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Monitoring the effects of timber harvest on annual water yield

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Abstract

Paired catchment studies have been used as a method to assess the effects of vegetation removal (timber harvesting) on streamflow responses including lowflows and peakflows, but particularly annual water yield. Paired catchment studies in the United States reporting on the effects of timber harvesting on annual water yields were compiled. In general, changes in annual water yield from forest cover reduction (or catchment area harvested) of less than 20% could not be determined by hydrometric or streamflow measurement methods. The catchment studies were discriminated by hydrologic region, defined by temperature and precipitation regimes. This regionalization suggested that as little as 15% of the catchment area (or basal area) could be harvested for a measurable increase in annual water yield at the catchment level in the Rocky Mountain region as compared with 50% in the Central Plains, although system responses are variable.

Given changing world-wide objectives for forest land management, hydrologists will be asked to develop monitoring programs to assess the effects of multiple and temporally and spatially distributed land use activities on water resources. Less catchment area will be disturbed, thus monitoring programs must be carefully designed to obtain useful information. The concept of hydrologic recovery, i.e. return to pretreatment condition tends to be based on annual water yield, but also needs the evaluation of streamflow generation and routing mechanisms including lowflows and peakflows when compared with the pretreatment condition.

1. Introduction

The first paired catchment study in the United States began in 1909 at Wagon Wheel Gap, Colorado to assess the effect of timber harvesting on annual water yield (Bates and Henry, 1928). Since then, a number of different catchment studies

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have been done to assess the effects of vegetation removal or vegetation type conversion on water yield (Meginnis, 1959; Hibbert, 1967; Burgy and Papazafiriou, 1971). In the mid-1950s, such catchment studies numbered approximately 150 (Holschen, 1967). An early review (Hibbert, 1967) on the effects of forest harvesting on water yield made the following generalizations: (1) reduction of forest cover increases water yield; (2) establishment of forest cover (afforestation) decreases water yield; (3) response to treatment is highly variable and unpredictable.

Catchment research reached a zenith around 1965, coincident with the recognition of the need for a more holistic approach to studying forest ecosystems (Hornbeck and Swank, 1992). Catchment studies were expanded beyond water quantity and the hydrologic cycle to include nutrient cycling. Measurements of inputs and outputs, especially in precipitation and streamflow, were used for chemical budgets for plant nutrients and pollutants. Physical, chemical, and biological processes were identified and quantified in the nutrient cycles. But, have all the questions about the effect of timber harvesting on water yields been answered?

The 1967 review was updated in 1982 with the addition of 55 catchment studies (for a total of 94) (Bosch and Hewlett, 1982). Most of these studies dealt with deforestation rather than afforestation. Variability in increased annual water yield from vegetation removal was still observed, although, systematic differences were evident when the catchment studies were subdivided by forest cover type (Bosch and Hewlett, 1982). The inference was that coniferous forests, deciduous hardwoods, brush and grass cover have (in that order) a decreasing influence on water yield. A 10% change in cover caused approximately a 40 mm change in annual water yield for coniferous forests, 25 mm for deciduous forests, and 10 mm for brush or grass cover (Bosch and Hewlett, 1982).

Changes in water yield from reductions of less than 20% in forest cover could not be determined by measurements (hydrometric method) (Bosch and Hewlett, 1982). The effect of zero treatment must be zero and therefore small harvest areas (less than 20% of the catchment) may affect annual water yields but at a scale less than is measurable on a catchment basis (McMinn and Hewlett, 1975).

Inference drawn from time-trend studies is weaker than that from paired catchment studies simply because there is no climatic control to separate vegetal cover effects from climatic effects (Whitehead and Robinson, 1993). Paired, nested or grouped catchment studies were considered strong evidence, and studies based on after-the-fact analyses of existing data, or less rigorous experiments on large catchments were considered circumstantial evidence (Hewlett, 1971).

Summary or guidance documents to manage forests in the United States for increased annual water yields by vegetation manipulation (timber harvesting) have been prepared by regional forest cover type (Douglass, 1983; Harr, 1983; Hibbert, 1983; Kattelman et al., 1983; Troendle, 1983). The accuracy or general applicability of these guidance documents has not been evaluated.

