to be most important for describing the width of streams when it is comparable in size to the streams. When wood is much longer, then additional increases in wood length do not change the way wood interacts with the channel since the majority of the wood is outside of the channel. When the stream is much wider than the wood, a similar effect is expected. In that situation, LWD can only be close to the bank on at most one side of the stream. Zhang, Rutherfurd, and Marren (2015) found that when LWD at a given orientation is closer to the bank, the impact on shear stress is greater. Taking distance from the

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bank as the most important predictor of how important a single log is in altering channel properties, then decreasing the size of LWD after a certain point does not change the ability of the wood to be close only to one bank. Thus, we expect LWD to be less important in two cases: 1) where streams are very narrow and 2) where streams are very wide. In other words, when discharge is outside a certain range, we expect the impact of LWD on stream width to decrease since channels are either very wide in comparison to wood length or very narrow. We see visually in Figure 6 (a) that when streams are wider than about 25 m, the points deviate significantly from the otherwise apparently linear trend. In fact, we find that there is a linear relationship with Pearson correlation coefficient of 0.75 for streams smaller than 25 m wide, more significant than the ln-ln relationship for all data. This stronger correlation aligns well with our hypotheses about when wood should have an impact on stream morphology. While we are unable to say with confidence whether or not there is a difference between spring-fed streams with or without wood, we find that deviation from the relationship occurs where expected if wood were driving the relationship.

In the case of runoff-fed streams, although the best fit matches closely with that for spring-fed streams, we find it likely that this relationship does not hold in general for runoff-fed streams. Since there is a strong bias in our set of runoff-fed streams toward high-discharge streams, with over 70% of the runoff-fed streams exhibiting a discharge higher than 5 m^3/s and most over 50 m^3/s, it may be coincidence that the runoff-fed streams included in this study are about as wide as the wood found in them. The difficulty in identifying runoff-fed streams in geologic settings in which spring-fed streams occur prevents us from assessing more fully the relationship between wood length and stream width in runoff-fed streams in a comparable geologic setting.

5.4 Using LWD and discharge to describe stream width

The large Pearson Correleation Coefficients for the relationships in spring-fed streams between discharge and width as well as wood length and width indicate that combining both pieces of data into a single model could provide increases in model performance. This initial thought is borne out by the increase in adjusted R^2 and decrease in AICc for the model $w = lQ^b$ compared to the relationships for either wood length or discharge alone. However, when the analysis is repeated for streams narrower than 30 m (where wood is close to the width of the channel), the most significant relationship becomes $w = al^b$, depending only on wood length.

For runoff-fed streams, we repeat the same analyses, and we find no improvement in model performance by including both variables (Q and l). Unlike for the case of spring-fed streams, when we again restrict the streams included to those narrower than 30 m, the significance of the relationship between wood length and stream width (model 2) drops significantly, making the relationship $w = aQ^b$ the most significant of the tested relationships. This result agrees with our hypothesis that the good fit between wood length and width is coincidental since removing streams where wood should be less important causes the significance to fall instead of rise. Thus, we conclude that model 2 is likely not the best model for the case of all runoff-fed streams. The next best candidate is model 4, although model 1 is nearly as effective. This suggests that discharge is also the more important model factor for all runoff-fed streams, not just those smaller than 30 m.

The finding that model 4 performs well for both spring-fed and runoff-fed streams is particularly interesting since the form ($w = lQ^b$) resembles the Leopold and Maddock formula except with l instead of a. Thus, we can think of l as a useful factor in understanding the coefficient a.

6 Conclusions

We were able to use high-resolution satellite imagery to reproduce measurements taken in the field by Whiting and Moog (2001), Hygelund (2002) and new measurements taken for this article. Remote sensing tools provide a more straightforward way to effectively collect data at a large number of field sites.

We verify the result of Whiting and Moog (2001) that spring-fed streams are generally wider than their runoff-fed counterparts. We also identify differences in dynamics of LWD between spring-fed and runoff-fed streams which underline the importance of peak flow and flow variability when identifying stream dynamics in relation to LWD load. While we are unable to isolate LWD as the cause of the difference in morphology between spring-fed and runoff-fed streams, we note that a model for stream width in spring-fed streams based solely on wood length l is the best model tested in this study for streams comparable in size to LWD. We therefore recommend further study into mechanisms by which LWD may control the width of spring-fed streams. This result provides deeper insight into what controls the width of streams in general by demonstrating a strong relationship between wood length and stream width when discharge is controlled. The importance of LWD in determining channel width also has management and restoration implications.

Data availability. Datasets related to this article can be found at https://github.com/lapidesd/Lapides_Manga_2019 (Lapides and Manga, 2019).

Author contributions. Dana Lapides performed data collection and analysis and interpretation of results. Michael Manga suggested the project idea and provided substantive feedback and ideas for analysis methods and interpretation.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This work was partially funded by the Hellman Foundation and the University of California, Berkeley.

https://doi.org/10.5194/esurf-2019-60
Preprint. Discussion started: 24 October 2019

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