SECTION 12

YIELD AND SOURCES

SEDIMENT PLAGUES COMMUNITY WATER SUPPLIES

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ABSTRACT

This paper presents a history of the City of Jacksonville, Illinois' water supply and how reservoir sedimentation has effected the community water supply. Watershed erosion and sedimentation data and information were collected and evaluated by present Soil Conservation Service procedures. Watershed erosion is based on historical agricultural and sedimentation records and from detailed reservoir sediment surveys conducted in the community's three water supply reservoirs. The results of the surveys are summarized and variables in reservoir sedimentation rates are discussed.

INTRODUCTION

Reservoir sedimentation and accompanying water pollution often plague communities that rely on surface water reservoirs for their water supply. Reservoir sedimentation of Jacksonville surface water supplies is fairly typical of the challenges most communities, that rely on surface water reservoirs for their water supply, must face.

The community's park and recreation department and the community's water department were interested in knowing the extent to which the community's surface water resources were being affected by sedimentation. They requested the Soil Conservation Service to conduct reservoir sediment surveys of the three community reservoirs. Reservoir sediment surveys were conducted for Morgan Lake and Lake Mauvaise Terre during the fall and winter of 1989. A third community reservoir, Lake Jacksonville, was surveyed in November, 1986 when the lake was drained. While conducting the reservoir sediment surveys, a search of historical records was made and revealed an interesting account of 115 years of sedimentation, pollution and population changes that forced the community to make changes in its water supply.

SETTING

Jacksonville, Illinois, is located in west central Illinois, 35 miles west of Springfield, the state capitol. The climate is temperate continental with an average precipitation of 37 inches per year. Average annual runoff is about 8.5 inches per year. The drainage area and reservoirs are in the northwestern part of the Springfield Plain, Figure 1. The Springfield Plain is distinguished by its flatness and the shallow entrenchment of the drainageways. Here in the western part of the Springfield Plain the drainageways are more entrenched. The surface is covered with 8 to 12 feet of loess which overlies an average of 50 feet of Illinoian till. The till is fairly dense and usually yields less than 10 gallons per minute of water except in gravel seams which yields more. The till is underlain by as much as +200 feet of Pennsylvanian age rock which is stratified shales, limestones, sandstones and coal. These rocks also yield relatively small amounts of water. The deeper lying sandstones yield larger quantities but deep wells in the area are poor quality containing sulfides and other non-desirable dissolved minerals.

The community of Jacksonville was founded in and had a population of 446 in 1830. Community growth was fairly rapid and by 1870, the population had grown to 9,365. Jacksonville became an important railroad community with three lines. Since 1870 the community Jacksonville has grown to its present population of 20,284 (1980).

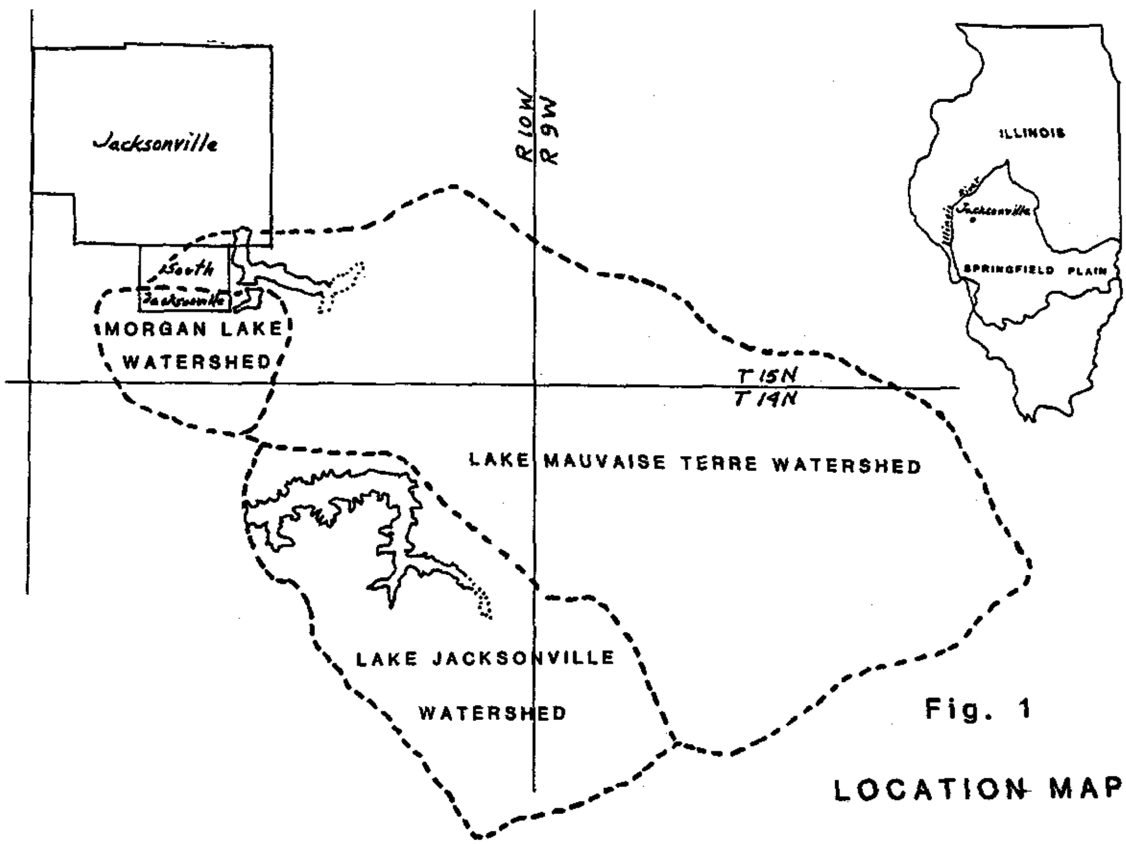

Fig. 1

LOCATION MAP

WATER SUPPLY DEVELOPMENT

Jacksonville's water needs prior to 1869 were probably met by the base flow in Mauvaise Terre Creek, the spring in what is now Nichols Park and hand dug wells, cisterns, and other small catchments.

The citizens of Jacksonville on June 15, 1869, voted the first bond issue for a waterworks in the amount of $150,000. Strong springs bubbled forth from the ground just southeast of the present pavilion and these springs were the main source of supply for the small pond which formed there. A dam was built across the northern outlet of the pond and Lake Morgan was formed with a capacity of 41,000,000 gallons. A clay tile line was laid to the pumping station, which was constructed about one mile north near the present water purification and pumping plant. Water was pumped from this station to a distribution reservoir of 2,500,000 gallons capacity on College Hill, at a height of 86 feet above the pumping station. This system was put into operation on January 20, 1875.

Four years later, 1879, was a season of drought from spring to autumn. In 1881 and again in 1887, a pump was installed in an abandoned coal shaft for temporary but expensive relief. The cities attempt to use wells for water supply included drilling an existing 1600 foot well to 2343 feet in 1885, the Decker well to 3100 feet in 1888, another well near the Decker well in 1890 and, in 1895 the American well to 3118 feet. The water from these wells was either inadequate or contained considerable hydrogen sulphide gas and mineral matter making it unfit for domestic use. By 1914 only one of these wells had minimal flow.

A small dam was constructed on Mauvaise Terre Creek in 1899 to augment the water supply when the yield of the wells became inadequate to meet the demand. In 1904 the Jacksonville Water Company obtained a franchise to supply the city with a suitable water supply, from 14 wells which were sunk to bedrock in the alluvial deposits of the Illinois River at a depth of 68 to 70 feet. This project was abandoned in 1912 because of burst lines, litigation and reorganization. By 1910 it was common to shut off the water supply to maintain fire protection. Five wells were made in the drift (unconsolidated material) in the lowlands of Mauvaise Terre Creek valley. This well field was subject to contamination due to the overflow of the polluted waters of Mauvaise Terre Creek.

In 1917 a cooperative study of the community's water supply was made by the State Board of Health, Geological Survey and the State Water Survey. In 1918, a consulting engineering firm recommended the construction of a reservoir on the south branch of Mauvaise Terre Creek. In 1921 the reservoir, Lake Mauvaise Terre was completed and just two years later a shortage in the reservoir required water to be pumped from the well field. In the next ten years, Lake Mauvaise Terre proved to be inadequate on many occasions. The city hired an engineering firm to investigate the various methods of providing an adequate water supply including dredging of Lake Mauvaise Terre. The construction of Lake Jacksonville was chosen to meet the water needs of the community. Lake Jacksonville, located on Sandy Creek 2 1/2 miles south of Lake Mauvaise Terre, was completed in 1939. Gravity pipe flow from this lake flows into the south branch of Mauvaise Terre Creek which flows into Lake Mauvaise Terre.

The three lakes, Lake Morgan, Mauvaise Terre and Jacksonville, provided an adequate water supply for the community until the drought period of 1952 and 1953, when another engineering report was initiated to evaluate methods to provide additional water supply. In 1959 a 13 foot diameter, 100 feet deep collector well was constructed along the Illinois River and a pump and pipe line was installed to deliver water to Jacksonville 19 miles to the east. In 1982 two additional gravel pack wells were installed near the collector well. The present daily use is 4 million gallons per day with 80 percent coming from the well field and only 20 percent from the three reservoirs.

RESERVOIR SEDIMENT SURVEYS

Through time and community growth, three reservoirs were constructed with the primary purpose of providing water to the community of Jacksonville, present population of 20,284 (1980). Recreation, aesthetic, fire protection, and biological enhancement are other community benefits from the construction of these three reservoirs. The following reservoir water capacity sediment surveys were conducted for these three lakes.

Morgan Lake	June 1952	August 1989	
Lake Jacksonville	June 1952		November 1986
Lake Mauvaise Terre	June 1952	June 1979	December 1989

The 1952 surveys were part of a cooperative study which was done for the following purposes: To develop for Illinois the relation of sediment yield to watershed characteristics, to determine the effect of conservation practices on reservoir sedimentation, and to establish the relation of reservoir sedimentation to reservoir and sediment characteristics.

The 1986 and 1989 surveys were conducted to determine the volume and weight of the sediment that had accumulated in the reservoirs, the rate of reservoir sedimentation, and the existing volume of water remaining in each reservoir.

Morgan Lake

Morgan Lake was constructed in 1875. A reservoir sediment survey of Morgan Lake was conducted by the Soil Conservation Service in August 1989. No record of sediment removal from the lake was found, but a city park employee related that some minor dredging was done about 1977 but no records of the amounts or location of the area dredged are known. Seven ranges were surveyed in the lake area and two ranges were surveyed in the area of areated sediment above the present lake level. Part of the original bottom was very firm and deeper than expected indicating that much of the area was excavated during construction and was probably used for fill for the dam. The calculated results of the survey in tables 1 and 2 show that at the time of the survey the annual sedimentation rate for the lake was 0.53 tons per watershed acre and the trap efficiency of the lake was approximately 60 percent.

Approximately 0.88 tons per watershed acre is transported to the lake each year. Of this about 0.35 tons per watershed acre passes through the lake on into Lake Mauvaise Terre.

Lake Mauvaise Terre

Lake Mauvaise Terre was constructed in 1921. An engineering report of the community water supply in 1931 studied the possibility of dredging Lake Mauvaise Terre to increase its capacity. The first reservoir sediment survey of the lake was conducted by the State Water Survey in June 1952. A second survey was also done by the State Water Survey in June 1979. The most recent survey of the lake was done by the Soil Conservation Service in

August and December 1989. This sediment survey included 43 acres above the present lake area that had filled with sediment and is presently overgrown with mature bottom land trees.

A total of 18 sediment ranges were surveyed for Lake Mauvaise Terre. This reservoir sediment water quality survey was done by probing and sounding the original bottom and present bottom at 50 foot intervals. Four water quality parameters were measured and recorded at 100 foot intervals along the ranges. Five submerged sediment samples were collected by hand sampling. The five areated sediment samples were collected by using a track mounted power probe.

The two previous reservoir sediment surveys made in 1952 and 1979 did not include surveying in upstream areas which has filled with sediment. This upstream area now has a very dense vegetation and numerous trees up to two feet in diameter. Root systems are well developed and may account for a small percentage of the sediment volume in this area. The calculated results of the survey are in tables 1 and 2. The sedimentation rate in Lake Mauvaise Terre at the time of this survey was calculated to be 1.04 tons per year from each watershed acre. The trap efficiency of the reservoir is about 65 percent. About 0.56 tons per acre per year passes through the lake into Mauvaise Terre Creek downstream of the lake.

RESULTS OF RESERVOIR SEDIMENT SURVEYS
For
JACKSONVILLE, ILLINOIS

TABLE 1

		Morgan Lake	Lake Mauvaise Terre	Lake Jacksonville	Comments
Date Storage Began		1875	1921	1939(use 40)	
Age to 1990		115	69	50	
Watershed Acres	w/lake	1760	20,750	6880	
	w/o lake	1745	20,596	6390	
Lake Surface Areas	Initial	18.2	245	469	
	1st Survey		188 (52)	477(52)	
	2nd Survey		169 (79)		
	Last Survey	15.0(89)	154(89)	490(86)	
	Projected to 1990	15.0	154	490	
Capacity Acre Feet	Initial	168	1,820	7058	
	1st Survey		1,015(52)	6879(52)	
	2nd Survey		628(79)		
	Last Survey	40	563(89)	6266(86)	
	Project 1990	39	554	6235	
Sediment Accum. Acre Feet	1st Survey		805(52)	184(52)	
	2nd Survey		1,192(79)		
	Last Survey	128	1,320(89)*	792* (87)	*1.25 Shore E./Yr.
	Project 1990	129	1,332	823	*75 AcFt Deposited above orig storage
Sediment Accum. Acre Ft.	Ave. An.	1.11	19.4	16.8	Last Survey
	An. %	0.66	1.05	0.23	Last Survey
	Years Remaining	33	30	378	Constant Sediment. Rate
Erosion Delivered T/Yr.	1st Survey		20,553	14,371	
	2nd Survey				
	Last Survey	980	21,349	23,665	*1,760 Shore E.
Erosion Deposited T/Ac/Yr	1st Survey	.61	1.04	1.9	
	2nd Survey				
	Last Survey	0.53	1.04	3.4	

Lake Jacksonville

The dam that created Lake Jacksonville reservoir was completed in 1939. The first reservoir sediment survey of the reservoir was conducted by the State Water Survey in June 1952. A second survey was conducted by the Soil Conservation Service in November 1986 after the lake had been drained and was in early stages of refilling. The calculated results of the 1986 survey in tables 1 and 2 show the annual sedimentation rate for the lake was 3.4 tons per watershed acre and the trap efficiency was 95 percent.

TABLE 2 SEDIMENT VOLUME = EROSION SOIL LOSS (Tons/Acre Feet) (Tons/Watershed Acre)

	MORGAN LAKE 1875-1990 (115) 1,746 Ac.					LAKE MAUVAISE TERRE 1921 -1990 (69) 20,569 Ac.					LAKE JACKSONVILLE 1939 (40)-1990 (50) 6,390 Ac.				
	#/cu'	Tons/ Ac Ft.	Ac.Ft./YR Sed.	Tons	Tons/ WS Ac.	#/cu'	Tons/ Ac.Ft.	Ac.Ft./Yr Sed.	Tons	Tons/ WS Ac.	#/cu'	Tons/ Ac.Ft.	Ac.Ft./Yr. Sed.	Tons	Tons/ WS Ac.
1952*	47.7	1039	1.02	1060	0.61	50.9	1109	19.5	21625	1.04	39.7	865	15.3	13263	1.9
1952**	41.2	897	1.02	915	0.52	48.2	1050	19.5	20471	0.99	32.5	718	15.3	10830	1.57
1979						48.5	1055	20.5	21628	1.05					
1986											66	1437	15.6	23665	3.4
1989	45.1	982	1.11	1090	0.62	53.0	1154	19.1	22048	1.06					

* From State Water Survey Report of Investigations 37, 1959

** From Interagency Committee on Water Resources Sedimentation Bulletin Number 6, 1957

Land Use and Erosion

Table 3 shows land use by acres and percent and gross watershed erosion by land use category. The 1959 figures shown on the table are from Stahl and Bartelli 1959 and were "computed by the method of Van Doren and Bartelli". The 1987 and 1989 erosion figures are based on USDA Universal Soil Loss Equation. These erosion figures are 2.4 to 3.5 times higher than 1959 gross sheet and rill erosion. The 1987 and 1989 figures include ephemeral erosion and all other forms of water erosion such as streambank, gully roadside and scour. The ephemeral gully and other water erosion amount to approximately 15 percent of the calculated 1987-89 sheet and rill erosion.