The review of timber harvesting effects on water yield using catchment studies is updated in this paper. Paired catchment studies have often been used to assess potential water yield changes from different land use activities or natural disturbances including timber blowdown (Swank et al., 1988), insect infestations

(Bethlahmy, 1974; Love, 1955), forest fire (Helvey and Tiedemann, 1978; Helvey, 1980), grazing (Higgins et al., 1989), afforestation (Ayer, 1968; Smith, 1992; Schneider and Ayer, 1961), vegetation type conversion (Pitman, 1978; Swank and Miner, 1968; Swank and Douglass, 1974), selective understory timber harvesting (Johnson and Kovner, 1956), riparian vegetation conversion (Rich and Gottfried, 1976), partial cutting (Lynch and Sopper, 1970) and selective timber harvesting (Troendle and King, 1985; Hibbert and Gottfried, 1987). Has the state-of-knowledge been improved since 1982?

Literature searches were conducted using on-line search capabilities in GeoRef, Selected Water Resource Research Abstracts and UnCover. This literature review includes 95 studies done in the United States only. As recognized earlier, the presentation and interpretation of results is a potential limitation in some catchment studies (Hewlett et al., 1969; Hewlett, 1971). Studies were compiled and summarized as published. No judgements were made on the quality of research. Several authors had to be contacted to obtain clarification or information not included in the published work. No data were added to the compilation that were not previously published and referenced as literature cited.

2. Results and discussion

Catchment studies were summarized by location, catchment, area, elevation, catchment aspect, soil type, vegetation, mean annual streamflow, mean annual precipitation, percent catchment area harvested, water yield increase and hydrologic region (Table 1). The annual precipitation for the study catchments ranged from 450 to 2730 mm (Table 1). The study catchments were categorized by dominant vegetation cover type including chaparral, conifer, hardwoods and mixed conifer–hardwoods. The pretreatment vegetation conditions included natural and undisturbed forest stands, regenerated forests and vegetation type conversions, i.e. grass to forest. Catchment studies were not discriminated by forest cover history, since this observation was often not included in the studies, but may account for some of the observed variability in water yield response. Besides chaparral, which is restricted to areas of low annual precipitation, all forest cover types were represented over the range of annual precipitation. The 1982 review suggested a need for catchment studies in conifer forests within the annual precipitation range of 600–1200 mm (Bosch and Hewlett, 1982). This update shows this need has been met.

Mean annual streamflow and mean annual precipitation data were used as reported, although some authors stated that further data collection suggested different values. No data were changed in the compilation (Table 1). The percent catchment area harvested was assumed to be directly proportional to basal area, thus a 25% basal area removal equated to harvesting 25% of the catchment area. No attempt was made to separate harvest area location in the catchment or harvest type on water yield, which may also account for some of the observed variability in water yield. The water yield increase was the maximum increase reported in the 5 years since treatment. Usually, the maximum increase in annual water yield occurred the year

Table 1
Summary of paired catchment studies used to assess water yield changes after vegetation removal

