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ORIGINAL ARTICLE

Conversion to pine: Changes in timing and magnitude of high and low flows

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Abstract

Understanding watershed responses to extreme events is important for assessing potential impacts of floods, droughts, episodic pollution, and other external driving variables on watershed resources. In this study, we combine trend and frequency analyses with paired watershed techniques to evaluate the long-term high- and low-flow data from Coweeta Hydrologic Laboratory in North Carolina, USA in an attempt to quantify and interpret responses to extreme flow events in managed and unmanaged watersheds. Two experimental watersheds were converted from mixed deciduous forest cover to pine (*Pinus strobus* L.) in 1957 and 1956, respectively and two others were kept untreated to serve as control watersheds. Seventy years of annual streamflow (instantaneous maximum, minimum, and mean) time series data from watersheds 1, 2, 17, and 18 were analyzed with a Mann–Whitney–Pettitt test to identify and compare change points. Mean annual streamflow increased in both watersheds for 10–12 years after harvests, but the more effective factor on the flow series was the growth of pine plantations. Maximum flows of 2-, 5-, and 10-year return periods decreased after planting pine, but there was no difference for larger flow events compared to deciduous forest. For minimum flows, pine stands were more effective compared to maximum flows as minimum flows decreased for all return periods.

Keywords: *Species conversion, high and low flows, time series analysis.*

Introduction

Changes in forest cover can affect the hydrologic system in a watershed considerably. Many studies have been implemented to highlight forestry–water relationship because vegetation is generally the only tool that can be managed toward regulating streamflow in forested watersheds. Maintenance of a forest structure toward an optimal water production objective is a significant issue in many countries and can be only achieved with the knowledge provided from experimental watersheds.

Forest structure defined by many parameters including species composition, age, density, and floor properties as well as treatments have been investigated thoroughly in the last century from various hydrological aspects (Brown et al., 2005; Özyuvaçlı et al., 2004; Sahin and Hall, 1996; Swank et al., 1988). However, the impacts of some forestry treatments on flow characteristics (e.g. low flows, peak flows, zero flows) are not deeply understood

and quantified yet. In general sense, forests are known to reduce high flows and therefore are a natural solution against floods (Robinson et al., 2003). This statement is definitely valid in many cases, but some forest types can be more effective against floods due to structural characteristics like species composition, stand density, stratification, and so on.

The role of forests and forestry treatments on high flows has been documented in number of papers (Cosandey et al., 2005; Swank et al., 1988; Swank et al., 2001; Tu et al., 2005), but not much study has been carried out to look solely at the low flows (Johnson, 1998). There are two basic constraints for investigating the effects of forestry treatments on extreme flows; long-term reliable continuous streamflow data and control watersheds to eliminate climatic variations. In this study, we analyzed 70 years of streamflow data belonging to treatment

and control watersheds to identify the effects of species conversion on mean, high, and low flows.

The published works on forestry treatments–low flow relationship have been reported by Johnson (1998) and Robinson et al. (2003). Johnson concluded after reviewing several studies mostly from UK that clearfelling increases low flow levels but then low flow levels start to decrease some 5–10 years after plantation as the canopy closes. Robinson et al. (2003) found small and short duration (1–3 years) increases in low flow levels after cutting treatments and decreases after canopy closure for both coniferous and deciduous forests. The effect was more drastic for conifers. The peak flow levels on the other hand reduced 10–20% in coniferous stands after canopy closure. The reduction was rapid in the early years and then progressively slowed. Cutting effects on stormflow runoff at Coweeta watersheds in North Carolina, USA were investigated by Swank et al. (2001) to conclude that many flow parameters including peakflow rate, recession time and quickflow volume changed from 5 to 15% except time to peak flow. The species conversion from deciduous to pine was also evaluated from monthly streamflow point of view (Swank et al., 1988; Swank & Vose, 1994) but effects on extreme flows remained unstudied.

