

Seeing the climate through the trees: observing climate and forestry impacts on streamflow using a 60-year record

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Abstract

Paired watershed experiments involving the removal or manipulation of forest cover in one of the watersheds have been conducted for more than a century to quantify the impact of forestry operations on streamflow. Because climate variability is expected to be large, forestry treatment effects would be undetectable without the treatment–control comparison. New understanding of climate variability provides an opportunity to examine whether climate variability interacts with forestry treatments, in a predictable manner. Here, we use data from the H. J. Andrews Experimental Forest, Oregon, USA, to examine the impact of the El Niño–Southern Oscillation on streamflow linked to forest harvesting. Our results show that the contrast between El Niño and La Niña events is so large that, whatever the state of the treated watershed in terms of regrowth of the forest canopy, extreme climatic variability related to El Niño–Southern Oscillation remains the more dominant driver of streamflow response at this location. Improvements in forecasting interannual variation in climate might be used to minimize the impact of forestry treatments on streamflow by avoiding initial operations in La Niña years. Copyright © 2014 John Wiley & Sons, Ltd.

Key Words paired watershed; forest hydrology; ENSO; H. J. Andrews

INTRODUCTION

Paired watershed[†] experiments have been used in forest hydrology for over 100 years (Engler, 1919; Bates, 1921; Bates and Henry, 1928), and such studies have been reviewed extensively (Bosch and Hewlett, 1982; Best *et al.*, 2003; Andréassian, 2004). The method was refined at the Coweeta Hydrological Laboratory from the 1930s onwards (for review, see Swank and Crossley, 1988) and has remained essentially unchanged since it was first formulated: identify two contiguous watersheds, as similar as possible in terms of climate, soil, topography and forest cover, and monitor meteorological conditions and stream flow for several years under these similar conditions of forest cover. Then, alter one of the watersheds in terms of its forest cover and continue the measurements as before, until the effects of the land use change upon the timing and amount of streamflow and the flux of particulate and dissolved material carried by the streams has been determined by comparison of hydrological records from the two watersheds. Such an approach can be applied to afforestation, deforestation, regrowth and forest conversion (Best *et al.*, 2003).

Although some studies have pointed out weaknesses in the before–after statistical treatment approach for paired watershed studies (e.g. Alila *et al.*, 2009) and offered alternative model-based approaches (Seibert and McDonnell, 2010), little work has examined the effects of climate variability

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[†]Given the location of the study area and names used at the H. J. Andrews Experimental Forest, we use here the American term ‘watershed’ to denote the drainage basin or watershed.

on streamflow in the context of the paired watershed approach. The paired watershed experimental design ‘controls’ for climate variability, but within this control, climate variability may interact with forestry treatments. Here, we examine the effect of forest harvesting on streamflow using paired watershed data from the H. J. Andrews Experimental Forest, Oregon, USA, to test the hypothesis that climate can be ignored. Links between the El Niño–Southern Oscillation (ENSO) and significant interannual variability in streamflow in the Cascade Mountains of north-western USA are well known (Piechota *et al.*, 1997; Hamlet and Lettenmaier, 2007; Abatzoglou *et al.*, 2014). In general, the warm phase (El Niño) of the ENSO cycle results in below average streamflow in the Cascades and *vice versa* in La Niña events – ‘in general’ because there are different types of El Niño events (Fu *et al.*, 1986), and so precipitation and streamflow responses may vary for a given type of event. For both El Niño and La Niña events, precipitation and streamflow anomalies are amplified on the high-precipitation, windward side of the Cascade Mountains (Leung *et al.*, 2003), the location of our study site.

Using paired watershed analysis from the H. J. Andrews Experimental Forest, Oregon, USA, we ask the question: how does post-treatment run-off vary depending on interannual climate variation? The significance of improved understanding of the influence of climate for landscape management is also briefly discussed.

