Progress in Physical Geography
2017, Vol. 41(1) 124–133

DOI: 10.1177/0309133317692411
journals.sagepub.com/home/ppg
SAGE

Frederick J. Swanson's 1976–1979 papers on the effects of instream wood on fluvial processes and instream wood management

Virginia Ruiz-Villanueva
University of Geneva, Geneva, Switzerland

Markus Stoffel
University of Geneva, Geneva, Switzerland

Abstract

The recognition of instream wood as a key element of river ecosystems and a driver of fluvial processes is now well established, but it did not start until the second half of the twentieth century. A landmark reference work which led to the development of concepts and methods which are still employed in instream wood studies today was the work by Frederick J. Swanson and his papers published between 1976 and 1979. In this article we revisit these papers, highlighting the pioneering observations about the effects of instream wood on fluvial morphology, the description of the instream wood sources and recruitment processes and the discussion about management of wood in rivers. The instream wood research has grown dramatically since the late 1970s, however many knowledge gaps remain; this short historical review illustrates the importance of continuing and developing those research lines into the future.

Keywords

Large wood, organic material, woody debris, organic debris, Swanson

I Introduction

Large wood in rivers (i.e. instream wood) is a key element of fluvial ecosystems (Gregory et al., 2003; Gurnell et al., 2002; Le Lay et al., 2013; Ruiz-Villanueva et al., 2016a; Wohl, 2011, 2013, 2017), and is currently considered as important as sediment and riparian vegetation for the functioning of river systems (Roni and Beechie, 2013). However, the recognition of wood as a driver of fluvial processes did not start until the second half of the twentieth century. This may explain why wood (and even riparian vegetation) was not generally included in *classic* conceptual models of rivers (e.g. Lane, 1955; Leopold and Maddock, 1953; Mackin, 1948), and why only few allusions to instream wood can be found in the literature from the late 1800s and early 1900s. In the case of these rare exceptions, the focus is usually related to the occurrence of natural wood rafts in the USA (Brown, 1817; Chemekov, 1955;

Corresponding author:
Virginia Ruiz-Villanueva, Institute for Environmental Sciences, University of Geneva, Geneva 1205, Switzerland.
Email: virginia.ruiz@unige.ch

Clay, 1948; Dobbie and Wolf, 1953; Lobeck, 1939; Lyell, 1830; Kaatz, 1955; Wadsworth, 1966). During the past few decades, however, interest among scientists and river managers in instream wood has increased significantly, which is also reflected by the increasing number of publications. We analysed this evolution in the ISI Web of Science database and found 19,818 records between 1904 and 2016 (using as keywords: 'woody debris', 'large wood', 'large organic material', 'instream wood', 'in-stream wood', 'large organic debris', 'river' and 'stream'; this resulted in an extended analysis different from that of Ruiz-Villanueva et al., 2016a). We observe that records were largely absent until the second half of the twentieth century. These publications may also include aspects that are not exclusively related to instream wood in the strictest sense (i.e. some are also related to agriculture, archaeology, biochemistry, biomass estimation, biodiversity, biology, construction and engineering), but the evolution illustrates the enormous advances in scientific understanding, particularly over the last few decades (Figure 1).