In a broad sense, widely accepted results on the effects of forests on high and low flows have been (Eisenbies et al., 2007; Robinson et al., 2003; Serengil et al., 2007): (1) forest cutting increases the frequency of low and high flows, (2) the regrowth decreases these flows, more rapidly in the early years of canopy closure, and (3) pine forests are more effective than deciduous forests to decrease streamflow due to larger interception potentials but effects on extreme flows are not well-documented.

In this study, we focus on forest type and extreme flows and hypothesize that pine forests response to large storm-flow events over a threshold are quite similar with mixed deciduous forests but conversion to pine affects low flows at all magnitudes.

Materials and methods

Study watersheds

The Coweeta Hydrologic Laboratory is located in the Nantahala Mountain Range of western North Carolina, on latitude 35°03'N, longitude 83°25'W (Figure 1). Thirty-two streams draining experimental watersheds have been instrumented with weather stations and weirs and studied since the establishment of the lab in 1934. Currently 16 weirs are in operation (Swank & Crossley, 1988). Climate is classified as Marine, Humid Temperate and

characterized by mild winters and cool summers with abundant and uniform precipitation in all seasons. Precipitation is modified by topography in the region. Average annual precipitation varies from 1700 mm at lowest point (680 m) to 2500 mm on upper elevations (>1400 m). Rain falls in all months while snow comprises 2–10% of annual precipitation. Even though the region has a humid character there have been dry periods starting up with 1925 drought. The years 1941, 1954, 1986, and 1998 are also determined in the precipitation records as drought years. The periods of 1985–1988 and 1998–2001 were multiple year drought periods. The underlying bedrock consists of quartz diorite gneiss, metasandstone and pelitic schist, and quartzose metasandstone. Soils are deeply weathered and average about 7 m in depth (Swank et al., 2001).

The vegetation of control watersheds (W2 and W18) is composed of mixed hardwoods (*Quercus prinus* L., *Acer rubrum* L., *Quercus coccinea* Muenchh., *Quercus rubra* L.). *Quercus prinus* has the highest relative basal area of 21.3%. The total average basal area is 25.6 m²/ha which makes around 3044.3 stems/ha.

Field methods

Four experimental watersheds (W1, W2, W17, and W18) of Coweeta Hydrologic Laboratory were used in this study. W1 and W17 were subject to forestry treatments, W2 and W18 were kept untreated and referred as controls (Table I). The first two were instrumented in 1934, while W17 and W18 in 1936 with V-notch weirs. Some properties of these watersheds are given below (Table I).

W1 was prescribed and burned in 1942. All trees and shrubs within the cove-hardwood type were killed with herbicides in 1954. The cove hardwood type is one of the three forest types in the region and represents the forests in stream valleys, coves, and lower mountain slopes. This treatment was applied to 25% of both land area and total watershed basal area. It was retreated for three consecutive growing seasons to disable any vegetative activity. All trees and shrubs were cut and burned in 1956–1957. No products were removed from the site and white pine (*Pinus strobus* L.) was planted in 1957. In subsequent years, pine was released from hardwood competition by cutting and chemicals as necessary. All woody vegetation of W17 was cut in 1940 and regrowing seedlings were also cut annually thereafter in most years until 1955. No products were removed from the watershed. White pine was planted in 1956. The watersheds W2 and W18 were kept untreated as controls for W1 and W17, subsequently (Swank & Crossley, 1988).

