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Reply to comment by Bathurst on "A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments"

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> In our idealized view of science, an observation that runs contrary to the general dogma is precisely not to be ignored, since in theory, a single inconsistency is sufficient to topple the entire scientific edifice. These "anomalous" results should attract powerful attention simply because they are difficult to absorb in the standard view and could lead to new paradigm shifts (Kuhn, 1970).
>
> Kiang [1995, p. 348]

1. Introduction

Alila et al. [2009], *Kuraś et al*. [2012], *Green and Alila* [2012], and *Schnorbus and Alila* [2013] illustrated using case studies in snow and rain-on-snow environments why we must use frequency pairing (FP) and called on the forest science community to abandon the traditional chronological pairing (CP) methods in the study of forests and floods. We thank James Bathurst for providing us this opportunity to explain why we remain opposed to the use of CP in all hydroclimate environments including rain dominated.

The main thrust of the outcome of our work on this topic is that the CP-based research question: "what is the difference in magnitude between preharvest and postharvest floods when the same watershed with and without forest cover is subject to the same storm (pluvial) or freshet season (nival)?" leads to answers that are irrelevant to whether forest harvesting affects floods. Decades of literature guided by such a CP-based research question has reinforced the belief [*DeWalle*, 2003, p. 1255] that forest cover affects small and medium but not larger floods or that the effects of forest cover become less important as the size of the flood event increases. *Alila et al*. [2009] and *Green and Alila* [2012] assert that such a precept is scientifically indefensible because this CP-based research question (1) cannot reveal the critical effects of forests on the frequency and (2) most importantly, do not lead to the correct effect on the magnitude of floods. *Alila et al*. [2009] and *Green and Alila* [2012] maintain that the correct question guiding the science of forests and floods should be: What is the difference in magnitude (frequency) between preharvest and postharvest peak flow events of the same frequency (magnitude)? Therefore, the pairing must be of equal frequency (FP) and not chronology (CP). *Kuraś et al*. [2012], *Green and Alila* [2012], and *Schnorbus and Alila* [2013] FP-based analyses of postharvest flow data in snow environments led to outcomes that run counter the prevalent wisdom in hydrological science, namely: forest cover can affect the magnitude and frequency of not only small and medium but also the larger 10, 20, and 50 year floods and such effects can actually increase with an increase in event size with no apparent no-effect threshold at least within 20–100 years of postharvest flow record. Therefore, we argue that CP has concealed the effects of forests on larger floods.

Bathurst [2014] acknowledges that CP does not invoke the dimension of flood frequency and that a change in frequency is an essential facet of the forests and floods relation, yet long ignored in decades of CP-based studies. *Bathurst* [2014] is also not disputing the newly emerging FP-based insights on the effects of forests on flood frequencies from our work on this topic. At the same time, he suggests not letting go of the long history of CP-based study outcomes on the effects on the magnitude of floods. It is on this basis that he puts forward a summary of a current understanding of the effect of forests on floods which combines the decades of CP-based and our more recent FP-based outcomes as follows:

1. Forests can reduce the magnitude of floods produced by given moderate rainfall events but may not be effective in reducing the magnitude of floods produced by more extreme rainfall events and

2. Forests can reduce the frequency with which a given flood peak occurs and this effect may be greater for larger floods than for smaller floods.

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Bathurst's [2014] suggested understanding is misleading because the above CP-based point (1) and FP-based point (2) are two contradictory and irreconcilable outcomes, i.e., forests cannot reduce the frequency of large floods without reducing their magnitude.

In section 2, we reveal how CP stems from an uncontrolled experiment that does not properly isolate the effects of forests on the magnitude of floods and this is why it must not be used for investigating how forests affect flooding. In section 3, we advance additional arguments for why forests and floods relations must not be investigated by comparing preharvest and postharvest discharge versus rainfall regressions. In section 4, we explain why the effects of forests on the magnitude of floods even in rain environments should not be expected to always decrease with an increase in flood size. We conclude by arguing that "throwing out the baby (CP) with the bathwater (CP-based study outcomes)" is the only way to emerge from this era of confusion and incorrect perceptions that forests have no effects on large floods.