METHODS

We examined streamflow records for two first-order watersheds (WS) in the H. J. Andrews Experimental Forest, WS1 and WS2. In both cases, daily mean flows (mm) are available from 1 October 1952 to 30 September 2011; the water year (WY) is taken to begin on 1 October so the records cover 59 complete WYs. In addition to run-off totals, flow duration curve (FDC) analysis and Q-frequency analysis was used (Q1, Q5, Q10 and Q90; where, for example, Q10 is the discharge exceeded on 10%

of days for the period in question). The paired watersheds WS1 and WS2 have been described in many publications (e.g. Jones and Grant, 1996), so only a brief summary is provided here. WS1 and WS2 are low elevation watersheds (460–990 m and 530–1070 m above sea level, respectively: Jones and Grant, 1996). Mean annual precipitation (1958–2012) at the nearby CS2MET rain gauge is 2259 mm. Over 90% of the annual precipitation falls between October and May; some fall as snow. Results are confined here to the extended winter November to May (n-m) inclusive because over 90% of run-off occurs during this time. Given a control period of nine WYs, we have likewise divided the treatment period (TP) into five 9-year periods to enable comparison (Table I).

Watershed 1 was 100% clear-cut from 1962 to 1966 and broadcast burned in 1967. The adjacent WS2 was used as a control watershed. Before treatment, the vegetation of both watersheds consisted of old-growth Douglas fir (*Pseudotsuga menziesii*) with western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*) in closed-canopy stands ranging from 150 to 500 years in age. Data from the control period (data from the November to May period for WYs 1953–1961 inclusive) were used to predict WS1 response in the post-TP (Burt and Swank, 1992): total streamflow (Q_{n-m}) and number of Q10 days ($Q10_{n-m}$). Although the sample size is necessarily limited in each case ($n=9$), the regression equations were highly significant in both cases: $R^2=91\%$, $p<0.0001$. Examination of FDCs also followed the approach of Burt and Swank (1992), allowing the influences of climate and land use to be compared over the study period. Flow data were divided into the control period (WYs 1953–1961) and five periods post-treatment (all 9 years long to match the control period).

We used sea surface temperature anomaly data for the NINO34 region (120°W–170°W, 5°S–5°N) of the equatorial Pacific Ocean (Kaplan *et al.*, 1998) to characterize ocean–atmosphere conditions in the Pacific, for which large positive values represent El Niño events and large negative values signify La Niña conditions. An

Table I. Summary data for the control and five treatment periods

Period	WS1 Q_{n-m}	WS2 Q_{n-m}	Difference	Max NINO34	Min NINO34
Control (1953–1961)	1301	1437	–136	1.1	–0.9
Treatment 1 (1967–1975)	1514	1351	163	1.0	–1.6
Treatment 2 (1976–1984)	1272	1174	98	0.5	–1.0
Treatment 3 (1985–1993)	1124	1004	120	1.6	–1.4
Treatment 4 (1994–2002)	1336	1299	37	2.0	–1.1
Treatment 5 (2003–2011)	1188	1152	36	1.2	–1.2

All results are for the extended winter November to May.

Total run-off (TOT) is in millimetres.

Values listed for the NINO34 index are the maximum and minimum November to May (n-m) average during each period.

Dates refer to water years.

