HYDROLOGIC PERFORMANCE OF ERODED LANDS STABILIZED WITH PINE

by

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Southern pines, particularly loblolly, are ideal for erosion control, and millions have been planted on the middle and upper southern Coastal Plains to heal and restore the productivity of abused and abandoned lands. Earlier research in northern Mississippi indicated that such plantings reduced sediment production to insignificant amounts and perhaps reduced runoff. In this paper we examine the runoff and sediment yield characteristics of eight small, pine-covered watersheds with a wide range of soil and antecedent erosion conditions. The results demonstrate the importance of soil information for predicting hydrologic behavior and show that average annual water and sediment yields can be satisfactorily predicted from annual precipitation and soil survey information. We discuss the efficiency of pine plantings in controlling flood flows and sediment yields, and we point out possibilities for managing the plantations to increase groundwater recharge.

Description

Measurements

Runoff and sediment from three small catchments of loblolly pine near Oxford, Mississippi, have been measured since 1958. Similar data have been gathered since 1964 from five additional watersheds near Coffeeville, Mississippi, some 34 air miles distant. Instrumentation of the Oxford units has been described (4). The only modification for the Coffeeville units was the use of punch-type, analog-to-digital recorders (1). The physical characteristics of the eight units are summarized in Table 1.

Precipitation was measured with networks of standard and recording gages. Mean annual long-term rainfall in the study area is about 52 inches. Annual rainfall ranged between 37.67 and 70.60 inches during the five study years, 1964-1968 (Appendix Table 2). Surprisingly, the Coffeeville watersheds during these years received averages of 4.10, 6.53, 9.18, 0.87, and 13.30 inches less than the ones near Oxford.

1/ The coauthors are stationed at the Forest Hydrology Laboratory which is maintained by the Southern Forest Experiment Station in cooperation with the University of Mississippi. The catchments at Oxford were installed under a cooperative arrangement with the State Conservationist of Mississippi, Soil Conservation Service.

TABLE 1. CHARACTERISTICS OF STUDY WATERSHEDS

Location and watershed number	Drainage area	Soils			Range in elevation	Pine c/ stems 3.5 inches dbh and larger
		Loessial a/	Coastal plain b/	With restricted internal drainage		
	Acres	*------------Percent------------*			*Feet*	*Number/acre*
Oxford						
1	3.35	29	71	0	68	381
2	3.58	46	54	0	60	306
3	2.60	100	0	47	40	445
Coffeeville						
1	6.95	100	0	74	43	162
2	4.77	100	0	93	59	177
3	5.91	36	64	35	63	232
4	4.06	11	89	11	58	236
5	3.67	7	93	7	62	270

a/ Memphis, Loring, Providence, and Lexington series (originally silt-loams developed from wind-deposited loess).

b/ Principally Ruston series.

c/ Oxford units were cruised at age 19 (1958) and Coffeeville units at age 24 (1964).

Analyses for this paper were confined to annual and average annual precipitation, runoff, and sediment (Appendix Table 2). We sought relationships that would explain the variation in runoff and sediment production among the eight catchments. Simple predictive regression models were developed from data collected during the 5 years 1964-1968.2/ Subsequent data will be used to test the ideas and models presented.

Soils

Two major groups of Red-Yellow Podzolic soils are represented. Loess soils cover three units entirely and varying amounts of the ridges and upper slopes of the others. Soils developed from Coastal Plain deposits, primarily Ruston, cover the remainder of the watersheds except for small areas of alluvial soils along drainageways. All the units were severely eroded when planted and three of the units at the Coffeeville location include large, deep gullies. The loessial soils were originally silt loams; the Coastal Plain soils, sandy loams. Most surface soils are now heavier textured due to past erosion. The proportions of loess and Coastal Plain soils are shown in Table 1, and a further breakdown is given in Appendix Table 3.

Cover Conditions

With the exception of C-4, all the watersheds were occupied by well-distributed, predominantly pole-size pine throughout the study. Crown cover was essentially complete, and almost all soil surfaces were covered with pine litter. On C-4 at age 24 (1964), 18 percent of the soil surface was not covered by litter; most bare soil was in two partially healed gullies. On the other four Coffeeville catchments, 93 percent or more of the soil was protected; ovendry weights of the forest floor ranged from 7.2 to 9.0 tons per acre.