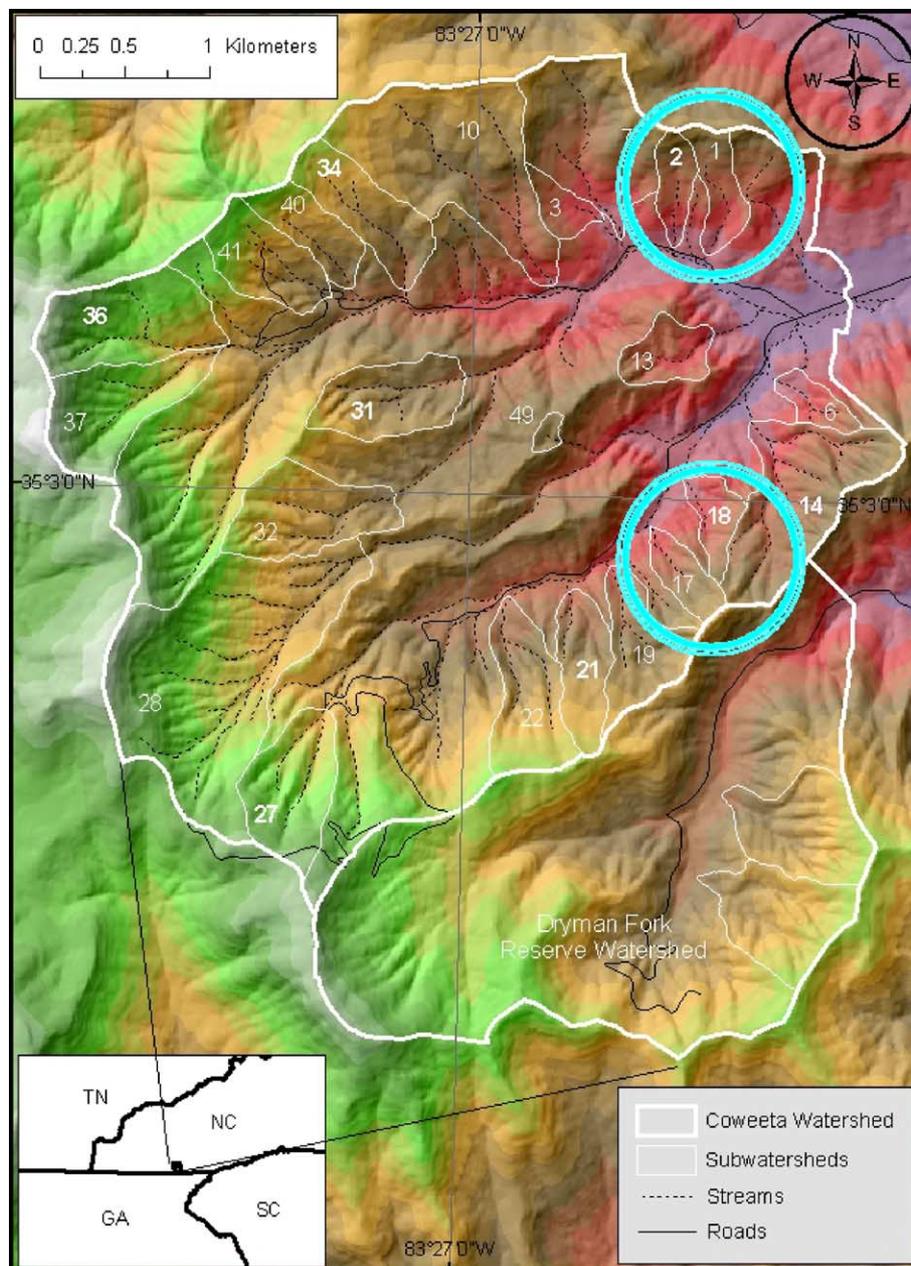


Figure 1. Experimental watersheds in Coweeta Hydrologic Laboratory, USA.

Table I. Some properties of experimental watersheds (modified from Swank and Crossley, 1988).

Watershed number	Name of stream	Area (ha)	Elevation at weir (m)	Maximum elevation (m)	Aspect	Annual precipitation (mm)	Mean annual temperature (°C)	Evaporation (mm)
1	Copper branch	16	705	988	S	1771.7	12.6	892
2	Shope branch	12	709	1004	SSE	1771.7	12.6	892
17	Hertzler branch	13	760	1021	NW	1939.0	12.6	892
18	Grady branch	13	726	993	NW	1939.0	12.6	892

Data sets

Annual instantaneous maximum, minimum, and daily mean flow series between 1934 and 2004 were used in trend analysis and quantile estimation.