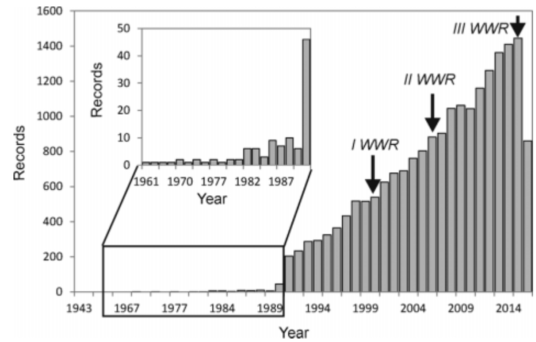

Figure 1. Temporal evolution of the 19,818 records found in the ISI Web of Science database (accessed in September 2016) between 1904 and 2016 using as keywords 'woody debris', 'large wood', 'large organic material', 'instream wood', 'in-stream wood', 'large organic debris', 'river' and 'stream'. The small graph shows the 1960s to 1990s. Black arrows show the three international conferences on wood in world rivers (WWR). The first conference (I WWR) was held in October 2000 at Oregon State University in Corvallis, Oregon (USA), and the main contributions from this first event were subsequently published in a book entitled *The Ecology and Management of Wood in World Rivers* (Gregory et al., 2003) a few years later. In August 2006, II WWR took place at the University of Stirling, Scotland, and related papers were published in a special issue of *Earth Surface Processes and Landforms* in 2007 (Gurnell, 2007). Recently, in July 2015, the conference III WWR was held at the University of Padova, Italy, and some of the presented contributions have been published in a special issue of *Geomorphology* (Picco et al., 2016). The lower number in 2016 shows only records up to September 2016.

The first studies on instream wood that we are aware of were carried out in the United States, with one of the pioneering works realized by Zimmerman et al. (1967) in the Sleepers River basin in Vermont. This paper had a significant influence on future research, as it was one of the earliest works focusing on the interactions between vegetation (including instream wood) and fluvial geomorphology. Several unpublished reports and papers followed, such as those by Froehlich (1971), Froehlich et al. (1972), Lammel (1972) and Colman (1973). These studies generally aimed at quantifying volumes and weights of instream wood in streams of the US Pacific Northwest (Figure 2).

However, a landmark reference work which led to the development of concepts and methods that are still employed in instream wood studies today was the one by Frederick J. Swanson and colleagues (Figure 3) and his papers published between 1976 and 1979 (Keller and Swanson, 1979; Swanson and Lienkaemper, 1978; Swanson et al., 1976). These papers and the papers published in the following years (e.g. Harmon et al., 1986; Swanson 2003; Swanson et al., 1982, 1984, 1998) are frequently cited (e.g. Keller and Swanson, 1979 has more than 540 citations since 2000 and more than 780 citations since it was published, according to Google Scholar, accessed in September 2016) and can still be considered basic references for research on wood in rivers. In this Classics Revisited contribution, we examine his early papers.

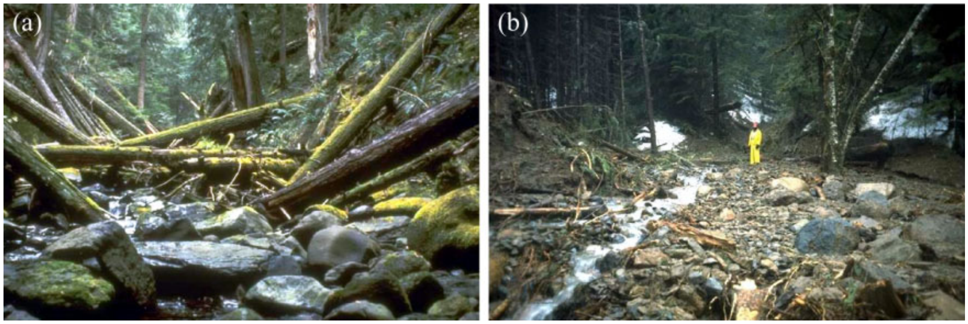

Figure 2. (a) Stream in an old-growth forest on the Andrews Experimental Forest in western Oregon (Photographer: Art McKee, 1988); (b) Fred Swanson (in yellow) in a stream upstream from Lookout Creek (Photographer: Gordon Grant, 1996). Source: H. J. Andrews Experimental Forest Online Image Library.

Figure 3. (a) Fred Swanson leading a field tour in the H. J. Andrews Experimental Forest in 2003 (Photographer unknown; source: H. J. Andrews Experimental Forest Online Image Library); (b) Fred Swanson at Chaitén, an active volcanic caldera in the Andean Mountains of Chile in 2010 (photograph courtesy of Frederick J. Swanson).

