Referee #1:

Summary: The authors have addressed a comparison of the influence of large wood in the channel morphology of spring-fed streams vs runoff-fed streams. This issue has been very little studied, and the authors have highlighted its importance. In general, they have produced a very interesting manuscript. I have several observations, some more relevant than others, and I will list all of them following the text. I consider that some of my observationem are important and need to be solved, so my recommendation is to accept with Major Revision this manuscript. I am not asking for additional analyses, but parts of the manuscript must be revised and completed. I am willing to revise a new version of this article.

Abstract: 1. Page 1, line 2. The authors write: "Due to the distinctive damped hydrograph of spring-fed streams, large woody debris is less mobile in spring-fed than runoff-fed stream channels". As the authors are introducing the reader to the topic, I suggest completing the phrase with a few words about the distinctive hydrograph of runoff-fed streams; this can appear a little obvious, but I consider it will complete the picture. 2. Page 1, phrase between lines 4 to 6, "We used high-resolution satellite imagery . . .. . . 38 spring-fed and 20 runoff-fed streams". This statement does not fully agree to what is written between lines 60-64, so please revise and rewrite. 3. Page 1, line 8. Additionally, to what? Please revise and complete. 4. Page 1, phrase between lines 6 to 9: what about wood jams? 5. Page, the last phrase of Abstract is very close to a repetition of the previous one. I suggest rewriting and merging them in just one phrase.

Introduction: 6. Page 2, line 26: environmental variables, such as? Please revise and complete. 7. Page 2, phrase beginning in line 30, about the Griffiths et al (2008) publication. The authors write that the study in Arizona was of spring-fed streams, but this phrase ends mentioning a comparison to runoff-fed streams. Please revise and rewrite accordingly. 8. Page 2, phrases between lines 33 to 42. The authors introduced the issue of LWD, and the differences of LWD load between streams. I consider that information of LWD recruitment mechanisms and sources and characteristics of riparian forests in these streams is needed.

Field area: 9. Page 3, line 68. Not clear what the spring-fed streams in El Tatio Geyser Field in Chile are really providing to this research. These streams do not have LWD (see page 5, line 96). This needs extra explanation, here, and in the rest of the manuscript.

Methods: 10. Page 4, line 108. Please complete giving the dimensions of the LWD. 11. Page 4, line 108. Please complete giving the resolution of the high-resolution imagery. dimensions of the LWD. 12. Page 6, line 128. The precision of the technique of measuring length in Google Earth Pro was tested for longer LWD pieces, but what for shorter pieces? Please complete.

Discussion: 13. Page 14, line 285, the authors mention wood loading. Please explain and complete because this issue is not addressed or described in previous chapters (Methods, Results). 14. Page 15, line 327, the authors seem to consider that most longer wood pieces are outside of the channel. I am not convinced at all with this asseveration; if outside, are these long logs spanning the channel? Please revise and explain. 15. Page 16, line 332. LWD can be less important where streams are very narrow and where streams are very wide, but this is always in relation to wood dimensions (length in this case). Please complete. 16. Page 16, lines 334-336 and then 352 and 356, the authors discuss about streams narrower than 25 and 30 m. Why this difference? Please explain.

Response to Referee #1:

Summary response to review: Thank you for your comments. We have altered the manuscript to address the concerns that were raised. The bulk of the comments address the scaling between channel dimensions and LWD size. This perspective is valuable and greatly appreciated. Specific changes are detailed below.

Response to comments on abstract: We have altered the abstract to 1. add a statement about the hydrograph of runoff streams, 2. Include the full content of lines 60-64, 3. Correct language for clarity, 4. Add a statement about logjams, 5. Remove repetitive phrases.

Response to comments on introduction: We have altered the introduction to 6. Clarify the meaning of the sentence, 7. Clarify the intent of the Griffiths et al (2008) study, 8. Describe recruitment mechanisms.

Response to comments on Field area: We have altered the field area section to 9. Describe why the El Tatio streams were included in this study. They are the most reliable example of spring-fed streams not containing wood. In order to assess whether wood causes spring-fed streams to be wide, we would like to compare spring-fed streams with wood to spring-fed streams without wood. The only other spring-fed streams in this study that don't contain wood likely had wood in the past since they run through forested watersheds.

Response to comments on methods: 10. The table contains stream width and LWD dimensions. We altered the methods section to 11. State the likely resolution of Google Earth Pro imagery and 12. Describe why precision was tested only for longer LWD pieces. All of the LWD observed at the site visited was long. There were no shorter pieces available.