Catchment	Area (ha)	Elev. (m)	Aspect	Soils	Vegetation	Mean annual precip. (mm)	Mean annual stream flow (mm)	Area cut (%)	Water yield increase (mm)	WRENS	Reference
Hubbard Brook, NH #2	16		S	Sandy loam	Hardwoods	1220	710	100	343	1	Hornbeck et al. (1970)
#5	35		S	Sandy loam	Hardwoods	1220	710	30	500	1	Hornbeck (1975)
Marcell, MN #4	26	438		Peat	Aspen		762	100	117	1	Verry (1972, 1976, 1987)
White Hollow, TN	694	410	SE	Silt loam	Mixed hardwoods	1180	460	34	0	2	Tennessee Valley Authority (1961)
Fernow, WV #1	30	755	NE	Silt loam	Hardwoods	1520	580	85	130	2	Reinhart et al. (1963) Kochenderfer et al. (1983, 1990)
#2	15	780	S	Silt loam	Hardwoods	1500	660	36	64	2	Patric (1980) Kochenderfer et al. (1983, 1990)
#3	34	805	S	Silt loam	Hardwoods	1500	610	13	8	2	Reinhart et al. (1963)
#3	34	805	S	Silt loam	Hardwoods	1500	610	8	0	2	Reinhart et al. (1963)
#3	34	805	S	Silt loam	Hardwoods	1500	610	91	253	2	Patric (1971, 1980)
#3	34	805	S	Silt loam	Hardwoods	1500	610	6	0	2	Reinhart et al. (1963)
#4	39	805	S	Silt loam	Hardwoods	1500	610	0	0	2	Patric and Reinhart (1971)
#5	36	780	NE	Silt loam	Hardwoods	1470	760	14	0	2	Reinhart et al. (1963)
#5	36	780	NE	Silt loam	Hardwoods	1470	760	20	36	2	Reinhart et al. (1963)
#6	22		SE	Silt loam	Hardwoods	1440	490	50	165	2	Reinhart et al. (1963)
#6	22		SE	Silt loam	Hardwoods	1440	490	50	269	2	Kochenderfer and Wendel (1983)
#7	24	800	NE	Silt loam	Hardwoods	1470	790	50	261	2	Reinhart et al. (1963)
#7	24	800	NE	Silt loam	Hardwoods	1470	790	50	155	2	Kochenderfer and Wendel (1983)
Leading Ridge, PA #2	43	358	S	Silt loam	Mix hardwood	1000	320	20	68	2	Lynch and Sopper (1970)
Coweeta, NC #1	16	840	S	Loam	Hardwoods	1730	740	100	150	2	Swank and Miner (1968)
#3	0	825	SE	Loam	Hardwoods	1810	610	100	127	2	Johnson and Kovner (1956)
#6	9	793	NW	Loam	Hardwoods	1850	840	80	265	2	Swift and Swank (1981)
#7	59	900	S	Loam	Hardwoods	1825	1140	100	260	2	Swank et al. (1988)
#10	86	975	SE	Loam	Hardwoods	1850	1070	30	25	2	Johnson and Kovner (1956)
#13	16	810	NE	Loam	Hardwoods	1900	890	100	375	2	Swank and Helvey (1970)
#13	16	810	NE	Loam	Hardwoods	1900	890	100	362	2	Swift and Swank (1981)
#17	14	885	NW	Loam	Hardwoods	1890	780	100	414	2	Douglass and Swank (1972, 1975) Douglass (1983)
#19	28	960	NW	Loam	Hardwoods	2000	1220	22	71	2	Johnson and Kovner (1956)
#22	34	1035	N	Loam	Hardwoods	2070	1280	50	189	2	Hewlett and Hibbert (1961)