The annual mean ratio (AMR), annual maximum ratio (AXR), and annual minimum flow ratio (ANR) between treatment and control watersheds (Q_{W1}/Q_{W2} and Q_{W17}/Q_{W18} for mean, min and max flows) were used to construct six new time series (AMR Q_T/Q_C , AXR Q_T/Q_C , ANR Q_T/Q_C for both pairs of W1/W2 and W17/W18) in order to minimize the effects of climatic variation. The advantage of paired watershed approach is to eliminate the influence of variations in climatic parameters. The annual variations in precipitation and evapotranspiration that could conceal the effects of the treatments can be eliminated to some extent by employing the Q_T/Q_C ratios.

There is a wide range of methods and data requirements to evaluate extreme flows. Kite (1988) discussed the usage of annual- and partial-duration series in extreme flow analyses and stated that maximum instantaneous flows derived from a continuous hydrograph would be preferable for investigating flood events. A brief discussion is also available in Malamud and Turcotte (2006) on maximum and partial series and distribution functions used in flood analysis.

In this study, the high- and low-flow estimations for various return periods have been performed for comparing the forest types, not for calculating exact high- or low-flow amounts. Therefore, ratios were discussed instead of magnitudes.

Shift analysis

Many parametric and nonparametric tests have been suggested for trend and shift analysis of hydrologic time series in the literature. Salas (1993) explained many of them, while Hirsch et al. (1993) gave a detailed discussion on parametric and nonparametric tests. Double mass analysis is the most common hydrologic method to determine the change points (CPs) in paired time series. However, Mann–Whitney–Pettitt test is preferred in this study as it gives the exact change year (shift point) and significance. Kiely (1999) used it to find the CPs in precipitation while Tu et al. (2005) applied to discharge series.

Equation 5 was used to determine the approximate significance of CPs (Kiely, 1999). Some authors preferred to employ t test to compare the subsets of pre and posttreatment following a parametric homogeneity test (Tu et al., 2005). We did not perform a t test but tested all flow ratio series ($Q_{W1}/$

Q_{W2} and Q_{W17}/Q_{W18}) for independency with correlograms. In Mann–Whitney–Pettitt test, the time series (length $T; x_1, \dots, x_T$) is considered as two samples represented by x_1, \dots, x_t and x_{t+1}, \dots, x_T . The indices $V(t)$ and $U(t)$ are calculated from

$$V_{t,T} = \sum \text{sgn}(X_t - X_j), \quad (1)$$

$$U_{t,T} = U_{t-1,T} + V_{t,T} \text{ for } t = 2, T, \quad (2)$$

$$\begin{aligned} U_{t,T} &= V_{t,T} \quad \text{sgn}(x) = 1, \text{ for } x > 0 \\ \text{sgn}(x) &= 0, \text{ for } x = 0 \\ \text{sgn}(x) &= -1, \text{ for } x < 0 \end{aligned} \quad (3)$$

The most significant CP is found where the $|U_{t,T}|$ value is maximum:

$$Kt = \max |U_{t,T}| \quad (4)$$

The approximate significance probability $p(t)$ for a CP is

$$p(t) = 1 - \exp(-6 U_{t,T}^2 / T^3 + T^2) \quad (5)$$

Quantile estimation statistics

In hydrology, the percentiles or quantiles of a distribution are often used as design events. We employed this basic and common procedure to compare the responses of deciduous and coniferous forests to floods. The 100 p percentile or the p th quantile x_p is the value with cumulative probability p :

$$F_x(x_p) = p$$

The 100 p percentile x_p is called the 100(1- p) percent exceedence event because it will exceed with probability 1- p . Return period (or recurrence interval) is often specified rather than the exceedence probability (Stedinger et al., 1993). For example, the annual maximum flood-flow or low flow exceeded with a 1% probability in any year is called the 100th year flood- or low-flow event.