TABLE 3 RESERVOIR DRAINAGE AREA, LAND USE AND EROSION

		CROPLAND	GRASSLAND	WOODLAND	OTHER LAND* OTHER EROSION	TOTALS	TONS/AC EROSION*
MORGAN LAKE 1,760 Ac.	1959						1.9**
	1989	73%	13%	1%	13%	100%	
	Acres	1283	230	17	230	1760	
	Tons	11,082	230	17	549	11,878	6.7
LAKE MAUVAISE TERRE 20,750 Ac.	1959						3.4**
	1989	84%	6%	2%	8%	100%	
	Acres	17,474	1245	415	1616	20,750	
	Tons	152,161	6225	1660	11,829	171,875	8.3
LAKE JACKSONVILLE 6,880 Ac.	1959						2.4**
	1987	77%	3%	10%	10%	100%	
	Acres	5310	211	678	681	6880	
	Tons	43,607	422	2712	2764	49,505	7.2

*Includes water areas
** Sheet and Rill Erosion only

Summary

Jacksonville's three surface water reservoirs were built over a 65 year period from 1875 to 1940. Since Jacksonville was founded in 1830, droughts, reservoir sedimentation and increased demand have forced the community to increase the available water supply by increasing storage volumes and adding supplemental wells to supply the water needs. Sedimentation in the water supply reservoirs has restricted their use to about 20 percent of the community needs. At present, 80 percent of the water needs is from wells located in the Illinois River valley. The water from these wells is pumped 19 miles and 150 feet in elevation at a cost of $210,000 per year. Presently the main uses of the three lakes is for recreation, wildlife and asethetics. These uses are severely limited due to sedimentation.

Conclusion

Jacksonville's three water supply reservoirs provide an historical record of reservoir sedimentation. Table 4 shows the most significant factors that effect reservoir sedimentation. These are reservoir capacity, trap efficiency, sediment transport and weight of sediment. The comparison indicates that there are significant differences in sedimentation that are not readily explained. The age of the reservoir may be the most important item to explain these significant differences. Here are a few reasons that may help explain why age is an important factor.

1. Sediment consolidates with time and with increase in depth of burial.
2. Sediment fills and occupies the water area that was the settling medium for transported sediment.
3. The accumulations and decay rates of organic material, both transported with sediment and aquatic, change with time and burial.
4. Vegetation in the upstream area increases sediment volume by root growth expansion.
5. Vegetation consolidates sediment by removal of water, added weight, and vibration of the sediment by wind, against tall trees.
6. Sediment is taken up by vegetation mainly in large trees.
7. Water chemistry can change with time causing changes in sediment suspension and precipitation of sediment.
8. Biota such as bottom excavating carp and crawfish resuspend sediment.
9. Subtle or drastic changes in watershed runoff erosion and chemistry occur with time and affect reservoir sedimentation rates.

TABLE 4 SOME RESERVOIR COMPARISON FACTORS

	Watershed Size Ratio	Reservoir Age Ratio	Annual Capacity Loss %	Annual Surface Acres Loss	Annual sediment Deposited Ac. Ft.	Annual Sediment Deposition Tons/WS Ac.	Percent W.S. Size Orig. Storage Remaining	1990 W.S. Size vs Capacity W.S. in.	Av. Wt. Sediment #/Cu. Ft.
MORGAN LAKE	1.0 1760 Ac	1.0 115 Yrs	.66	0.03	1.11	0.53	24	0.27	45.1
LAKE MAUVAISE TERRE	11.8 20750 Ac	0.6 69 Yrs	1.05	1.32	19.1	1.06	27	0.32	53
LAKE JACKSONVILLE	3.9 6880 Ac.	0.43 50 Yrs	0.23	+0.42	16.8	3.5	88	10.8	66

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GEOMORPHIC DISTINCTIONS OF CHANNELS IN AGRICULTURAL WATERSHEDS

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ABSTRACT

Four types of channels are identified and compared in a commonly observable, geomorphic-based hierarchy applicable in agricultural watersheds. Of the four types, two are nonincised channels (rills and upland channels, the latter including "ephemeral gullies") and two are incised channels ("classic" gullies and entrenched channels).

A rill develops where sheet flow becomes concentrated sufficiently to exceed the channelization threshold. Rills occur on a slope, have long profiles parallel to it, and are completely obliterated by tillage practices. Although rills are generally the smallest channels in an agricultural drainage net, size is not a distinctive criterion for identifying rills.

An upland channel conveys ephemeral or intermittent flow and occupies a permanent location between topographically oppositional hillslopes above the valley floor. Rarely higher than fourth order, upland channels may exist in cropland, woodland, pasture, rangeland, hayland, farmsteads, and along roads and fences. An upland channel is most commonly a first-order channel existing where a grassed waterway is needed in cropland, and has been termed an "ephemeral gully" in this setting. Upland channels not in cropland may convey significant sediment from agricultural lands, but heretofore have not been widely considered.

A gully is an incised channel that has ephemeral or intermittent flow, a low width-depth ratio, steep banks, contains a headcut and commonly other knickpoints, and has been incised during a renewed cycle of degradation. It typically is eroded headward along a previously ungullied channelway or one with older gully-fill alluvium, although it may form in a previously unchanneled area.

An entrenched channel is a narrow, deep, and usually straightened valley-floor channel, usually of fourth order or greater, that is dominated by "classic" gully processes of mass wasting and knickpoint development and movement, has become incised during a renewed cycle of degradation, and conveys perennial flow.

INTRODUCTION

Four basic categories of channel erosion are generally recognized in agricultural watersheds (Figure 1). Two of these, 1) rill erosion, and 2) "classical" gully erosion, are basic types of sediment transfer on and

COMPARISON OF CHANNELS IN AGRICULTURAL WATERSHEDS
BASED ON OBSERVATIONS IN WESTERN IOWA

	NONINCISED CHANNELS		INCISED CHANNELS	
	RILL	UPLAND CHANNEL	GULLY	ENTRENCHED CHANNEL
LANDSCAPE LOCATION	SHOULDER, BACK, OR TOE SLOPE	SHOULDER, BACK, OR TOE SLOPE	ANYWHERE	VALLEY FLOOR
HIERARCHY IN NETWORK	SMALLER THAN FIRST ORDER	ALL FIRST ORDER CHANNELS; SOME SECOND AND THIRD ORDER CHANNELS	ANY ORDER DEPENDING ON SIZE AND STAGE	FOURTH ORDER OR HIGHER
PLAN VIEW AND PATTERN	PARALLEL, DENDRITIC, TRELLITIC, OR DISTRIBUTARY; STRAIGHT	ENDS ON TOE SLOPE, OR IS TRIBUTARY; STRAIGHT TO SINUOUS	CONTINUOUS OR DISCONTINUOUS; STRAIGHT TO SINUOUS	CONTINUOUS, SCALLOPED BANKS, LATERAL GULLIES & INCISED CHANNELS; USUALLY STRAIGHT
DRAINAGE AREA	POORLY DEFINED, DIFFERENT FOR DIFFERENT RUN-OFF EVENTS	CONSISTENTLY DEFINABLE BY DIFFERENT OBSERVERS AND AT ALL SCALES OF STUDY, INCLUDING USING TOPOGRAPHIC MAPS AND AIR PHOTOS. STAYS THE SAME FROM EVENT TO EVENT AND YEAR TO YEAR, PRACTICABLY		
RELATION TO HILLSLOPE	ON SLOPE	BETWEEN OPPOSITIONAL SLOPES	ON OR BETWEEN SLOPES	CUT IN VALLEY-FILL SEDIMENTS
LONG PROFILE	PARALLEL TO ADJACENT SLOPE PROFILE	DIFFERENT FROM ADJACENT SLOPE PROFILE	SAME OR DIFFERENT, NICKPOINTS	VARIES WITH STAGE OF EVOLUTION
GRADIENT	SAME AS ADJACENT SLOPE	LESS THAN ADJACENT SLOPE	USUALLY LESS THAN ADJACENT HILLSLOPE	SAME OR LESS THAN ADJACENT VALLEY FLOOR
CHANNEL SHAPE	LOW TO HIGH W/D RATIO	LOW TO HIGH W/D RATIO	LOW W/D RATIO, V-SHAPED	LOW W/D RATIO, PARAHEXAGONAL
FLOW TYPE	EPHEMERAL	EPHEMERAL TO INTERMITTENT	EPHEMERAL TO INTERMITTENT	PERENNIAL
DOMINANT PROCESS	NONCOHESIVE CHANNEL SCOUR	NONCOHESIVE & COHESIVE CHANNEL SCOUR & FILL	MASS WASTING; PLUNGE POOL SCOUR; DEGRADATION/AGGRADATION COUPLETS; ALTERNATE BAR DEVELOPMENT	
HYDRAULIC GEOMETRY	CHANNEL IS ADJUSTED TO RUNOFF EVENTS OCCURRING SINCE TILLAGE		HYDRAULIC GEOMETRY RELATIONS DO NOT APPLY; IN DISEQUILIBRIUM	
RELATION TO TILLAGE IF IN CROPLAND	OBLITERATED, BY TILLAGE, OCCUR IN VARIABLE LOCATIONS EACH YEAR	TILLED IN, BUT CHANNELS RECUR IN ESSENTIALLY SAME CHANNEL LOCATION	PREVENT TILLAGE, CANNOT BE CROSSED BY COMMON IMPLEMENTS	NOT CROSSABLE, MAY BE SLUMPING AND/OR LATERALLY ERODING, MAY HAVE PROMINENT LATERAL GULLIES AND PIPES
MOST COMMON SIZE	LESS THAN ONE SQUARE FOOT, LESS THAN FOUR INCHES DEEP	ONE SQUARE FOOT TO FOUR SQUARE FEET, LESS THAN TWO FEET DEEP	ANY SIZE	MORE THAN FOUR FEET DEEP AND EIGHT FEET WIDE
TYPICAL OCCURRENCE IN AGRICULTURAL WATERSHEDS	CROPLAND DIRT ROADS ROADCUTS WASTE PILES BADLANDS FEEDLOTS	WOODLANDS FARMSTEADS PASTURE FENCELINES HAYLAND RANGELAND CROPLAND (EPHEMERAL GULLIES)	CROPLAND HAYLAND PASTURE ROAD FENCELINE FIELD BORDER WATERWAY RANGELAND WOODLANDS	MISSOURI RIVER TRIBUTARIES IN IN WESTERN IOWA AND MISSOURI; MISSISSIPPI RIVER RIVER TRIBUTARIES IN WEST TENNESSEE

Figure 1

between farm fields that have been widely recognized, investigated, and quantified for many years (Bennet and Lowdermilk 1938; Wischmeier and Smith, 1978; Foster, 1982; Betts, 1990). A third type, erosion in initial upland channels, including those that have been termed "Ephemeral Cropland Gullies", or "Ephemeral Gullies" (here termed EG channels), has been emphasized in agricultural research only in the past decade (Mildner, 1983; Foster and Lane, 1983; Foster et. al., 1985, Thorne et. al., 1985; Laflen et. al., 1985; Foster, 1986; Watson et. al., 1986; Thomas and Welch, 1988; Merkel, Woodward, and Clarke, 1989). Erosion in still larger entrenched stream channels is a fourth type that presents significant problems in many regions of the U. S. and elsewhere (Daniels and Jordan, 1966; Schumm et. al., 1984).

It is now well known that estimates of both quantities of soil lost by upland channel erosion and the diminished values of soil-depleted areas adjacent to EG channels in farm fields are essential in the quantification of total soil erosion and related land damages. As a consequence of the relatively recent recognition and investigation by agricultural geologists and engineers of EG channels as distinct and important elements of agricultural watersheds, and because of parallel work by geomorphologists in nonagricultural settings as well, this geomorphic identification, distinction, and comparison of the four types of channels was attempted. The comparison is based chiefly on field observations and data of channel process and morphology in western Iowa and Colorado.

HIERARCHY OF CHANNELS

Rills

Rills are common, easily identified features on farm fields (Figures 1 and 2). The fundamental morphologic characteristics of rills are 1) they are the smallest channels that form on a slope; 2) their gradients are essentially the same as the adjacent slope; 3) their longitudinal profiles essentially parallel the slope profile; 4) they are readily obliterated by normal tillage operations in cropland; and 5) they do not necessarily occur in the same location every year. The two exclusive requisites for rill identification are that they occur on a slope rather than between opposing slopes, and they are completely obliterable by tillage.

Size is not an exclusive determining factor in rill identification. Rills may vary markedly in size, pattern, and location. They may be very small channels a few millimeters wide or deep, or they may be channels as large as a meter wide and many centimeters deep. Rills are rarely deeper than the effective tillage depth, which in western Iowa is usually on the order of three to seven inches and is usually less than the depth of deepest tillage by an implement. Rills may be parallel, or they may have dendritic, trellitic, or other tributary patterns (Schumm, Mosley, and Weaver, 1987). Rills may occur in isolation on a hillside. Generally only small plants will be obliterated by rill erosion--larger plants will intercept and divide the flow of water in rills. Large rills may be common on steep slopes or along tilled furrows between plant rows. Some rills may be significantly larger than small EG channels (Figures 3 & 4).

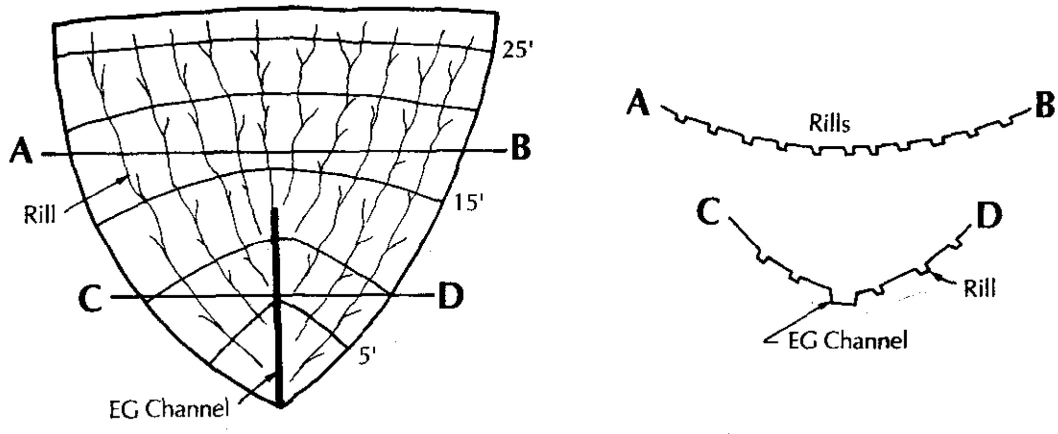

Figure 2. **Schematic map of a first-order basin in cropland illustrating the differences between rills and EG channels in plan and profile.**

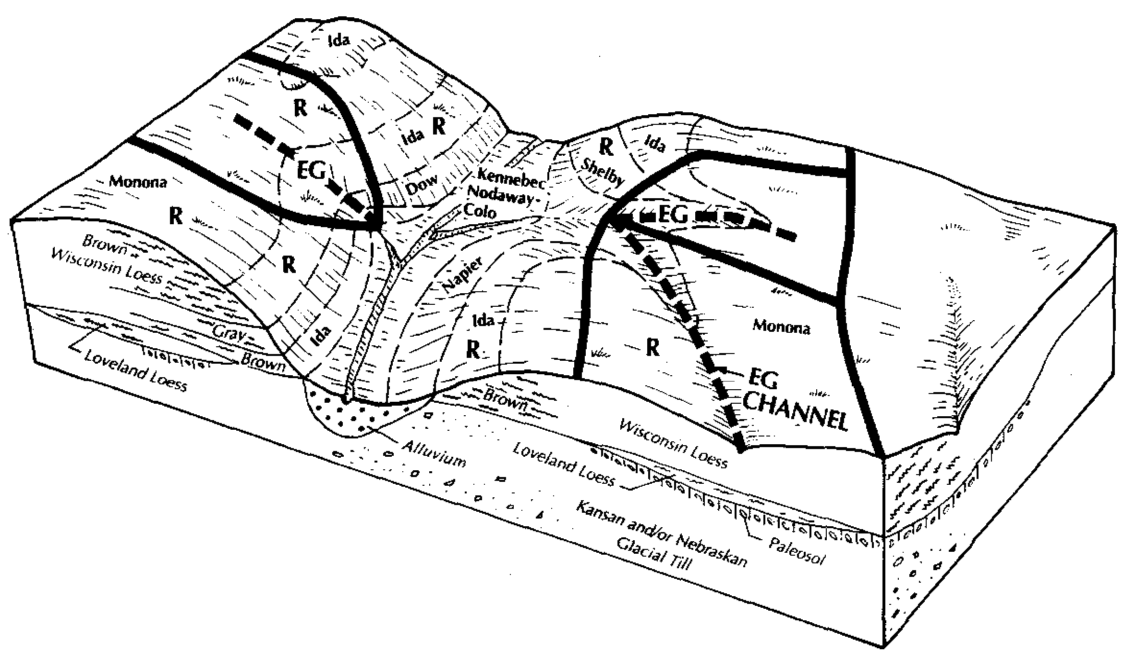

Figure 3. **Block diagram of relationships of typical EG channels and landscape position and soil type, based on observations in western Iowa.**

Upland Channels

An upland channel conveys ephemeral or intermittent flow and occupies a permanent location between topographically oppositional hillslopes above the valley floor (Figures 2, 3 and 4). Rarely higher than fourth order, upland channels may exist in woodland, pasture, hayland, rangeland, farmsteads, and along roads and fences, as well as in cropland. An upland channel is most commonly a first-order channel existing where a grassed waterway would usually be installed in cropland, and has been termed an "ephemeral gully" (EG channel) in this setting. Upland channels not in cropland may convey significant sediment from agricultural watersheds, but heretofore have not been included consistently in estimates of erosion.

