ground water

Technical Note/

Estimating Ground Water Yield in Small Research Basins

by Elon S. Verry[1]

Abstract

An analysis of ground water recharge in 32 small research watersheds shows the average flow of ground water out of the watershed (deep seepage) is 45% of streamflow and ranges from 8 to 350 mm/year when apportioned over the watershed area. It is time to meld ground water and small watershed science. The use of well networks and the evaluation of ground water well hydrographs or the use of ground water models to estimate deep seepage from small research basins is highly recommended. Future investigators are now armed with better tools necessary to estimate all the water and nutrients and have no need to quietly assume deep seepage is zero.

Introduction

Streamflow increases following logging, fire, or insect mortality are quite variable and difficult to predict, even when results are evaluated using paired watersheds. The paired watershed approach uses (usually) two adjacent watersheds similar in size and geology, at which precipitation and streamflow are measured during a calibration period commonly lasting five to 15 years (Bates and Henry 1928). Following this calibration period, an equation is developed to predict streamflow on the "treatment" watershed (usually a tree harvesting treatment) from the "control" watershed streamflow where mature forests remain. The excess of streamflow on the treatment watershed above that predicted from the control is assigned to the treatment effect (tree harvesting), and the predicted treatment watershed streamflow is related to variation in precipitation Still, streamflow response is variable, even when separate areas have similar precipitation. In theory, streamflow change with tree removal should be similar among watersheds where climate, original vegetation, soils and annual precipitation are similar To test this theory, I regressed first-year streamflow response to tree removal (or long-term streamflow reduction with tree regrowth) against annual precipitation and examined the data to determine the maximum water yield response.

Because trees, especially tree groups, have different effective transpiration rates (Federer 1973, Swank and Crossley 1988), I limited the evaluation to hardwoods or widely spaced conifers (e g., ponderosa and pinyon pine, and juniper) and excluded densely spaced conifer plantations or natural stands from the evaluation Other things being equal, an envelope curve encompassing a data array of first-year streamflow change, as a function of annual precipitation, should estimate the maximum reduction in evapotranspiration and interception associated with tree harvesting. This assumes the entire effect of reduced evapotranspiration and interception is measured as an increase in streamflow, and ignores any potential changes to ground water recharge. Responses well below the envelope curve are evidence of significant water loss from the watershed via ground water flow ("deep seepage") not measured at the stream gauge. In this paper, deep seepage is defined as ground water that flows out of the watershed without first discharging to the stream upstream of the stream gauge. It is, therefore, not accounted for at the stream gauging station.

Most data came from Bosch and Hewlett's summary of 94 paired or monitored, single watersheds First-year (or second-year if treatments were imposed well into the first year) responses were used for 30 basins with hardwood and widely spaced conifers. Additionally, two basins not in Bosch and Hewlett's 1982 summary were included (Hornbeck et al 1993). Two of the 32 basins (Hubbard

[1]USDA Forest Service, North Central Research Station, Grand Rapids, MN 55744
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Brook No. 2 in New Hampshire and Marcell No 4 in Minnesota, (Table 1) have explicit estimates of ground water flow bypassing the stream gauge. At Hubbard Brook, a thin (4 m) layer of till overlies bedrock consisting of pelitic schists with granitic dikes. The amount of ground water recharge (depth of water over the entire basin) to bedrock for high-elevation sites at Hubbard Brook is estimated at 25 mm (Tiedeman et al. 1997; Rosenberry and Winter 1993). The amount of ground water recharge at Marcell occurs through a clay loam till over deep sands and varies from 50 to 200 mm (Nichols and Verry 2001) As a check on use of the envelope curve, these two locations with first-year streamflow responses, enhanced with ground water recharge estimates, should fall on or near a theoretical envelope curve

Data from eight watersheds were closely aligned on a theoretical envelope curve at the upper edge of the water yield response data array. These eight responses were used in a linear regression to approximate the position of the envelope curve and its 95% confidence interval.