The easiest and common approach for estimating an extreme flow magnitude for a design purpose is to fit the data to a theoretical frequency distribution. The available distributions for maximum and minimum events and the limitations of the methodology are given by Kite (1988) and Stedinger et al. (1993). The two important points related with this procedure are: (1) The length of available flow records and (2) choosing the best distribution, the data fits. However, the method is quite common, simple, and well documented (Chow et al., 1988; Dalrymple, 1960; Kite, 1988).

W17 data were not suitable for this analysis as it included a long duration of subsequent clear-cuts between 1940 and 1955, which might influence both maximum and minimum series. The treatments in

W1 during the period before the conversion represented more slight and short lived impacts. Hence, it was easier to detect and exclude the biased data from the set. Actually, the only data point excluded for maximum flows were 1957, just after the clear-cut. Event sizes for return periods of maximum and minimum flows were calculated for pre- and post-CP periods of W1 and W2 annual instantaneous data. The following distributions were used based on *probability plot regression* (Stedinger et al., 1993) and parameters were estimated by *method of moments*. The density functions are:

TYPE III EXTREMAL (for annual min values)

$$f(x) = (\alpha/\beta)[(x - \gamma)/\beta]^{x-1} e^{-[(x-\gamma)/\beta]^\alpha} \quad (6)$$

LOG-PEARSON TYPE III (for annual max values)

$$f(x) = [(e^{\gamma/\beta} x^{\beta-1}) / |\beta| \Gamma(\alpha)] [(1 - x^{-\beta})]^{x-1} \quad (7)$$

- α : shape parameter,
- β : scale parameter,
- γ : location parameter.

Results

Change points (CPs) in the time series

Annual fluctuations and a changing trend after 1960s were two common features of the time series of mean annual runoff ratio (AMR) of W1/W2 and W17/W18.

The CP detected using Mann–Whitney–Pettitt test for both AMR series (AMRw1/w2 and AMRw17/w18) was 1968 as seen in Figure 2. The peak point of the $U_{1,T}$ indicating the CP identified 1968 as a year that mean annual flow of watersheds 1 and 17 started to change substantially. Annual variations did not affect the peak of $U_{1,T}$.

Table II. Change points years, way of change (decrease or increase), and the significance of shift for all time series. Less significant CPs are also given as secondary.

Time series	W1/W2		W17/W18	
	Primary	Secondary	Primary	Secondary
AMR	1968-D-0.99	1980-D-0.98	1968-D-0.99	1980-D-0.98
AXR	1976-D-0.98	N/A	1972-D-0.99	N/A
ANR	1965-D-0.99	1978-D-0.81	1966-D-0.99	1995-I-0.98

Less significant CPs (secondary) detected on both series corresponded to 1980, when planted pine stands have been 23 (W1)–24 (W17) years of age. This secondary CP was not identified on AXR and ANR series (Table II). The 1980 also indicated a starting point of a period with more variable flow characteristics for both series as seen in Figure 2.

The 1942 prescribed burn in W1 and 1940 clear-cut in W17 were clearly seen on the graph as spikes (Figure 2). The clear-cuts just before the conversions (1955–1956) looked like less effective in spite of the larger amount of annual precipitation (1957 precipitation was 2167 mm, while 1943 was 1705 mm) as the standing volume had already been decreased significantly by subsequent cuts or chemical applications in the previous years. If we wanted to separate the time series of both catchment pairs visually in Figure 2, we would identify two series with different means, connected with a shift (jump) period.

The Mann–Whitney–Pettitt test results for maximum (AXR) and minimum flows (ANR) are given below (Figures 3 and 4, Table II).