At age 23 (1962), less than 0.5 percent of the soil surface on the three Oxford units was unprotected. The forest floor averaged 1.02 ± 0.06 inches in depth and weighed 6.04 ± 0.34 tons per acre. On C-1, C-2, and C-3, respectively, 80, 59, and 24 percent of the pines were slash pine (*Pinus elliottii* Engelm.). The rest of the pines, except for a few naturally seeded shortleaf (*Pinus echinata* Mill.), were planted loblolly (*Pinus taeda* L.).

The Oxford catchments supported an average of 377 stems per acre larger than 3.5 inches (Table 1). A pulpwood thinning on the Coffeeville units, plus additional salvage of ice-damaged timber on C-1 and C-2, had reduced tree numbers to a range of 162 to 270 per acre at the start of the study period.

2/ Sediment data are for years 1965-1968 due to site disturbance during installation of Coffeeville units.

Results and Discussion

Annual Water Yields

An earlier paper (5) showed that annual runoff from the three Oxford catchments varied directly with the proportion of watershed area with loessial soils. Runoff from each of four covers in northern Mississippi for the 3 years (1959-1961) was also greatest from units with all loess soils (4). However, these studies were limited to three watersheds of each land use or forest type. The present study provided an opportunity to examine the soil-runoff relationship in greater depth.

It appeared, from plotting respective 5-year means of the runoff/precipitation ratios (RO/P) over the proportion of loess soils on each watershed, that the Oxford and Coffeeville locations represented two discrete populations of runoff potential (Figure 1). However, as will be shown, it was the proportion of loess soil with poor internal drainage caused by a fragipan which proved to be the key variable. Storm runoffs were generally greater and had longer recessions from watersheds with fragipan soils. Such pans tend to perch water during the wet winter and spring seasons, and, at least for one previously studied situation, both the rate and volume of post-storm flows were related to the volume of water held in detention storage over the fragipan (5).

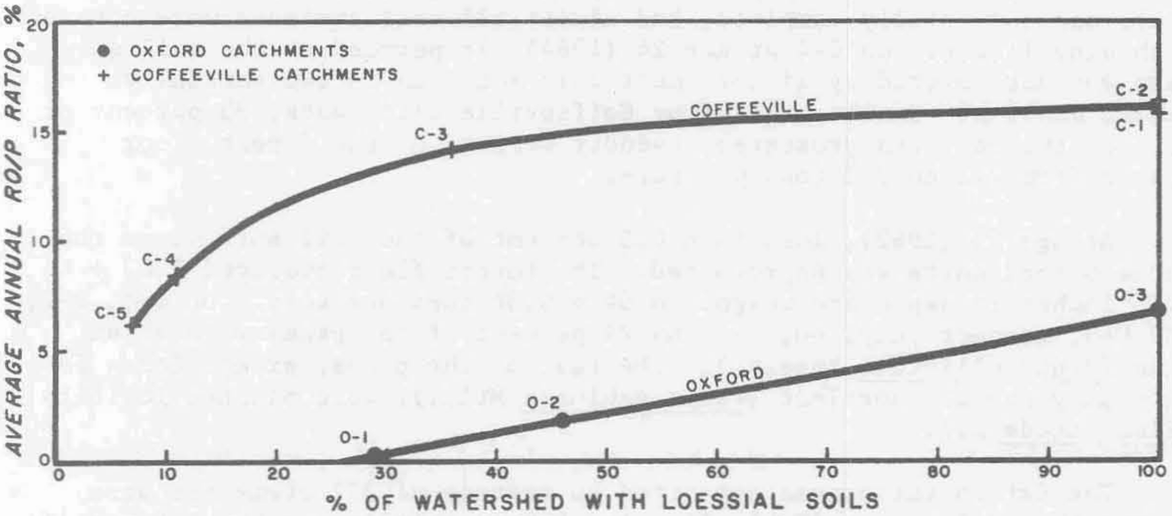

Figure 1. Apparent influence of loess soils on average annual runoff at two locations.