Initial upland channels in cropland were first termed "ephemeral gullies" by Mildner (1983). These channels have long been recognized by hydrologists and geomorphologists as first-order channels, those smallest channels without tributaries that begin the drainage network in uplands (Horton, 1945; Strahler, 1964; see Gregory and Walling, 1973, for discussion and references) They also have been termed simply "waterways" or "concentrated flow channels" (Foster, 1982).

Unlike classic gullies, EG channels can be crossed with traditional farm implements but they are typically not obliterated completely by tillage each year. This is because the opposing slopes adjacent to an EG channel allow runoff to reestablish a channel in the same location each year. Consequently, EG channels are perennial channels, and because of their common location in the uplands of the drainage net, they normally convey ephemeral flow. EG channels typically become larger with each passing year because attempts to totally fill the eroded area by tillage are not usually successful.

To avoid confusing rills and EG channels in fields containing row crops that are cultivated, such as corn or soybeans, EG channels are recognized as erosionally developed channels that are larger than the tilled furrows between crop rows. This convention is used because the furrows will be sites of first concentrated flow, and they thus may be mistaken for parallel rills. Some furrow rows may be eroded to as much as two feet wide and a half a foot deep in western Iowa. Nevertheless, they are obliterated by tillage each year, and have the morphologic properties of rills.

Recognition of the above factors allows the consistent identification of EG channels in the field (Figures 3 and 4). EG channels will occupy first order channel locations downstream from rills, and will be recurring sites of concentrated flow. Slopes adjacent to the EG channels will have opposing gradients, and the profiles of the EG channels themselves will be characteristically concave upward and different from the profile of the adjacent hillside. EG channels commonly contain weeds that become established after the crop becomes eroded.

EG channels and other upland channels are readily identified in the field, but their locations and dimensions can be adequately quantified by other methods as well. They can be mapped on U.S.G.S. 7 1/2 minute topographic maps in western Iowa, because they coincide with the v-shaped contours representing first-order channels on hillsides. They also are demarcated by soil scientists on soil surveys, but their demarcation is not always consistent from one soil survey to another. We have found that the best method of identifying upland channel location, length, and drainage area is to use stereoscopic pairs of air photos, backed up by a field check. Work thus far indicates that EG channels in the loess hills area of western Iowa are typically 91% first-order channels, 7.5% second order, 1% third-order, and 0.5% fourth-order (paper in preparation).

Classical Gullies

Like rills, "classical" gullies have been recognized and investigated for many years (Bennett and Loudermilk, 1938; see Schumm et. al., 1984 for references). Gullies are incised channels (Figure 1) that are narrow, deep, steep-sided, contain knickpoints, and have been incised during a renewed cycle of incision, usually along a previously ungullied channelway or one with a an older stabilized or aggraded gully. Gullies are characterized by one or more headcuts or knickpoints (also termed overfalls or waterfalls), which are abrupt and prominent changes in elevation along the long profile of the channel. In practice, gullies in farm fields are defined as erosional channels that cannot be crossed with tractors or other normally used tillage equipment.

Gully erosion is cyclic and episodic (Antevs, 1952; Ireland and others, 1939; Peterson, 1950; Brice, 1966), and thus cannot be consistently and reproducibly predicted by measurements of distances of gully headcut recession averaged over time. Nevertheless, rates of gully headcut extension and size of headcut in general have been found to be proportional to drainage area, discharge magnitude, and discharge duration (Bradford and Piest, 1977; Beer and Johnson, 1963; Ireland et.al, 1939). In addition, the physical properties and stratification of the sediment being incised (usually alluvium, but also colluvium, loess, or any other cohesive, uncemented, unconsolidated sediment), and the influence of a high water table causing a gaining-flow gully (analagous to a gaining stream), are important factors in rate of headcut movement (Bradford and others, 1973).

Entrenched Channels

Entrenched channels are incised channels along valley floors, usually of fourth or higher order in the drainage network. They are dominated by processes of channel-bed scour, channel widening by mass wasting of steep banks and removal by large discharges, bends with locally heavy bank attack, formation of alternate bars along the thalweg, and major and minor knickpoint development and movement. They convey perennial flow and adjust rapidly to large runoff events. They are typically narrow, deep, and usually have resulted from the artificial straightening of an earlier channel on the valley floor.

In western Iowa, some entrenched channels experienced severe entrenchment after a simple furrow was plowed along the valley to provide drainage for flooding of a meandering channel on the valley floor. Many channels, however, were straightened by dredging, and have since incised from twenty to thirty feet into the valley alluvium (Daniels, 1960; Piest and others, 1977; Daniels and Jordan, 1966). Entrenched channels experience a complex evolutionary development, similar to large "classic" gullies (Piest et. al., 1976; Schumm et. al., 1984; Simon, 1989).

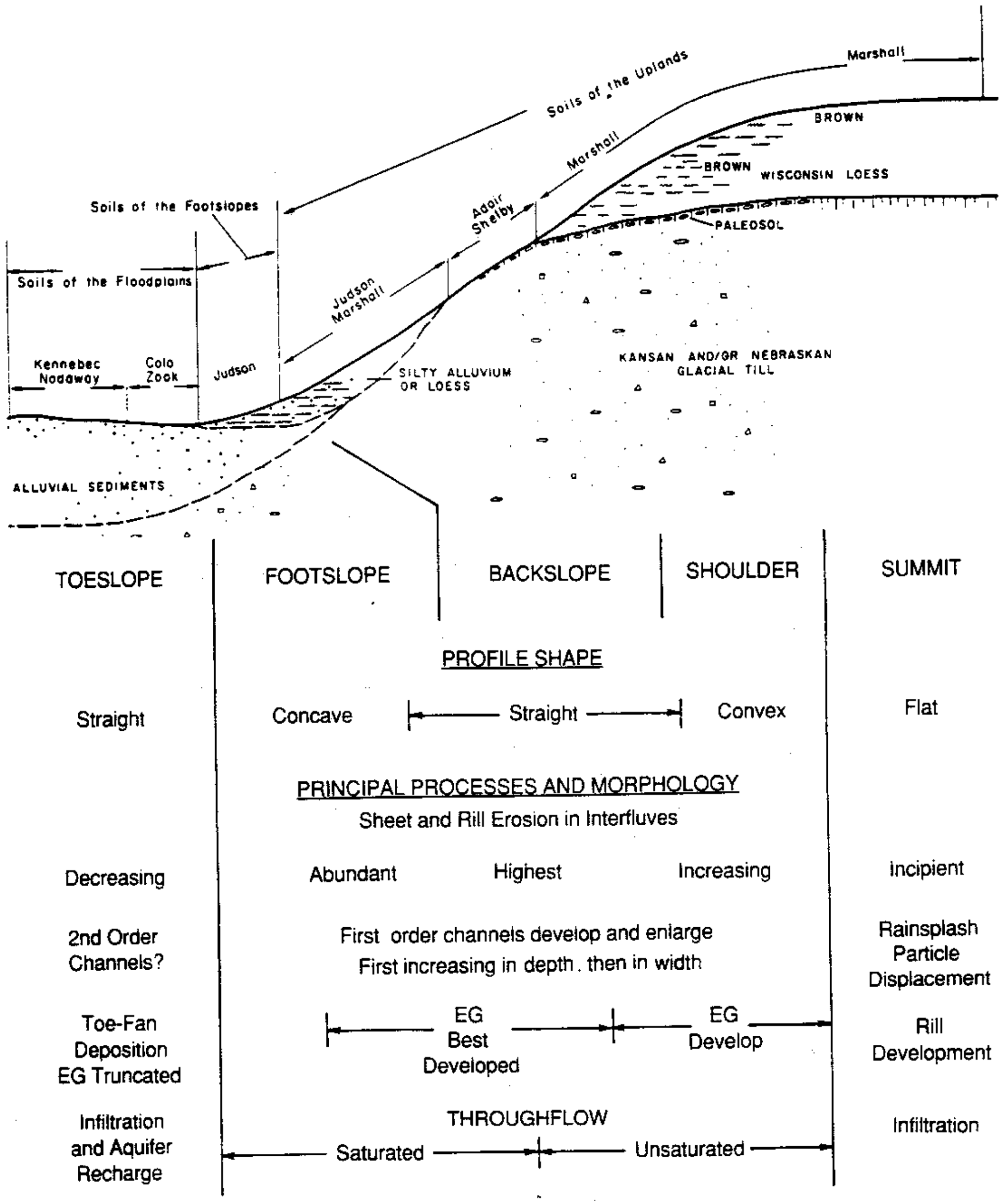

Figure 4. Cross-sectional diagram of relationships of form and process of EG channels in western Iowa and slope position and soils.

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STOP SEDIMENT ON THE WATERSHED, NOT IN THE STREAM

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ABSTRACT

Thirty years ago, the chaparral cover of a research watershed in central Arizona was destroyed by an intense wildfire. Today, the chaparral canopy has regained about 90% of its original density. At some locations, dense stands of chaparral grew; at others, bare ground remained. While in 1988 the average sediment delivery from bare areas amounted to 2324 kg ha^{-1} yr^{-1}, it was only 0.4 kg ha^{-1} yr^{-1} from chaparral buffer strips. In 1989, a drought year, the respective data were 21 and 0 kg ha^{-1}. In 1988, average overland flow from bare areas was 15 mm yr^{-1}, while practically no flow left the buffer strips. In contrast to the bare areas, the ground surface in five buffer strips was covered with litter and duff and was underlain by well-developed soil. Thus, high infiltration rates led to absorption of overland flow and sediment deposition in the strips. Large volumes of uncompacted sediment are stored at the buffer strips overlying coarse-grained, granite derived soils. This storage is easily transportable and would have a major negative impact if an intense wildfire, followed by storms, should strike again. Therefore, research and actions are required to prevent future intense wildfire in chaparral and to find means of protecting the buffer strips.

INTRODUCTION

Interrelationships between the watershed and its stream network are still poorly understood and much of the literature on the subject is based on inference. This paper rests on field research in both the watershed and stream system.

The primary objective of watershed management is to maintain their components intact to prevent sediment delivery into stream channels. But the problem becomes more complicated if the sediment is readily available on the watershed: how do you prevent it from entering the stream? On our research watershed, burned 30 years ago by an intense wildfire, chaparral canopy cover has recovered to 90% of the original. Yet sediment is still being produced on the watershed. Relatively large bare areas, interspersed among shrubs, have neither organic cover nor top soil, and generate overland flow and sediment.

In the stream network, immense volumes of sediment have been deposited by storms following the fire. Later storms were not sufficient to remove it, leaving the network in a very unstable condition.

Our research objective was to determine the routing of the sediment produced on the watershed, from the site of production to and through the channel network. This knowledge should serve as a guide for future management actions.

PAST WORK

By far, most research in chaparral ecosystems has been done in California. Sediment surface movement seems to be dominated by dry processes in the southern California steeplands (Wohlgemuth, 1985). This contrasts with Arizona chaparral, where rainfall is the main agent (Heede, 1989). Reports on the effects of wildfire in chaparral are numerous, but most are short-term studies (Heede et al., 1988).

Rowe (1948) demonstrated that repeated fires in southern California chaparral led to the formation of erosion pavements (matrices of different rock and pebble sizes on the ground surface) with high soil erosion rates as compared with the undisturbed floor under shrub cover. Rice (1974) suggested that, in fully vegetated chaparral, overland flow is a rare event. Wohlgemuth (1985) found in the San Gabriel Mountains of southern California that aspect and slope had no significant influence on sediment production. The annual sediment transport had a mean magnitude of 65 ± 57 cm^3 cm^{-1} yr^{-1}.

A detailed study of erosion processes by Brock and DeBano (1982) showed that overland flow increased manyfold when vegetation and litter were removed. They also demonstrated that litter cover is more important in controlling erosion (surface wash) than slope angle, because it increases infiltration and reduces overland flow. Indeed, relatively small increases in litter volume caused substantial increases in infiltration.

STUDY AREA

El Oso Creek watershed (drainage area, 2.5 km^2) is located in central Arizona on the east flank of the Mazatzal Mountains. Average elevation is 1100 m; bedrock geology consists predominantly of deeply weathered coarse-textured Precambrian granite. During the two study years, average annual precipitation was 414 mm, only 33% of which fell in summer. Extremely high summer temperatures (up to 43°C) reduced the effective precipitation substantially.

El Oso Creek is a fifth-order stream, about 5000 m long. Its overall gradient is 12.4%. Channel fills up to 25-m depth were determined seismographically, and the deposits were estimated at 2.5×10^6 m^3 (Laird, 1986).

METHODS

At different elevations and aspects, 10 hillslope segments or microwatersheds, representing topographic swales, were selected and surveyed. Five microwatersheds had only bare ground cover, while the other five had bare ground cover with a relatively dense strip of chaparral on their downhill border. Strip width ranged between 2.5 and 4.5 m. To prevent breaching of the swale boundaries by intense overland flows, sheet-metal strips were sunk into the ground. At the downhill side of the microwatersheds, 4-m-long runoff collector troughs caught and conveyed the water-sediment mixture into tanks for volumetric measurements. A precipitation network was installed.

RESULTS

Table 1 presents average annual overland flow and sediment delivery from the two types of microwatersheds. In evaluating this table, one must consider that 1989 was a drought year in Arizona. For example, in 1988 the average total annual sediment delivery from the microwatersheds with bare area amounted to 2324 kg ha^{-1} yr^{-1}, while in 1989 it was only 21 kg ha^{-1} yr^{-1}.

Table 1.--Annual overland flow and sediment delivery from the two vegetation cover types in a chaparral woodland, 1988 and 1989.