II The significance of instream wood on fluvial processes

Working as a research associate at the School of Forestry at Oregon State University, Corvallis, USA, Frederick J. Swanson presented one of his earliest works on instream wood at the 'Workshop on Logging Debris in Streams', held in Corvallis in September 1975. This contribution was published in 1976 by the US Department of Agriculture (General Technical Report PNW-56). In this report, Swanson, George W. Lienkaemper (his colleague and graduate student at that time) and James R. Sedell (also research associate at that time at Oregon State University), with the help of Robert L. Beschta (Oregon State University), presented results from field observations from five low-order stream reaches located in the western Cascade Range.

Part of this work was a continuation and extension of the work made by Froehlich et al. (1972). They mapped roughly 250 m length of each reach and presented some of the maps in the report (probably inspiring themselves by the primitive sketches shown in the paper by Zimmerman et al., 1967). In these maps and the accompanying descriptions, the authors described the great influence of wood on the streams, such as the formation of scour and plunge pools formed downstream of wood accumulations, and the high percentage of steps formed by logs, contributing to a significant amount of the gradient reduction along the streams. They also described significant channel widening associated with wood deposits and the diversion of flow caused by obstacles. The authors then quantified sediment storage related to wood accumulations. As well as the description of morphological effects of wood, the authors used dendrochronology (dating small trees growing on wood accumulations and dating scars on living trees damaged by the recruited trees when falling into the river) to date the residence time of wood in the streams, and this together with the description of the decay stage (i.e. degree of decomposition) allowed them to reconstruct the instream wood dynamics. They concluded that in these small streams wood was relatively stable, with residence times between 20 and 100 years. In general, they pointed out that logs in small streams were not transported over long distances after recruitment. In one of their study reaches of Mack Creek, the authors found significant differences related to logging of the streamside forest in previous years. In this reach, the amount of wood was reduced and they also observed that the wood left in the stream had very low influence on the morphology and sediment dynamics. In a further study, published in 1978, Swanson and Lienkaemper compared the amount (i.e. load) of instream wood in streams flowing through stands of different stages of recovery following major wildfires (75-, 85-, 90- and 135-year-old stands). They found that some quantities of instream wood remained after the fire, but realized that a time of non-production of instream wood generally exists during early stages of stand development until the post-fire stand is old enough to produce and deliver big wood to the stream. They concluded that large organic material (i.e. instream wood) is a primary factor determining the biological and physical character of small- and intermediate-sized streams in forested landscapes of the Pacific Northwest (Swanson and Lienkaemper, 1978).

In a following paper, published in 1979, Edward A. Keller and Swanson compared observations made in steep mountain streams of western Oregon with observations made in low-gradient meandering streams in Indiana and North Carolina, USA. As they hypothesized, the amount of wood, its distribution and its impacts on geomorphology were quite variable and different in low-gradient meandering rivers as compared to small, high-gradient streams. They claimed that, although in small streams wood accumulates randomly, it is distinctly concentrated and sorted as a result of transportation in larger rivers. In low-gradient meandering streams (Campbell Creek, Wildcat Creek and Mallard in North Carolina), they observed that single logs produced channel shifts as a result of enhanced bank erosion, incision of chutes and even meander cutoffs. The authors also observed that braided channel patterns were formed downstream of wood accumulation. In Mallard Creek, they analysed in detail the effects of one large wood jam located in the outer bank of a meander. This wood jam resulted in increased bank erosion, channel widening, development of scour holes, mid-channel bars and a high-water channel produced by the diverted flow. They noticed that the mid-channel bars were evolving into small islands as they were vegetated, defining for the first time the influence of instream wood in river island development, a phenomenon which was also discussed subsequently by Fetherston et al. (1995) and Mikuś et al. (2013). They also dated some of the sprouting living trees on these incipient islands and related the growth date with the date of the wood accumulations. The authors then claimed that the relative importance of instream wood in affecting inorganic sediment storage and energy dissipation in streams decreases with channel slope. In low-gradient streams, much in-channel inorganic sediment storage occurs in point bars, riffles and floodplains, whereas in steep streams, these inorganic sediment storage sites are often not present, and thus wood accumulations and logs may account for a much larger portion of total inorganic sediment storage. In this seminal paper, the authors defined and illustrated for the first time the functioning of a log step, which has been frequently reproduced since and cited in the scientific literature (e.g. Abbe and Montgomery, 2003; Marston, 1982; Scott et al., 2014; Wallerstein and Thorne, 2004; Wilcox and Wohl, 2006).