#28	144	1200	NE	Loam	Hardwoods	2270	1530	51	220	2	Hewlett and Douglass (1968)
#37	44	1280	NE	Loam	Hardwoods	2240	1590	100	255	2	Swift and Swank (1981) Swank (1988)
#40	20	1035	SE	Loam	Hardwoods	1950	1050	27	0	2	Johnson and Kovner (1956)
#41	29	1065	SE	Loam	Hardwoods	2030	1290	53	55	2	Johnson and Kovner (1956)
Coastal Plain, MS #1	1		E	Silt loam	Mixed hardwood	1350	0	100	47	3	Ursic (1970)
#3	1		E	Silt Loam	Mixed hardwood	1350	0	100	75	3	Ursic (1970)
Grant Forest GA #18	33	165	SW	Sandy loam	Hardwoods	1220	470	100	254	3	Hewlett (1979)
Upper Bear Cr. AL XF1	53			Sandy loam	Pine/hardwood	1400	0	52	102	3	Betson (1979)
XF2	53			Sandy loam	Pine/hardwood	1400	0	86	297	3	Betson (1979)
Alum Cr, AR #2	1	412	NE	Stoney loam	Pine/hardwood	1330	150	45	107	3	Rogerson (1979) in Bosch and Hewlett (1982)
#3	1	412	NE	Stoney loam	Pine/hardwood	1330	150	100	226	3	Bosch and Hewlett (1982)
Workman Cr. AZ	100	2225	SW	Clay loam	Conifer	833	86	32	32	4	Hibbert and Gottfried (1987)
Workman Cr. AZ	100	2225	SW	Clay loam	Conifer	833	86	73	67	4	Hibbert and Gottfried (1987)
Workman Cr. AZ	100	2225	SW	Clay loam	Conifer	833	86	40	45	4	Hibbert and Gottfried (1987)
Workman Cr. AZ	100	2225	SW	Clay loam	Conifer	833	86	83	107	4	Hibbert and Gottfried (1987)
Workman Cr. AZ	100	2225	SW	Clay loam	Conifer	810	86	1	0	4	Rich and Gottfried (1976)
S. Fork	100	2225	SW	Clay loam	Conifer	813	87	45	0	4	Rich (1965)
N. Fork	100	2225	SW	Clay loam	Conifer	810	86	32	51	4	Hibbert (1979)
Wagon Wheel Gap, CO	81	3110	NE	Clay loam	Aspen	544	157	100	25	4	Van Haveren (1988)
Wagon Wheel Gap, CO	81	3110	NE	Clay loam	Aspen	536	157	100	47	4	Bates and Henry (1928)
Chicken Cr. UT						1900	1000	100	245	4	Johnston (1984)
Blue Mts. OR #1		1523	NE	Ash	Larch, Doug fir	1355	472	50	248	4	Fowler et al. (1987)
#2		1523	NE	Ash	Larch, Doug fir	1355	460	50	147	4	Fowler et al. (1987)
#3		1523	NE	Ash	Larch, Doug fir	1355	372	50	111	4	Fowler et al. (1987)
Fool Creek, CO	289	3200	N	Granitic	Pine/spruce	760	280	40	147	4	Troendle and King (1985)
Fool Creek, CO	289	3200	N	Granitic	Pine/spruce	635	283	40	119	4	Troendle and King (1985)
Fool Creek, CO	289	3200	N	Granitic	Pine/spruce	712	283	83	57	4	Alexander et al. (1985)
Fraser Forest, CO	289	3200	N	Granitic	Pine/spruce	712	283	66	54	4	Alexander et al. (1985)
Fraser Forest, CO	289	3200	N	Granitic	Pine/spruce	712	283	50	28	4	Alexander et al. (1985)
Deadhorse Cr. CO	270	3120	E	Granitic	Fir/pine	762	500	36	60	4	Troendle and King (1985)
St. Louis Creek, CO		3200	N	Granitic	Pine/spruce	712	88	13	0	4	Alexander et al. (1985)
St. Louis Creek, CO	289	3200	N	Granitic	Pine/spruce	712	283	100	88	4	Alexander et al. (1985)
Nat. Drainage, AZ	5	1420	SE	Quartz	Chaparral	452	34	100	0	4	Hibbert (1980)
WS c	5	1420	SE	Quartz	Chaparral	450	43	100	13	4	Hibbert (1980)
Beaver Creek, AZ #1	124	1700	W	Clay	Juniper	457	20	100	0	4	Brown (1971)
#3	146	1600	W	Clay	Juniper	457	18	83	30	4	Hibbert (1979)
	147			Stoney clay	Pinyon juniper	426	22	78	123	4	Baker (1984, 1986)

Table 1 (continued)

Catchment	Area (ha)	Elev. (m)	Aspect	Soils	Vegetation	Mean annual precip. (mm)	Mean annual stream flow (mm)	Area cut (%)	Water yield increase (mm)	WRENS	Reference
White Spar, AZ WS b	100	1910	SE	Granite	Chaparral	550	34	15	13	4	Hibbert (1980)
WS b	100	1910	SE	Granite	Chaparral	550	34	20	0	4	Hibbert (1980)
Three Bar, AZ WS c	39	1160	N	Clay loam	Chaparral	640	58	100	132	4	Hibbert (1967, 1969, 1971, 1979), Hibbert et al. (1974), Hibbert and Gottfried (1987)
WS b	19	1080	N	Granite	Chaparral	580	11	100	30	4	Hibbert (1967, 1969, 1971, 1979), Hibbert et al. (1974), Hibbert and Gottfried (1987)
WS f	28	1300	N	Granite	Chaparral	680	36	100	81	4	Hibbert (1967, 1969, 1971, 1979), Hibbert et al. (1974), Hibbert and Gottfried (1987)
WS b	19	1080	N	Granite	Chaparral	580	11	60	52	4	Hibbert (1967, 1969, 1971, 1979), Hibbert et al. (1974), Hibbert and Gottfried (1987)
Castle Creek, AZ	364		SE	Igneous	Pine	640	71	16.6	36	4	Rich and Thompson (1974) Rich (1972)
Thomas Cr. AZ	227	2600	S	Loamy	Mixed conifer	768	500	34	70	4	Gottfried (1991)