Subdrainage no.	Area ha	Average slope gradient %	Overland flow mm yr^{-1} 1988	Overland flow mm yr^{-1} 1989	Sediment delivery kg ha^{-1} yr^{-1} 1988	Sediment delivery kg ha^{-1} yr^{-1} 1989
			Bare areas			
1	0.01	39	3.3	0.2	863.34	2.02
3	.02	16	5.2	.3	2,973.89	9.96
4	.01	22	27.3	0	5,194.82	0
5	.06	35	37.0	2.2	2,470.23	94.32
10	.01	33	.7	0	38.39	0
Ave.			14.7	.5	2,324.37	21.26
			Areas with buffer strips			
7	.01	40	0	0	0	0
8	.01	35	0	0	0	0
9	.01	33	.3	0	2.18	0
17	.01	19	0	0	0	0
18	.21	64	0	0	0	0
Ave.			.1	0	.44	0

Comparison of the two-year averages of overland flow and sediment delivery for the two types of microwatersheds shows that buffer strips withheld all flows and practically all sediments. As repeatedly described in the literature, the organic ground cover available in the strips increased water infiltration and eliminated the vehicle for sediment transport. Infiltration was also enhanced by the sediment deposited at the buffer strips. Permeameter observations indicated that these deposits have high hydraulic conductivities, i.e., 12.20 mm h^{-1} compared with 6.72 mm h^{-1} for the bare areas (Heede et al., 1988). Insufficient numbers of replications did not allow statistical testing. The depositional process resulted in substantial accumulations of sediment at the uphill side of the strips, which reached depths up to 0.5 m.

Slope gradient influenced neither flow nor sediment. In 1988, a 39% slope produced 3 mm yr^{-1} of flow and 863 kg ha^{-1} yr^{-1} sediment, while a 16% slope had 5 mm yr^{-1} and 2974 kg ha^{-1} yr^{-1} of flow and sediment, respectively. Obviously, other variables play a role also.

Production of flow and sediment (Table 2) is much higher in summer than winter due to the high intensity summer storms that produce higher flow and sediment volumes.

The great variability of the data for sediment delivery between the individual subdrainages also suggests that factors other than those considered enter into the processes. This variability also existed between years which, due to the drought, was extreme during the two years of investigation. Absolute data, unless based on long-time records and expressed in error or probability terms, are therefore not useful. The importance of the study results lies in the fact that immense differences existed between sediment delivery from vegetation buffer strips and bare ground.

DISCUSSION AND CONCLUSION

Inspection of the chaparral buffer strips on the watershed indicated not one instance where a buffer strip was overrun by flow and sediment. It is probable of course that large storms would produce enough overland flow to overrun the buffer strips. In our arid conditions, storms are very scattered in time and space, and it is possible that sufficient time has elapsed since the occurrence of such a storm to allow eradication of all signs. Litter fall and duff development may have been the agents to hide the event.

Bare areas are distributed in a mosaic pattern on the watershed. Thus sediment transport, occurring by surface movement, takes place stepwise; continuous transport is rare. Even if sediment could move downslope toward the channel, most would finally be stopped by the continuous chaparral buffer strip lining the channels. Due to the greater soil moisture there, these strips are generally very dense.

Table 2.--Seasonal overland flow and sediment delivery from the two vegetation cover types in a chaparral woodland, 1988 and 1989.

Subdrainage no.	Overland flow mm season^{-1}				Sediment delivery kg ha^{-1} season^{-1}			
	Winter		Summer		Winter		Summer	
	1988	1989	1988	1989	1988	1989	1988	1989
				Bare area				
1	0	0	3.3	.2	0	0	863.34	2.02
3	2.2	.1	3.0	.2	203.42	2.00	2,770.47	7.96
4	16.0	0	11.3	0	401.75	0	4,793.07	0
5	8.9	.8	28.1	1.4	173.91	6.04	2,296.32	88.28
10	.2	0	.5	0	1.76	0	36.63	0
Ave.	5.5	.2	9.2	1.8	156.17	1.61	2,151.97	19.65
				Areas with buffer strips				
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	.3	0	0	0	2.18	0	0	0
17	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0
Ave.	.1	0	0	0	.44	0	0	0

A large volume of sediment is being stored by the many buffer strips on the watershed. Derived from coarse-grained granite that has weathered into small particles (diameter about 0.5 cm), the material is cohesionless and therefore would be easily transported again if the buffer strips were destroyed by a future intense wildfire. A subsequent storm could set vast masses of material into motion. Thus, a negative feedback mechanism exists and must be realized by management.

Large quantities of post-fire sediment are also being stored in the stream channel network itself because of a lack of major storm events. These deposits are still increasing in size, as evidenced by large and small in-channel fans. These are fed by steep-gradient tributary streams, most of them twice as steep as the main channel. Due to the sediment deposits, the new main channel is wide and shallow, creating flows of small depth with decreased competence for sediment transport. The loose, cohesionless deposits absorb great amounts of water, decreasing the chances for the occurrence of a channel-cleaning flow. Yet, if such a major flow should occur, a large portion of the 2.5 x 10^6 m^3 of material could be set into motion toward an important reservoir about 3 km downstream from the watershed. To prevent this, expensive channel control structures would be required. It would likely be much less costly to find and apply measures to protect the buffer strips and retain the sediment on the watershed if a wildfire strikes. For example, controlled burning, with the objective to prevent future "hot" fires, could be designed to leave existing buffer strips intact or create new ones. In short, we should learn to prevent damage in the first place, and eliminate the need for future "band-aid" corrective actions.

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CHANGES IN SEDIMENT STORAGE IN THE SOUTH FORK SALMON RIVER, IDAHO

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INTRODUCTION

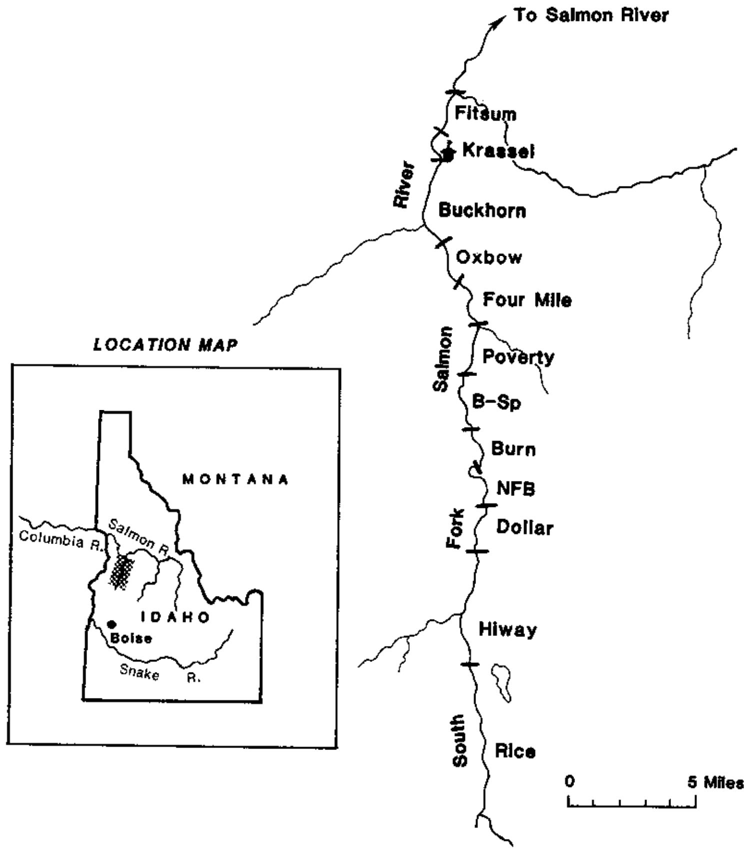
Protection of salmon and steelhead spawning and rearing areas from sedimentation is a critical concern in the South Fork of the Salmon River in Idaho. The headwaters of the river are situated in the Idaho Batholith, which is best characterized as a steep, granitic formation with shallow, coarse textured, highly erodible soils (Figure 1). Excessive sedimentation resulting from a combination of extensive logging and road construction, and wildfire buried much of the prime spawning and rearing habitat in the river following large storm events in the winter of 1964-65 (Seyedbagheri et al, 1987). A survey conducted in 1965 estimated that about 1.5 million cubic yards of sediment was stored in the upper 59 miles of the river and its tributaries, or about 7 times normal (Arnold and Lundeen 1968). The U.S. Forest Service responded by imposing a moratorium on logging activities and instituted a watershed rehabilitation program that included widespread road closure and stabilization. The Forest Service also developed a comprehensive program to monitor long-term river responses that included photo points, channel profile cross-sections, particle size distribution transects and channel bed core samples.

Channel profile changes documented a lowering of the bed elevation averaging 0.06 feet (1.8cm) from 1966 to 1971, and 0.036 feet (1.1cm) from 1973 to 1979 (Megahan et al 1980). Channel cross sections showed that the percentage of sands (< 4.75 mm size) on the streambed surface in spawning areas dropped an average of about 28 percent from 1966 to 1985. Core sampling beneath the surface of spawning areas over the same time period showed an average reduction in the percentage of sands of about 20 percent. Cross sections in rearing areas showed an average reduction in surface sands of about 15 percent between 1966 and 1978. The results of these time trend studies suggest that a change in the total volume of sediment storage was occurring as fines were moved out of the system. In order to evaluate this, the volume of sediment stored in the river was reassessed in 1989 to provide a comparison to the original sediment storage survey conducted in 1965 by Arnold and Lundeen (1968). The particle size distribution on the bed surface and the distribution of the finer sediment deposits by channel bedforms were characterized at the same time.

STUDY AREA

The study area drains a 397 square mile watershed in central Idaho, approximately 18 miles east of McCall and 20 miles northeast of Cascade, Idaho (Figure 1). The study reach encompasses 46 miles of the mainstem of the South Fork Salmon River from Rice Creek to the confluence with the East Fork of the South Fork Salmon River (Figure 1). Channel elevations within the study reach range from 5400 ft. to 3663 ft and gradients are less than 2 percent. The watershed is composed of steep, forested terrain with shallow, coarse-textured soils derived from the granitic rocks of the Idaho Batholith. The mean annual precipitation is 36 inches, most of which occurs in the winter as snow. It is not uncommon for rain to occur during snowmelt, and localized, high-intensity rainstorms of short duration are expected in the summer. The normal base flow discharge at the lower end of the study area is about 100-125 CFS, and the average annual peak flow at the same site is about 4000 CFS (Arnold and Lundeen 1968).

Figure 1. South Fork of the Salmon River



METHODS

Arnold and Lundeen divided their survey area into reaches ranging in length from 7,150 to 52,000 feet based on geographic landmarks (Table 1). Within these reaches, we further subdivided the channel into sections ranging from about 1,000 to 3,000 feet long based on gradient and uniformity of bed composition, with the help of large scale aerial photos. Each section was sampled with step-toe transects to provide an estimate of the average particle size distribution of the streambed surface. Large scale aerial photos were not available for the upper reach of the river so channel sections were based on access points and step-toe transects were placed at set intervals.

The sampling methodology closely followed the methods used in the 1965 sediment survey, with some modifications to accomodate the changed conditions in 1989. Lloyd Lundeen, the hydrologist who conducted the original survey, returned to the South Fork Salmon River for a week to demonstrate the techniques used in 1965 to estimate the volume of sediment storage in the river. Mr. Lundeen indicated that in 1965, the recently introduced sediment were easily identified by their color and the proponderance of sands. Storage estimates were made by probing, digging, and resurveying channel profile cross-sections where they existed, and included considerable ocular estimates of the volume of sediment storage in bars based on bar width and length and differences in bed elevations of the bar surface and the streambed. Mr. Lundeen felt that there were probably a few cases where sediment deposits above the bankfull level were included in the survey. Estimates of the particle size composition of sediment deposits were based on size classes of 0.1-2.0mm, 2.1-51mm, 51.1-152mm, 152.1mm-61cm.

Table 1. Sand and Gravel in South Fork Salmon River

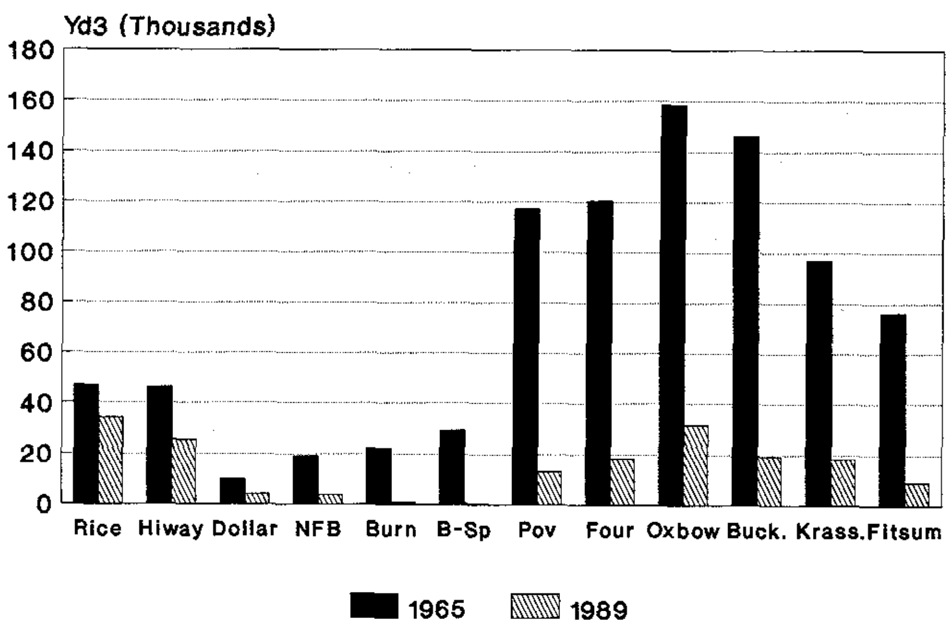
			SEDIMENT SIZE				
			0-2.0 mm		2.1-51.0 mm		Change
REACH	LENGTH (feet)	DRAINAGE ($mile^2$)	1965 (yd^3)	1989 (yd^3)	1965 (yd^3)	1989 (yd^3)	0-51 mm (%)
Rice	52,000	77.6	34,369	22,105	12,595	12,167	-27
Hiway	33,700	65.5	30,973	17,786	15,082	7,897	-44
Dollar	15,350	138.8	6,227	2,398	3,597	1,582	-59
NFB	14,700	163.8	12,598	1,812	6,550	1,793	-81
Burn	10,500	175.9	15,072	321	7,194	270	-97
B-SP	16,900	180.5	21,348	173	7,944	146	-99
Pov.	13,300	203.3	87,755	9,471	29,448	3,656	-89
Four.	22,200	208.5	77,750	13,833	42,759	4,322	-85
Oxbow	10,250	246.4	116,565	11,209	42,028	20,370	-80
Buck	31,050	268.3	87,012	12,246	59,342	7,344	-87
Krass.	7,150	325.2	71,370	10,212	25,692	8,177	-81
Fitsum	15,350	330.8	52,552	3,829	23,681	5,200	-88
TOTAL			613,591	105,395	190,394	72,924	-78

Because of changes in the appearances of sediment deposits since 1965 and in order to avoid much of the subjectivity used in the original survey, we chose to define the study methodologies and boundaries more objectively. A series of three to six step-toe transects were sampled in each of the channel sections. Transect sites were chosen to provide a representative sample of the sediment storage. Surface particle size and sediment depth were recorded at the technician's toe at paced intervals of 5 feet across the channel. A total of 70 to 100 samples of sediment particle size and depth was collected in each channel section. Channel width was defined as the bankfull width, and the depth of deposition was determined with a stainless steel probe equipped with a 10 pound slide hammer. "Bottom" of a deposit was defined as bedrock or the depth at which the strength of the sediment resisted further penetration from 3 free drops of the slide hammer. Surface particle size was recorded in size classes of 0-2.0 mm, 2.1-6.0 mm, 6.1-51.0 mm, 51.1-152.0 mm, 152.1-254.0 mm, and > 254.0 mm. Preliminary tests with the probe showed that penetration provided a good index of the sand sediment sizes (<6.0 mm). The channel bedform such as point bar, rock eddy, bank, etc. at the sample point was also recorded. Unusual features that were not adequately represented by transects, such as large sand bars, were individually sampled and mapped and the sediment storage calculated independently from the transects. Volume of sediment storage in each channel section was calculated using the average deposit depth of the individual sample sites. Particle size of the deposits was based on the average percentage of the size classes of the surface sediments.