In their paper, Keller and Swanson also dedicated one section to the description of the double effect of instream wood on bank stability. On the one hand, they explain how instream wood generally increases bank stability by creating zones with concentrated turbulence where stream energy is dissipated. They also described and analysed how roots contributed to erosion resistance along Mallard Creek by showing that 73% of the total bank length was protected by root reinforcement. On the other hand, they also described how wood may contribute to bank instability by directing the flow against banks and increasing lateral channel migration. Keller and Swanson (1979) highlighted the role of the sequence of floods on wood dynamics, a topic which is still of great interest for today's scientific community (MacVicar and Piégay, 2012; Millington and Sear, 2007; Ravazzolo et al., 2015; Ruiz-Villanueva et al., 2016b; Schenk et al., 2014).

III The origin of instream wood accumulations

In the three papers analysed in this contribution, Frederick J. Swanson and his colleagues described the origin of instream wood. In his early paper published in 1976, Swanson and co-authors described the main recruitment processes that deliver wood to water courses. These processes were (i) strong winds that deliver whole trees blown into streams or adjacent hillslopes and then slide to the channel; (ii) undercutting of stream banks, which the authors defined as an effective process able to deliver massive and (initially) stable root wads and tree trunks into the channel; and (iii) mass movements, such as slumps, earthflows, debris slides and avalanches, processes that according to the authors' findings commonly resulted in what they called 'debris torrents'. Swanson and colleagues defined this phenomenon for steep low-order streams, usually triggered during extreme discharge events by slides from hillslopes, delivering large quantities of organic and inorganic material to the stream channel. This wood then moves downstream, or breakup of wood accumulations in the channel occurs (Swanston and Swanson, 1976). This term was not frequently used later on, but replaced by 'congested transport' or 'sporadic recruitment' instead (Braudrick et al., 1997; Wohl, 2011). Similar processes can, however, also occur in higher-order streams, when the flow has the power to transport large quantities of wood, as has been observed recently in Canada and Switzerland (Boivin et al., 2016; Ruiz-Villanueva et al., 2017).

However, Swanson and co-workers also claimed that most wood accumulations are formed by a variety of interacting mechanisms operating intermittently throughout the history of the accumulation. This could be the first time that the disturbance-cascade approach was discussed in relation to wood recruitment, but it was further developed in subsequent papers (Nakamura and Swanson, 2003; Nakamura et al., 2000; Swanson et al., 1998).

In the paper published in 1979, Keller and Swanson presented for the first time a conceptual model of instream wood dynamics, in which they represented the main biological and physical factors and the driving variables influencing the recruitment or input transfer processes and the output processes, including the decomposition and respiration process delivering carbon to the atmosphere and the transport of dissolved, particulate and coarse organic matter to floodplain and downstream areas. In another conceptual model, they illustrated the different input and output processes and their spatial variability along the river length and within the different stream orders (as the channel widens and delivery of wood to the river decreases). They developed this conceptual model for the Lookout Creek-McKenzie river system in Oregon, but the same concept is true for many regions in the world and can still be extensively applied today. These models have been often used in the more recent literature, as for example in Harmon et al. (1986), in which Swanson was also co-author, or in the review paper of Gurnell (2013). They can be also considered the preceding works to the well-established quantitative framework for wood budgets proposed by Benda et al. (2003) and Benda and Sias (2003).