Willow Cr. AZ					Mixed conifer	749	512	62	96	4	Gottfried (1983)
Coyote Cr., OR #1	69	900		Gravel loam	Doug fir	1230	630	50	60	5	Harr (1976), Harr et al. (1979)
#2	68	900		Gravel loam	Doug fir	1230	630	30	119	5	Harr (1976), Harr et al. (1979)
#3	50	900		Gravel loam	Doug fir	1230	630	100	360	5	Harr (1976), Harr et al. (1979)
Fox Creek, OR (#1)	59	955		Silt loam	Doug fir	2730	1750	25	0	5	Harr et al. (1979)
#3	71	900		Silt loam	Doug fir	2730	1750	25	0	5	Harr (1980)
Deer Creek, OR	303	312		Marine sandstone	Doug fir	2480	1910	25	150	5	Harris (1973, 1977) Harr (1976)
Needle Branch, OR	71	312		Perm sandstone	Doug fir	2480	1885	82	615	5	Harris (1973, 1977) Harr (1976)
HJ Andrews, OR #1	96	700	NW	Loam	Doug fir–W. hem	2390	1380	100	462	5	Rothacher (1970)
#3	101	760	NW	Loam	Doug fir–W. hem	2390	1350	30	297	5	Harr (1976), Harr et al. (1979)
#6	13	900	S	Volcanic	Doug fir–W. hem	2150	1290	100	425	5	Harr (1976), Harr et al. (1979, 1982)
#7	21	900	S	Volcanic	Doug fir–W. hem	2150	1290	60	240	5	Harr (1976), Harr et al. (1979, 1982)
#10	9	500	S	Volcanic	Doug fir–W. hem	2330	1650	100	400	5	Harr (1976), Harr et al. (1979)
Placer County, CA	5	168	N	Clay loam	Oak woodland	640	145	99	154	7	Lewis (1968)
San Dimas, CA	354	840	S	Sandy loam	Chaparral	650	64	1.7	6	7	Rowe (1963)
Ouachita, OK											
WS #10	5.74		W	Loam	Oak–hickory	1317	1652	50	510	8	Miller et al. (1988)
WS #11	4.93			Loam	Oak–hickory	1317	370	0	0	8	Miller et al. (1988)
WS #12	5.91		WNW	Loam	Oak–hickory	1317	1652	100	752	8	Miller et al. (1988)
WS #14	4.35		N	Loam	Oak–hickory	1317	1652	50	558	8	Miller et al. (1988)
WS #15	5.11		NW	Loam	Oak–hickory	1317	1652	100	524	8	Miller et al. (1988)
WS #17	4.15		SE	Loam	Oak–hickory	1317	1652	50	382	8	Miller et al. (1988)
WS #18	4.08		SE	Loam	Oak–hickory	1317	1652	100	306	8	Miller et al. (1988)

after treatment, however there were several instances owing to unusual precipitation patterns, where the maxima occurred several years after treatment.

A synthesis of the earlier world-wide data base (Bosch and Hewlett, 1982) coupled with work in England on the effects of deforestation (or harvesting) on annual water yield increases presented the following relation (Calder, 1993)

$$Y = 3.26(x)$$

$$r^2 = 0.50$$

$$\mathrm{SE} = 89 \text{ mm}$$

where Y is millimeters of annual water yield increase and x is the percent of catchment deforested. The United States data base as compiled here (Fig. 1) gave the following relation