RESULTS and DISCUSSION

The results presented here focus on the amount of sand and gravel (sizes 0mm-51mm) stored in the river system because this size range has the greatest impact on salmon spawning habitat and is the most mobile. Table 1 summaries the channel storage of sand and gravel in 1965 and 1989, and the changes in the volume of storage. Limiting measurements of sediment storage to that below the bankfull level in 1989 may account for some of the reduction in channel sediment storage. However, it is clear that a large volume of sediment moved out of the study area in the 24 year span between the surveys (Figure 2). Overall, there was a 78% reduction in the volume of channel storage. The relatively small reduction in sand/gravel size sediment in the upper reaches (Rice, Hiway, and Dollar) may be due to additional sedimentation caused by high intensity storm floods in the early 1980's, and smaller flows and stream power than in the lower reaches. The large volume of sediment in Poverty in 1965 reflects tremendous sediment loads from the Burn reach, located upstream of Poverty (Figure 1) (Arnold and Lundeen 1968).

Figure 2. Sand and Gravel (0mm-51mm)



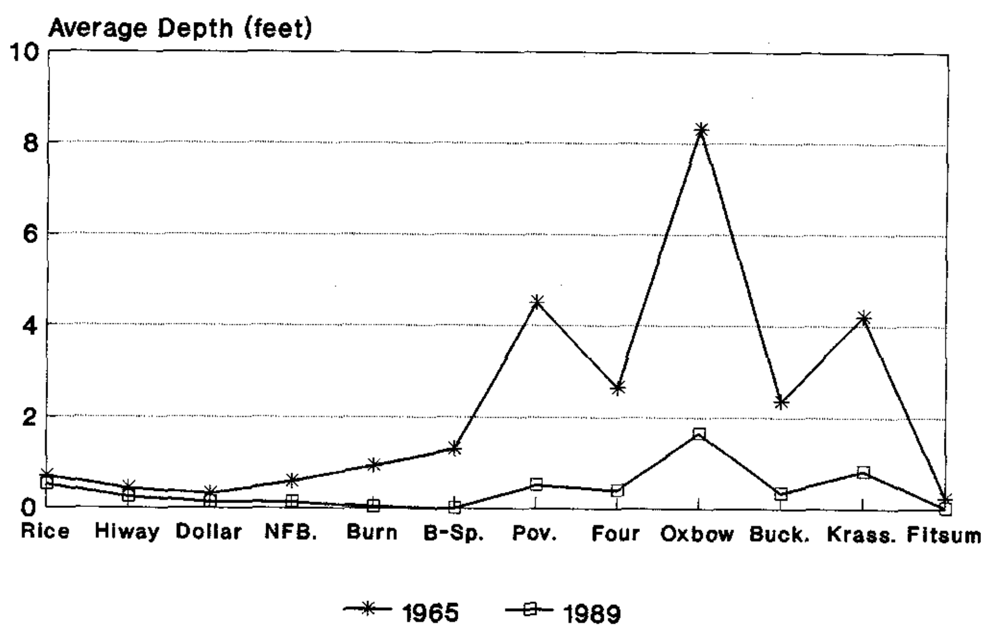
The flows required to transport this volume of sediment out of the study area in 24 years were not extraordinary. Annual discharge for the South Fork Salmon River at Krassel in 1965 is estimated at 272,200 cfs-days. Discharge exceeded the 1965 level in 1971, 1974, and again in 1982, presumably providing the stream power needed to transport stored sediment (Williams and Megahan). Maximum daily flows with estimated return frequencies of 5 or 10 years occurred 3 times between 1967 and 1986 (Table 2). The fact that the stream bed elevations lowered between 1965 and 1979 (Megahan et al 1980), and that this study found smaller volumes of sand and gravel storage suggest that stream power has been sufficient to transport sediment out of the study area at a greater rate than new sediment has been supplied. This suggests that the sources of sediment have been stabilized to some degree since 1965.

Table 2. Annual and Daily Discharge for South Fork Salmon River at Krassel Ranger Station, Idaho

Water Year	Annual Discharge (cfs-days)	Daily Discharge (cfs-day)	Return Frequency (years)
1965*	272,200	----	----
1966*	131,300	----	----
1967	197,100	3510	1.25
1968	156,400	2360	1.05
1969	222,700	3550	1.25
1970	215,800	4380	2.00
1971	300,500	4670	5.00
1972	232,600	5230	5.00
1973	125,400	2250	1.05
1974	355,400	6200	10.0
1975	189,100	3380	1.25
1976	227,900	3220	1.25
1977	65,600	687	<1.05
1978	233,700	3290	1.25
1979	121,300	2490	1.05
1980	206,200	3310	1.25
1981	197,500	3200	1.25
1982	297,400	4560	2.00
1983*	229,400	----	----
1984*	223,200	----	----
1985*	138,500	2400	1.05
1986	229,600	5350	5.00

*estimated from Johnson Creek data

Figure 3. Average Depth of Sand and Gravel

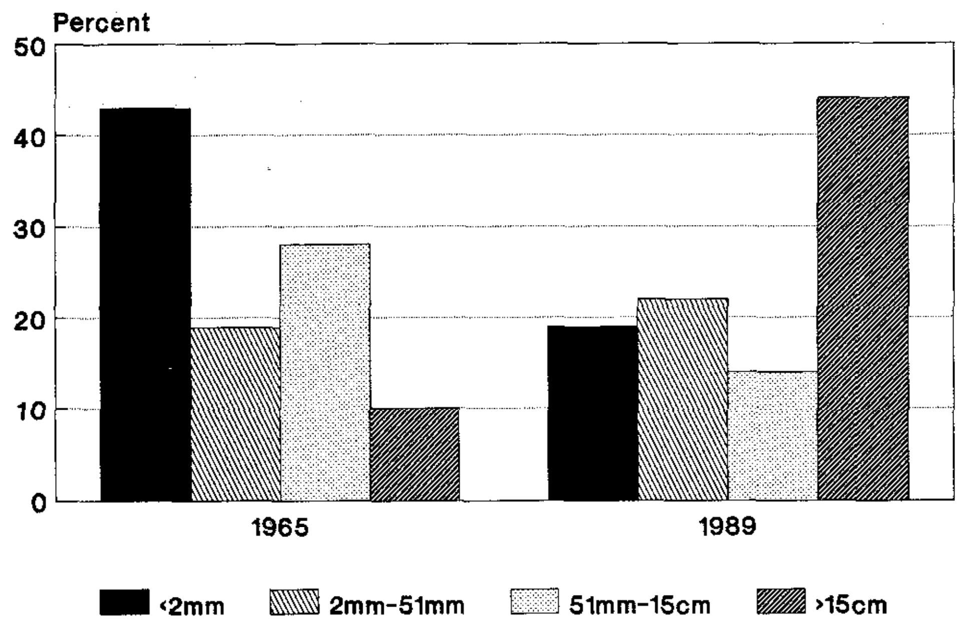


The average depth of sand and gravel deposition across an entire reach may be a more useful index than total sediment volume. The average sand and gravel deposition was deeper in the lower river reaches; in both 1965 and 1989, the greatest depth was recorded in the Oxbow reach which includes a river oxbow rich in sand (Figure 3). The Poverty (Pov.) reach includes the prime salmon and steelhead spawning habitat in the upper part of the South Fork Salmon

River; the high concentration of sand and gravel in this reach in 1965 created concern for the survival of the fisheries. By 1989, the average depth of sand in this area was greatly reduced.

The particle size distribution on the surface of the stream bed has also shifted since 1965. The 1989 survey indicated that the <2mm fraction has decreased relative to the other sizes while the >51mm fraction has increased. The average particle size distribution for all river reaches shows the largest percent of sediment in 1965 was <2mm, and the smallest percent of sediment was >15cm. In 1989, the fraction >15cm was the most abundant while that of <2mm ranked 3rd of the 4 groups (Figure 4). These results support the trends in particle size distribution reported by Megahan et al (1980) and suggest a loss of finer sediment and an uncovering of the larger material. For example, in the Poverty Reach in 1965, the greatest percent of surface material was <2mm, but in 1989 material >15cm dominated the surface.

Figure 4. Average Particle Size Distribution



CONCLUSION

A large volume of sediment was deposited in the upper 60 miles of the South Fork Salmon River in 1965. A survey of the sediment storage in 1989 demonstrated that large amounts of material, primarily sands, have been transported out of the study area in the ensuing 24 years. Although the amount of lost material may have been slightly overestimated because the original survey probably included material above the bankfull level, as much as 78% of the sand and gravel appears to have moved out of the study area since 1965. The particle size distribution of the stream bed describes a shift toward larger particles since 1965. The decrease in the amount of stored sediment suggests that the sources of sediment have stabilized to some degree, and that stream power has been sufficient to transport sediment out of the study area at a greater rate than new sediment has been supplied.

ACKNOWLEDGEMENTS

The authors wish to thank Lloyd Lundeen for his valuable assistance with the methodology and Heidi Thompson for her tenacious assistance with data collection.

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GREATLY IMPROVING STREAM SEDIMENT YIELD ESTIMATES

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ABSTRACT

Quantitative estimates of stream sediment yields have usually been made from stream sediment measurements by using empirical relations. The relation between sediment load (S) and discharge (Q) in a stream is defined by a sediment rating curve $\hat{S} = aQ^b$, in which a and b are determined from the regression equation $\log S_i = \log a + b \log Q_i$, where $\hat{S}$ is the estimated sediment load and S_i is the observed sediment load for Q_i. The sum of the residuals $(\log S_i - \log \hat{S}_i)$ is zero, but the sum of $(S_i - \hat{S}_i)$ is always non-negative, leading to considerable underestimation of the annual sediment yield. Studies indicate that the conventional use of the sediment rating curve developed from logarithmic regression can lead to underestimation of the annual sediment yield by 20 to 50%. Estimating parameters a and b by using nonlinear regression greatly reduces such bias. Other factors which lead to incorrect estimation of sediment yields are seasonality, sharp bends in sediment rating curves, use of average daily flows, and high ratio of peak to average flows in small drainage basins. Underestimation caused by these different factors is illustrated by analyzing historical data for a number of watersheds in the Midwest. Some remedies are identified for greatly improving stream sediment yield estimates by reducing biases and errors caused by various factors.

INTRODUCTION

Accurate and reliable estimates of stream sediment yields are needed for optimal design and operation of reservoirs, for identification of future environmental problems associated with reservoir sedimentation, and for optimal management of navigable streams, rivers, and waterways. The sediment yield from a drainage basin depends on the temporal and spatial distribution of precipitation, soil properties, land use, stream geometry and slopes, and geomorphologic properties of the basin. Because of complex interrelationships which are not well understood, it has not been possible so far to combine these and other relevant parameters into a single sediment yield equation. As a result, the stream sediment yield is usually estimated by developing empirical sediment rating curves from records of measured stream discharges and sediment concentrations, and then using them with the flow duration curves or the historical flow record over a long period of years to determine average annual sediment yields. The most commonly used equation for a sediment rating curve is

$$\hat{S} = aQ^b, \text{ or } \log \hat{S} = \log a + b \log Q \qquad (1)$$

in which $\hat{S}$ is the predicted sediment load, Q is streamflow, and a and b are a constant and an exponent, respectively, which are conventionally estimated from least squares regression analysis on logarithms of measured S and Q values. Although $\Sigma(\log S_i - \log \hat{S}_i) = 0$, $\Sigma(S - \hat{S})$ is always non-negative (it is zero if the correlation coefficient is 1.0). This leads to substantial underestimation of sediment yield. The least squares regression minimizes $\Sigma(\log S_i - \log \hat{S}_i)^2$ but not $\Sigma(S_i - \hat{S}_i)^2$.

The sum of squares of residuals, SSR, is given by

$$SSR = \sum_{i=1}^{N} (\log S_i - \log \hat{S}_i)^2 \quad (2)$$

in which N is the number of observations or measurements. The mean square error, MSE, is defined as

$$MSE = \frac{1}{N-2} SSR \quad (3)$$

Ferguson (1986) used a bias factor, which varies with the MSE, for correcting the value of a, but the exponent b was not modified. The corrected value of a (a') is given as

$$a' = a \exp [2.65 \text{ MSE}] \quad (4)$$

The adjustment factor is obtained from the following equation:

$$\log S_i = \log \hat{S}_i + \varepsilon_i = \log a + b \log Q_i + \varepsilon_i \quad (5)$$

$$\text{Variance } (\varepsilon) = MSE \quad (6)$$

The model then becomes

$$S_i = a\, Q_i^{b}\, \eta_i; \text{ where } \eta_i = 10^{\varepsilon_i} \quad (7)$$

$$E(\eta_i) = \exp\, [MSE(\ln 10)^2/2] \quad (8)$$

$$S = a\, Q^b \exp\, (2.65 \text{ MSE}) \quad (9)$$

Values of S compiled from equation 9 are always greater than those obtained from equation 1, because MSE > 0. Bias is unity if MSE = 0 (perfect fit).

An alternative approach would be to evaluate parameters a and b by nonlinear least squares regression on S and Q. Then,

$$S_i = \hat{S}_i + e_i = \alpha\, Q_i^{\beta} + e_i \quad (10)$$

in which e is the error of the nonlinear prediction model. Unbiased estimates of α and β are obtained with expected values of e being zero and Σe_i^2 being minimum (Singh et al., 1986).

SEDIMENT RATING CURVES AND YIELDS

The expressions for the sediment rating curves and average annual stream sediment yields are developed here for three basins by using the conventional or log-transformed regression (LTR), with Ferguson's adjustment of parameter a (FRG) and nonlinear regression (NR). The three streams and basins used as examples are: Elkhorn Creek near Frankfort, Kentucky, with drainage area 1,225 sq km, mean flow 17.53 m^3/s, and number of observations (N) = 35; Salamonie River near Warren, Indiana, with drainage area 1,100 sq km, mean flow 10.76 m^3/s, and N = 118; and South Hogan Creek near Dillsboro, Indiana, with drainage area 98.0 sq km, mean flow 1.21 m^3/s, and N = 88.

The results of the analyses, including the parameter values, average annual stream sediment load L, and sum of squares of residuals of sediment loads (SSR'), are given in Table 1, as obtained with the three methods. Data points and regression curves for LTR, FRG, and NR are shown in Figure 1.

Table 1. Comparison of Results with the Three Methods

Stream	Method	Parameters		L	SSR'
Salamonie R.	Log-transform (LTR)	a=3.60	b=1.28	42,460	7.27×10^7
N=118	Ferguson's (FRG)	a'=5.27	b=1.28	62,200	3.90×10^7
MSE=0.144	Nonlinear (NR)	α=2.01	β=1.57	80,880	1.13×10^7
S. Hogan Cr.	Log-transform (LTR)	a=4.21	b=1.16	2,600	3.36×10^5
N=88	Ferguson's (FRG)	a'=6.77	b=1.16	4,200	2.14×10^5
MSE=0.179	Nonlinear (NR)	α=4.79	β=1.57	8,200	2.18×10^4
Elkhorn Cr.	Log-transform (LTR)	a=0.38	b=1.61	34,500	3.38×10^7
N=35	Ferguson's (FRG)	a'=0.52	b=1.61	46,800	1.53×10^7
MSE=0.115	Nonlinear (NR)	α=0.17	β=1.90	60,780	5.60×10^5

The SSR' and L values are obtained from:

$$SSR' = \sum_{i=1}^{N} (S_i-\hat{S}_i)^2 \qquad (11)$$

$$L = 365 \sum_{i=1}^{m} \overline{S}_i \ (\Delta P)_i \quad \text{in tons/yr} \qquad (12)$$

In equation 12, m is the number of probability bands, $(\Delta P)_i$ is the width of the i-th band, and $\overline{S}_i$ is the arithmetic average of $\hat{S}$ values for the beginning and end discharges of the i-th band or time interval. Typical values of ΔP range from 0.001 - 0.003 for high flows, to 0.02 - 0.1 for low flows. About 75% of the annual load is carried by flows equaled or exceeded only about 10% of the time.