SCIENTIFIC BRIEFING

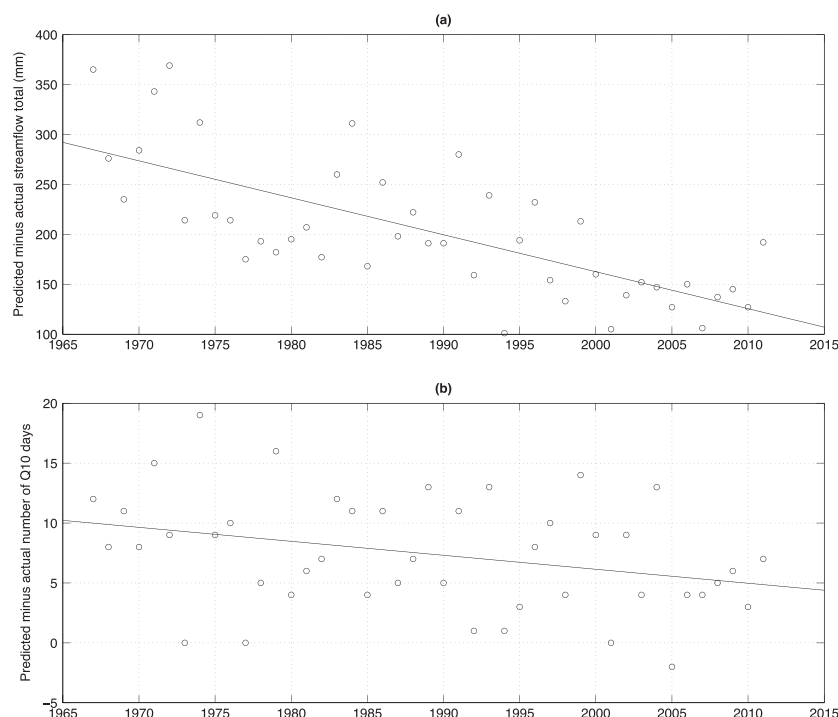


Figure 1. The difference between actual and predicted values for WS1 for (a) streamflow (mm) and (b) the number of Q10 days. Both plots cover the extended winter period November through May

extended series of SST anomaly data for equatorial regions of the Pacific Ocean based on Kaplan *et al.* (1998) is available at <http://iridl.ldeo.columbia.edu/SOURCES/Indices/nino/EXTENDED/>.

RESULTS AND DISCUSSION

Changes in water yield

Figure 1 shows the difference between predicted and actual values for Q_{n-m} and $Q10_{n-m}$. The influence of clear-cutting on streamflow in WS1 is unambiguous (Table I, Figure 1). In the control period, WS2 was wetter in every year except one; after clear-cutting, this has happened only twice in 45 years (1997 and 2007). Despite the sustained increase in streamflow following clear-cutting at WS1, the response of both watersheds is very similar, dominated by rainfall inputs in both cases as expected. Annually, 59% of rainfall was converted into run-off at WS1 and 56% at WS2, and there were highly significant correlations between P_{n-m} and Q_{n-m} in both cases (WS1: $R^2=0.93$, WS2: $R^2=0.94$) as expected.

In TP 1, Q_{n-m} from WS1 increased by 16% (Table I). Total streamflow from WS1 was 300 mm greater than predicted at the start of the TP (Figure 1a). Thereafter, there was a steady and highly significant decline ($p < 0.0001$), but the predicted annual difference is still about 100 mm today, and it may be several decades before total flow again becomes greater in WS2, as it was during the control period. It is apparent therefore that a 40-year-old forest still

loses less water by evaporation and more in run-off than an old-growth stand. The pattern for predicted difference in number of $Q10_{n-m}$ events is more variable, but there is nevertheless a clear pattern in the post-TP (Figure 1b): an initial increase of about 10 $Q10_{n-m}$ days per year and thereafter a steady, statistically significant ($p=0.038$) decline. However, when interannual climate variability is taken into account, some interesting and potentially important effects appear: Streamflow response is not solely determined by the impact of forestry operations. This has been overlooked because the paired watershed experimental design, which estimates the effect as the difference between treatment and control (used to estimate treatment), has removed the climate variability.