IV Early concerns about instream wood management

Frederick J. Swanson was very much aware of the impacts that different management strategies of instream wood will have on the fluvial ecosystem. He was a pioneer in discussing perception towards instream wood among foresters, engineers and biologists, an issue which has been analysed in more detail subsequently (Chin et al., 2008; Le Lay et al., 2008; Piégay et al., 2005). In their papers, Swanson and co-authors claimed that management should aim at maintaining the concentrations and size distributions of instream wood in a manner which is typical of undisturbed channels. They argued that clean-up and clear cutting of streamside forest may result in removing valuable components of habitats for fish and other organisms and that these impacts might eventually trigger more frequent ‘debris torrents’. The authors also described how the extraction of the largest pieces may result in higher mobility of smaller pieces, and that these pieces could move downstream during extreme flows, which might allow them to gain sufficient momentum to move otherwise larger stable pieces, and thus again initiating a ‘debris torrent’. Swanson and Lienkaemper (1978) also considered the indirect reduction of instream wood storage associated to some management practices in riparian vegetation, such as removing standing and living trees. The combination of these management strategies would result in a significant reduction of instream wood and, according to the authors, in a decrease in the quality of the river ecosystem. The importance and benefits of wood in river ecosystems is now well known (Gregory et al., 2003); however, these practices have been and still are frequently applied, especially in Europe, but also elsewhere in the world (Wohl, 2014). As already pointed out by Swanson, determining optimum amounts of instream wood is difficult; despite the significant advances made during the last decades, data from many regions is still very scarce or even non-existent (Ruiz-Villanueva et al., 2016a; Wohl, 2017). Moreover, wood storage is not a static or constant value, but changes with time, and the amount of wood that is deposited in a stream at one time represents only the conditions at that time, and results from recent, antecedent events and the position within the river network. So, as we can read in his paper published in 1976, ‘the great complexity of stream environment means each site must be treated on an individual basis’ (Swanson et al., 1976). Some of the early management recommendations summarized in Swanson’s papers are still debated today, such as the questions concerning whether to leave or reintroduce large, stable pieces of wood into watercourses, or whether to maintain buffer strips along the streams to sustain natural sources of instream wood. However, in urbanized areas, especially in mountain regions, potential hazards related to wood and flooding make management challenging

Figure 4. (a) Fred Swanson and congressional staffers in the H. J. Andrews Experimental Forest (Photographer: Lina DiGregorio, 2008; source: H. J. Andrews Experimental Forest Online Image Library); (b) Fred Swanson listening to Hervé Piégay explanations of instream wood in the Ain River, France, in 2003 (Photograph courtesy of Hervé Piégay).

(Lassettre and Kondolf, 2012), and a clear and unique strategy to maintain the ecological benefits of wood and avoid the related hazards does not yet exist (Mao et al., 2013; Ruiz-Villanueva et al., 2016a; Wohl et al., 2016).

V The legacy of Swanson's studies

Reading Swanson's early papers, one question stands out: why did this work emerge in the Pacific Northwest of the US? According to Frederick J. Swanson himself, there may be three important reasons: first, the existence of productive forest with decay-resistant wood which results in large amounts of instream wood; second, an interdisciplinary team (i.e. stream and forest ecologists, hydrologists, forest engineers and geomorphologists) interested in the ecological role of instream wood from many viewpoints, including the role of instream wood in carbon and nitrogen budgets; and, third, a high level of concern in land-management communities about costs of operations and environmental protection (Swanson, 2016, personal communication).

The instream wood research has grown dramatically since the late 1970s, and new approaches have been developed recently. Particularly important to improve our current knowledge of wood dynamics in rivers are the advances in technologies for the acquisition and use of high resolution satellite and aerial pictures, or the development of new monitoring and tracing techniques (Ruiz-Villanueva et al., 2016a). Nevertheless, this recent growth in the overall understanding of instream wood is inarguably and intellectually linked to the research, publications and lasting legacy of Frederick J. Swanson (Figure 4) and the three milestone publications discussed here. These papers presented and discussed for the first time the main aspects of instream wood impacts on fluvial systems, its dynamics and its management. Many of the ideas presented in these papers are still reviewed and used nowadays in many other regions.