2. CP Does Not Fully and Properly Isolate the Effect of Forests on Floods

Bathurst [2014] states that if we remain opposed to the use of CP we should explain why it is inappropriate for addressing such questions as "Would the flood response to a given rainfall event have been as big (or bigger) if the forest cover had not been lost?" Our response to this is simple—this type of questions imposes on us an answer that is irrelevant to whether the loss of forest cover affects floods. This is because fixing the storm to evaluate the difference in magnitude between preharvest and postharvest floods does not isolate the effects of forest cover on the magnitude of such a flood. The magnitude of a flood is affected by not only the storm but also by the antecedent moisture condition in the watershed, and it is critical to recognize that this is true with or without the forest cover. In an experiment meant to isolate the effects of forest cover on the magnitude of the flood these two factors must be simultaneously fixed in the forested and unforested watersheds so their effects can be controlled. But is fixing these two factors even possible when in fact they are both affected either directly or indirectly by forest harvesting? Tree removal suppresses evapotranspiration and hence increases antecedent moisture conditions. As a consequence, some medium-size storms that never produced large preharvest floods when falling on wetter antecedent conditions can produce postharvest floods as big if not bigger than those generated by larger storms. Since the number and type of storms and their associated antecedent moisture conditions responsible for these floods are both changing as a result of harvesting neither the storm input nor the antecedent moisture conditions can be fixed (or blocked, to use an experimental design terminology). Therefore, as we already demonstrated in our published work on snow environments and now extend to rain environments, the premise that a CP-based change in magnitude is a measure of the effects of forest cover on floods, which guided a century of peer reviewed literature on this topic, is scientifically incorrect and misleading.

The question then becomes; what should we fix (or block) in order to simultaneously control the combined effects of antecedent moisture conditions and storm input? We argue that flood frequency plays this fundamental role. This is because frequency, which is determined by considering the full posttreatment time series of floods concurrently, encapsulates the simultaneous effects of the hydrometeorological factors responsible for the flood. The designation of a rank (a surrogate of frequency) to a specific event in a time series of floods, for instance the 10th largest observation, is determined by how its magnitude compares in relation to all other flood observations in the time series. But the magnitude of this 10th largest flood event is affected, as discussed earlier, by the antecedent moisture conditions and the storm input. This is why fixing the frequency is the only way to simultaneously control their effects and hence isolate the effect of forest cover on the magnitude of floods.

CP has dominated the forest science literature for over a century and the prevalent consensus from such a body of literature is that the forest cover in rain environments is not affecting events larger than the 2 year [e.g., *Thomas and Megahan*, 2001, p. 182], 5 year [e.g., *Beschta et al*., 2000, p. 117], and 10 year [e.g., *Calder*, 2005, Figure 2.6; *Bathurst et al*., 2011a, p. 9] floods. In contrast, the few studies that have used FP, although not commonly cited by forest hydrologists or land use policy advocates, showed how forest removal can increase the magnitude across a much wider range of return periods [*Svoboda*, 1991, Figures 5 and 6; *Reynard et al*., 2001, Figure 5; *Brath et al*., 2006, Figure 8; *Birkinshaw et al*., 2010, Figure 8]. In all these independent studies, such increase in absolute terms is larger as the event size increases and the larger the flood the more frequent it becomes with no apparent threshold beyond which forests have no effects, at least not

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before the 50 and 100 year return periods. Consequently, the answer to the CP-based and FP-based research questions can lead to diametrically opposite conclusions about how forests affect floods in rain environments and they cannot both be right. In science, often several methods can be used to analyze the same data set and one is judged superior to the others. However, in this case CP is flawed and must be abandoned because it stems from an uncontrolled experiment that leads to a change in magnitude that does not properly isolate for the effects of forests on the floods. Late 1970s and early 1980s work of John Hewlett [*Hewlett et al*., 1977, 1984], which demonstrated that the storm input is neither the dominant nor the only factor affecting storm flow or peak discharge from forested watersheds, lends support to our argument against CP. Decades of isotope hydrology work reviewed by *Buttle* [1994] demonstrated that storm induced runoff, even during peak discharge, in forested basins is composed of mostly old or preevent water, which further supports our argument against CP. *Swift et al*. [1975, p. 670] stated: "Streamflow from a watershed is influenced by both: events in past months and current ET and precipitation. Therefore, streamflow (magnitude) cannot indicate day-to-day water use by vegetation." Characteristics of soil moisture reservoirs and their effects on subsurface runoff travel time to streams can create lagged effects in streamflow response of the order of months in some forested watersheds [*Jones and Post*, 2004]. In our opinion, there should be no room for CP-based lines of reasoning or CP-based study outcomes in a scientifically defensible understanding of how forests affect floods.