ENSO effects on flow

For both watersheds, there is a significant relationship between total streamflow (Q_{n-m}) and the NINO34 index:

$$\text{WS1 : } Q_{n-m} = 1307 - 195 \text{ NINO34}_{n-m}, R^2 = 0.18, p = 0.004 \quad (1)$$

$$\text{WS2 : } Q_{n-m} = 1214 - 200 \text{ NINO34}_{n-m}, R^2 = 0.18, p = 0.005 \quad (2)$$

This confirms earlier research that streamflow tends to be higher in La Niña events and lower for El Niño events. Not surprisingly, rainfall amounts are strongly correlated

Table II. Mean values for a range of flow statistics at WS1 and WS2, for the treatment period (1967–2012) and for El Niño and La Niña events

		Q_{n-m}	$Q90_{n-m}$	$Q10_{n-m}$	$Q5_{n-m}$	$Q1_{n-m}$	$Q90_{j-o}$
WS1	Mean: all years	1289	212	36	18	3	110
	La Niña years	1628	212	53	26	4	103
	El Niño years	918	212	21	10	1	91
WS2	Mean: all years	1200	210	35	16	3	124
	La Niña years	1557	212	53	25	4	120
	El Niño years	824	210	20	8	1	97

All results are for the November to May (n-m) extended winter, except that summer low flow data ($Q90_{j-o}$) are included in the right-hand column. Variables are defined in the text.

Values of the NINO34 index greater than one standard deviation either side of the mean were used to identify El Niño and La Niña events.

Note that this yields fewer ‘ENSO’ periods than listed by Leung *et al.* (2003). The year 1983 was an exceptionally wet El Niño; following Piechota *et al.* (1997), this was excluded from the calculations.

with ENSO conditions too. Mean rainfall for November to May is 1912 mm, averaging 1638 mm in El Niño events and 2263 mm for La Niña events. The number of days per year receiving 25 mm or more (medium and high-flow events as defined by Seibert and McDonnell, 2010) increases from 20 (El Niño) to 30 (La Niña); the mean is 24.

There is also a significant lag between ENSO conditions and streamflow response that may be helpful for forecasting purposes: Q_{n-m} in both watersheds is significantly correlated with the average NINO34 value for the previous summer, June through October ($NINO34_{j-o-1}$: i.e. the NINO34 average for the 5 months immediately preceding the November to May period):

$$WS1 : Q_{n-m} = 1333 - 265 NINO34_{j-o-1}, R^2 = 0.24, \\ p = 0.0008 \quad (3)$$

$$WS2 : Q_{n-m} = 1240 - 272 NINO34_{j-o-1}, R^2 = 0.24, \\ p = 0.0009 \quad (4)$$

This raises the possibility of flow forecasting and varying management decisions, a matter to which we return later.

Table II shows the influence of El Niño and La Niña events on the streamflow regime: As expected, El Niño events are drier than normal. There is lower total streamflow (Q_{n-m}) and fewer high-flow days ($Q10_{n-m}$, $Q5_{n-m}$, $Q1_{n-m}$); low flows ($Q90_{n-m}$) are not affected in winter, although they are in summer (results not shown). Table II shows that, averaged over the entire TP, both watersheds have very similar results, emphasizing the way in which hydroclimatic variability, as influenced by ENSO, introduces a source of variability of equivalent magnitude to that provided by land use change. Table III presents $Q10_{n-m}$ data for the control and post-TPs. In all cases except the control period, the number of $Q10_{n-m}$ days in an El Niño event is below the mean; in 1958 (control period), the El Niño was anomalously wet that accounts for above average $Q10_{n-m}$ days. The large contrast between El Niño and La Niña events is once again very clear, indicating that, whatever the condition of the treated watershed in terms of regrowth of the forest canopy climatic variations related to ENSO remain the more dominant driver of streamflow variability at this location.