An analysis of variance of the 40 annual RO/P ratios for the eight watersheds indicated 3/ that the chief source of variation was among

3/ All confidence limits and standard errors of means are at the 67-percent level; tests of significance related to analyses of variance are at the 95-percent level.

rather than within watersheds. The eight average annual RO/P ratios were then regressed over the proportion of watershed area occupied by upland soils characterized by a fragipan (and including small areas of poorly drained, alluvial-colluvial soils along the drainageways). The regression was significant and a transformation of the soil variable improved the fit:

$$\hat{Y} = 7.115 \text{ Log}_{10} (X+1) + 0.646$$

where: $\hat{Y}$ is the mean RO/P ratio expressed as a percent, and X is the percent of watershed area with fragipan and other poorly drained soils.

This equation explained 83 percent of the variation in the RO/P ratios ($r^2 = 0.829$).

Because the nonlinear trend of this equation, and particularly the rapid increase of runoff over the 0- to approximately 15-percent range of X,[4/] was not anticipated, the physical information for the watersheds in this range was examined for possible explanations. Although all the watersheds were severly eroded when planted to pine, O-1 and O-2, yielding low amounts of runoff, did not have the deep and extensive gullies of C-4 (near-vertical walls over 15 feet high) and C-5. In addition, the main drainageway on O-1 (the watershed yielding minimum runoff), although gullied to depths of over 6 feet, runs through an area of deep sandy soils (Eustis series), and upslope runoff could infiltrate through the channel surface. C-4 and C-5 also have active seeps in the larger gullies during wet conditions that feed directly to the main drainageway, while runoff from the three Oxford units is largely ephemeral. These conditions tended to reduce runoff from O-1 and O-2 and increase it from C-4 and C-5.

Runoff from C-3 also appeared high compared to O-3. The main drainageway on C-3 extends almost to the watershed divide, and also borders and has cut into the shallow fragipan (Providence series) on the upper slope. A large gully near the center of the watershed seeps water under wet conditions, and the main drainageway runs over an imperfectly drained soil (Collins series). In contrast, the fragipan on the upper slopes of O-3 is deeper (Loring series), and any overland flow from the upper slopes and runoff in most of the channel itself must pass over loess without a fragipan (Lexington series). This soil, considering the low runoff from O-1 (29 percent Lexington) and O-2 (46 percent Lexington), is obviously permeable.

Arguments on the effects of arrangement of soils and depth to fragipan on runoff volumes appear to be supported by other studies. O-3 values roughly fall in line with those for three slightly eroded catchments of depleted hardwoods, one with 100-percent Providence (fragipan) and two with well-drained soils on the lower slopes. Mean RO/P values for these four units plot close to a straight line over a 35- to 100-percent range of X without an exceptionally high value (12.17 percent,

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4/ The graph for this equation is not shown, but see Figure 2 which is similar and includes the individual values.

1959-63) for the fragipan catchment. A severely eroded abandoned-field catchment of fragipan soils, however, had a very high mean RO/P value (23.74 percent, also for 1959-63) while the values for two similarly eroded abandoned fields with 62 and 64 percent of the soils restricted and with Ruston soils downslope were much lower (7.03 and 8.21 percent). Fragipans at shallow depths due to erosion increase runoff; permeable soils on the lower parts of catchments tend to reduce it.

Due to soil positions and the severe erosion and gullying on the Coffeeville units, the equation probably predicts the upper limits of the mean RO/P ratio for the pine type. If 0-3 was somewhat unique in the sample, the equation may overestimate runoff from units with arrangements of soils similar to those on this watershed.

For most practical purposes, it is better to slightly overestimate rather than underestimate runoff, and for this reason the regression was solved omitting 0-3. With the same X and Y variables:

$$\hat{Y} = 7.994 \text{ Log}_{10} (X+1) + 0.524$$

This equation explained 98 percent of the variation in RO/P ratios ($r^2 = 0.978$). Figure 2 shows the equation with confidence limits (narrow band). Within the wide band are the probable limits of error for predicting the mean RO/P ratio for an individual watershed.