3. Using Discharge Versus Rainfall Regressions Leads to Misleading Conclusions

Bathurst [2014] defends the use of peak discharge versus storm size regressions of postharvest and preharvest conditions, which is a traditional CP-based method of investigating the effects of forest cover on the magnitude of the flood for a specific rainfall event and hence deserves a closer scrutiny [e.g., *Caissie et al*., 2002; *Iroumé et al*., 2006; *Bathurst et al*., 2011a]. This method can lead to erroneous conclusions of how forests affect floods because the storm or new water is once again neither the dominant nor the only variable controlling flood generation in forested watersheds [*Hewlett et al*., 1977, 1984; *Buttle*, 1994]. Even if data analyses revealed a significant partial correlation between the magnitude of the discharge and the storm characteristics, the vertical difference between the two regression models must not be used as a measure of the effect of forest cover on the magnitude of floods as suggested by *Bathurst* [2014, Figure 1a]. This is because even a small unexplained variance in the magnitude by such regression models can translate into large changes in the frequency of floods, especially at the upper tail of the frequency distributions [*Green and Alila*, 2012].

In CP-based analysis, the intersection of discharge versus rainfall regressions has been mistakenly used to determine the threshold flood size beyond which forests have no effects on floods [e.g., *Bathurst et al*., 2011a]. The size of the storm or its return period is not a determinant of "postharvest" flood size. This is because some medium storms falling on wet antecedent moisture conditions can produce floods as large as or larger than those generated by bigger storms falling on dry antecedent moisture conditions [*Adams and Howard*, 1986]. Forested watersheds are not paved parking lots and therefore the return period of the storm is not necessarily the same as that of the corresponding flood. Again, this is because floods are affected not only by the severity of the storm but also by the antecedent soil moisture condition [*Hewlett et al*., 1977, 1984; *Buttle*, 1994], which is in turn affected by the within and between season variability of both rainfall and evapotranspiration regimes [*Sivapalan et al*., 2005]. It is true that for some rain regimes, the effects of antecedent soil moisture on large floods may decrease with increasing return period of the flood [*Wood et al*., 1990]. In such regimes, however, an open question is where "large" begins or how rare must floods be for antecedent soil moisture to have no effects on floods? [*Sturdevant-Rees et al*., 2001, p. 2161]. The convergence of preharvest and postharvest flood frequency curves in relative or absolute terms does not necessarily translate into forest harvesting not affecting larger floods simply because modest differences in magnitude between the two upper tails of the flood frequency distributions, even within measurement or modeling uncertainties, can lead to large changes in frequency [*Alila et al*., 2009; *Green and Alila*, 2012]. If it exists, the threshold event beyond which forest cover has no effect on the magnitude and frequency of floods can only be determined using an FP-based analysis. In this context, the no-effect threshold would be marked by the merging of the preharvest and postharvest flood frequency distributions into a single curve [e.g., *Bathurst*, 2014, Figure 1b, but not Figure 1a].

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Bathurst [2014] confuses the FP-based convergence of preharvest and postharvest flood frequency distributions with the CP-based convergence of preharvest and postharvest regressions when he states "Nevertheless both field data and model studies support the general trend toward either absolute or relative convergence at large events [*Bathurst et al*., 2011a, 2011b]." *Bathurst et al*. [2011a, 2011b] used CP to test the hypothesis that the effects of forest cover on the magnitude of flood peaks become less important as the size of the hydrological event increases. We reiterate that if investigated using a CP framework such hypothesis tells us nothing about the correct change in magnitude and equally important it does not recognize the fact that floods could also be greater in frequency, i.e., more frequent. A CP-based change in magnitude may be decreasing, in relative or in absolute terms, as the size of the preharvest flood or its generating storm increases, but this is irrelevant and does not necessarily translate into forest harvesting not affecting floods of any size, especially larger floods.

4. Forests Effects on the Magnitude of the Flood Always Decreasing With an Increase in Flood Size: A CP-Based Misconception?