FDC analysis

Figure 2 shows FDCs for the control period and all post-TPs. During the control period, WS2 streamflow

Table III. Number of days November to May when streamflow exceeded $Q10_{n-m}$

		Control	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5
WS1	Mean: all years	36	43	34	30	39	32
	La Niña year	58	84	47	49	50	44
	El Niño year	42	17	6	18	29	16
WS2	Mean: all years	46	41	31	25	40	33
	La Niña year	79	87	46	45	53	50
	El Niño year	48	18	2	18	30	13
Years	La Niña	1956	1974	1976	1989	2000	2008
	El Niño	1958	1973	1977	1992	1998	2010

Given the small number of El Niño and La Niña events in each period, results from specific years rather than mean values are given. The years selected had the largest values of the NINO34 index within each period: positive for El Niño and negative for La Niña. Again, 1983 is excluded from the analysis

SCIENTIFIC BRIEFING

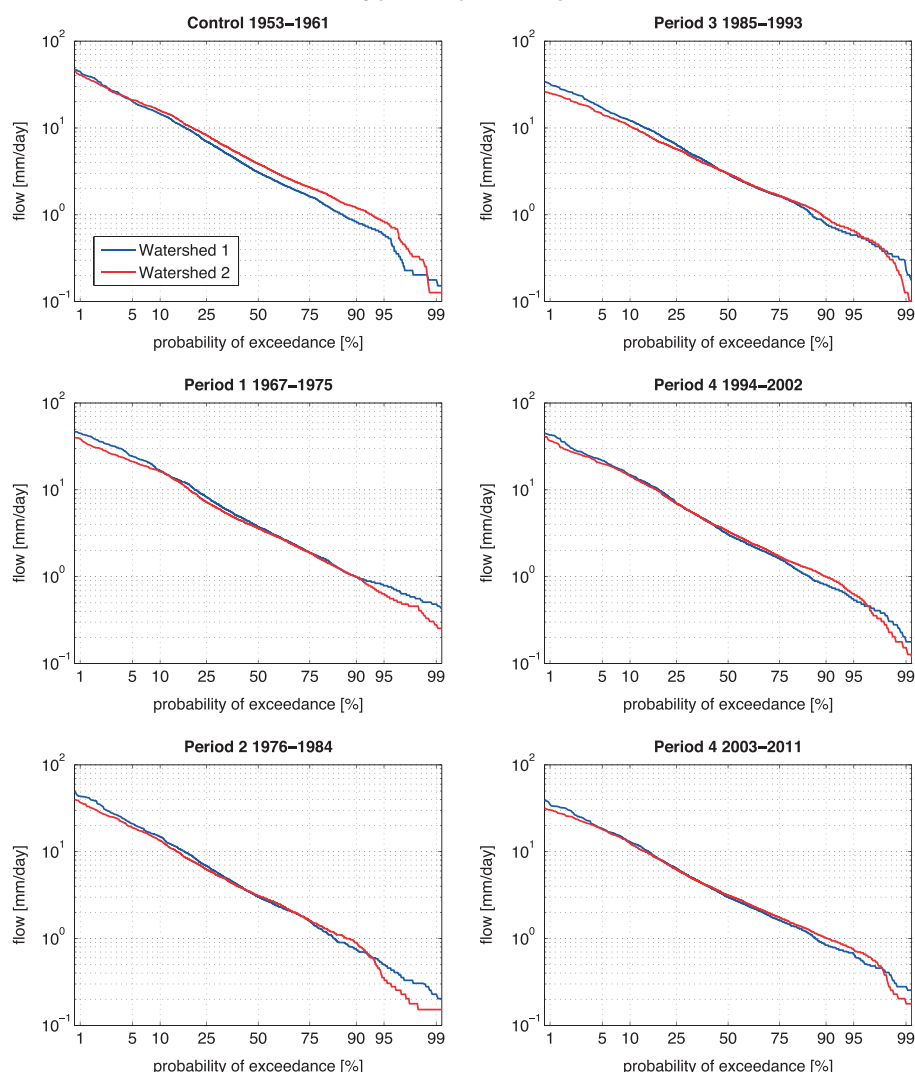


Figure 2. Flow duration curves for the control period and five treatment periods. WS1 is shown in blue and WS2 in red

exceeds WS1 except for the highest flows (Q3–Q1) where WS1 has marginally higher run-off for a given flow frequency. In the first TP, WS1 exceeds WS2 at above average flow frequencies and at the lowest flows, showing that the additional run-off because of clear-cutting affects both stormflow and baseflow. By the fifth period, WS2 exceeds WS1 across most of the flow range, but WS1 still has higher numbers of high discharge, low-frequency flows.