Response to comments on discussion. We altered the discussion to 13. A clearer description of the meaning of the sentence, 14. Explain that we suggest that longer wood is spanning the channel or the majority of a given piece (not the majority of wood pieces) is outside the channel when the channel is comparatively narrow, 15. Clarify that channel width is in comparison to wood dimensions, and 16. Describe that streams wider than 30 m (corrected to 30 in all places) are significantly wider than LWD in this study. Thus, we hypothesize that LWD length should be more important for streams narrower than 30m than those wider than 30m in this study.

Referee #2:

Overall Summary: This article makes observations and comparisons in stream width and wood loading between spring fed streams versus run-off streams of similar discharges. The topic is interesting and the authors provide some compelling data gathered from remote sensing to broaden the traditional perspective that stream width is mostly a function of discharge to also viewing wood as a primary driver of stream widths. The paper is well written and the statistics well done. I originally reviewed this article for another journal and supplied a fairly critical review with the suggestion to reject based on some very major concerns. I was pleasantly surprised to find that this version of the manuscript is substantially altered from the original submission and thoroughly addressed most of my concerns from the original review. It is very much improved and is now ready for publication. I suggest accept with minor edits.

Comment 1: The presence of wood jams versus single logs plays a role in not just channel width, but impacts whether channels are multi-thread versus single thread. Often jams are a forcing mechanism for multi-thread channels. I would have like to see this pointed out/ discussed a little bit within the introduction and in context of the case study streams. Were all the streams studied single channel streams? Or did the run-off streams have multi-threads along with the log jams? I don't expect this to become a major point of the paper, but I do think it is salient when interpreting the width of streams due to wood loading. Example locations to include this- ex. Lines 55-58. Wood accumulations may not just increase width or width to depth ratios, especially for places where they promote avulsions and multi-threads (see 10.1525/bio.2013.63.6.6, 10.1177/0309133314548091)

Comment 2: Line 53: This hypothesis could have a citation to back it up

Comment 3: It was unclear to me which study streams had erodible beds versus which ones didn't. Some descriptions mentioned that the stream went through erodible materials (i.e. glacial outwash, alluvium, etc) but other areas just mentioned that the underlying hardrock geology. It is important to know if all the streams in this study had erodible banks versus streams in bedrock channels. Can all the streams adjust their planform to the flow and to wood? Perhaps table one can include a field that specifies whether banks were erodible or not.

Comment 4: Caption for figure 4 should mention that these two streams have similar flow.

Comment 5: Results presented in line 237 should be highlighted more in the conclusion etc. As yet there really isn't that much in the wood literature looking at the accuracy of measuring wood from aerial photographs or satellite imagery. This is a valuable contribution and it would be nice to see it a little more light shone on it, rather than having it be buried in the middle of the paper.

Comment 6: Symbol shapes in legend in Figure 5 don't match symbols in plot

Comment 7: The findings regarding differences in mobility between spring fed and run-off could be highlighted more strongly in the discussion. They were presented in the results and thus should be discussed more fully in the discussion. For example, I found the increase in std deviation of width with stream width to be an interesting finding. . . but the speculation that this has to do with mobility and wood travelling further a little bit contradictory with your finding that the wider spring fed streams have less mobility than the narrower run-off streams. Some more discussion about mobility differences is warranted.

Comment 8: Personally I prefer the acronym LW rather than LWD. I don't like the negative connotation of 'debris' assigned to LW in streams. I would encourage the authors to consider not using LWD (keep it as a key word for searchability)

Comment 9: The last sentence of the conclusion seems out of place. I would delete it. Since the paper never really goes into management, it seems out of place to mention it out of nowhere in the last sentence of the paper.

Response to Referee #2:

Response to review summary: Thank you for your comments. We have altered the manuscript to address the sugestions and concerns that were raised. This review is thorough and thoughtful, and much appreciated. Specific changes are described below.

Comment 1: Thank you for pointing out the importance of logjams for causing channels to develop multiple threads. There are small reaches in some of the streams in this study that are multi-threaded, and these reaches contain a significant amount of wood and logjams. We included this observation in the manuscript and added a brief statement about the impact of logjams on multi- or single-threads in channels around Line 55, as recommended.