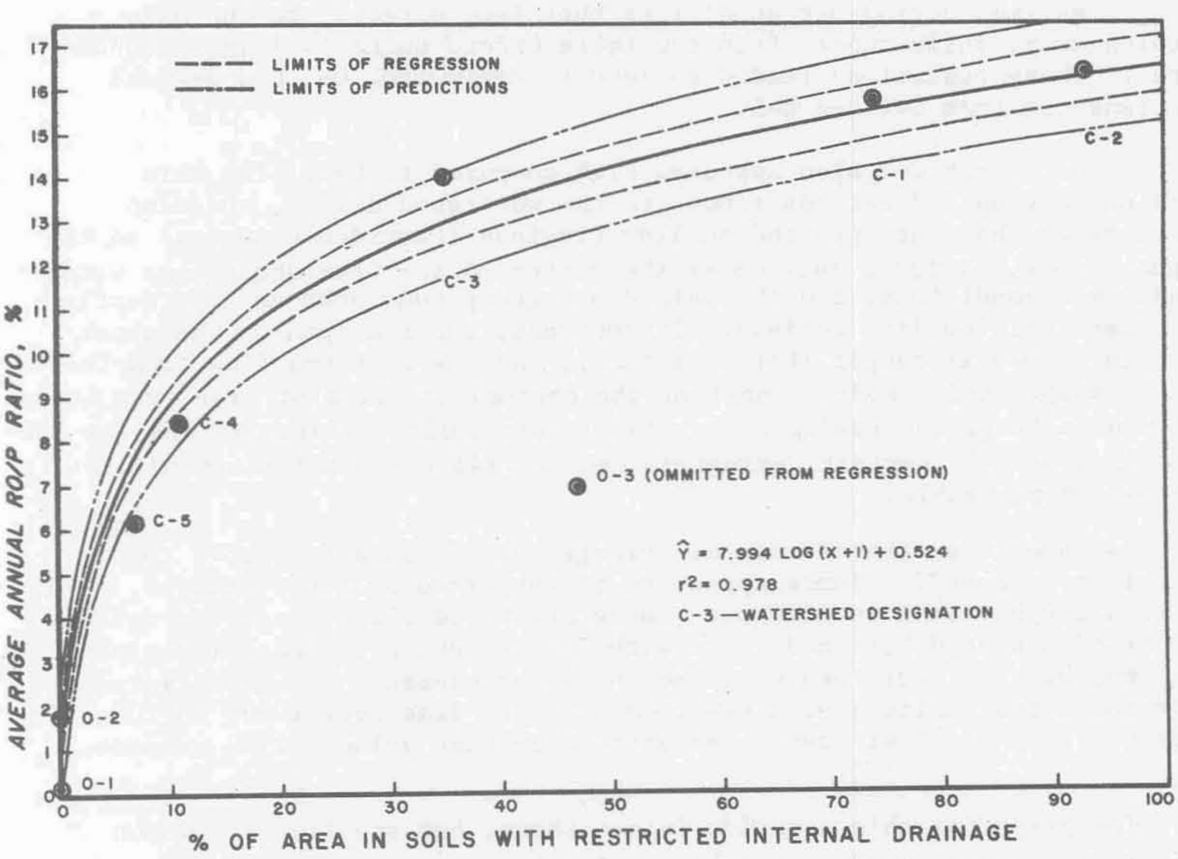

Figure 2. How annual runoff from eroded lands stabilized with pine varied with soil characteristics.

Using this equation, mean annual runoff for a watershed with soils of unrestricted internal drainage would be 0.5 percent of the average annual rainfall; that from a watershed with 100-percent fragipan and other poorly drained soils would be 16.5 percent. The difference in estimated annual runoff for a period during which average annual precipitation equalled the long-term mean would be over 8 inches.

Despite difficulties associated with various arrangements of soils, mapping soil boundaries accurately, differences in erosion and gullying, and varying depths of fragipans (at or near the soil surface on many eroded segments of the units), the equation appears quite satisfactory for predictive purposes and has several interesting connotations. For one, a relatively small proportion of fragipan or poorly drained soils on a drainage unit can apparently exert a relatively large influence on water yield. If one can assume that there had to be considerable overland flow from all the catchments to create the severe erosion existing at the time the pine was planted, it is evident that the pine is most effective in minimizing stormflows, and hence sediment, from catchments of Coastal Plain soils similar to those represented on the study watersheds. These soils are important and widespread not only in Mississippi but throughout the southern Coastal Plain. Well-drained loessial soils appear to respond similarly.