Figure 3 includes FDCs for the largest El Niño and La Niña events in each period (as measured by the NINO34 index). In the control period, there is limited contrast between the 2 years (El Niño: 1958, La Niña: 1956) because this particular El Niño was quite wet so run-off remained quite high. The FDC for WS2 is only a little above that for WS1 in the La Niña year, but the difference between watersheds is much greater in the drier El Niño

year. In the control period therefore, WS2 always produced more run-off, especially in drier years.

In the first post-TP, El Niño and La Niña years are very different. For the El Niño year (1973); the WS1 curve is entirely above that for WS2, as would be expected immediately after clear-cutting. However, for the La Niña year (1974), the very wet conditions seem to generate particularly high streamflow from WS2 that has higher low flows and only falls below WS1 for the highest flows. The same patterns are seen in period 2. For later periods, FDCs for both watersheds are very similar but low flows in El Niño years are once again higher in WS2. The differences between El Niño and La Niña years are least in period 4, probably because again the El Niño year was relatively wet. In the other periods, there is a clear difference between FDCs in El Niño and La Niña years; both watersheds have a very similar response for a given year.

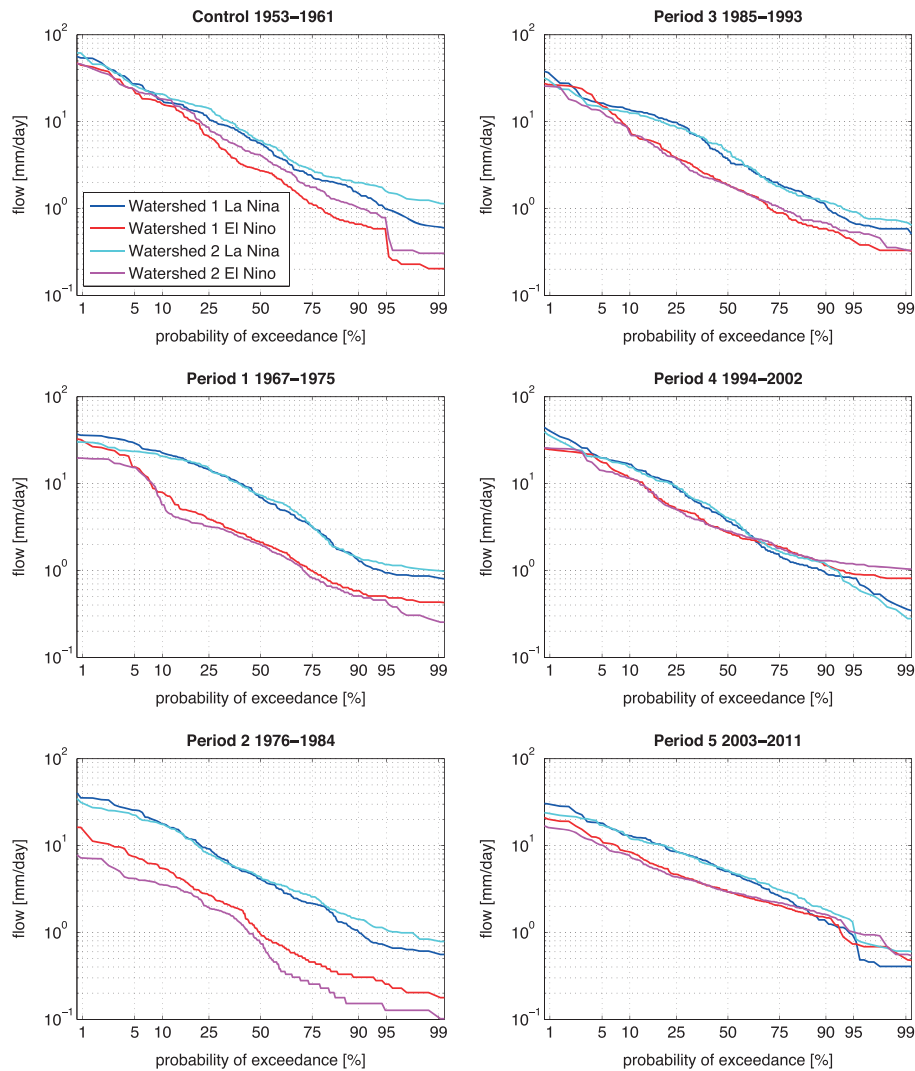


Figure 3. Flow duration curves for the two watersheds for the control period and five treatment periods. The years selected had the largest values of the NINO34 index within each period: positive for El Niño (red lines) and negative for La Niña (blue lines). For each pair of lines, WS1 is the darker colour and WS2 the paler colour

It is self-evident that run-off will be higher in wet years and *vice versa*. What is apparent here is that high-frequency climate variation obscures the emerging pattern associated regrowth following clear-cutting. Unlike the results presented by Burt and Swank (1992), where clear differences between treatment and control FDCs were sustained throughout the TP, here, the main contrast in FDCs is between wet and dry years, not between treatment and control. True, the expected pattern of change with forest regrowth is observed: The difference between expected and actual Q_{n-m} from WS1 falls by about 150 mm over 40 years (Figure 1a); at the same time, the number of Q10 events is halved. Nevertheless, significant short-term climatic variability imparts considerable noise to the hydrological record and obscures the longer-term trend driven by land use change. Moreover, the two watersheds appeared to behave somewhat