Results

Figure 1 shows the array of first-year streamflow response (Q_1) versus annual precipitation (P) in millimeters for 32 watershed studies. Eight of the points at the upper edge estimate a theoretical envelope curve as a function of annual precipitation.

$$Q_1 = 59 + 0.27P \qquad (1)$$

where F = 708, $\alpha = 2 \times 10^{-7}$, and $R^2 = 0.99$

The two sites with known values for ground water recharge are shown as black dots, open diamonds below the black dots indicate only the measured streamflow response. Response data from watersheds with both measured streamflow and ground water seepage should fall on the envelope curve Inclusion of the highest data value (black diamond) may have unduly influenced the regression, however, its exclusion yields virtually the same envelope curve ($Q_1 = 61 + 0.28P$). Additionally, there is visually no difference between sites in semiarid vs. humid areas with respect to the

Table 1
Changes in Water Yield Following Tree Harvesting or Tree Growth

No.	Country	Location	Watershed Name/No.	Area Ha	Vegetation Tree Type	Annual Precip. Mm	Annual Stream Flow w/trees mm	Treatment	1st or 2nd Yr. Stream Flow Respon. mm
1	U S A	Beaver Cr UT	1	124	Juniper & Pinyon	457	20	100% cable and burn	0
2	U S A	Beaver Cr UT	3	146	Juniper & Pinyon	457	18	83% herb	10
3	U S A	Beaver Cr UT	3	147	Juniper & Pinyon	457	18	83% herb	30
4	U S A	Wagon Wheel Gap CO	B	81	84% Aspen 12 Con	536	157	100% clearcut	34
5	U S A	Wagon Wheel Gap CO	B	52	84% Aspen 12 Con	536	157	100% clearcut	47
6	U S A	Entiat WA	McCree Cr	514	Pondersa & Dg Fir	579	112	100% burned	91
7	U S A	Entiat WA	Burns Cr	563	Ponderosa & Dg Fir	597	155	100% burn	74
8	U S A	Placer Co CA	C	5	Oak Woodland	635	145	99% killed	111
9	U S A	3Bar AZ	C	39	Chaparral	638	58	100% burned	132
10	U S A	Sierra Ancha AZ	Workman	100	Ponderosa	813	87	83% clearcut	112
11	U S A	Marcell MN*	4	34	Aspen	817	114	100% upland clearcut	114
12	U S A	Marcell MN**	4	34	Aspen	817	162	100% upland clearcut	180
13	Japan	Kitatani	Kitatani	17	Akamatsu	1113	290	100% clearcut	205
14	Japan	Tatsunokuchiyama-Minamitani		23	Akamatsu	1153	293	100% clearcut	209
15	U S A	Leading Ridge PA, 1977*	2	43	Central hardwoods	1265	682	100% clearcut	239
16	U S A	Fernow WVA[4]	7	24	Mixed hardwoods	1217	658	100% clearcut	258
17	U S A	Grant Forest GA	18	165	Hardwoods	1219	467	100% clearcut	254
18	U S A	Hubbard Brook NH*	2	16	Hardwoods	1336	902	100% clearcut	312
19	U S A	Hubbard Brook NH**	2	16	Hardwoods	1336	902	100% clearcut	337
20	Austral	Melbourne, Victoria	Graceburn	2500	Eucalyptus	1460	850	fire and regrowth	240
21	U S A	Fernow WVA	3	34	Mixed hardwoods	1500	607	91% clearcut	253
22	U S A	Fernow WVA	1	30	Mixed hardwoods	1524	584	85% clearcut (cc)	130
23	U S A	Coweeta NC	1	16	Mixed hardwoods	1725	739	100% cc and some burn	150
24	U S A	Coweeta NC	3	9	Mixed hardwoods	1814	607	100% clearcut to agr	127
25	U S A	Coweeta NC	6	9	Mixed hardwoods	1854	838	80% clearcut to grass	265
26	U S A	Coweea NC	17	14	Mixed hardwoods	1895	775	100% clearcut	414
27	U S A	Coweeta 1940	13	16	Mixed hardwoods	1900	889	100% clearcut	362
28	U S A	Coweeta 1963 repeat	13	16	Mixed hardwoods	1900	889	100% clearcut	375
29	Kenya	Kimakia	A	35	Montane and bamboo	2014	568	100% clearcut	457
30	U S A	Coweeta NC	37	44	Mixed hardwoods	2244	1583	100% clearcut	255
31	NZ	Maimai	M7	4	Mix beach and hardwood	2600	2600	100% clearcut	650
32	Japan	Kamabuchi	2	3	60% hardwood, 40% con	2641	2075	100% clearcut	218