It is a misconception to expect that preharvest and postharvest flood frequency curves will always converge with an increase in flood size, as implied by *Bathurst* [2014, Figure 1]. Such a misunderstanding is also at the origin of CP-based line of reasoning. *Green and Alila* [2012], *Kuraś et al*. [2012], and *Schnorbus and Alila* [2013] illustrated how harvesting in snow environments can increase the temporal variability of the flood response, which in turn translates into a divergence of the flood frequency curves; hence, the effects of harvesting on the magnitude of flood increases with an increase in flood size. This new insight has been attributed to the effects of forest clearing on the energy available for snowmelt, increased synchronization of runoff, and increased efficiency in the delivery of melt runoff to streams [*Green and Alila*, 2012, Figure 7]. We contend that even in some rain environments preharvest and postharvest flood frequency curves can still diverge. A case in point are the FP-based analyses published by *Svoboda* [1991, Figures 5 and 6], *Birkinshaw et al*. [2010, Figure 8], and *Brath et al*. [2006, Figure 8] in which tree removal also increased the variability of the floods around their mean value causing the preharvest and postharvest flood frequency curves to diverge at higher return periods with no apparent no-effect threshold at least not before the 100 year flood event level. A plausible explanation for such divergence, which should be the subject of rigorous testing in the future, is that forest clearing suppresses evapotranspiration causing the watershed to be flashier in flood response. In addition, a more responsive watershed, in turn, can cause some of the temporal variability of rain to be more directly mirrored in the variability of the floods, as opposed to being attenuated by the available watershed moisture stores. Therein lies the significance of the temporal variability of the meteorology and its effects on antecedent moisture conditions and hence evapotranspiration on the forests and floods relations [*Berris and Harr*, 1987, p. 141]. It is common knowledge that the magnitude and frequency of floods, making up the upper tail of a flood frequency distribution, are sensitive to even small changes in the variability of the floods around their mean value. Until recently, the effects of harvesting on the variability in the flood response and most importantly its effects on the magnitude and frequency of large floods has never been invoked in nearly a century of forest hydrology literature on this topic. This is in part due to our being misdirected by the use of regression instead of frequency distribution models, and by the use of CP as opposed to FP.

5. Conclusions

Bathurst [2014], like most others in the literature, confuses the FP-based supposed convergence of preharvest and postharvest flood frequency distributions with the misleading CP-based convergence of preharvest and postharvest regression models [e.g., *Bathurst et al*., 2011a, 2011b]. Forest hydrologists have always used the latter to support their claim that forest harvesting does not affect events larger than 10, 5, and even the 2 year floods [*Alila et al*., 2009 for references]. The CP-based physical explanation taught to students in forest hydrology textbooks for a century and repeatedly used to support such a claim is that "[t]he forest influence becomes less important as the storm size, or flood size, increases; the chief mechanisms, interception, and greater diversion to soil moisture storage, become relatively ineffective when these capacities are greatly exceeded by the volume of storm rainfall" [*Lee*, 1980, p. 280]. As it is often the case, this explanation mistakenly considers the sizes of storm and flood as being interchangeable. Forest hydrologists have for so

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long attempted to disprove the "theory" that forests do not affect large floods using the convergence of two regression models. Meanwhile forests and floods remained perhaps the most contentious topic in forest hydrology. *Platt* [1964, p. 350] states:

> "Whether it is hand-waving or number-waving or equation-waving, a theory is not a theory unless it can be disproved. . .That is, unless it can be falsified by some possible experimental outcome. . .A failure to agree for 30 years [over a century in our case] is public advertisement of a failure to disprove."