differently in wet and dry years, at least in TPs 1 and 2 (Figure 3) with relatively higher flows from WS2 in wet years. Given our improved knowledge of climate variability and its potential to produce differential effects on streamflow in control *versus* treated watersheds, the control period in a paired watershed experiment should be long enough to capture this variability.

A control out of control?

Table I shows that the control period had the highest run-off total for WS2, but there are no significant trends over time for precipitation (P), streamflow (Q) or temperature (results not shown). What is significant is an increase in the difference between P and Q ($P - Q$: $r=0.37$, $p=0.005$, $n=55$). This suggests an increase in evaporation for the November to May period, which could be the

results of a combination of combined changes in temperature and wind speed. Further work is needed on this intriguing finding, which is beyond the scope of this discussion, but it suggests a possible nonstationarity in the control. Various alternative hypotheses for the apparent long-term trend in declining Q/P at WS2 include release of understory hemlock because of cumulative mortality of the 500-year old over-storey Douglas fir or changing temperature. There is no long-term trend in measured (i.e. near ground level) temperature but in a stepwise multiple regression analysis of the long-term P–Q trend, without itself being a significant addition, temperature does increase the variance explained from 14% to 21%. If temperature change were involved, this might be evident from aforementioned canopy measurements, but unfortunately, we do not have records of air temperature trends at the top of the canopy (which is 80–90 m tall).

This apart, the control period is notable for its lack of extreme ENSO conditions, compared with all but TP 5. This means that, with hindsight, the control period did not include the very dry or very wet conditions usually associated with El Niño and La Niña events, respectively, meaning that the full range of possible climatic variability was not experienced during the control period. Nine years is a typical – even generous – length of control period but not long enough perhaps?