Comment 2: We added a citation for logjams in runoff-fed streams in the hypothesis on Line 53, as recommended.

Comment 3: For clarity, we included a statement at the beginning of the field area section that notes that all streams in the study run through erodible material. The underlying hardrock geology is required to produce the upwelling of flow for the spring-fed channels, but the channels themselves are able to adapt quickly.

Comment 4: We added q_95 values to the caption for Figure 4 to demonstrate that the streams have similar flow.

Comment 5: It is nice to hear that quantifying the accuracy of satellite-derived wood measurements is so valuable. We added an extra couple of sentences in the conclusion to highlight that the comparison between field measurements and remote sensing yielded good agreement, increasing confidence in the accuracy of remote sensing for producing quantitative results.

Comment 6: We added symbol shapes to a legend in Figure 5 so that both colors and shapes are clearly labeled in the figure.

Comment 7: We added more discussion about wood mobility, specifically focused on the finding of increased std of wood length with increasing stream width in spring-fed streams. The std for wood length in runoff-fed streams is generally comparable with the std for wood length in larger spring-fed streams in the same geographic area. Although mobility appears to be higher in runoff-fed streams than spring-fed streams, the increase in std with increasing stream width in spring-fed streams may be indicative of increased mobility compared to smaller spring-fed streams. There is likely a maximum std given the population of wood available in a geographic area.

Comment 8: We appreciate the suggestion to replace the acronym LWD with LW to avoid the negative connotations associated with ‘debris.’ We now use the acronym LW.

Comment 9: We removed the last sentence of the conclusion.

~~Woody debris~~ Large wood 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~~ (as compared to large peaks visible in the hydrographs of runoff-fed streams), large wood is less mobile in spring-fed than runoff-fed stream channels, so wood is more likely to remain in place than form logjams as in runoff-fed streams. 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~~ wood length, and channel width in 38 spring-fed and 20 runoff-fed streams, additionally responding to a call for increased use of remote sensing to study wood dynamics and daylighting previously unpublished data. 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~~ 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 transport a proportionally larger amount of sediment in everyday flows than high-flow events, leading to different channel responses to ~~environmental variables~~disturbance, such as flow obstacles(Whiting and Stamm, 1995). Spring-fed streams are a promising test group for understanding some of the controls on stream width since their stable hydrographs reduce the number of variables impacting the channel.

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~~ comparing spring-fed to runoff-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~~wood (LW). The streams studied by Whiting and Moog (2001) had high discharge and significant amounts of ~~LWD~~LW, while the streams studied by Griffiths, Anderson, and Springer (2008) had very low discharge and essentially no ~~LWD~~LW.

In streams included in this study, LW is typically recruited through wind storms, death by bark beetles, and undercutting banks. The presence of ~~LWD~~ LW increases variance in channel width, demonstrating the capacity to either constrict or widen (Montgomery et al., 2003). Channel widening associated with ~~LWD~~ LW 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.~~ LW. However, with multiple single logs in a stream, the effect is enhanced when single logs are very close together but dampened when they are moderately closely spaced (Zhang, Rutherfurd, and Marren, 2019). In contrast, removal of ~~LWD~~ LW 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~~ LW constriction of channel width is streambank stabilization by ~~LWD~~ LW (Montgomery et al., 2003).

Despite evidence that ~~LWD~~ LW impacts channel dimensions, ~~LWD~~ LW was absent from early discussions of channel geometry (Gleason, 2015). We hypothesize that ~~LWD~~ LW widens spring-fed streams. In general, the stability of ~~LWD~~ LW in channels is related to flow characteristics of the stream and the size of ~~LWD~~ LW (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~~ LW 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~~ LW 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 mobility promotes the development of logjams in runoff-fed streams (e.g., Martin and Benda, 2001) and explains the paucity of logjams in spring-fed streams, where single logs may dominate the population of LWD. We LW. In addition to the impacts on channel widening, the presence of logjams may impact morphology by forcing a multi-threaded rather than a single-thread channel (Wohl, 2014; Polvi and Wohl, 2013). With a low abundance of logjams in spring-fed streams, we thus expect that the wood interaction mechanism explored by Zhang, Rutherfurd, and Ghisalberti (2016) for single logs in single-thread streams (i.e. an increase in bank erosion) may dominate, leading to channel widening associated with the presence of LWDLW. 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.

The purpose of this study is to examine the empirical relationship between LWD LW 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 LW and width of stream channels. This study is limited to exploring width as opposed to width:depth ratio due to the use of remote sensing for data collection.