We contend that the convergence of two regression models imposed by CP [e.g., *Bathurst et al*., 2011a, 2011b; *Bathurst*, 2014, Figure 1a] is a nontestable hypothesis that does not necessarily translate into the presupposed convergence of two flood frequency relations. FP is not a new concept in hydrology and is an established "paradigm" in climatology [*Katz and Brown*, 1992; *Katz*, 1993; *Wigley*, 2009]. However, in forest hydrology literature CP methods and lines of reasoning dominate. It is not by coincidence that the few FP-based studies have demonstrated a strong causal relation between forest cover and large floods. Perhaps they are rarely cited because their outcomes do not reaffirm what has been proclaimed as dogma [*DeWalle*, 2003, p. 1255], that forests do not affect large floods. This is yet another reason why CP must be abandoned and why CP-based studies must not be used to defend the flawed hydrological "wisdom" of how forest cover affects large floods in basins of all sizes and hydroclimate regimes. We suggest that CP is, perhaps, archival hydrology's most serious misconception that has been long hinted to by forest hydrology's most luminous figures [*Hewlett and Helvey*, 1970, p. 779; *Leopold*, 1981; *Harr*, 1986, p. 1096; *Berris and Harr*, 1987, p. 141]. Misconceptions in archival science are often not easily or quickly corrected and need wide recognition if they are to be overcome [*Kiang*, 1995, p. 347].

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References

Adams, B. J., and C. D. D. Howard (1986), Pathology of design storms, *Can. Water Resour. J.*, *11*, 49–55.

Alila, Y., P. K. Kuraś, M. Schnorbus, and R. Hudson (2009), Forests and floods: A new paradigm sheds light on age-old controversies, *Water Resour. Res.*, *45*, W08416, doi:10.1029/2008WR007207.

Bathurst, J. C. (2014), Comment on ''A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments'' by K. C. Green, and Y. Alila, *Water Resour. Res.*, *50*, doi:10.1002/2013WR013613.

Bathurst, J. C., et al. (2011a), Forest impact on floods due to extreme rainfall and snowmelt in four Latin American environments 1: Field data analysis, *J. Hydrol.*, *400*, 281–291, doi:10.1016/j.jhydrol.2010.11.044.

Bathurst, J. C., et al. (2011b), Forest impact on floods due to extreme rainfall and snowmelt in four Latin American environments 2: Model analysis, *J. Hydrol.*, *400*, 292–304, doi:10.1016/j.jhydrol.2010.09.001.

Berris, S. N., and R. D. Harr (1987), Comparative snow accumulation and melt during rainfall in forested and clear-cut plots in the Western Cascades of Oregon, *Water Resour. Res.*, *23*(1), 135–142.

Beschta, R. L., M. R. Pyles, A. E. Skaugset, and C. G. Surfleet (2000), Peak flow responses to forest practices in the western cascades of Oregon, USA, *J. Hydrol.*, *233*, 102–120, doi:10.1016/S0022–1694(00)00231-6.

Birkinshaw, S. J., J. C. Bathurst, A. Iroumé, and H. Palacios (2010), The effect of forest cover on peak flow and sediment discharge: An integrated field and modelling study in central-southern Chile, *Hydrol. Processes*, *25*(8), 1284–1297, doi:10.1002/hyp.7900.

Brath, A., A. Montanari, and G. Moretti (2006), Assessing the effect of flood frequency of land use change via hydrological simulation (with uncertainty), *J. Hydrol.*, *324*, 141–153, doi:10.1016/j.jhydrol.2005.10.001.

Buttle, J. M. (1994), Isotope hydrograph separations and rapid delivery of pre-event water from drainage basins, *Prog. Phys. Geogr.*, *18*(1), 16–41.

Caissie, D., S. Jolicoeur, M. Bouchard, and E. Poncet (2002), Comparison of streamflow between pre and post timber harvesting in Catamaran Brook (Canada), *J. Hydrol.*, *258*(1), 232–248.

Calder, I. R. (2005), *Blue Revolution: Integrated Land and Water Resource Management*, Earthscan, London.

DeWalle, D. R. (2003), Forest hydrology revisited, *Hydrol. Processes*, *17*, 1255–1256, doi:10.1002/hyp.5115.

Green, K. C., and Y. Alila (2012), A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments, *Water Resour. Res.*, *48*, W10503, doi:10.1029/2012WR012449.

Harr, R. D. (1986), Effects of clear-cutting on rain-on-snow runoff in western Oregon: A new look at old studies, *Water Resour. Res.*, *22*, 383–392, doi:10.1029/WR022i007p01095.

Hewlett, J. D., and J. D. Helvey (1970), Effects of forest clear-felling on the storm hydrograph, *Water Resour. Res.*, *6*, 768–782, doi:10.1029/WR006i003p00768.

Hewlett, J. D., J. C. Fortson, and G. B. Cunningham (1977), The effect of rainfall intensity on storm flow and peak discharge from forest land, *Water Resour. Res.*, *13*(2), 259–266.