In case of maximum flow ratios, annual fluctuations were also visible but a clear CP did not exist. The CP of annual maximum flows for both series

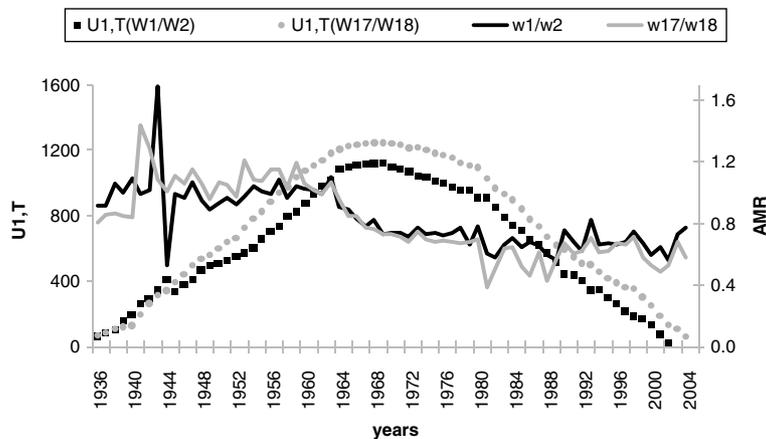


Figure 2. AMR curve and test statistics for W1/W2 and W17/W18. Note: W1 and W17 are treatment watersheds (converted to pine), W2 and W18 are control watersheds (natural mixed hardwood). AMR denotes annual mean flow ratios between the treatment and control watersheds. $U_{1,T}$ is the Mann–Whitney–Pettitt function. The peak point of the function indicates the change point (CP) at the time series.

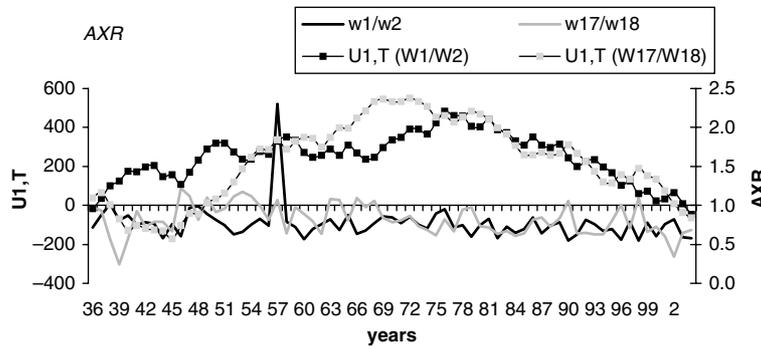


Figure 3. AXR curve and test statistic for W1/W2 and W17/W18. Note: AXR denotes annual maximum flow ratios between the treatment and control watersheds.

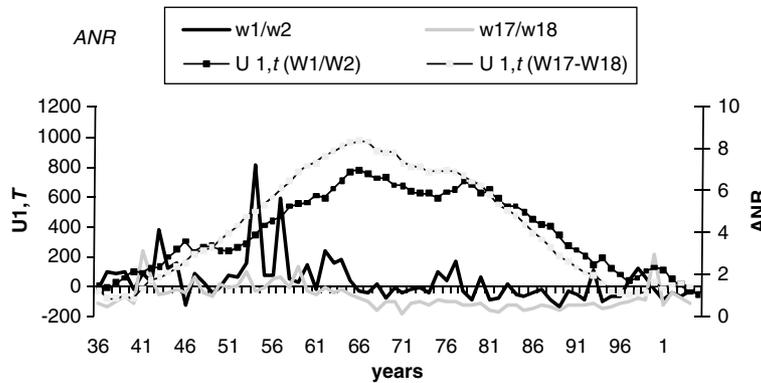


Figure 4. ANR curve and test statistic for W1/W2 and W17/W18. Note: ANR denotes annual minimum flow ratios between the treatment and control watersheds.

were detected for different but close years in 1970s according to test results (Table II). The 1956 clear-cut affected annual instantaneous maximum flow of W-1 as seen in Figure 3. However, such an individual step increase was not detected for other clear-cut treatments in W-1 or W-17. CP years for all time series are given in Table II.