*Data are from Bosch and Hewlett (1982) or Hornbeck et al 1983

**Basins with ground water studies (Hubbard Brook-Tiedeman et al, 1997 and Marcell Nichols and Verry 2000) have a second line of data with estimated ground water increases in water yields included

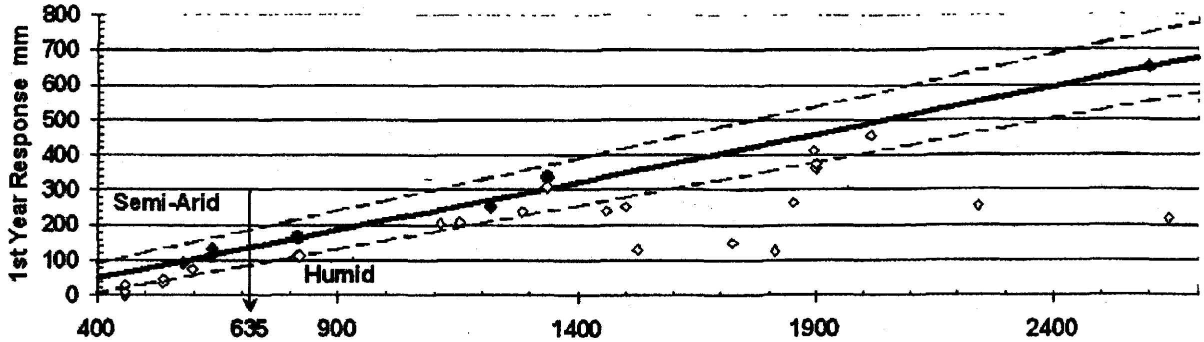

Figure 1. First- (or second-) year streamflow response to hardwood or widely spaced conifer removal. Black diamonds and black dots are used to generate an envelope curve for the entire data array. Black dots represent measured values for ground water recharge at the Marcell and Hubbard Brook sites (the open diamonds below the black dots represent streamflow only). See Table 1 for locations and data sources.

general relationship or the envelope curve (Figure 1). According to the regression model, removal of deciduous trees (or widely spaced conifers) from a basin should garner an extra water yield equivalent to 27% of the annual precipitation less a constant of 60 mm.

Locations plotting below the envelope curve indicate significant deep seepage (or leakage at the stream gauge). Sites significantly different from zero seepage fall below the 95% confidence limit (dashed lines in Figure 1). The estimates of deep seepage, including points that plot

Table 2

Predicted Total Water Yield Response to the First or Second Year after Tree Removel (in mm)