Hewlett, J. D., J. C. Fortson, and G. B. Cunningham (1984), Additional tests on the effect of rainfall intensity on storm flow and peak flow from wild-land basins, *Water Resour. Res*, *20*(7), 985–989, doi:10.1029/WR020i007p00985.

Iroumé, A., O. Mayen, and A. Huber (2006), Runoff and peak flow responses to timber harvest and forest age in southern Chile, *Hydrol. Processes*, *20*, 37–50, doi:10.1002/hyp.5897.

Jones, J. A., and D. A. Post (2004), Seasonal and successional streamflow response to forest cutting and regrowth in the northwest and eastern United States, *Water Resour. Res.*, *40*, W05203, doi:10.1029/2003WR002952.

Katz, R. W. (1993), Towards a statistical paradigm for climate change, *Clim. Res.*, *2*, 167–175, doi:10.3354/cr002167.

Katz, R. W., and B. G. Brown (1992), Extreme events in changing climate: Variability is more important than averages, *Clim. Change*, *21*, 289–302, doi:10.1007/BF00139728.

Kiang, N. Y. S. (1995), How are scientific corrections made?, *Sci. Eng. Ethics*, *1*(4), 347–356, doi:10.1007/BF02583252.

 © 2014. American Geophysical Union. All Rights Reserved.

Kuhn, T. S. (1970), *The Structure of Scientific Revolutions*, 2nd ed., Univ. of Chicago Press, Chicago, Ill.

Kuraś, P. K., Y. Alila, and M. Weiler (2012), Forest harvesting effects on the magnitude and frequency of peak flows can increase with return period, *Water Resour. Res.*, *48*, W01544, doi:10.1029/2011WR010705.

Lee, R. (1980), *Forest Hydrology*, Columbia Univ. Press, New York.

Leopold, L. B. (1981), The topology of impacts, in *Cumulative Effects of Forest Management on California Watersheds, Spec. Publ., 3268*, 65 pp., Div. of Agric., Sci., Univ. of Calif., Berkeley, Calif.

Platt, J. R. (1964), Strong inference, *Science*, *146*, 347–353, doi:10.1126/science.146.3642.347.

Reynard, N. S., C. Prudhomme, and S. M. Crooks (2001), The flood characteristics of large UK rivers: Potential effects of changing climate and land use, *Clim. Change*, *48*(2–3), 343–359.

Schnorbus, M., and Y. Alila (2013), Peak flow regime changes following forest harvesting in a snow-dominated basin: Effects of harvest area, elevation, and channel connectivity, *Water Resour. Res.*, *49*, 517–535, doi:10.1029/2012WR011901.

Sivapalan, M., G. Blöschl, R. Merz, and D. Gutknecht (2005), Linking flood frequency to long-term water balance: Incorporating effects of seasonality, *Water Resour. Res.*, *41*, W06012, doi:10.1029/2004WR003439.

Sturdevant-Rees, P., J. A. Smith, J. Morrison, and M. L. Baeck (2001), Tropical storms and the flood hydrology of the central Appalachians, *Water Resour. Res.*, *37*(8), 2143–2168, doi:10.1029/2000WR900310.

Svoboda, A. (1991), Changes in flood regime by use of the modified curve number method, *Hydrol. Sci. J.*, *36*(5), 461–470, doi:10.1080/02626669109492531.

Swift, L. W., W. T. Swank, J. B. Mankin, R. J. Luxmoore, and R. A. Goldstein (1975), Simulation of evapotranspiration and drainage from mature and clear-cut deciduous forests and young pine plantation, *Water Resour. Res.*, *11*(5), 667–673.

Thomas, R. B., and W. F. Megahan (2001), Reply to comment on ''Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon,'' *Water Resour. Res.*, *37*, 180–183, doi:10.1029/2000WR900277.

Wigley, T. M. L. (2009), The effect of changing climate on the frequency of absolute extreme events, *Clim. Change*, *97*, 67–76, doi:10.1007/s10584-009-9654-7.

Wood, E. F., M. Sivapalan, and K. Beven (1990), Similarity and scale in catchment storm response, *Rev. Geophys.*, *28*(1), 1–18, doi:10.1029/RG028i001p00001.

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