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. All streams included in this study have erodible banks. Streams in this study are generally single-threaded with some examples of multi-threaded reaches in channels, generally coinciding with large amounts of LW.

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.

~~29~~

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).

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. These streams are included for comparison between spring-fed streams with and without wood since these streams are above treeline and have no recent history of LW. Other spring-fed streams with no visible LW in this study may have had LW in recent history since the watersheds they run through contain forests.

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~~ LW (e.g., Leckie et al., 2005; Senter et al., 2017). Using Google Earth Pro high-resolution imagery ~~,~~ (generally 0.15m

	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.

resolution–high enough resolution to get accurate measurements, as suggested by Ruiz-Villanueva et al. (2016)), 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~~ LW 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 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%) ~~gives us identifies~~ suggests relatively high precision for the technique. All LW observed via satellite imagery and in the field at this location was long, so no estimates on accuracy of the method for measuring small pieces of LW were possible.

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~~ LW in this study. As a result, we noted orientation of ~~LWD~~ LW 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 period at any site (Arguez et al., 2010), although local conditions may deviate from regional averages. We primarily observed single pieces of LWD LW 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. These data also allow for a sense of how close LW is to one another. This is important since the effect of LW on bank erosion is increased when single logs are close together (Zhang, Rutherfurd, and Marren, 2019). 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. $w = aQ^b$
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 0-20°. While the aggregate histograms exhibit clear results, many individual histograms demonstrate differences from these trends (see supplement). We considered whether basin size impacted the results since larger basins tend to transport more wood (Ruiz-Villanueva et al., 2016), but that observation does not explain the data aberrations. 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~~ LW 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. The high density of single logs means that LW is closely spaced in the streams in this study. 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. This also led to more difficulty in measuring orientation of single logs in some runoff-fed channels when multi-threaded channels made determining orientation with flow more difficult.

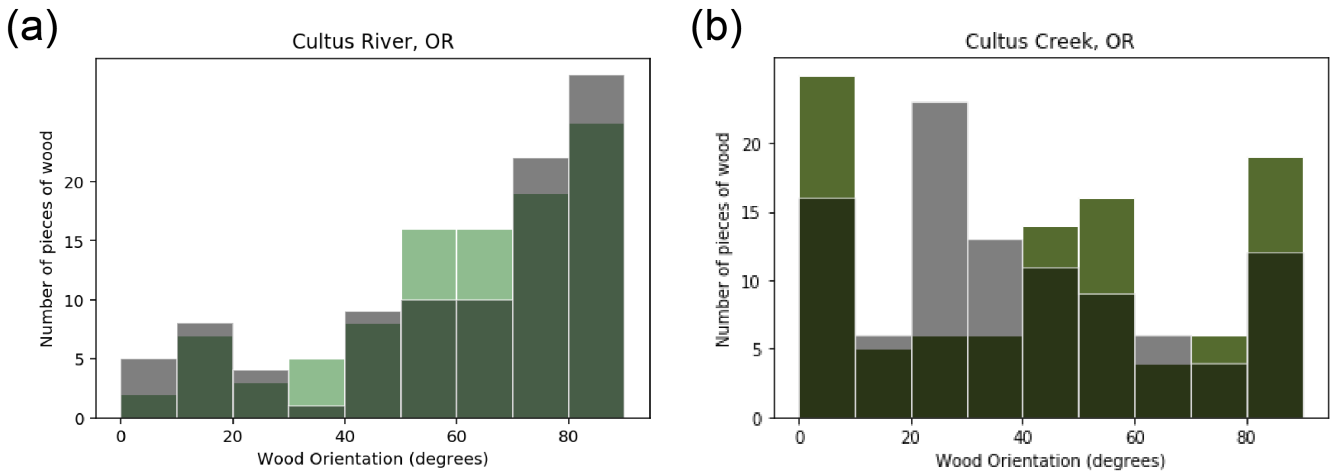

Figure 1. Orientation of ~~woody debris~~ wood was measured from adjacent bank for approximately 100 pieces of ~~woody debris~~ wood using Google Earth Pro (green). Hygelund (2002) measured orientation of ~~woody debris~~ wood in the field (transparent black). Data are shown together for (a) Cultus River 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.