No. Location	Watershed No.	Annual Precip.	Predicted Total Water Yield Response	First or Second Year Streamflow Response	Predicted Total Water Yield Response	Estimated Deep Seepage	Deep seep. Below Envelope Curve
1 Beaver Cr, UT	1	457	64	0	64	**64**	**22**
2 Beaver Cr, UT	3	457	64	10	64	**54**	**12**
3 Beaver Cr, UT	3	457	64	30	64	**34**	
4 Wagon Wheel Gap, CO	B	536	86	34	86	**52**	**8**
5 Wagon Wheel Gap, CO	B	536	86	47	86	**39**	
6 Entiat, WA	McCree	579	97	91	97	**6**	
7 Entiat, WA	Burns Cr	597	102	74	102	**28**	
8 Placer Co.	C	635	112	111	112	**1**	
9 3Bar, AZ	C	638	113	132	113	-19	
10 Sierra Ancha, AZ	Workman Cr	813	161	112	161	**49**	
11 Marcell, MN	4	817	162	114	162	**48**	
12 Marcell, MN w/gw	4	817	162	180	162	18	
13 Kitatani	Kitatani	1113	242	205	242	**37**	
14 Tatsunokuchiyama-MN		1153	252	209	252	**43**	
15 Leading Ridge, PA, 1977	2	1285	288	239	288	**49**	
16 Fernow, WV	7	1217	270	258	270	**12**	
17 Grant Forest, GA	18	1219	270	254	270	**16**	
18 Hubbard Brook NH	2	1336	302	312	302	−10	
19 Hubbard Brook, NH w/gw	2	1336	302	337	302	35	
20 Melbourne, Victoria	Graceburn	1460	335	240	335	**95**	33
21 Fernow, WV	3	1500	346	253	346	**93**	30
22 Fernow WV	1	1524	352	130	352	**222**	159
23 Coweeta	1	1725	407	150	407	**257**	189
24 Coweeta	3	1814	431	127	431	**304**	235
25 Coweeta	6	1854	442	265	442	**177**	107
26 Coweeta	17	1895	453	414	453	**39**	
27 Coweeta 1940	13	1900	454	362	454	**92**	21
28 Coweeta 1963 repeat	13	1900	454	375	454	**79**	8
29 Kimakia	A	2014	485	457	485	**28**	
30 Kericho Sambret	37	2244	547	255	547	**292**	**214**
31 Mamai	M7	2600	643	650	643	7	
32 Kamabuchi	2	2641	654	218	654	**436**	350

Deep seepage to ground water (bold values) is estimated by subtracting measured first or second year responses from the predicted "envelope curve" response (Figure 1). Bold values in the last column are significantly different ($\alpha = 0.05$) from the "envelope cureve" regression significantly distant from the theoretical envelope curve, are tabulated in Table 2. The assigned numbers for each watershed included in Table 2 are arranged 1 through 32 (left to right, in Figure 1). Note that watersheds Nos. 16 and 17 have nearly identical values and plot as one black diamond.

Twenty-seven basins indicate deep seepage based on their position below the envelope curve The amount of deep seepage varies from 1 to 436 mm (0.04 to 17 inches) annually. Thirteen basins have deep seepage significantly beyond the 95% confidence interval (CI, ranging from 8 to 350 mm [0.3 to 14 inches]).

The estimated amounts of deep seepage average 98 mm ± 43 mm (95% CI) and amount to two to five times the measured first-year streamflow response. The deep seepage estimates average 45% of measured streamflow on treed watersheds prior to harvest Deep seepage is a significant component of water and nutrient budgets for many small research watersheds.

References

Bates, C.G., and A.J. Henry. 1928. Forest and streamflow experiments at Wagon Wheel Gap, Colorado. *U.S. Weather Bureau Monthly Weather Review* supplement no. 30, 79.

Bosch, J.M., and J.D. Hewlett. 1982 A review of catchment experiments to determine the effect of vegetation changes on water yield and evaporation. *Journal of Hydrology* 55, no 1982. 3–23.

Federer 1973 Forest transpiration greatly speeds streamflow recession. *Water Resources Research* 9, no. 6, 1599–1604.

Hornbeck, J.W., M.B Adams, E.S. Corbett, E.S Verry, and J.A Lynch. 1993. Long-term impacts of forest treatments on water yield A summary for northeastern USA *Journal of Hydrology* 150, 323–344.

Nichols, D.S., and E.S Verry 2001 Stream flow and ground water recharge from small forested watersheds in north central Minnesota. *Journal of Hydrology* 245, 89–103

Rosenberry, D.O., and T.C Winter 1993. The significance of fracture flow to the water balance of a lake in fractured crystalline rock terrain *Proceedings of Memoires of the XXIVth Congress International Association of Hydrogeologists-Hydrogeology of Hard Rocks*. June 28- July 2, Ås, Norway, 967–977. Kenilworth, U.K.: International Association of Hydrogeologists.

Swank, W.T., and D.A Crossley Jr. (eds.) 1988. *Forest Hydrology and Ecology at Coweeta*. New York: Springer-Verlag

Tiedeman, C.R., D.J. Goode, and P.A. Hsieh. 1997. Numerical simulation of ground water flow through glacial deposits and crystalline bedrock in the Mirror Lake area, Grafton County, New Hampshire. U.S Geological Survey Professional Paper 1572, 50.