During recent years, interest in restoring and rehabilitating stream habitats has been renewed, together with the understanding of the importance of instream wood. Scientists and river managers have recognized that this key element is missing from many streams; therefore, this short historical review of the impact of Swanson's research helps also to illustrate the importance of continuing and developing those research lines into the future.

Acknowledgments

The authors thank David Butler for his invitation to write this article. We also thank Frederick J. Swanson for his useful comments on an early version of the manuscript, and Hervé Piégay for the graphical material and the fruitful discussions.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Funding

The authors received no financial support for the research, authorship and/or publication of this article.

References

Abbe TB and Montgomery DR (2003) Patterns and processes of wood debris accumulation in the Queets river basin, Washington. *Geomorphology* 51: 81–107.

Benda LE and Sias JC (2003) A quantitative framework for evaluating the mass balance of in-stream organic debris. *Forest Ecology and Management* 172: 1–16.

Benda L, Miller D, Sias J, et al. (2003) Wood recruitment processes and wood budgeting. In: Gregory SV, Boyer KL and Gurnell AM (eds) *The Ecology and Management of Wood in World Rivers*. Bethesda, MD: American Fisheries Society, 49–73

Boivin M, Buffin-Bélanger T and Piégay H (2016) Interannual kinetics (2010–2013) of large wood in a river corridor exposed to a 50-year flood event and fluvial ice dynamics. *Geomorphology*. Epub ahead of print 8 July 2016. DOI: 10.1016/j.geomorph.2016.07.010.

Braudrick CA, Grant GE, Ishikawa Y, et al. (1997) Dynamics of wood transport in streams: a flume experiment. *Earth Surface Processes and Landforms* 22: 669–683.

Brown SR (1817) *The Western Gazeteer*. Auburn, NY: H. C. Southwick.

Chemekov Yu F (1955) Debris dams, their formation and development. *Proceedings of the Russian Geographical Society* 87: 134–138 (in Russian).

Chin A, Daniels MD, Urban MA, et al. (2008) Perceptions of wood in rivers and challenges for stream restoration in the United States. *Environmental Management* 41: 893–903.

Clay C (1948) The Colorado River raft. *Southwestern Historical Quarterly* 52: 410–426.

Colman SM (1973) *The history of mass movement processes in the Redwood Creek basin, Humboldt County, CA*. MS Thesis, Pennsylvania State University, USA.

Dobbie CH and Wolf PO (1953) The Lynmouth flood of August 1952. *Proceedings of the Institute of Civil Engineers* 2: 522e588.

Fetherston KL, Naiman RJ and Bilby RE (1995) Large woody debris, physical process and riparian forest development in montane river networks of the Pacific Northwest. *Geomorphology* 13: 133–144.

Froehlich HA (1971) Logging debris: managing a problem. In: Krygier JT and Hall JD (eds) *Forest Land Uses and Stream Environment, a Symposium*. Corvallis, OR: Oregon State University, 112–117.

Froehlich HA, McGree D and Sedell JR (1972) Natural debris within the stream environment. Coniferous forest biome. *US Int Biol Program Intern Rep* 96: 1–9.

Gregory SV, Boyer KL and Gurnell AM (2003) *The Ecology and Management of Wood in World Rivers*, vol. 37 (American Fisheries Society Symposium). Bethesda, MD.

Gurnell AM (2013) Wood in fluvial systems. In: Shroder J and Wohl E (eds) *Treatise on Geomorphology*, vol. 9, 236: 163–188. San Diego, CA: Academic Press.

Gurnell AM, Piégay H, Swanson FJ, et al. (2002) Large wood and fluvial processes. *Freshwater Biology* 47: 601–619.

Harmon ME, Franklin JF, Swanson FJ, et al. (1986) Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research* 15: 133–302.

Kaatz MR (1955) The Black Swamp: A study in historical geography. *Annals of the Association of American Geographers* 45: 1–35.

Keller EA and Swanson FJ (1979) Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes* 4: 362–380.

Lammel RF (1972) Natural debris and logging residue within the stream environment. Master's thesis, Oregon State University, Corvallis.