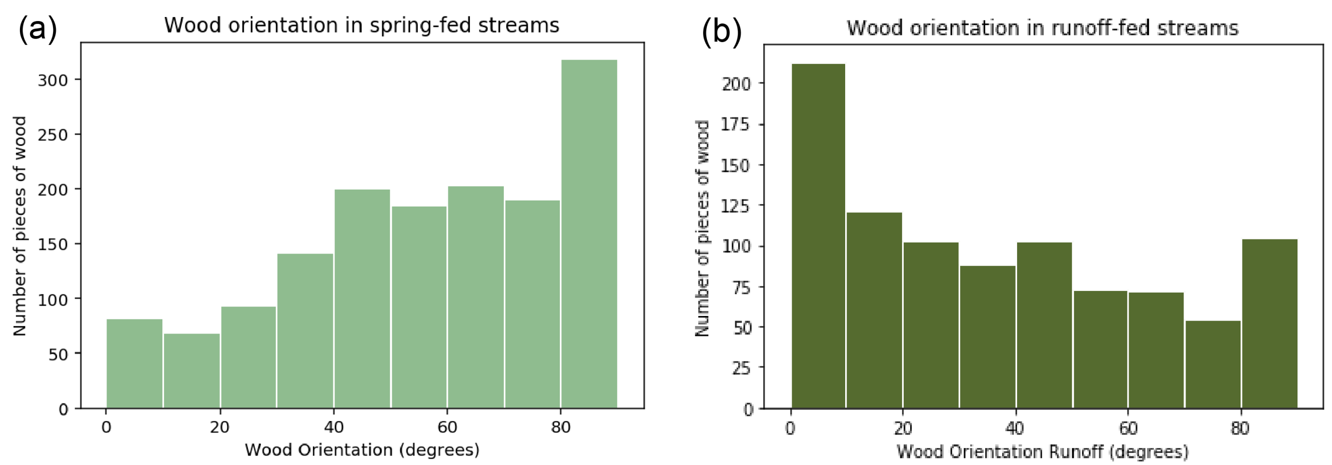

Figure 2. Using google Earth Pro, orientation of ~~woody debris~~ wood was measured from adjacent bank for approximately 100 pieces of ~~woody debris~~ wood in each stream which had clear enough imagery to reliably identify ~~LWD~~ LW (marked by a † in Table 1). Histogram data are aggregated for (a) 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°.

We verify conclusions about residence of ~~LWD~~ LW 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~~ LW at each site. In each spring-fed stream, we were unable to detect any changes in wood placement at any site. In all

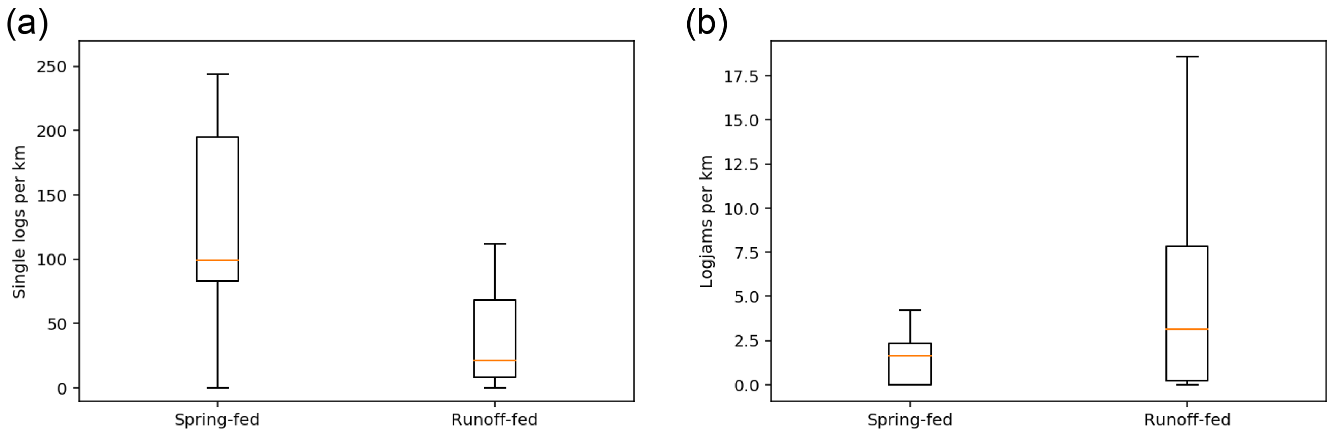

Figure 3. Boxplot representing the number of (a) single logs and (b) logjams identified per km via satellite imagery on spring-fed and runoff-fed streams.