Conversely, the opportunity for largely eliminating stormflows from eroded fragipan soils by establishing pine may be limited. This contention is supported by a study in which two severely eroded abandoned-field catchments covered with dense broomsedge (<u>Andropogon</u> spp.) were burned (<u>3</u>). Stormflows from one eroded catchment (25 percent fragipan) increased 48 percent at the level of the pretreatment mean during the first year after burning. Changes in cover were obviously important. Identical treatment on a second catchment (100 percent fragipan) significantly increased peak discharges, but here, where the opportunity for soil water storage was limited, the volumes of runoff were unchanged. Here soil rather than cover was the dominant influence.

Another implication from Figure 2 is that pine plantations on Coastal Plain soils can be manipulated to increase groundwater recharge. Tree populations can be regulated over a wide range with minor losses in fiber production (<u>6</u>). However achieved, a reduction in population would tend to leave a higher reserve of soil water at the advent of the recharge season, thus improving the opportunity for recharge to subroot levels. It appears such management could be practiced on catchments of Coastal Plain soils similar to O-1, O-2, C-4, and C-5 without unduly increasing the flood risk, even for events with high antecedent soil-water conditions. The highest stormflow from this group of catchments during the 5-year period was 2.05 area-inches from O-2. This flow resulted from an 18-hour, 7.00-inch rain having a return period between 50 and 100 years. The highest rainfall at Coffeeville was 5.74 inches, with a maximum stormflow of 1.17 inches; the greatest stormflow of 1.50 inches resulted from an intense 3.80-inch storm. Except for infrequent large, intense rains, stormflows from these four Coastal Plain units seldom exceeded 1 area-inch.

Following similar reasoning, high tree densities should be maintained on fragipan soils to maximize rainfall interception, depth of the forest floor, and potential soil-water storage. Thinning under these soil conditions holds little promise for increasing groundwater recharge since water is being rejected during much of the winter-spring recharge season. Reducing flood flows should be the primary hydrologic consideration in managing such areas.

The regression (Figure 2) was recast for predicting probable maximum annual runoff, using the highest annual RO/P ratio for each watershed during the 5-year period (again omitting 0-3). This equation (Figure 3) with X and Y as previously defined is:

$$\hat{Y} = 11.902 \, \mathrm{Log}_{10} \, (X+1) + 2.116$$

$$r^2 = 0.912$$

Here, the predicted RO/P ratio (expressed as a percent) for a watershed of well-drained soils is 2.1; that for a watershed with 100-percent poorly drained soils is 26.0.

The three equations should have utility for other water yield or flood prevention purposes, such as the design of flood storage structures.

