comment

Water sustainability and watershed storage

The paired watershed approach is the most popular tool for quantifying the effects of forest watershed management on water sustainability. But this approach does not often address the critical factor of water stored in the landscape. Future work needs to quantify storage in paired watershed studies to inform sustainable water management.

J. J. McDonnell, J. Evaristo, K. D. Bladon, J. Buttle, I. F. Creed, S. F. Dymond, G. Grant, A. Iroume, C. R. Jackson, J. A. Jones, T. Maness, K. J. McGuire, D. F. Scott, C. Segura, R. C. Sidle and C. Tague

Countries around the globe are mobilizing to meet the 17 Sustainable Development Goals (SDGs) of the United Nations' 2030 Agenda for Sustainable Development[1]. SDG 15 is focused on 'sustainable forest management'. With about 30% of the world's land surface covered by forests, this goal is vitally needed against a backdrop of stunning land-use change (Fig. 1)[2]. Most of this change is occurring in the headwaters of larger watersheds around the world. These headwaters are where partitioning occurs between water used by vegetation and the water that leaves the watershed via streamflow. At risk are the forested headwaters that support over half of the drinking water in the United States, for example, and sustain water supply for billions of people worldwide.

Paired watershed studies — where one watershed serves as a reference, while the adjacent watersheds are treated by various forest management approaches (for example, forest harvesting, road construction, afforestation) — have been the standard approach for over 100 years[3] for quantifying the effects of forest cover change on streamflow. The paired watershed approach quantifies simply the precipitation inputs and streamflow outputs and uses before–after statistical approaches to quantify change. There are now more than 250 papers from at least 150 paired watersheds around the world, focused mainly on forest harvesting effects on headwater annual water yield.

While paired watershed studies have been vitally important to show locally the consequences of forest manipulation on streamflow, generalizing these findings and making predictions from them across diverse climate, geology, vegetation and topographic settings has been difficult.

Paired watershed studies are a major source of information on annual water yield, a key measure of 'water sustainability' — but the factors influencing the control variables on sustained annual water yield in forested headwaters are not well understood.

Fig. 1 | Old-growth forest clearcut in the Gordon River Valley near Port Renfrew, British Columbia. Big Lonely Doug, Canada's second-largest Douglas-fir tree, stands alone in the background. Credit: T. J. Watt, Ancient Forest Alliance.

Previous synthesis efforts have shown that there are very complex interactions between the controls, with many different possible outcomes to forest harvesting. Paired watershed studies have revealed everything from increases to decreases to no change in annual streamflow in response to forest harvesting[4,5]. This has flummoxed attempts at prediction. The response of streamflow to harvesting a given percentage of forest area in watersheds varies considerably across sites. The threshold percentage for detection of change is often noted as 20%, but there is considerable variability in streamflow response with percent watershed area harvested[6]. Some studies with 100% forest removal have shown no response of annual streamflow; and some watersheds with <20% forest removal have shown an observable response. All this illustrates the difficulty in predicting, a priori, the outcome of forest cover change on streamflow. This is problematic for SDG 15 because variable outcomes of paired watershed experiments contribute to uncertainty about how forests should be managed for water sustainability.

So why are responses to cover change so variable? Water flow pathways and very complex interactions between controls are one reason. The interactions of canopy and root processes with these water flow pathways can express themselves differently at different scales — and the emergent behaviour from the single-tree level to a hillslope to a watershed is poorly documented or known[7]. The so-called reference watershed may be dynamic and changing with time. In snow-dominated areas, snow and radiation responses to forest change can vary widely between climates. Changes in intercepted water storage by the canopy can also play a role. Still other reasons can relate to the types of vegetation that return after forest harvest — including their rate of growth, rooting and water-uptake dynamics as well as leaf area and phenology.

But perhaps the biggest and least-studied effect on response variability is subsurface storage. This belowground storage is defined as the water in the rooting zone, or affected by it, that influences how precipitation is partitioned between transpiration and streamflow. This 'frontier beneath our feet'[8] has not been widely dealt with in the paired watershed approach. And almost no paired watershed studies have included observations of water-table dynamics before and after forest harvest.

Studies of belowground storage[9] in forested landscapes highlight its critical control on both streamflow and transpiration. Root-zone moisture storage capacities have been shown to be highly affected by forest conversion[10]. Furthermore, studies have shown that ecosystems can 'dynamically design' their root systems to cope between droughts[11], with some species tapping rock moisture in weathered rock beneath the soil profile[12]. The age of water that leaves that storage and enters into the streamflow varies from years to decades — hinting at considerable reservoirs of stored water in soil, weathered rock and glacial deposits that paired watershed studies often ignore.

Recent stable isotope analysis[13] and remotely sensed data[14] have shown that trees can use belowground storage reservoirs that are seemingly disconnected to streamflow. And the water used by trees can be many decades old[15], well beyond the timescale of the paired watershed annual water balance calculation. The ability of deep-rooted trees to access stored water has fundamental implications for the sensitivity of streamflow to forest management. However, relatively little is known about how forest access to these different water storages evolves following disturbance.

So, what is the way forward? Paired watershed studies are still needed as they are often the last bastion of long-term hydrological records in an era of steep declines in monitoring stations[16] — and are still vital for this reason alone. Nevertheless, we need to confront the water storage issue if we want to address the SDGs, as water storage differences across sites, and the adaptation of forest access to storage, may help explain the very different paired watershed responses. The old forest water sustainability question was: How does harvesting affect flow? The new forest water sustainability question incorporates watershed storage and thus becomes: 'How does water storage and evolution of forest access to that storage influence the water cycle, particularly the partitioning of precipitation between transpiration, evaporation and streamflow?'