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~~LW. We suggest that no large run-off events occurred during the 3-year period for which clear imagery are 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~~ LW 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 1.5 m^3/s with $q_{95} = 2.8$ m^3/s (USGS, 2018). Despite the similar peak flows, Cultus River (30.0$\pm$3.0 m) is nearly five times wider than Cultus Creek (6.9$\pm$ 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.

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

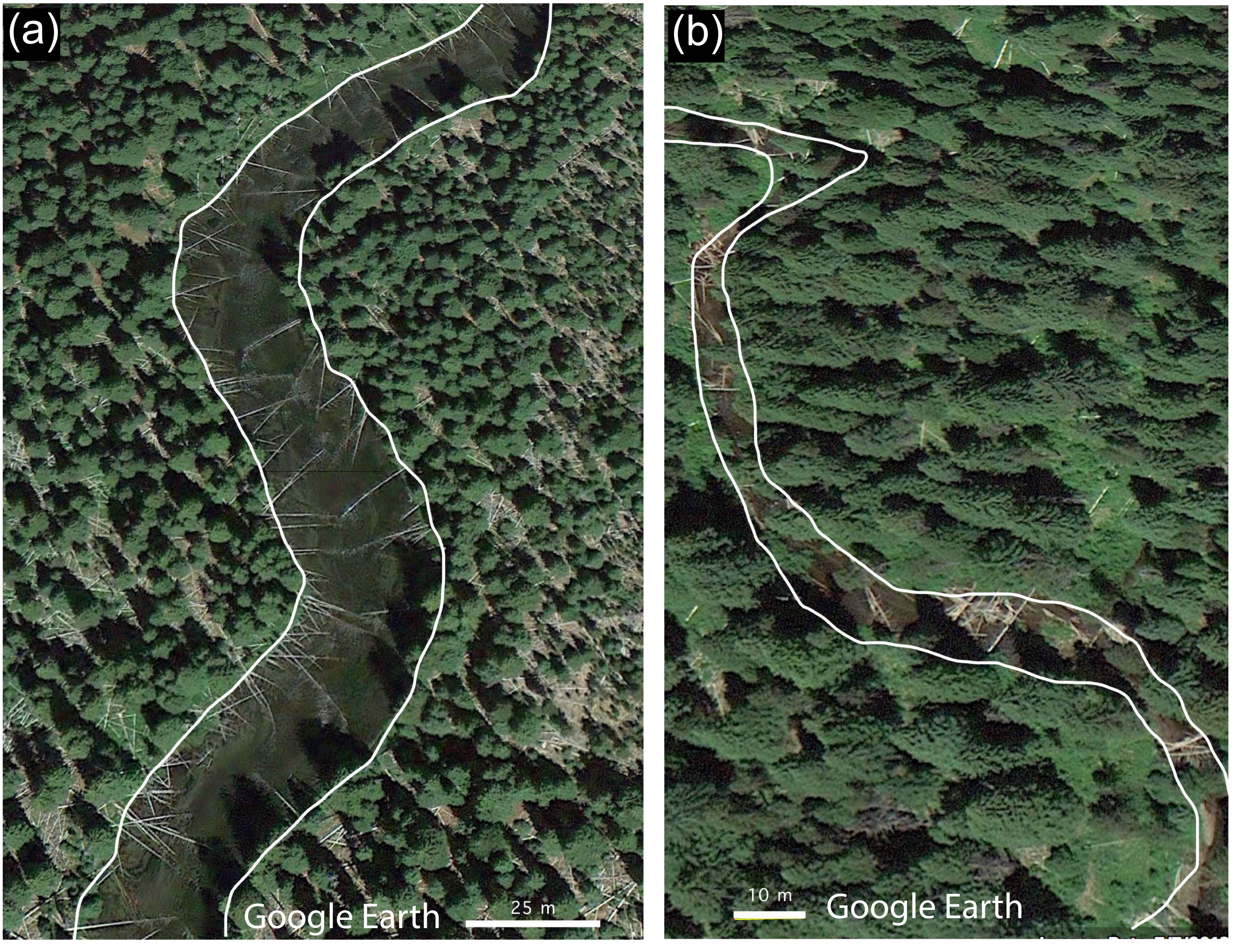

Figure 4. Google Earth Pro high-resolution imagery showing (a) Cultus River ($q_{95} = 2.8$ m^3/s) and (b) Cultus Creek (($q_{95} = 2.3$ m^3/s). Stream channels are outlined in white, and flow direction is down from the top of the image in both panels. These images are representative of the general wood 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).