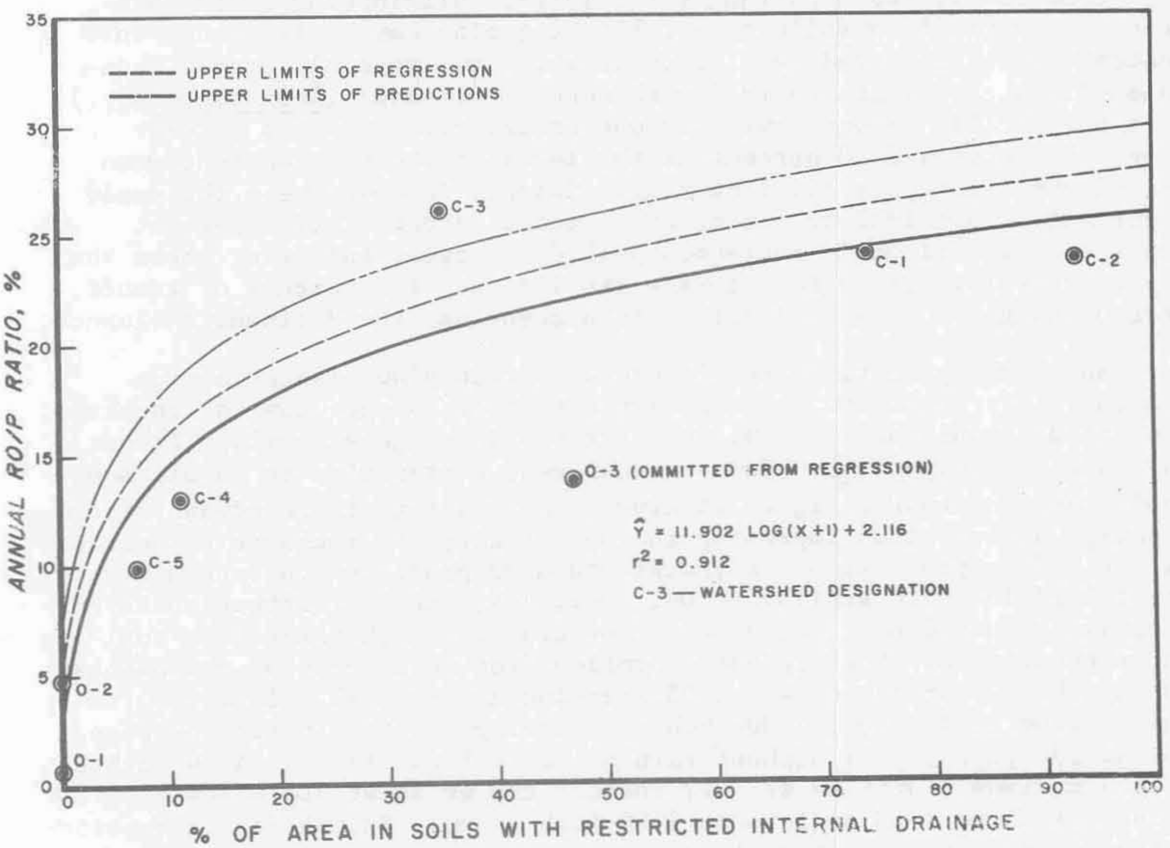

Figure 3. Probable maximum runoff is predictable from soil characteristics.

The prediction equations are, of course, for small drainage units, and the question of their utility for larger watersheds is of paramount interest. A big gap in runoff information is that for areas larger than a few acres but smaller than 40 to several hundred acres. Data for such areas are practically nonexistent for a single cover type; however, information from the 88-acre Pine Tree Branch watershed in eastern Tennessee (2) provided an opportunity to test the prediction equation. The major treatment on this eroded area was pine planting, mostly in 1946, but continuing through 1950. Average annual runoff as a percent of average annual precipitation by 5-year periods is shown below:

Period	Average annual precipitation	Average runoff	Ratio of average 5-year runoff to average 5-year Precipitation
	(Inches)	(Inches)	(Percent)
1941-1945	48.99	11.32	23.1
1946-1950	59.34	14.73	24.8
1951-1955	46.90	8.52	18.2
1956-1960	46.44	5.57	12.0
5/ 1961-1965	48.16	5.12	10.6
5/ 1966-1970	49.09	4.71	9.6

Fifty-one percent of the Pine Tree Branch watershed has a fragipan soil (Providence), and an additional 8 percent has poorly drained alluvial soils. The equation based on all eight watersheds estimated that 12.8 percent of rainfall would be runoff considering just the proportion of Providence soils and 13.3 percent using the Providence plus the poorly drained alluvial areas. Using the 13.3-percent estimate, the equation overestimated runoff by 0.61, 1.28, and 1.82 inches for the last three consecutive periods, during which the pines were 11 to 25 years old. This information at least suggests that the prediction equation may be extrapolated to areas larger than the study watersheds. The Pine Tree Branch data also suggest that the major reduction in storm runoff resulting from planting severely sheet-eroded and gullied lands may occur by about plantation age 15. Records for 0-3 starting in 1958, when the trees were 19 years old, roughly confirm this conclusion; no improvement was noted between the next two consecutive 6-year periods:

Period	Average annual precipitation	Average runoff	Average annual RO/P ratios
	(Inches)	(Inches)	(Percent)
1958-1963	51.72	2.96	5.36
1964-1969	55.55	3.91	6.82

Sediment Yields

Annual yields for the eight catchments for the last four study years averaged 0.031 ± 0.005 ton per acre. Clearly, there is a minimum of sediment production from eroded slopes covered with pine litter. The

5/ Unpublished data furnished by Carl D. Eklund, Head, Hydrology Section, Tennessee Valley Authority, Knoxville, Tennessee.

small yields (which include organic matter) probably originate from incompletely healed areas and from channels exposed when occasional high peak flows remove litter or prevent its accumulation. However, assuming such areas occupy just 1 percent of the average drainage area, 1 inch of erosion from them would take 50 years.