The SSR' values obtained with the NR method were reduced to 1.7%, 6.5%, and 15.5% of the SSR' values obtained with the LTR method for Elkhorn Creek, S. Hogan Creek, and Salamonie River, respectively. These are significant improvements. A lower SSR' value usually indicates a better fitting of the rating curve to the data. Generally, the improvements increase with an increase in value of parameter b. The annual sediment yields obtained with the conventional LTR method are only 32% (for S. Hogan Creek), 52% (for Salamonie River), and 57% (for Elkhorn Creek) of those obtained with the nonlinear regression -- serious underestimations indeed!

SEASONAL VARIABILITY AND SEDIMENT LOADS

Sediment load and stream discharge relations for various seasons tend to differ considerably because of seasonal patterns of precipitation, land cover, and land use. In the Midwest, for example, the sediment loads for the months of April to June are usually higher than for the period July to March, for similar discharges. The runoff in the latter season, which is generally from low-intensity rainfall over land covered with well-established crops, from rainfall on basin soils deficient in soil moisture, or

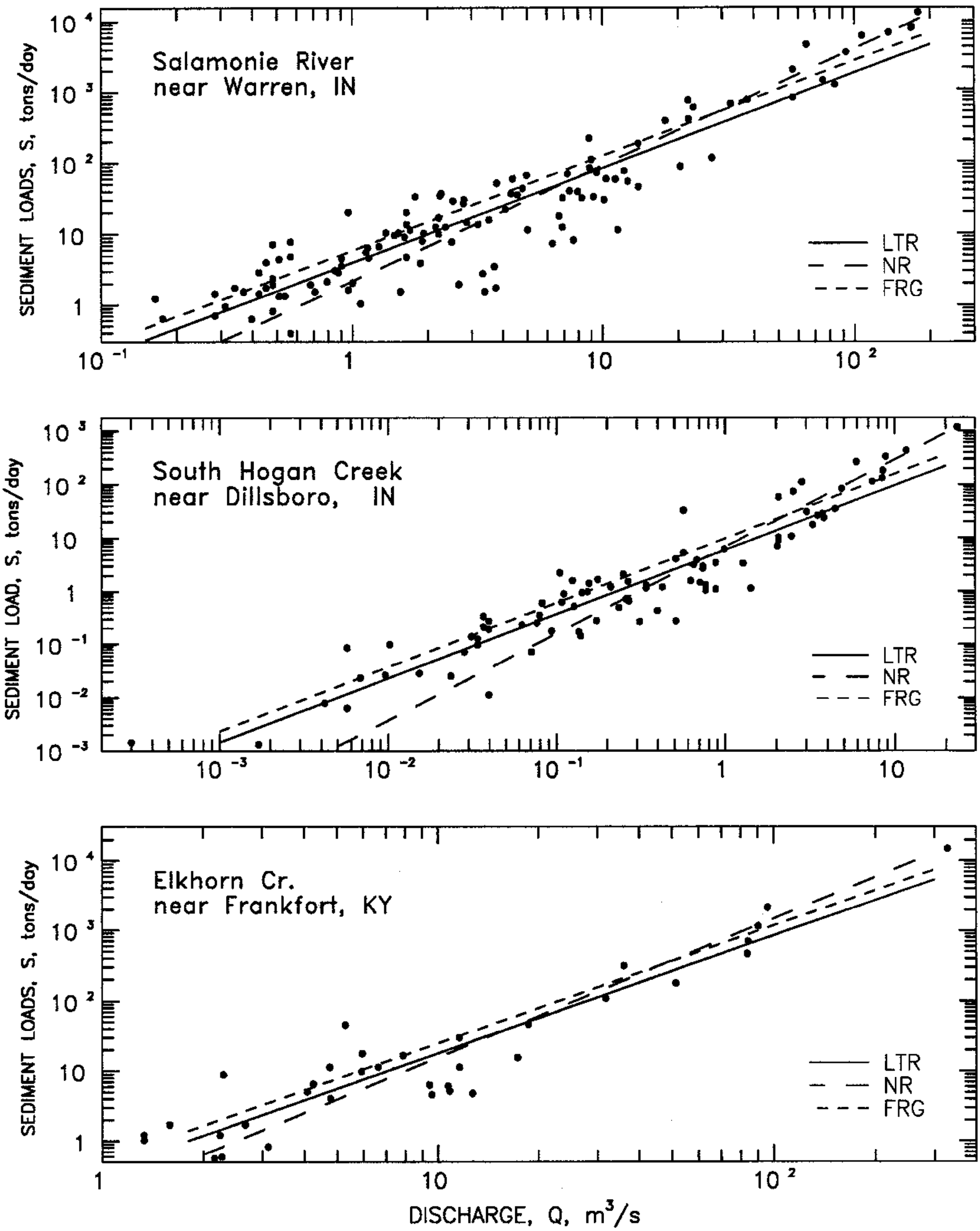


Figure 1. Streamflow Versus sediment load data and regressions

from snowmelt, causes considerably less erosion and low sediment concentrations. During the April-June period, the ground is usually disturbed as a result of agricultural activities, and the runoff is caused by precipitation in the form of intense storms over rather saturated soils, leading to higher erosion and sediment concentrations. Seasonality of sediment rating curves and loads is shown in Figure 2 for East Nishnabotna River at Red Oak, Iowa, which drains an area of 2,315 sq km.

If seasonal variation is evident, then sediment loads should be determined for each season. Seasonality of sediment transport may also be indicated if the MSE of the regression is high. The most practical solution to this problem will be to separate the data into seasons, develop seasonal flow duration and sediment rating curves, and combine seasonal loads to arrive at the annual load (Singh and Durgunoğlu, 1989).

PRONOUNCED BREAKS IN RATING CURVES

High values of MSE or mean square error of regression do not necessarily imply seasonality. The plot of S versus Q data for Rapid Creek near Iowa City, Iowa, in Figure 3 clearly indicates an obvious break or steepening of the rating curve for discharges exceeding 4 m^3/s, and a flattening for discharges below 0.02 m^3/s. This mixed behavior is difficult to estimate by using the conventional regression method because the points of inflection or break are not known *a priori*. In the example shown, the sediment load will be underestimated at the lower and higher ends of the flow spectrum. Underestimation at the higher end is especially important because this portion contributes a very substantial portion of the total sediment load. The condition can be mitigated by fitting two regression lines to the data (intersecting at the point of inflection), by iterative optimization, or by developing a nonlinear rating curve of the form $S = \alpha Q^{(\beta+\gamma Q)}$. The parameters α, β, and γ may be estimated by using a suitable nonlinear programming algorithm.

AVERAGE DAILY FLOW

Usually the average annual sediment load is determined by integrating the sediment loads corresponding to the flows represented by the flow duration curve, or by averaging annual sediment loads compiled for a long period of historical daily flow record. The flow duration curve is also based on average daily flows reported by the U.S. Geological Survey. The average daily flow, Q_{av}, is obtained from

$$Q_{av} = \int_{t=0}^{1} Q \, dt \tag{13}$$

in which dt is a small fraction of a day. The daily sediment load L computed from instantaneous or short-interval flows, Q, is given by

$$L = \int_{t=0}^{1} S \, dt = \int_{t=0}^{1} a \, Q^b \, dt \tag{14}$$

in contrast to that calculated from Q_{av}, or

$$L' = a \, Q_{av}^{\,b} \tag{15}$$

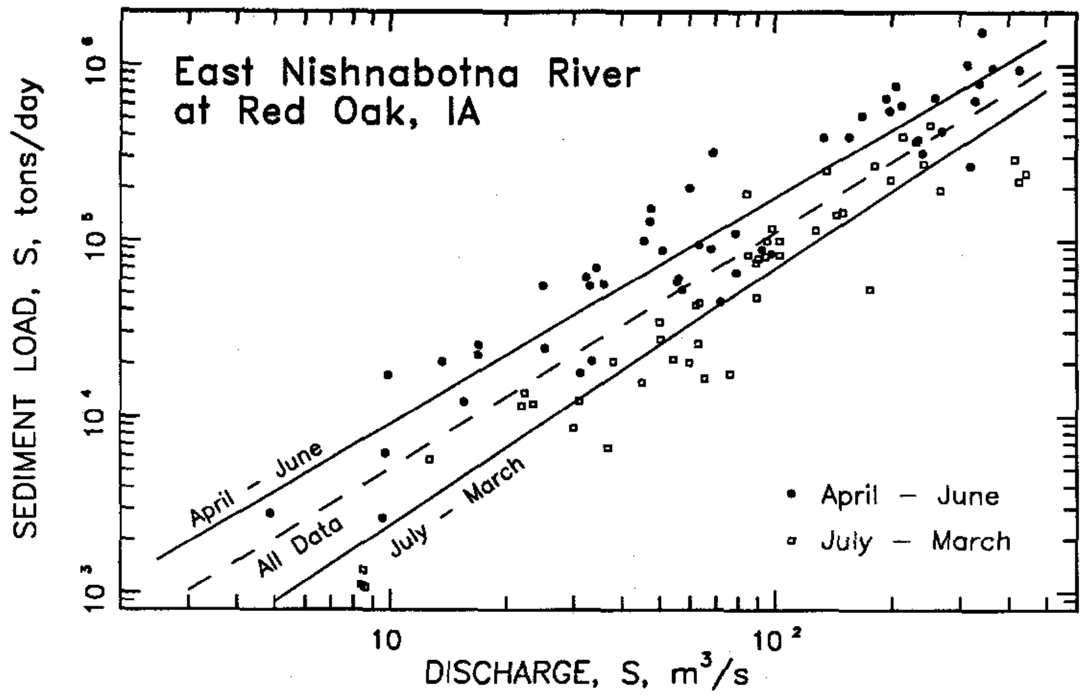


Figure 2. Seasonal streamflow versus sediment load curves

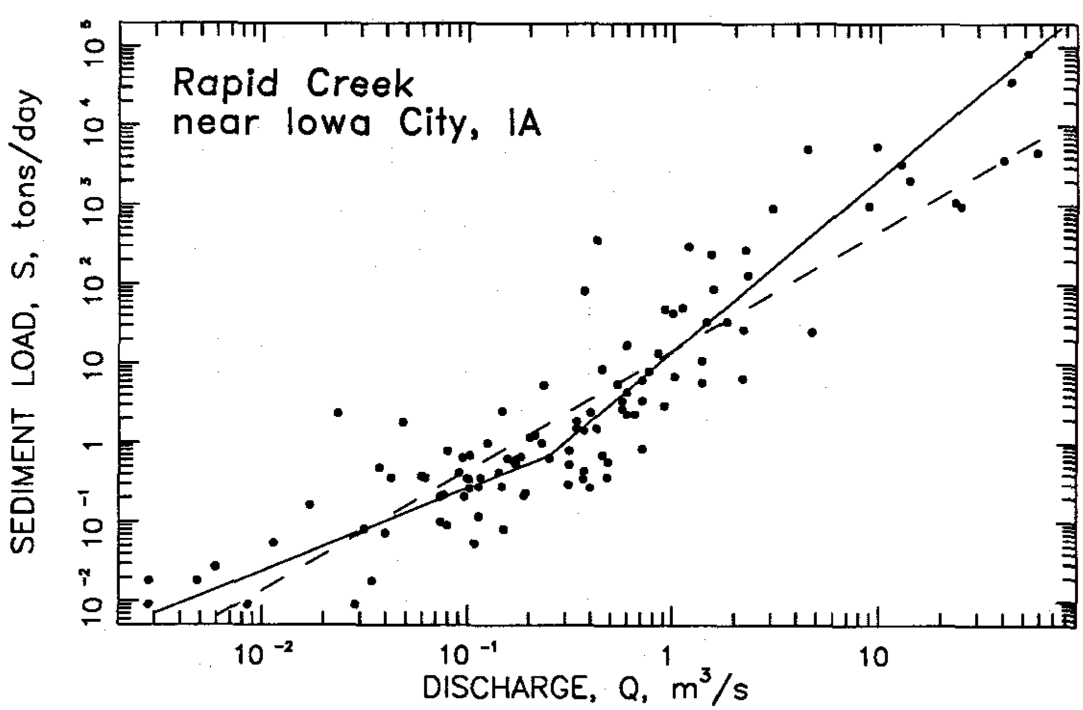


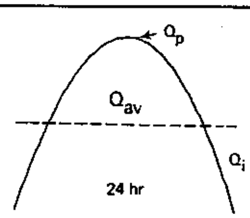
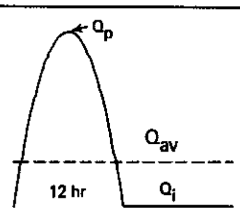
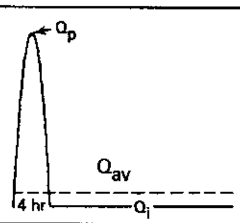
Figure 3. Steepening of the sediment rating curve

The percent underestimation of daily sediment load is given by $\{(L-L')/L\} \times 100$, and it is always positive for $b>1$ (a and b can be replaced by α and β if nonlinear regression is considered). This underestimation increases with increases in b and with variations in discharge during the day.

The discharge variation during a day is usually inversely related to the size of the drainage area. For example, the ratio of average daily flow to peak flow during the day can vary from 0.6 to 0.9 for large basins, but it may be as low as 0.1 or less for a small basin for which the runoff hydrograph rises and falls within a few hours. Thus, the sediment load for a stream with a small drainage area can be drastically underestimated if the daily average flows are used for computing the sediment load, rather than an expression like equation 14.

The effect of using average daily flows for estimating sediment loads can be analyzed by using three different-size watersheds and four feasible values of b. It is assumed that ratio r (mean daily flow divided by the instantaneous peak flow during the day) varies from 0.6 to 0.83 for a large basin, from 0.33 to 0.63 for a medium-sized basin, and from 0.10 to 0.18 for a small basin. For the large basin, it is assumed that the flow peaks and returns to its initial level within 24 hours. For medium-sized and small basins, these periods are 12 and 4 hours, respectively. The total daily sediment loads, L and L', are computed by using equations 14 and 15, and the percent load underestimation by $\{(L-L')/L\} \times 100$. The results are given in Table 2. The underestimation greatly increases as the drainage area becomes smaller and the b value becomes higher.

Table 2. Underestimation of Daily Sediment Loads for Different Scenarios

Basin Size	Hydrograph Shape	Percent underestimation = $\{(L-L')/L\} \times 100$			
		b = 1.3	b = 1.5	b = 1.7	b = 1.9
LARGE		(0.3 - 3.0)	(0.5 - 5.0)	(1.0 - 8.0)	(1.1 - 11.3)
MEDIUM		(1.2 - 12)	(2.5 - 22)	(4.0 - 31)	(5.4 - 40)
SMALL		(15 - 35)	(27 - 54)	(40 - 68)	(50 - 78)

OTHER CONSIDERATIONS

There are other sources of underestimation in estimating sediment yields. The variation in sediment load carried at similar discharges for the rising and falling limbs of the hydrograph, armoring effects due to depletion of readily erodible material after successive storms, temporal and spatial storm distribution over a basin, and the combined effects of these factors must be addressed satisfactorily. Another serious problem is the preponderance of sediment load observations for low and medium flows. Considering that 80 to 90% of the sediment load is carried during 10 to 15% of the highest flows, it is essential that sediment sampling programs be greatly modified so that at least 50 to 80% of suspended sediment load monitoring is done during high flows. Total sediment load includes suspended sediment load and bed load. The latter is accounted for by increasing suspended sediment load by 5 to 15%, depending on the particular basin soils, stream slopes, and meteorologic and hydrologic considerations.