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

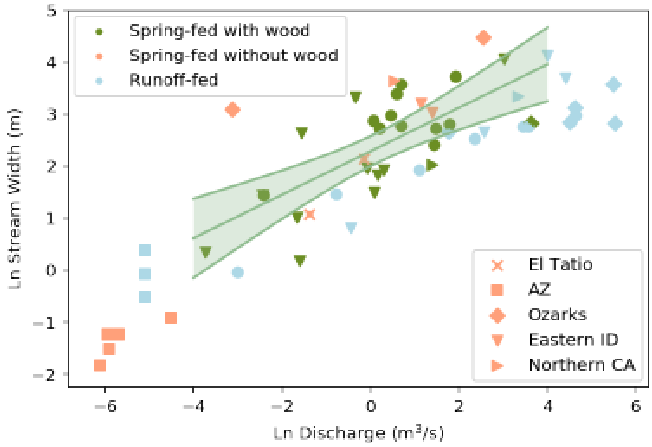

Figure 5. Relationship between bankfull discharge (or 1.25 year flow as an approximation to bankfull discharge for some runoff-fed streams marked in Table 1) and stream width plotted on a ln-ln plot for spring-fed streams with wood (dark green), spring-fed streams without wood (orange), and runoff-fed 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~~ Stream types are ~~the same~~ denoted by color, as shown in ~~Figure 6~~the top left, ~~with~~ and locations are denoted by shape, as shown in the ~~addition of x's for the El Tatio Geyser Field streams~~bottom right. 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.

is much lower than for the other two groups, indicating that there is another very important factor needed to describe width adequately.

4.3 ~~LWD~~ LW and Width

We compare the stream widths we measured to those measured by Whiting and Moog (2001) for ~~a subset of the streams contained in this study~~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~~ LW at Cultus River, OR ([43.82381, -121.79687]) to remotely sensed wood length data for 10 pieces of ~~LWD~~ LW 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.

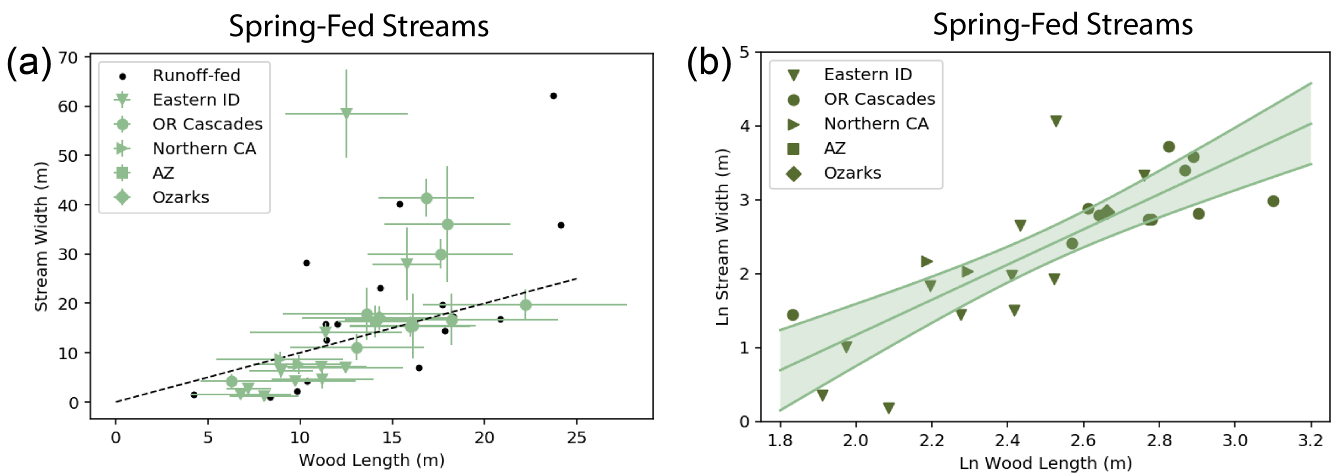

Figure 6. Wood length and stream width were measured using Google Earth Pro satellite imagery. The relationship between wood length and stream width for spring-fed streams is shown (a) on a plot with $width = length$ shown as a dashed line and error bars showing the standard deviation and runoff-fed 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.