The ranking of watersheds from highest to lowest in terms of average annual yields was: C-4, C-3, C-2, C-1, C-5, O-3, O-2, O-1 (Appendix Table 2). C-4, with the largest area of exposed soil and with peak flows approaching those from units with much larger volumes of stormflow, also had the highest yield for a single year--0.113 ton per acre. Yields from C-4 do not fully represent the pine cover, but they do demonstrate that much of the sediment movement, even from large, incompletely healed gullies, is contained within the catchment and that a complete ground cover is not necessary to reduce sediment yields to low levels. The higher yields from C-3, C-2, and C-1, as will be shown, resulted from high volumes of annual runoff.

Refinement of the data, though seemingly superfluous considering the low yields,provided insight into the erosional processes on pine-covered catchments and lead to a simple prediction equation.

The concentration of sediment per acre-inch of runoff (flows exceeding 0.0186 cfs [6/]) averaged 0.011 ± 0.002 ton for the eight watersheds during the four years (1965-1968). An analysis of variance of average annual sediment concentrations (omitting O-1 due to limited data) indicated that the main source of variation was among rather than within watersheds. Soils per se, however, did not seem to be correlated with sediment concentrations in any meaningful way. A well-developed forest floor was apparently equally effective on the major soil types represented. It was then determined that sediment concentrations were independent of individual stormflow volumes, and of annual or average annual water yields. Slopes of the following regressions did not differ significantly from zero: average concentrations per stormflow regressed over stormflow volumes, either excluding C-4 ($n = 201$) or including C-4 ($n = 237$); annual sediment concentrations regressed over annual runoffs excluding C-4 ($n = 24$) or including it ($n = 28$); and average annual concentrations regressed over average annual runoffs ($n = 8$).

These analyses suggested that sediment production was a direct function of runoff volumes. The regression of average annual sediment yields over average total annual water yields ($n = 7$, C-4 omitted as not being representative of the pine cover) was significant:

$$\hat{Y} = 0.0065X + 0.0003$$

where: $\hat{Y}$ is the average annual sediment yield in tons/acre/year and X is mean total annual runoff in area-inches.

6/ Flows less than 0.0186 cfs, consisting of tail-end stormflow recessions and seeps, were considered sediment free and not sampled. They also were omitted when calculating sediment concentrations for individual and annual stormflows.

The slope of this regression did not depart significantly from the overall average sediment yield per area-inch of runoff and the regression could be expressed as:

$$\hat{Y} = 0.0066X$$

This equation explained 76 percent of the variation in average annual sediment yields ($r^2 = 0.761$). The standard error of estimate ($S_{y.x}$ = 0.010 ton) was relatively large, but the equation would be satisfactory for any practical purpose.

In conclusion, by choosing one of the previously presented equations (depending on the particular objective), RO/P ratios can be predicted to estimate the probable maximum annual runoff and sediment production and both average annual runoff and sediment yields from small, severely eroded catchments healed with pine. All that is needed is annual precipitation and soil survey information.