$$Y = 2.46(x)$$

$$r^2 = 0.17$$

$$\mathrm{SE} = 149 \text{ mm}$$

$$n = 95$$

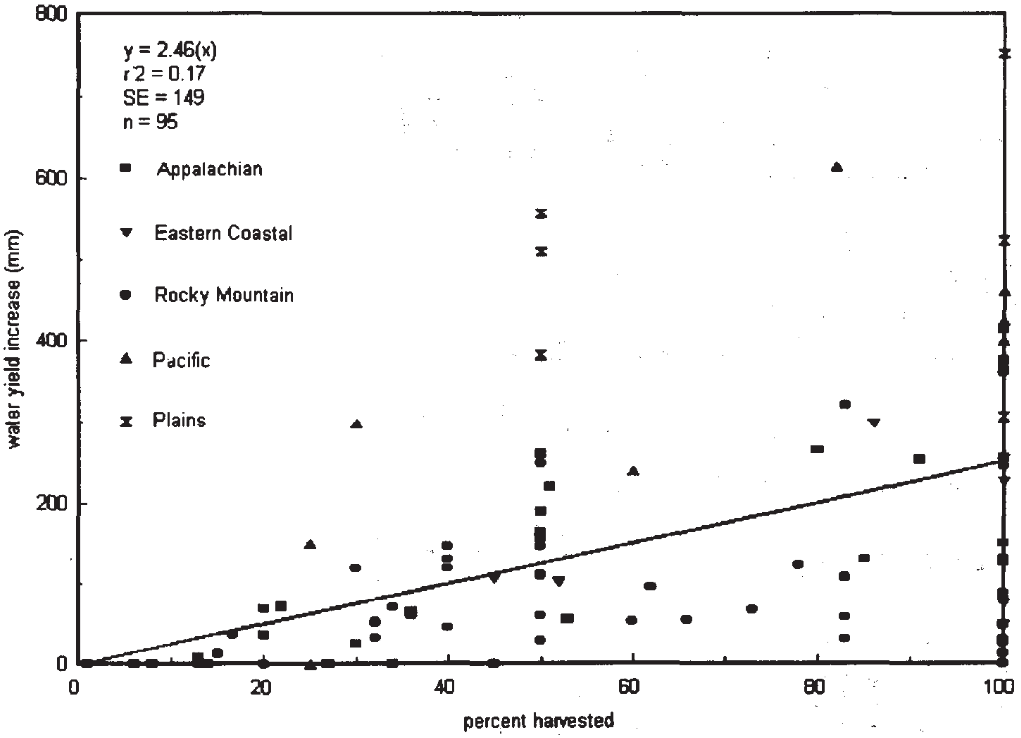

Fig. 1. Annual water yield increase (mm) following percent of catchment harvested. Catchment area harvested was assumed equal to basal area removed.

Additional studies have apparently not improved the global model, and suggest that additional investigations are needed. The paired catchment procedure, usually involves the development of a regression of water yield (or other metric) between the paired catchments. The pretreatment regression has a certain confidence interval associated with the line. The posttreatment water yield and confidence interval has to be greater than the least significant difference (LSD) of the pretreatment regression and confidence interval to be considered significant. Several studies reported zero increase in annual water yield after treatment. It was indeterminate if the water yield increases were really zero, or if they were not greater than the LSD and reported as zero. Any measurement of a treatment effect has to be larger than the error associated with that measurement to be considered a treatment effect. These zero values were left as zero values in the data summary. A summary regression using pooled variance for all studies could not be calculated, since individual study regression confidence intervals (or LSD) were often not reported.

The paired catchment concept allows for variation in annual precipitation and hence streamflow. 'No treatment should have no effect on annual water yield', therefore, the regressions were forced through the origin.

How much of the catchment can be harvested before the annual water yield increase is significant? The plot of annual water yield increase (mm) versus percent harvested for all studies (Fig. 1) suggests that approximately 20% of the catchment vegetation cover must be harvested for a measurable increase in annual water yield. The 20% value is from visual interpretation of the plot and not the regression intercept. This result confirms the measurable threshold suggested earlier (Bosch and Hewlett, 1982). Catchment studies with less harvested areas have had measurable increases in water yield; conversely, studies with 100% harvest have had no measurable increase in annual water yield (Fig. 1). As mentioned earlier, this variability may be the result of harvest location, harvest type, pretreatment vegetation cover or measurement error.

Simple linear regressions between water yield increase and percent harvested were developed for each hydrologic region. The hydrologic regions were defined by distinct precipitation patterns and streamflow regimes following the hydrology chapter in WRENSS, Water Resources Evaluation of Nonpoint Source pollution from Silvicultural activities, a guidance document for hydrology and sediment changes as related to forest land use activities (notably timber harvest) (U.S. Environmental Protection Agency, 1980). The hydrologic regions were defined as Appalachian Mountains, Eastern Coastal Plain, Rocky Mountain/Inland Intermountain, Pacific Coast, Central Plains, Continental /Maritime Province, Central Sierra Province, New England and Upper Lake States.

The Appalachian Mountain hydrologic region data base of 29 studies suggests that 20% of the catchment needs to be harvested for a measurable increase in annual water yield. Harvesting all catchment vegetation resulted in annual water yield increases from zero to over 400 mm. Each 10% increase in area harvested increased annual water yield by 28 mm (Table 2).