CONCLUSIONS

The use of a sediment rating curve developed from regression of log-transformed S and Q values causes substantial to severe underestimation in stream sediment yield estimates. This can be largely mitigated by using nonlinear regression on S and Q. Further improvement in load estimates can be achieved by identifying the existence of seasonal sediment rating curves and any breaks in slopes of the rating curves, and by considering the suggested procedure to take them into account in developing load estimates. The underestimation caused by the use of average daily flows instead of short-interval flows can vary from considerable to extreme, depending on the size of the drainage basin and the value of the exponent in the sediment rating curve. This underestimation must be mitigated, especially for small drainage basins, by developing adjustment factors based on average daily flows and continuous flows for a selected number of days representing the overall flow spectrum. Sediment monitoring programs should be greatly modified to collect more of the data during high flows for better defining and improving confidence in the upper part of the sediment rating curve.

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BRUSH CONTROL AND SEDIMENT YIELD

by

Kenneth G. Renard, Fatima A. Lopez, and J. Roger Simanton[1]

ABSTRACT

Eight small watersheds in southeastern Arizona on the Santa Rita Experimental Range were instrumented in 1975 and 1976 to quantify the impact of mesquite control on runoff and sediment yield. Four pairs of contiguous watersheds, one treated and one for control, under four grazing practices were equipped with raingages, precalibrated supercritical runoff measuring devices and automatic sediment sampling equipment as a part of the experiments. Brush control was accomplished by girdling individual mesquite plants with diesel fuel in one of each pair of watersheds. Vegetation, runoff, and sediment yield changes are discussed and analyzed as a result of the experiments on one pair of the watersheds. The procedure used to synthesize the sedigraphs and annual yield is discussed for watersheds 1 (control) and 2 (treated).

INTRODUCTION

Vegetation composition manipulation has been proposed in Arizona for water yield enhancement for many years (Barr 1956, Ffolliott and Thorud 1974, Hibbert 1965, and Horton 1976). Research scientists in the US Forest Service have investigated the topic in small watersheds in numerous vegetation life zones from the more humid alpine areas to the drier chaparral zones. Converting from woody species to grass communities has generally been observed to enhance runoff. Such studies have not addressed what happens in more arid areas, nor have they addressed the erosion/sediment yield problem from such watersheds (Ffolliott and Thorud 1974).

In an effort to quantify the impact of vegetation manipulation in a more arid area (300-460 mm annual precipitation), watersheds in the Santa Rita Experimental Range 55 kms south of Tucson were instrumented in 1975 and 1976. The instrumentation consisted of a recording raingage, a precalibrated supercritical runoff flume (Smith et al. 1981), and an automatic total load sediment sampler (Renard et al. 1986). The experimental program consisted of four pairs of watersheds in different pastures. The pairs consisted of one watershed used as a control and one treated by girdling individual mesquite trees (*Prosopis velutina* Woot.) with diesel oil. No pretreatment water resource data were collected. It was assumed that hydrologic response changes would be reflected by different parameter values in a causal model.

In this paper, results are presented for one pair of watersheds, 1 and 2, with drainage areas of 1.64 and 1.77 ha, respectively (Fig. 1).

As the topographic maps illustrate, only the lower portion of each watershed has an incised drainage system. In earlier analysis on these watersheds, Lane et al. (1978) showed that significant errors in estimating runoff and erosion rates are possible where a watershed is assumed to contribute runoff uniformly over the entire area, when actually, only a portion of the area may be contributing, i.e., partial area response. Lane et al. (1978) showed that only 45 and 34% of watershed 1 and 2, respectively, normally contributed runoff. In subsequent analyses reported herein, this effect was ignored for lack of a definitive relation to describe the variable runoff area for different storm sizes.

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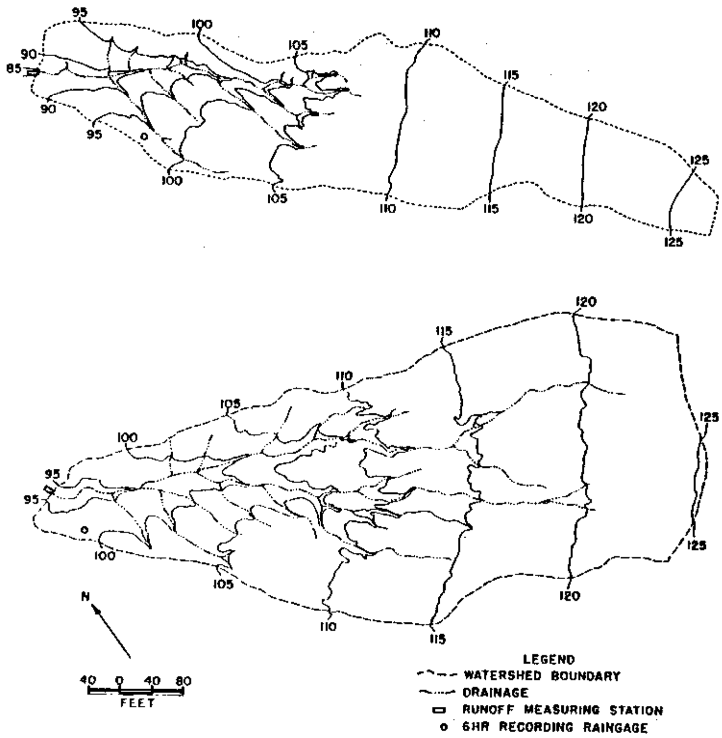

Figure 1. Topographic Map of Watershed 1 and 2
(Contours refer to elevations in feet above an arbitrary datum.
Elevation 100 is approximately 3400 ft. mean sea level. 1 ft = 0.305 m)

Mesquite trees were killed on watershed 2 in 1974. Vegetation measurements made above the incised lower portions of the watershed indicated that prior to treatment there were 2.4 perennial grass plants/m^2. By 1986, perennial grasses had increased to 13.9 plants/ m^2. However, over the same period, the perennial grass density on the untreated watershed 1 increased from 3.3 to 15.0 plants/m^2. From 1974 to 1986, percent mesquite cover decreased from 6.2 to 0.0 on the treated watershed and increased from 6.7% to 7.6% on the untreated watershed. Total shrub cover on the treated watershed was 22.3% in 1974 and 16.9% by 1986. The untreated watershed had 18.0% shrub cover in 1974 and 26.0% by 1986. Analysis of variance of grass and shrub vegetation changes from 1974 to 1986 between the two watersheds showed no significant ($P = 0.05$) differences.

Unfortunately, the vegetation measurements only indicate changes on watershed areas not significantly contributing to runoff. Vegetation composition also changed in response to precipitation but we were not able to define a predictable pattern.

SOILS

Soil of the two watersheds is comprised mainly of a Comoro sandy loam. This soil is well-drained, 150 cm or more in depth and formed in recent alluvium weathered from mixed rock. The lower portions of the watersheds, which show evidence of accelerated erosion, consist of a Sonoita gravelly sandy loam soil. This soil is well-drained, 150 cm or more in depth, and formed in old alluvium weathered from granite and related acid igneous rock. The soil surface is covered by 15 to 35% gravel and up to 5% cobbles.

The extreme variability of precipitation in southern Arizona is a problem in watershed studies. For example, Herschfield (1962) showed a coefficient of variation of annual precipitation of about 50% in southern Arizona, about the largest in the continental U.S. Thus, short hydrologic records can be suspect in the area. Knisel et al. (1979) used a "surplus-deficit" analysis to illustrate the departures of short precipitation records from long records. Such data for these Santa Rita Experimental Range watersheds were compared with US Weather Bureau data for the Tucson (University of Arizona) gage (Fig. 2).

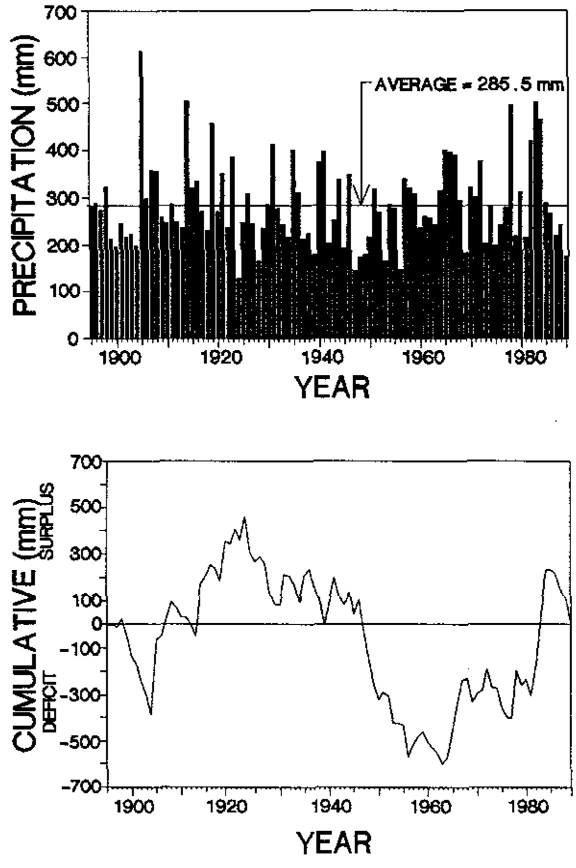

Fig. 2a. 1895-1989: Annual Precipitation and Cumulative Surplus and Deficit for Tucson (University of Arizona)

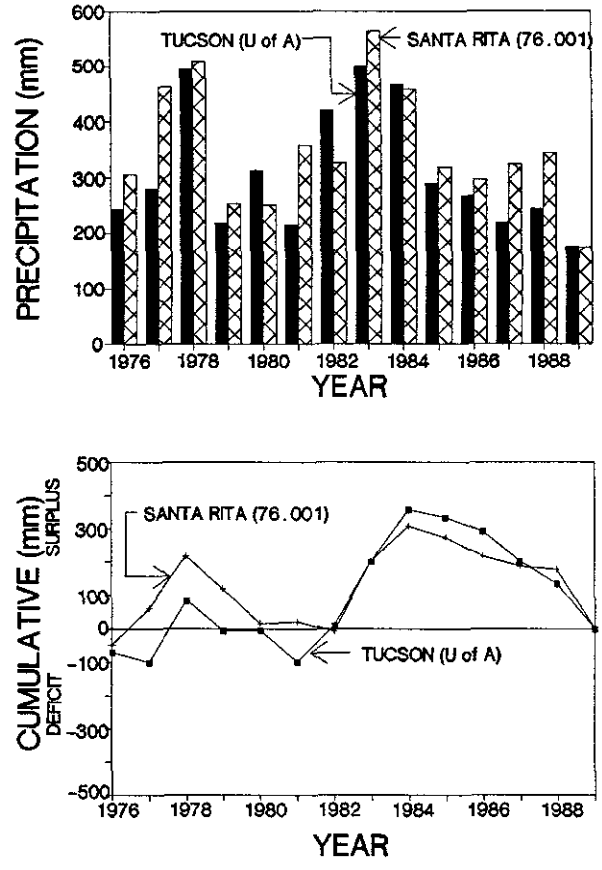

Fig. 2b. 1976-1989: Annual Precipitation for Santa Rita, RG76.001 (Average = 353 mm) and Tucson (University of Arizona) (Average = 311 mm) and Cumulative Surplus and Deficity

In Fig. 2a, the 94-year record for the University of Arizona station is presented in both the upper bar graph of annual values and in the lower cumulative surplus-deficit graph. Of particular significance is that the latter years, i.e., the period during which the Santa Rita watersheds were operated, were significantly wetter than the long term average (311 mm versus 285 mm) (Fig. 2b). Thus the precipitation and in turn, runoff and sediment yield, might be expected to be above average.

Short term precipitation amounts, provide better indicators of annual runoff than annual totals (Lane et al. 1984). To check whether the short 12-year precipitation records for the Santa Rita watersheds might be representative of longer records for other gages in the region, a frequency analysis was completed for annual maximum daily precipitation (Table 1) and annual maximum hourly precipitation (Table 2) using a computer program that fits the observed data with several frequency distributions (Reich et al. 1990).

Table 1. Annual maximum daily precipitation (mm) for Santa Rita (76.001), Walnut Gulch (63.024) and Tucson (University of Arizona) using log-normal distribution.

Probability	Station		
	Santa Rita	Walnut Gulch 63.024	Tucson
0.99	13.5	13.2	12.2
0.90	22.6	20.1	20.6
0.80	26.9	23.1	24.6
0.50	37.6	30.5	34.8
0.20	53.1	39.9	48.8
0.10	63.2	46.0	58.2
0.04	76.5	53.3	70.4
0.01	96.5	64.3	88.6

Santa Rita (76.001) has a 12-year record, Walnut Gulch (63.024) has a 34-year record, and Tucson (U of A) has a 50-year record.

Table 2. Annual maximum hourly precipitation (mm) for Santa Rita (76.001) and Walnut Gulch (63.024) using log-normal distribution.

Probability	Station	
	Santa Rita	Walnut Gulch 63.024
0.99	7.3	9.1
0.90	13.7	14.7
0.80	17.0	17.5
0.50	25.4	23.9
0.20	37.8	32.8
0.10	46.7	38.6
0.04	58.7	46.2
0.01	77.0	57.2

Santa Rita (76.001) has a 12-year record and Walnut Gulch (63.024) has a 34-year record.

Table 1 shows that the maximum daily amounts for more infrequent events (e.g. 5- through 100-year frequency) are larger than those from the longer records on the Walnut Gulch Experimental Watershed near Tombstone, AZ and for the University of Arizona gage in Tucson. Furthermore, the maximum hourly precipitation on the Santa Rita range is 35% more for the 100-year storm than that on Walnut Gulch (Table 2) whereas the amounts for more frequent events are less. This further illustrates why we might expect long term average runoff and erosion to be less than those reported.

RUNOFF AND SEDIMENT YIELD

Precipitation and runoff data from the two watersheds in this study are considered to be excellent. The sediment concentration-transport-yield data are often less than adequate. For example, four conditions are encountered with some regularity: (1) known flow, no recorded hydrograph; (2) recorded hydrograph but no concentration data; (3) recorded hydrograph but insufficient concentration data throughout the hydrograph; and (4) recorded hydrograph with sufficient concentration data to define the sedigraph. Only two of events in the entire record were in condition 1, many small events were in condition 2 (the sampler mechanism is activated at flow depths larger than 60 mm) and represent a very small portion of the total yield, numerous events were in condition 3 and about 75 events were in condition 4. Stated another way 66% of the sediment yield for watershed 1 came from condition 4 events, whereas on watershed 2, 37% of the sediment yield was produced by condition 4 events. Figure 3a and 3b illustrate a condition 4 storm on watersheds 1 and 2, respectively.

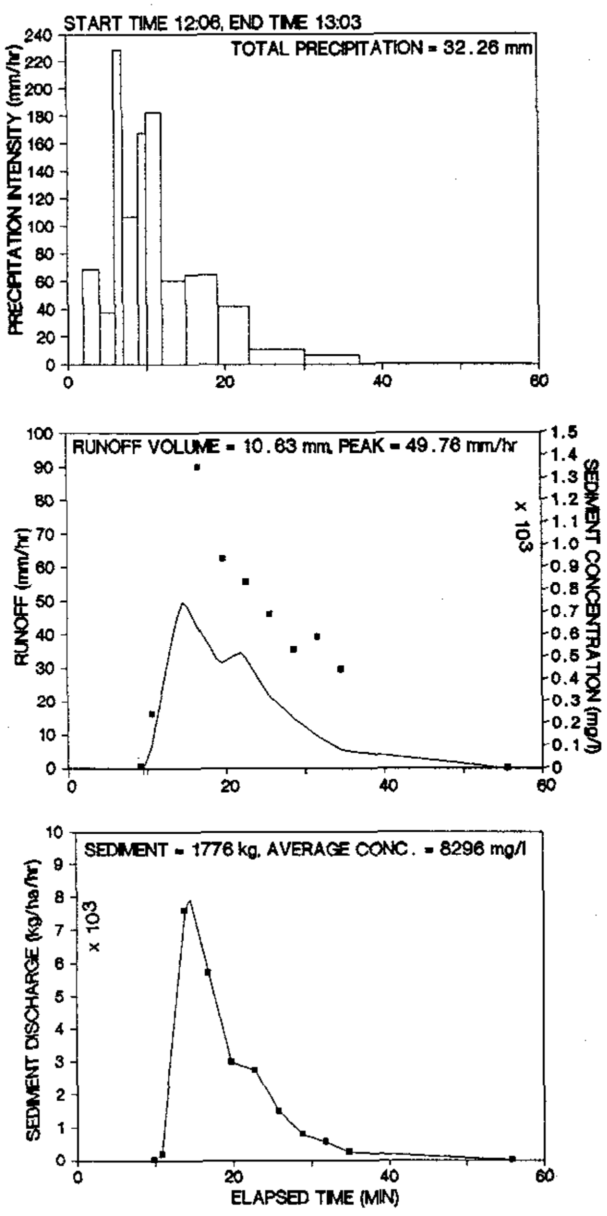

Figure 3a. Hyetograph, hydrograph, concentration data and sedigraph for watershed 1 on September 11, 1977.