Implications

Three implications can be drawn from this analysis of relevance to paired watershed experiments and the management of water resources in forested watersheds:

1. Wherever subtle processes are embedded within highly variable systems, a weak signal cannot be extracted from a noisy background without a long record (Burt, 1994). With respect to paired watershed experiments, this emphasizes the need for continued monitoring over long (treatment) periods, especially at locations such as H. J. Andrews where short-term climatic variation is significant compared with any long-term trend.
2. It follows that, if the study site is in a region affected by extreme climatic variation, then the control period must be long enough to capture this variability. Otherwise, the extreme differences in run-off, for example, between El Niño and La Niña conditions, might not be factored into calculations about available water resources. The expected increase in water yield would no doubt happen after deforestation, but there might well be more interannual variability than expected.
3. Provided that there is some leeway over and above economic considerations such as the price of timber,

then the ability to forecast rainfall and streamflow might help avoid excessive run-off and erosion by delaying harvesting operations for a year. Looking at correlations between NINO34 and streamflow the following winter, the earliest month to provide a significant correlation is June ($R^2=0.1329$, $p=0.016$); however, despite being statistically significant, the level of variance explained is low, and this would be a weak basis for forecasting. Nevertheless, since the June NINO34 index value would be available mid-July, this suggests that, if clear-cutting could be delayed until August, it would be possible to forecast whether the following winter is likely to be very wet (La Niña) or not so avoiding the possibility of high surface run-off on unprotected soil. However, these comments need placing in context: The treatment in WS1 involved clear-cutting old-growth (150–500 year old) forests; this has not been legal for 20 years in the Pacific Northwest. The only places where clear-cutting is being performed in the Pacific Northwest are private land on a 70-year rotation. Thus, our comment about forecasting might be relevant generally but not at H. J. Andrews specifically. Additionally, there are other practical issues related to harvest planning months or years into the future, including staffing and machinery. It is clear therefore that much more reliable forecasting methods will be needed before environmental impact can take priority over economic considerations.

CONCLUDING COMMENTS

Although it is intuitive that a wet year will have more run-off and sediment transport than a dry year, the results demonstrate that, whatever the condition of the treated watershed in terms of regrowth of the forest canopy, extreme climatic variations related to ENSO remain the more dominant driver of streamflow variability at this location. The important finding that streamflow response in both watersheds is significantly correlated with the average NINO34 value for the previous summer suggests the possibility of flow forecasting and improved management decision-making.

Although the paired watershed approach is not compromised via our observations (although we do note the arguments made by Alila *et al.*, 2009 that may compromise the paired watershed approach in other ways), this study suggests that greater caution is needed than previously realized in relation to the length of the initial control period. On the other hand, knowledge of potential climatic impacts may eventually benefit management decisions, avoiding particularly problematic La Niña-impacted weather conditions. The ability to reliably forecast streamflow could help avoid excessive impact by delaying harvesting operations.

The findings here demonstrate the need for long-term environmental monitoring to enhance decision-making and planning. Multidecadal data sets are needed to better understand forestry management and watershed impacts. Understanding the response of run-off to climate and forestry management is critical, but there may be unforeseen and unknown ecohydrological trends and effects that may only be revealed at long time scales. The findings here highlight the benefit of such observations.

Finally, our analysis reinforces the emerging consensus that interannual climate variability is high relative to long-term trends in climate (Abatzoglou *et al.*, 2014); it makes sense that interannual streamflow variability will be high as well. The Andrews Forest appears to be located at a latitude where it experiences climate variability associated with both the equatorial Pacific and the northern Pacific; future research might therefore explore the influence of indices in addition to ENSO (e.g. the Pacific Decadal Oscillation) to better explain streamflow variability. It is also the case that long-term climate change-related trends are evident in streamflow records for much of the Pacific Northwest, namely, increases in spring flow and declining late summer flow (Hatcher and Jones, 2013; Dettinger, 2014). In relation to controls on orographic rainfall, Luce *et al.* (2013) identified links between atmospheric circulation and precipitation totals in the Pacific Northwest similar to those identified by Burt and Howden (2013) for upland Britain and the Pacific Northwest. This raises the question as to whether significant climate variability effects on streamflow might also be apparent at other, midlatitude, west coast locations, such as Britain or Chile.

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