The Eastern Coastal Plain hydrologic region included seven studies. The smallest harvested area reported was 45% of the catchment area and increased annual water

Table 2
Regression model statistics for annual water yield increase versus percent harvest area for all studies and by hydrologic region

Hydrological region	Number	n	Slope	r^2	SE	p value	Threshold for response
All studies	–	95	2.46	0.17	149	0.0001	20
New England/Lake states	1	3	–	–	–	–	–
Appalachian Mountains and Highlands	2	29	2.78	0.65	75	0.0001	20
Eastern Coastal Plain and Piedmont	3	7	1.84	0.02	97	0.0051	45
Rocky Mountain Inland Intermountain	4	35	0.94	0.01	66	0.0001	15
Pacific Coast	5	12	4.40	0.65	118	0.0001	25
Continental/Maritime	6	0	–	–	–	–	–
Central Sierra Province	7	2	–	–	–	–	–
Central Plains	8	7	6.15	0.31	197	0.0009	50

The threshold of response is harvest area required for measureable increase in annual water yield.

yield over 100 mm (Table 1). Annual water yield increased over 250 mm when all vegetation was harvested. The conservative estimate is that 45% of the catchment must be harvested for a measurable increase in annual water yield. Each 10% increase in area harvested increased annual water yield by 18 mm (Table 2).

The Rocky Mountain/Inland Intermountain region data suggest that a 15% harvest area results in a measurable annual water yield increase (Table 2). When 50% of the catchment was harvested, annual water yield increases ranged from 25 to 250 mm and complete harvesting (100%) increased annual water yields from zero to over 350 mm. The results are variable especially above 30% harvested. The region had the lowest slope between annual water yield increase and percent harvested (Table 2).

The Pacific Coast hydrologic region data base of 12 studies suggests a 25% minimum harvest to obtain a measurable annual water yield increase (Table 2). An annual water yield increase of 615 mm was observed when 82% of a catchment was harvested. This particular study, located in the Oregon Coast Range, did not leave streamside vegetative buffers (Harris, 1973, 1977; Stednick, 1995). Catchments with 100% harvest, located in the Oregon Cascade Range, increased annual water yield from 400 to 460 mm. The linear model suggests approximately 50 mm for every 10% of the catchment harvested.

The Central Plains hydrologic region data base had no studies with less than 50% harvest, but all studies at 50% harvest had measurable water yield increases. The 50% area harvested for a measurable response is probably conservative (Table 2). Whole catchment harvesting (100%) had water yield increases from 306 to 752 mm (Table 1). All studies were conducted in one study area, but on multiple catchments. Additional research is warranted.

The Continental/Maritime Province (rain and snow) hydrologic region had no studies investigating the effects of vegetation removal on annual water yield. This province includes the northeast corner of Washington state, the Idaho panhandle and the northwestern tip of Montana. The effect of timber harvesting on hydrology has been an important issue here. This hydrologic transition zone includes rain, snow, and rain-on-snow precipitation events. The rain-on-snow hydrologic response is not well understood. Hydrologic studies in this region are needed.

The Central Sierra Province in central and southwestern California includes rain and snow precipitation events. Only two studies were found for this region: a chaparral conversion (decrease) of 1.6% increased annual water yield 6 mm (Rowe, 1963) and 99% vegetation removal in an oak woodland increased annual water yield 154 mm (Lewis, 1968). Given the range in responses, no model was calculated.

The New England and Upper Lake States region is snow dominated and only three studies were found documenting the effect of vegetation change or timber harvesting on annual water yield (Table 2). Catchment studies are being done in these areas and such results should be forthcoming. No model was calculated for this region.

Few comparative studies have been done on catchment results for a particular region. Comparison of northeastern United States sites, suggested a 25% reduction in basal area to obtain a measurable response in water yield (Hornbeck et al., 1993). Research at the Coweeta Experimental Forest, in the Appalachian Mountains, suggests a 10% reduction (Swank et al., 1988). Differences probably are due to accuracy of streamflow measurements and variability in study catchments. This compilation for the region suggests 20% for the Appalachian Mountains (Table 2).

A compilation of catchment studies in Canada also suggests a 20% minimum of catchment area harvest for a measurable annual water yield increase (Hetherington, 1987). The Canadian review suggested that each 10% increase in catchment area harvested may increase water yield by approximately 15 mm, but responses were again variable.

The simple linear regressions developed here are meant to serve as guidelines only for land managers and the scientists who measure the effects of land use activities on water resources. The WRENSS model should be reviewed for minimum detectable effect on annual water yield from timber harvesting (or vegetation conversion). A sensitivity analysis of the WRENSS computer model used to predict water yield following different silvicultural treatments was performed on model input parameters (Stednick and Potts, 1989).