The probability of all CPs was high in all series, but the trend in AMR and ANR series were more apparent compared to AXR as shown above. The ANR series were quite parallel with AMR series, however, CPs were 1965 and 1966, little earlier. An increase in low flows of W17 in the end of the century was not observed for W1.

Extreme flow analysis

The increase in annual maximum flows in both control and treatment watersheds after 1975 is given in Figure 5. Maximum flows estimated for return periods within 100 years, increased slightly after the CP year (1976) for both watersheds (W1 and W2) but with almost the same ratio (similar slope).

On the other hand, the pine stands affected the annual minimum flows with a quite different pattern

(Figure 6). The slope shifted considerably after the CP of 1965.

When maximum flow events that have return periods up to 10 years were compared a difference between pine and deciduous stands could be seen

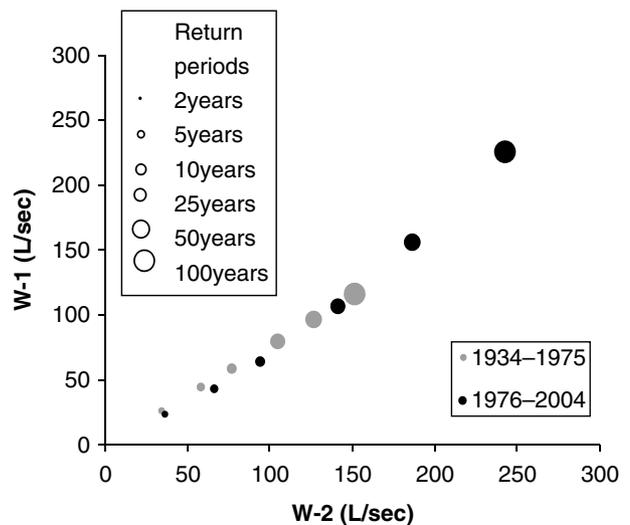


Figure 5. Scatter graph of maximum flow event sizes for before and after 1976.

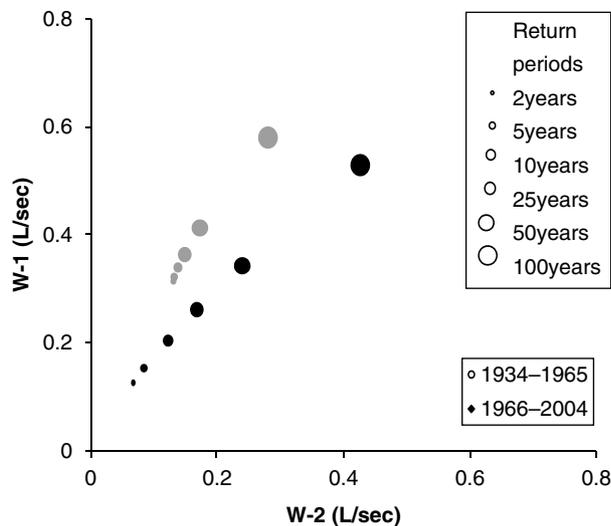


Figure 6. Scatter graph of minimum flow event sizes for before and after 1965.

but this difference disappeared for the larger events of longer return periods (Table III).

A similar situation also detected for minimum events. There is bigger difference for minimum events of shorter return periods than longer periods.

Discussion

The mean, high- and low-flow responses of forested watersheds to species conversion were dissimilar. The low flows of pine planted watersheds started to decrease after the age of 10–12 compared to native hardwood forests. The decrease was evident for all return periods. In addition to this, decrease in the magnitude of frequent (2-, 5-, and 10-year return periods) low flows were proportionally more (Table III) compared to less frequent (50- and 100-year return periods) low flows. These results suggest that the influence of vegetation cover (pine forest in this case) diminishes as the severity of dry conditions increases. Low frequency severe flow events are affected by the vegetation but not as much as frequent low flow events. This is the basic difference between low- and high-flow events. White pine forest is also effective on frequent high flows but has no influence on low frequency (25, 50, and 100 years)

high flow events. The other difference is the age when high flows are affected. The CP on AXR series was 1972 for W17 and 1976 for W1. This result suggests that the age of the pine stands was 16–20 (Table II) when high flows became influenced by pine stands.