Lane EW (1955) The importance of fluvial morphology in hydraulic engineering. *Proceedings of the American Society of Civil Engineers* 81: art. 745.

Lassettre NS and Kondolf GM (2012) Large woody debris in urban stream channels: redefining the problem. *River Research and Applications* 28: 1477–1487.

Le Lay YF, Piégay H, Gregory K, et al. (2008) Variations in cross-cultural perception of riverscapes in relation to in-channel wood. *Transactions of the Institute of British Geographers* 33: 268–287.

Le Lay YF, Piégay H and Moulin B (2013) Wood entrance, deposition, transfer and effects on fluvial forms and processes, problem statements and challenging issues. In: Shroder J and Wohl E (eds) *Treatise on Geomorphology*, vol. 12. San Diego, CA: Academic Press, 20–36.

Leopold LB and Maddock T Jr (1953) *The hydraulic geometry of stream channels and some physiographic implications*. Professional Paper 252, US Geological Survey, Washington, DC.

Lobeck AK (1939) *Geomorphology*, vol. 1. New York: McGraw Hill.

Lyell C (1830) *Principles of Geology*. London: John Murray.

Mackin JH (1948) Concept of the graded river. *Geological Society of America Bulletin* 59: 463–512.

MacVicar B and Piégay H (2012) Implementation and validation of video monitoring for wood budgeting in a wandering piedmont river, the Ain River (France). *Earth Surface Processes and Landforms* 37: 1272–1289.

Mao L, Andreoli A, Iroumé A, et al. (2013) Dynamics and management alternatives of in-channel large wood in mountain basins of the southern Andes. *Bosque (Valdivia)* 34: 15–16.

Marston RA (1982) The geomorphic significance of log steps in forest streams. *Annals of the Association of American Geographers* 72: 99–108.

Mikuś P, Wyzga B, Kaczka RJ, et al. (2013) Islands in a European mountain river: linkages with large wood deposition, flood flows and plant diversity. *Geomorphology* 202: 115–127.

Millington CE and Sear DA (2007) Impacts of river restoration on small-wood dynamics in a low-gradient headwater stream. *Earth Surface Processes and Landforms* 32: 1204–1218.

Nakamura F and Swanson FJ (2003) Dynamics of wood in rivers in the context of ecological disturbance. In: Gregory SV, Boyer KL and Gurnell AM (eds) *The Ecology and Management of Wood in World Rivers*, Symposium 37. Bethesda, MD: American Fisheries Society, 279–297.

Nakamura F, Swanson FJ and Wondzell SM (2000) Disturbance regimes of stream and riparian systems, a disturbance-cascade perspective. *Hydrological Processes* 14: 2849–2860.

Picco L, Bertoldi W and Comiti F (2017) Dynamics and ecology of wood in world rivers. *Geomorphology* 279: 10–11.

Piégay H, Gregory KJ, Bondarev V, et al. (2005) Public perception as a barrier to introducing wood in rivers for restoration purposes. *Environmental Management* 36: 665–674.

Ravazzolo D, Mao L, Picco L, et al. (2015) Tracking log displacement during floods in the Tagliamento River using RFID and GPS tracker devices. *Geomorphology* 228: 226–233.

Roni P and Beechie T (2013) *Stream and Watershed Restoration: A Guide to Restoring Riverine Processes and Habitats*. Chichester, UK: Wiley-Blackwell.

Ruiz-Villanueva V, Piégay H, Gurnell A, et al. (2016a) Recent advances quantifying the large wood dynamics in river basins: new methods and remaining challenges. *Review of Geophysics*. Epub ahead of print 17 September 2016. DOI: 10.1002/2015RG000514.

Ruiz-Villanueva V, Wyżga B, Mikuś P, et al. (2016b) The role of flood hydrograph in the remobilization of large wood in a wide mountain river. *Journal of Hydrology*. Epub ahead of print 15 March 2016. DOI: 10.1016/j.jhydrol.2016.02.060.