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APPENDIX TABLE 2. ANNUAL PRECIPITATION, RUNOFF, AND SEDIMENT ON OXFORD AND COFFEEVILLE WATERSHEDS

Calendar	Oxford				Coffeeville					
year	0-1	0-2	0-3	Mean	C-1	C-2	C-3	C-4	C-5	Mean
				Annual precipitation--Inches						
1964	60.99	60.81	60.95	60.92	58.37	58.37	55.62	55.88	55.88	56.82
1965	44.45	44.44	43.71	44.20	37.24	37.24	37.93	37.96	37.96	37.67
1966	51.72	51.34	52.58	51.88	41.70	41.70	42.75	43.68	43.68	42.70
1967	51.64	51.50	51.13	51.42	49.77	49.77	51.88	50.67	50.67	50.55
1968	70.70	70.56	70.54	70.60	56.48	56.48	56.24	58.64	58.64	57.30
Mean	55.90	55.73	55.78	55.80	48.71	48.71	48.88	49.37	49.37	49.01
				Annual runoff--Area inches						
1964	0.004	0.190	2.735	--	13.783	13.974	14.553	7.287	5.522	--
1965	.004	1.455	4.950	--	5.826	6.082	4.910	3.869	2.516	--
1966	.011	.318	1.590	--	3.499	4.312	3.282	2.129	1.384	--
1967	.000	.038	1.148	--	3.536	4.028	2.580	1.598	.805	--
1968	.511	3.421	9.699	--	13.636	12.871	10.376	6.427	5.672	--
Mean	0.106	1.084	4.024	--	8.056	8.253	7.140	4.262	3.180	--
				Annual runoff as percent of annual precipitation						
1964	0.00	0.31	4.48	--	23.61	23.94	26.16	13.04	9.88	--
1965	.00	3.27	11.32	--	15.64	16.33	12.94	10.19	6.63	--
1966	.00	.62	3.02	--	8.39	10.34	7.68	4.88	3.17	--
1967	.00	.08	2.24	--	7.10	8.09	4.97	3.16	1.59	--
1968	.72	4.85	13.75	--	24.14	22.79	18.45	10.96	9.67	--
Mean	0.14	1.83	6.96	--	15.78	16.30	14.04	8.45	6.19	--

APPENDIX TABLE 2 (CONT'D.)

Calendar year	Oxford				Coffeeville					
	0-1	0-2	0-3	Mean	C-1	C-2	C-3	C-4	C-5	Mean
	Annual sediment production--Tons per acre									
1964	0.000	0.000	0.009	0.003	a/	a/	a/	a/	a/	--
1965	.000	.003	.015	.006	0.055	0.110	0.052	0.113	0.017	0.069
1966	.000	.002	.008	.003	.032	.034	.045	.067	.039	.043
1967	.000	.000	.007	.002	.007	.029	.037	.016	.013	.020
1968	.006	.024	.038	.023	.038	.026	.069	.077	.014	.045
Mean	0.001	0.006	0.015	0.007	0.033	0.049	0.051	0.068	0.020	0.044
	Annual sediment concentration--Tons per acre-inch of runoff b/									
1964	--	0.000	0.004	0.002	a/	a/	a/	a/	a/	--
1965	--	.002	.003	.003	0.011	0.019	0.012	0.035	0.012	0.018
1966	--	.005	.005	.005	.009	.008	.014	.033	.031	.019
1967	--	--	.007	.007	.002	.008	.016	.010	.016	.010
1968	.012	.007	.004	.008	.003	.002	.007	.013	.004	.006
Mean	0.012	0.004	0.005	0.005	0.006	0.009	0.012	0.023	0.016	0.013

a/ Not considered due to site disturbance during 1963 installation.

b/ Confined to flows $\geqq$ 0.0186 cfs.

APPENDIX TABLE 3. SOIL SERIES ON STUDY WATERSHEDS

Soil series	Oxford			Coffeeville				
	0-1	0-2	0-3	C-1	C-2	C-3	C-4	C-5
	Percent of area							
Loess uplands								
Well drained								
Memphis	--	--	--	25.8	6.6	1.0	--	--
Lexington	29.4	46.3	53.4	--	--	--	--	--
With fragipan								
Loring	--	--	46.6	24.7	90.0	--	--	--
Providence	--	--	--	40.5	--	30.5	11.2	6.9
Loess flood plains								
Poorly drained								
Falaya	--	--	--	9.0	3.4	--	--	--
Collins	--	--	--	--	--	4.7	--	--
Coastal Plain uplands								
Well drained								
Ruston	45.8	43.5	--	--	--	63.8	87.4	92.3
Eustis	16.6	--	--	--	--	--	--	--
Alluvium	8.2	10.2	--	--	--	--	1.4	.8
Totals	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0