For the 25 spring-fed streams containing wood, we find that there is a power law relationship between ~~LWD~~ LW 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~~ LW 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~~ LW between streams. This variation is generally geographically explicable, with streams located near one another having similar ~~LWD~~ LW sizes. Also note that in Figure 6 (a), the standard deviation for wood length generally increases with increasing stream width. We speculate that 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~~ LW 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.

	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.

4.4 Using ~~LWD~~ LW 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.

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~~LW), 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~~ LW 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~~ LW 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~~ the residence location and time of LW 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~~ LW is stable in spring-fed streams and often mobile in runoff-fed streams in this study. Even so, wood in larger spring-fed streams is likely more mobile than wood in smaller spring-fed streams since the mean discharge is higher, although mobility in runoff-fed streams appears to be much greater. We also note that the standard deviation in wood length generally increases with increasing stream width in spring-fed streams, while standard deviation in wood length in runoff-fed streams is generally comparable with the standard deviation for larger spring-fed streams in the same geographic region in this study, supporting the hypothesis that increased wood mobility increases the standard deviation in wood length. 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 length (Kramer and Wohl, 2016). This difference suggests that adding a criterion for hydrograph variability may be useful in classifying streams by ~~LWD~~LW. 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; ?; Silver Creek, 2006)~~ (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~~ LW 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 than the width of the stream, then additional increases in wood length do not change the way wood interacts with the channel since the majority of the wood piece is outside of the channel ~~. When the stream is~~ since nearly all wood observed in spring-fed streams is oriented closer to perpendicular to the bank than parallel, causing wood to either span the channel or interact with the channel only for part of the LW length. Dixon and Sear (2014) note that LW longer than

2.5 times the channel width are generally immobile. While LW is immobile, though, the full length of the LW is relatively unimportant for its impact on stream width beyond the fact that it is longer than the channel is wide. Conversely, when the stream is much wider than the wood, ~~a similar effect is expected. In that situation, LWD~~ LW can only be close to the bank on at most one side of the stream. Zhang, Rutherfurd, and Marren (2015) found that when ~~LWD~~ LW at a given orientation is closer to the bank, the impact on shear stress is greater. Taking distance from the bank as the most important predictor of how important a single log is in altering channel properties, then decreasing the size of ~~LWD~~ LW after a certain point does not change the ability of the wood to be close only to one bank. Thus, we expect ~~LWD~~ LW to be less important in two cases: 1) where streams are very narrow in comparison to LW length and 2) where streams are very wide in comparison to LW length. In other words, when discharge is outside a certain range, we expect the impact of ~~LWD~~ LW 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. For streams in this study wider than 30m, streams are much wider than the LW found in or near them. In fact, we find that there is a linear relationship with Pearson correlation coefficient of 0.75 for streams smaller than ~~25~~ 30 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~~.~~, i.e. when LW is comparable in length to stream width. 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~~ LW 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. Streams narrower than 30 m are examined separately since this is the group of streams that we hypothesize should be most impacted by LW.

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. It is particularly notable that there is a significant overlap in confidence intervals for the wood lengths measured via remote sensing and in the field. This contribution increases confidence in the use of remote sensing to assess LW accurately and quantitatively. 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~~ LW 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~~ LW load. While we are unable to isolate ~~LWD~~ LW 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~~LW. We therefore recommend further study into mechanisms by which ~~LWD~~ LW 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).

7 ~~Appendix A~~

~~Individual histograms of wood orientation for spring-fed streams included in the histogram analysis. All histograms demonstrate preferential orientation of wood away from the flow direction, with most wood oriented 50-90°.~~

~~Individual histograms of wood orientation for runoff-fed streams included in the histogram analysis. Histograms in (a), (d), and (e) demonstrate wood orientation with flow.~~

~~We test the utility of five power law models shown in the legend in panel (a). The best fit is shown for (a) spring-fed streams and (b) runoff-fed streams for each model. The models are very similar to one another for runoff-fed streams, with the model $w = aQ^b$ based only on discharge performing the best. For spring-fed streams, the model based only on discharge performs worst, while the other models are similar to one another with the model $w = lQ^b$ performing best for the full set of streams, but the model $w = al^b$ based only on wood length performs best on streams narrower than 30 m.~~

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