Ruiz-Villanueva V, Galatiotto N, Bürkli L, et al. (2017) Understanding triggers and dynamics of wood-laden flash floods in mountain catchments: examples from the Zulg River (Switzerland). *Geophysical Research Abstracts* 19, EGU2017 (unpublished).

Schenk ER, Moulin B, Hupp CR, et al. (2014) Large wood budget and transport dynamics on a large river using radio telemetry. *Earth Surface Processes and Landforms* 39: 487–498.

Scott DN, Montgomery DR and Wohl EE (2014) Log step and clast interactions in mountain streams in the central Cascade Range of Washington State, USA. *Geomorphology* 216: 180–186.

Swanson FJ (2003) Wood in rivers: a landscape perspective. In: Gregory SV, Boyer KL and Gurnell AM (eds) *The Ecology and Management of Wood in World Rivers,* Symposium 37. Bethesda, MD: American Fisheries Society, 299–313.

Swanson FJ and Lienkaemper GW (1978) *Physical Consequences of Large Organic Debris in Pacific Northwest Streams*, USDA Forest Service General Technical Reports PNW-69. Portland, OR: US Department of Agriculture.

Swanson FJ, Bryant MD, Lienkaemper GW, et al. (1984) *Organic Debris in Small Streams, Prince of Wales Island, Southeast Alaska*. Gen. Tech. Rep. PNW-GTR-166. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 16 p.

Swanson FJ, Gregory SV, Sedell JR, et al. (1982) Land-water interactions: the riparian zone. In: Edmonds RL (ed.) *Analysis of Coniferous Forest Ecosystems in the Western United States*, US International Biological Program Synthesis Serial 14. Stroudsburg, PA: Hutchinson Ross Pub. Co.; [New York]: distributed worldwide by Academic Press, 267–291.

Swanson FJ, Johnson SL, Gregory SV, et al. (1998) Flood disturbance in a forested mountain landscape. *Bioscience* 48: 681–689.

Swanson FJ, Lienkaemper GW and Sedell JR (1976) *History, Physical Effects, and Management of Large Organic Debris in Western Oregon Streams*, USDA Forest Service General Technical Report PNW-56. Portland, OR: US Department of Agriculture.

Swanston DN and Swanson FJ (1976) Timber harvesting, mass erosion, and steep land forest geomorphology in the Pacific Northwest. In: Coates DR (ed.) *Geomorphology and Engineering*. Stroudsburg, PA: Dowden, Hutchinson, and Ross. Inc, 199–221.

Wadsworth AH Jr (1966) Historical deltation of the Colorado River, Texas. In: Shirley ML (ed.) *Deltas in Their Geologic Framework*, Houston Geological Society Special Publication. Houston, TX: Houston Geological Society, 99–105.

Wallerstein NP and Thorne CR (2004) Influence of large woody debris on morphological evolution of incised, sand-bed channels. *Geomorphology* 57: 53–73.

Wilcox AC and Wohl E (2006) Flow resistance dynamics in step-pool stream channels: 1. Large woody debris and controls on total resistance. *Water Resources Research* 42: W05418.

Wohl E (2011) Threshold-induced complex behavior of wood in mountain streams. *Geology* 39: 587–590.

Wohl E (2013) Floodplains and wood. *Earth-Science Review* 123: 194–212.

Wohl E (2014) A legacy of absence: wood removal in US rivers. *Progress in Physical Geogaphy* 38: 637–663.

Wohl E (2017) Bridging the gaps: An overview of wood across time and space in diverse rivers. *Geomorphology* 279: 3–26.

Wohl E, Bledsoe BP, Fausch KD, et al. (2016) Management of large wood in streams: an overview and proposed framework for hazard evaluation. *American Water Resources Association*. Epub ahead of print 7 February 2016. DOI: 10.1017/CBO9781107415324.004.

Zimmerman RC, Goodlet JC and Comar GH (1967) The influence of vegetation on channel form of small streams. *International Association of Scientific Hydrology Publications* 75: 255–275.