In the case of mean flows, Mann–Whitney–Pettitt test verified the early results of Swank et al. (1988). The authors analyzed the annual streamflow data of watersheds 1–2 and 17–18 between 1957 and 1983 and found that the effects of cutting on mean flows continued for about 10–12 years. According to our results, the major change that was detected on the mean flow series of treatment watersheds was caused by conversion to pine not the forest cutting. As the flow series extended until 2000s it was seen that cutting treatments had short lived impacts on the streamflows of both treatment watersheds (Figure 2) and major changes on mean flow series were due to the conversion to pine.

A high variation period between 1980 and 2000 was also seen in Figure 2. Considering that the stand structures on treatment watersheds have not changed by any kind of treatment after 1980s, the increased variations in annual mean flow ratios (AMR) can be explained by other stress factors. For example, in the period after 1980s, two main stress factors causing defoliation or tree mortality were effective at Coweeta forests; multiple year droughts and pine beetle outbreaks. Two major drought periods in Coweeta were between 1985–1988 and 1998–2001 (Kloppel et al., 2003). These multiyear periods definitely affected the flow features of both control and treatment watersheds.

The climatic cycles and tree mortality due to stress factors might be reasons of high variations on mean annual flows. The other reason may be long-term changes in precipitation attributes and streamflow. Our results related to quantile estimation suggest that extreme high flows increased for all return periods (2, 5, 10...) after 1975. In other words the frequency of extreme high flows increased in control watersheds around the same years conversion to pine started to affect daily high flows parallel with the previous studies. Kiely (1999) reported an increase in precipitation and discharge series after mid-1970s

Table III. Design flow ratios before and after the CPs.

Return periods		2	5	10	25	50	100
Q_{\max} W1/W2	Before CP (1934–1975)	1.05	1.02	1.02	1.02	1.02	1.02
	After CP (1976–2004)	0.86	0.86	0.91	1.01	1.03	1.03
Ratio (before/after)		1.22	1.19	1.12	1.01	0.99	0.99
Q_{\min} W1/W2	Before CP (1934–1965)	2.75	3.18	3.26	3.27	3.22	3.20
	After CP (1966–2004)	1.65	1.90	2.06	2.21	2.40	2.47
Ratio (before/after)		1.67	1.67	1.58	1.48	1.34	1.30

in Ireland in relation with North Atlantic Oscillation Index. This finding was parallel with the results of McCabe and Wolock (2002) that detected an increase in annual minimum and median daily streamflow series after 1970s in the USA. Tu et al. (2005) pointed 1980s as a CP in flood peaks in North Central Europe.

In watersheds 1 and 17, the increase in high flows after 1970s might have offset the effects of pine stands and caused the CPs to be less apparent. Therefore, the CPs for AXR series were less significant compared to AMR and ANR series, but still statistically strong (Table II). The increase in ANR series in 1990s which shows an increased low flows in pine covered watersheds can be related with tree mortalities due to pine beetle damage.

In conclusion, the increased high-flow event sizes after 1976 suggest that dimensions of high rainfall events in the region have increased after this point but similar slope of scatter plots for maximum flows reveals that conversion to pine has not changed the responses of watersheds to high precipitation events as we hypothesized above. Apparently, changes in precipitation attributes are a more efficient factor in the generation of large flood events compared to forest type. In other words, climate starts to control the extreme flow events after a threshold point of magnitude. However, the pine stands even in the larger return periods reduces low flows.

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