Streamflow responses to vegetation conversion depend both on the region's annual precipitation and on the precipitation for the year under treatment. Plots of annual water yield (streamflow) versus annual precipitation showed a better relation than plots of annual water yield increase versus annual precipitation, probably owing to the comparison of studies with rain, rain and snow, and snow-dominated precipitation patterns. Yield changes are greatest in high rainfall areas, but shorter lived because of rapid revegetation. The annual yield change resulting from treatment in high rainfall areas seems to be independent of the variation of rainfall from year to year (Bosch and Hewlett, 1982) and more a function of forest regrowth or leaf area index (Swank et al., 1988; Burt and Swank, 1992; Stednick, 1995). Part of the variability in annual water yield increases and streamflow response following timber harvesting, including partial cuttings, may be due to the physical location of harvest units with respect to the source area of streamflow (Bosch and Hewlett, 1982; Troendle and King, 1985; Stednick, 1995).

The basic premise of catchment ecosystem analysis is that the myriad of physical, chemical, and biological processes occurring within an ecosystem are interrelated (Hornbeck and Swank, 1992). Catchment ecosystem analysis can be used to evaluate how individual or combinations of land uses might affect nutrient cycles and subsequently forest and stream productivity and health. The use of catchments as the ecosystem boundary ensures that effects are integrated over a sizable landscape.

Recent efforts in catchment research have focused on the process of hydrologic recovery. Hydrologic recovery was defined as the return of annual water yield to pretreatment levels (Hibbert and Gottfried, 1987; Stednick and Kern, 1992; Hornbeck et al., 1993; Stednick, 1995). This simplistic approach tends to ignore streamflow generation and routing mechanisms on the watershed and landscape level. Hydrologic recovery should include returns of peakflows (Harr, 1976; Harr et al., 1979; Cheng, 1989; Stednick, 1995) and lowflows (Keppeler and Ziemer, 1990; Hicks et al., 1991; Whitehead and Robinson, 1993; Stednick, 1993) and hydrologic pathways affecting nutrient transport.

Owing to temporal variability in weather, and perhaps climate, catchment ecosystem analysis is necessarily long term. The concept of hydrologic recovery may have different meanings to different users (Thomas, 1990), none the less long-term monitoring is necessary to properly define system response and recovery (Stednick and Kern, 1992; Stednick, 1995) and should be supported by land management agencies.

The concept of hydrologic recovery is complex. Continuation of the Alsea Watershed Study in Coastal Oregon indicates streamflow generation and routing mechanisms were altered by timber harvesting and site preparation and have not returned to pretreatment conditions 28 years after harvesting although annual water yields are within pretreatment levels (Stednick, 1995).

3. Summary

In general, changes in annual water yield from harvesting of less than 20% catchment area or forest cover cannot be determined by streamflow measurements. The reduction of forest cover by less than 20% is seldom used in paired catchment studies. Most studies attempt to harvest (or otherwise disturb) the maximum area to assure a measurable response. There may be studies with forest cover reductions of less than 20% that were simply not published. Changing world-wide objectives for land management suggest forest cover reductions of less than 20% may become more common. Hydrologists will be asked to evaluate system responses to multiple and temporally and spatially distributed land use activities. The data synthesis presented here should enable land managers and researchers to prepare monitoring programs that address the effects of timber harvesting on water yields in different hydrologic regions.

Several studies as published did not include sufficiently detailed site characterization data. When authors were contacted to obtain missing information, the study was included in the data base, otherwise it was dropped. Authors of scientific papers or technical reports should be reminded that their effort should be fully documented and should be written with consideration for future utility. Scientific papers are often re-evaluated in the context of synthesis papers or used to extend existing data bases. Long-term effects of timber harvesting on water yield are important in both water resource management and evaluation of nutrient exports.

This literature review and synthesis considered the effect of timber harvesting on annual water yields. The variable responses of annual water yield to harvesting suggest both complex and perhaps non-linear responses. Long-term catchment studies are needed to evaluate these responses.

We are in the process of compiling literature on the long-term effects of timber harvesting on peakflows and lowflows. We would like to solicit your assistance in compiling both published and unpublished studies on the long-term effects of timber harvesting on peakflows and lowflows.

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