Beyond precipitation-in and streamflow-out, paired watershed studies could provide more and better inference if they collected and reported data on soil water and groundwater levels as well as plant water sources and stream water age using stable isotope tracers. This is a re-thinking of the paired watershed approach literally from the bottom up, where estimation of belowground water storage reservoirs and knowledge of how they are filled and drained are key to understanding how forests link to streams. How does water storage in the soil and in weathered and fractured rock get depleted during re-planting or natural regeneration? How does this relate to flow regime regulation? We can better answer these questions by combining the paired watershed approach with other hydrometric and isotope tracer techniques to help clarify our understanding of the varied responses of forested watersheds to harvesting. This is especially true as countries around the world face growing pressures to manage forests for all the goods and services they provide, including water.

As long-term watershed studies continue to expand around the world, it is important that they include strategies for stored water characterization. Indeed, this is starting to occur[17]. Knowing how and when stored water is routed through the forest watershed is an important step towards interpreting and synthesizing the many factors operating in forest watersheds that produce variable outcomes. This will aid policy guidance and ultimately inform sustainable forest management strategies for achieving SDG 15. ❐

J. J. McDonnell[1,2,3]*, J. Evaristo[4,5,6], K. D. Bladon[7], J. Buttle[8], I. F. Creed[9], S. F. Dymond[10], G. Grant[11], A. Iroume[12], C. R. Jackson[13], J. A. Jones[14], T. Maness[7], K. J. McGuire[15], D. F. Scott[16], C. Segura[7], R. C. Sidle[17] and C. Tague[18]

[1]Global Institute for Water Security, School of Environment and Sustainability, University of Saskatchewan, Saskatoon, Saskatchewan, Canada. [2]School of Resources and Environmental Engineering, Ludong University, Yantai, China. [3]School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK. [4]Department of Natural Resources and Environmental Science, University of Nevada, Reno, NV, USA. [5]College of Science and Mathematics, University of the Philippines Mindanao, Davao City, Philippines. [6]College of Natural Resources and Environment, Northwest A&F University, Yangling, China. [7]Department of Forest Engineering, Resources and Management, Oregon State University, Corvallis, OR, USA. [8]School of the Environment, Trent University, Peterborough, Ontario, Canada. [9]School of Environment and Sustainability, University of Saskatchewan, Saskatoon Saskatchewan, Canada. [10]Department of Earth and Environmental Sciences, University of Minnesota Duluth, Duluth, MN, USA. [11]Pacific Northwest Research Station, USDA Forest Service, Corvallis, OR, USA. [12]Faculty of Forest Sciences and Natural Resources, Universidad Austral de Chile, Valdivia, Chile. [13]Warnell School of Forest Resources, University of Georgia, Athens, GA, USA. [14]Geography, College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA. [15]Department of Forest Resources and Environmental Conservation and Virginia Water Resources Research Center, Virginia Tech, Blacksburg, VA, USA. [16]Department of Earth, Environmental and Geographic Sciences, University of British Columbia, Kelowna, British Columbia, Canada. [17]Sustainability Research Centre, University of the Sunshine Coast, Sippy Downs, Queensland, Australia. [18]Bren School, UC Santa Barbara, Santa Barbara, CA, USA.
**e-mail: jeffrey.mcdonnell@usask.ca*

Published online: 14 August 2018
https://doi.org/10.1038/s41893-018-0099-8

References

1. *Transforming Our World: The 2030 Agenda for Sustainable Development* (United Nations, 2015)
2. Hansen, M. C. et al. *Science* **342**, 850–853 (2013).
3. Bates, C. G. & Henry, A. J. *Mon. Weather Rev.* **56**, 79–85 (1928).
4. Bosch, J. M. & Hewlett, J. D. *J. Hydrol.* **55**, 3–23 (1982).
5. Stednick, J. *J. Hydrol.* **176**, 79–95 (1996).
6. Brown, A. E. et al. *J. Hydrol.* **310**, 28–61 (2005).
7. Sidle, R. C. et al. *Earth Sci. Rev.* **175**, 75–96 (2017).
8. Grant, G. E. & Dietrich, W. E. *Water Resour. Res.* **53**, 2605–2609 (2017).
9. Phillips, R. P. et al. *For. Ecol. Manag.* **380**, 309–320 (2016).
10. Nijzink, R. et al. *Hydrol. Earth Syst. Sci.* **20**, 4775–4799 (2016).
11. Gao, H. et al. *Geophys. Res. Lett.* **41**, 7916–7923 (2014).
12. Rempe, D. M. & Dietrich, W. E. *Proc. Natl Acad. Sci. USA* **115**, 2664–2669 (2018).
13. Evaristo, J. et al. *Nature* **525**, 91–94 (2015).
14. Good, S. P. et al. *Science* **349**, 175–177 (2015).
15. Zhang, Z. Q. et al. *Hydrol. Process.* **31**, 1196–1201 (2017).
16. Laudon, H. et al. *Nat. Geosci.* **10**, 324–325 (2017).
17. Chistina, M. et al. *Funct. Ecol.* **31**, 509–519 (2017).

Acknowledgements

We thank H. Savenije and S. Kampf for useful comments that improved the final version of this Comment.