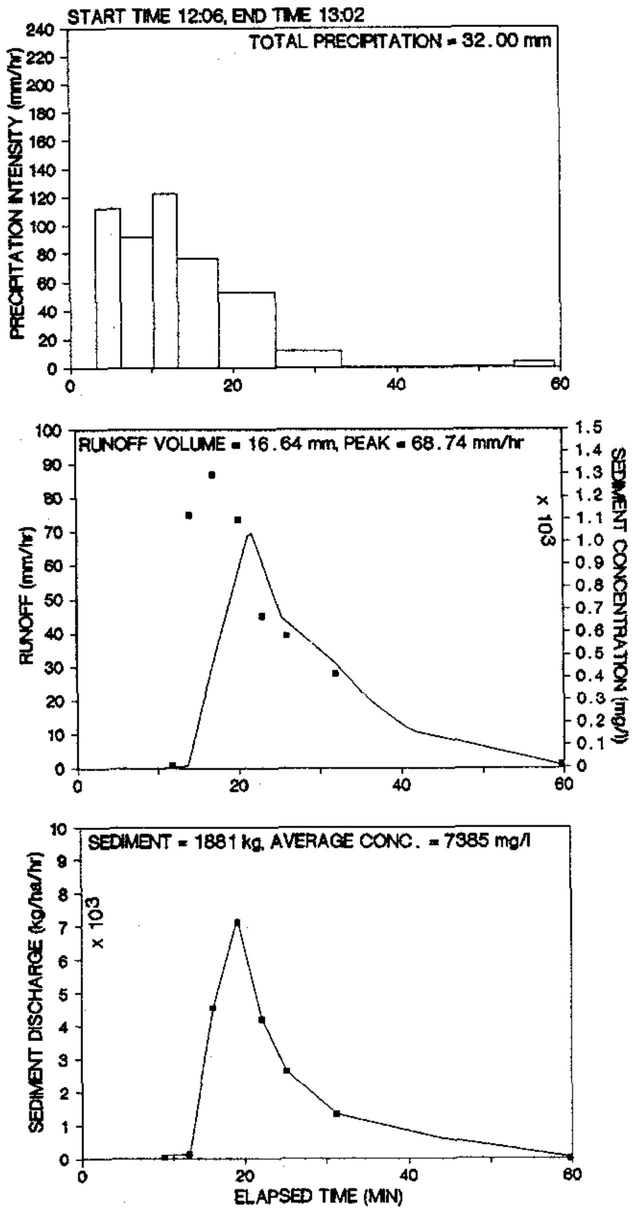

Figure 3b. Hyetograph, hydrograph, concentration data and sedigraph for watershed 2 on September 11, 1977.

The upper third of these figures are the hyetographs on each watershed as digitized from the cumulative recording raingage. The total precipitation depth is 32.26 and 32.00 mm for the watersheds. Runoff on the other hand was significantly different with 10.63 and 16.64 mm total runoff for watersheds 1 and 2, respectively. The squares in the center of each graph are the concentrations (mg/l) at specific times in the hydrograph. The lower portion of the graph is the sedigraph corresponding to the hydrograph with the squares being the transport corresponding to the concentration values. For this event, the total transport was only slightly greater on watershed 2 (1881 kg) than watershed 1 (1776 kg) despite the large differences in runoff volume.

Estimating Storm Soil Loss For Condition 1, 2 and 3 Events

To estimate the storm soil loss for conditions without adequate samples, several techniques were investigated as follows: (1) A simple two parameter model based on the notion of a linear reservoir with input proportional to the rate of rain splash erosion.

$$\hat{C}(t) = K_2 S(t) \qquad (1)$$

$$R(t) = I(t)\,[I(t) - \varphi] \qquad (2)$$

and

$$\int_{t_1}^{t_2} K_1\, R(t)dt = \int_{t_1}^{t_2} \hat{C}(t)dt + [S(t_2) - S(t_1)] = \int_{t_1}^{t_2} \hat{C}(t)dt + \left[\frac{\hat{C}(t_2)}{K_2} - \frac{\hat{C}(t_1)}{K_2}\right] \qquad (3)$$

where K_1 and K_2 are parameters to be optimized
$\hat{C}(t)$ is the predicted concentration at time t
$S(t)$ is the storage at time t
$R(t)$ is the product of rainfall rate and rainfall excess rate
$I(t)$ is the precipitation at time t
φ is the phi index, estimated for each event.

Although this model provided good fits to measured concentrations for single events, the parameters varied quite widely from event to event so it did not provide an estimator as good as a flow weighted mean concentration.

(2) Regression models were attempted which related storm soil loss to:

(a) R, the Universal Soil Loss Equation (Wischmeier and Smith 1978) rainfall-runoff factor for individual storms

(b) I(30), the maximum precipitation depth in 30-minutes

(c) P, Q and I_{max}.

Previous efforts (Simanton and Osborn 1983) on small watersheds on the Walnut Gulch Experimental Watershed near Tombstone, Arizona showed that the USLE R-factor gave good correlations with observed runoff and soil loss from individual flow events. Based on the current analyses and the earlier work, this model was used to estimate runoff and sediment yield from condition 1, 2, and 3 events. These estimates were included with measured values for condition 4 events to produce the summary data in Table 3. It is interesting to note that despite the close proximity (< 300 m apart), the two recording raingages showed generally greater precipitation on 2 than on 1 (7.5% difference). Though not significantly different (P = 0.05), the control watershed (1) had more average runoff (18.87 mm) than 2 (14.54 mm), the mesquite killed watershed and the mean annual sediment yield from watershed

Table 3. Summaries of annual data and statistics for the 13 year data set.

	Watershed 1 (Control)			Watershed 2 (Treated)			Ratio of Runoff	Ratio of Sediment Yield
	Rainfall mm	Runoff mm	Sediment Yield kg	Rainfall mm	Runoff mm	Sediment Yield kg	Q2/Q1	QS2/QS1
76	305.6	11.2	943	296.2	11.1	1,359	1.00	1.44
77	463.3	39.6	5,959	429.8	46.9	6,756	1.18	1.13
78	510.5	30.6	4,086	550.9	32.3	3,638	1.06	0.89
79	253.5	4.6	937	261.9	2.3	553	0.50	0.59
80	250.9	7.6	1,390	266.4	2.6	652	0.34	0.47
81	358.1	40.0	4,249	389.1	29.9	4,149	0.75	0.98
82	324.9	16.2	3,143	357.4	10.9	923	0.67	0.29
83	564.4	36.8	3,018	641.1	17.9	2,705	0.49	0.90
84	459.0	11.0	2,407	507.7	3.5	2,125	0.32	0.88
85	317.7	1.4	680	360.7	Trace	238	0.00	0.35
86	296.4	9.6	1,283	357.9	4.6	1,041	0.48	0.81
87	323.8	10.8	1,739	355.3	8.3	896	0.77	0.52
88	343.7	25.9	3,511	383.8	18.6	1,603	0.72	0.46
Mean	367.1	18.9	2,565	396.8	14.5	2,049		
Std	95.7	13.3	1,536	106.9	13.6	1,782		
Min	250.9	1.4	680	261.9	0.0	238		
Max	564.4	40.0	5,959	641.1	46.9	6,756		

1 was greater (2565 kg) than 2 (2049 kg) as would be expected with the corresponding differences in runoff. On a unit area basis, watershed 1 had 1564 kg/ha whereas watershed 2 had 1158 kg/ha. Stated another way, watershed 2 had 26% less sediment yield than watershed 1, the untreated watershed.

Some rainfall simulator experiments were performed in the Santa Rita Experimental Range in 1987 and 1988 using a rotating boom simulator. Interestingly, the measured soil losses from the simulator plots (Dr. William Emmerich, unpublished data) are significantly lower than those measured from the experimental watersheds indicating that much of the sediment yield originates from channel/gully erosion in such environments (Osborn and Simanton, 1989).

Observations in and adjacent to the incised channels on these watersheds revealed that the mesquite killed watershed (76.002) had more grass in the channel in the latter years of the study. This might well have a cause/effect relationship on the lower runoff and sediment yield.

The annual runoff and sediment yield ratios (watershed 2/watershed 1) are shown in the last two columns of Table 3. Of particular interest is that the ratios in the first few years are near unity and decrease appreciably in the later years. We hypothesize that vegetation cover conditions on watershed 2 took several years for new equilibrium conditions to establish (no grass seeding was done).

CONCLUSIONS

1. The precipitation during the period of monitoring is appreciably above the long term average.

2. Runoff from watershed 2 (mesquite killed) is less than that from the untreated control watershed despite the greater precipitation on the treated watershed.

3. Sediment yield from the treated watershed was 26% less than that from the untreated watershed based upon sampling and on estimation using the rainfall-runoff erosivity factor (R) from the Universal Soil Loss Equation.

4. The ratios of runoff and sediment yield for watershed 2 to 1 which initially were near unity decreased in time. We speculate that this decrease was associated with grass establishment in and adjacent to the ephemeral channels. These results are contrary to that observed in more humid forested watersheds in other places in Arizona following removal of forest cover.

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A PROCEDURE FOR ESTIMATING SEDIMENT YIELDS FROM FORESTED WATERSHEDS

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ABSTRACT

BOISED is the operational sediment yield model used by the Boise National Forest to evaluate the sediment impact from alternative land management scenarios. The model is a local adaptation of the sediment yield model developed by the Northern and Intermountain Regions of the U.S. Forest Service for application to forested watersheds associated with the Idaho Batholith. The procedure is commonly used in the preparation of environmental assessments and impact statements as a tool to evaluate the effects of alternative timber harvest activities, road locations and design, and the application of erosion mitigation practices. The procedure provides for estimation of on-site erosion, delivery to stream channels, and routing of sediment downstream to critical reaches where interpretation of sediment impact to water quality and fish habitat can be made.

The model produces quantified estimates of average annual sediment yields for the undisturbed condition, past activities, and activities proposed in the future. Management activities which can be modeled include road construction, timber harvest, and fire. While it is inappropriate to use the model as a highly reliable predictor of absolute quantities of sediment delivered to streams at specific times, it is appropriate to use model results for comparison of alternative management scenarios within a watershed. Because the model considers both on-site erosion and downstream sediment yield, application of best management practices for the protection of water quality and beneficial uses can be evaluated.

INTRODUCTION

The National Environmental Policy Act of 1969 (42 U.S.C. 4321) is one of the most far-reaching pieces of legislation to affect National Forests. Among other things, it mandates interdisciplinary planning and the use of analytical procedures so that the impacts of alternative courses of action can be made more explicit and visible to the public prior to decisionmaking.

Various procedures have been developed to estimate the effects of alternative soil disturbing practices on soil erosion (Wischmeier and Smith, 1978, Curtis and Darrach, 1977, Darrach and Curtis, 1978). Unfortunately, these methods have limited application in much of the mountainous West because they were developed on agricultural lands and are not well adapted to erosional processes common to forested watersheds.

A procedure has been developed on the Boise National Forest for predicting the cumulative effects of alternative land management practices, including road construction, timber harvest, and forest fire, on increasing sediment yield from forested watersheds. The procedure is encapsulated in a computer model named BOISED (Unpublished user guide by Boise National Forest, in preparation) and is patterned after the USDA Forest Service Regions 1 and 4 Sediment Yield Model (Cline, et. al., 1981). Although developed principally for watersheds associated with the Idaho Batholith, the processes described can be adapted to other forested areas provided some base research sediment yield data exists.

The BOISED model simplifies for analysis an extremely complex physical system and was developed from empirical data supplemented by extrapolation based on professional judgement and our current understanding of erosion and sediment transport processes on forested lands. In general, the procedure estimates on-site erosion from the time of its genesis until it decreases to pre-activity levels, modifies the amount of erosion according to general land unit characteristics, delivers the eroded material to the stream system, and routes the eroded material through the watershed to downstream sites where interpretation of effects are made. The systematic analysis tool is not generally recommended for watersheds greater than 50 square miles. All values are expressed in terms of average annual yields.

WATERSHED STRATIFICATION

Average annual erosion rates are estimated for homogeneous response units delineated according to hierarchical land systems inventory concepts described by Wertz and Arnold (1972). The basic unit for the procedure is the "landtype" defined as an area of land with similar landform, parent material, soil, and vegetation characteristics. Landtypes typically range in size from about 40 to several hundred acres. Landtypes are ideal for sediment modeling because many of the factors influencing slope hydrology and sediment delivery from slopes to streams are used to delineate landtypes. Among these are factors such as slope shape, gradient, roughness, dissection by drainageways, and the average distance to active drainageways. Specifics of landtype mapping for the Boise National Forest are fully described elsewhere (Wendt, et. al., 1975).

NATURAL SEDIMENT YIELD

Average annual natural sediment yield, expressed as tons per square mile of watershed area per year, serves as the beginning point for describing the undisturbed condition and as a baseline against which to interpret the magnitude of average annual management induced sediment yield increases. Most natural sediment yield from the Idaho Batholith comes from in-channel erosion of banks and stored sediment. The primary source of supply is assumed to be natural mass slope erosion processes (slumps and slides, debris avalanche-debris flow failures, and soil creep).

The potential hazard of natural mass soil movement can be estimated by evaluating site characteristics such as slope gradient, soil depth, subsurface drainage, soil texture, bedding structure and orientation, surface slope configuration, and precipitation input. A procedure for doing so is documented in the WRENSS Handbook (USDA Forest Service, 1980). This procedure was modified to reflect Boise National Forest conditions by changing weighting factors and adding new factors as appropriate (Unpublished report by J.F. Arnold, 1988).

Local sediment yield data was obtained from the USDA Intermountain Forest and Range Experiment Station's Tailholt-Circle End and Silver Creek Study Areas. Sediment yield measured at the mouths of twelve small granitic watersheds having slopes with gradients near 60 percent and ranging in size from 0.15 to 2.5 square miles, averaged 25 tons per square mile per year (Megahan, 1975; unpublished data, Intermountain Research Station, Boise, Idaho).

Mass erosion hazard ratings were determined for each of the measured watersheds and for each landtype on the Boise National Forest. A curve was constructed to estimate natural sediment yield from the hazard rating by assigning the lowest range of expected sediment yield (10 tons/mile^2/year) to the landtype with the lowest hazard rating and the highest yield (100 tons/mile^2/year) to the landtype with the highest hazard rating. Ratings for landtypes on the study watersheds and the corresponding measured sediment yields defined the middle range of the curve. Using the curve, natural sediment was estimated for each landtype based on the landtype's mass erosion hazard rating.

Computationally, total natural sediment for a watershed is the sum of the natural sediment yield for each landtype times its area. These values provide estimates of natural in-channel sediment yield for watersheds representative of the size from which the original data was collected averaging one square mile in size. As watershed size increases, unit area sediment yield decreases. The decrease is due to losses caused by sediment storage in tributary channels, floodplains, and behind organic debris. To account for this loss, a channel routing coefficient, using a relationship developed by Roehl (1962) is used. Roehl's relationship has been adjusted to provide a coefficient of 1.0 for one square mile watersheds as follows:

$$C = A^{-0.18}$$

where: C = channel routing coefficient; A = watershed area (square miles).

The channel routing coefficient is applied whenever watersheds greater than one square mile are modeled to correct for storage losses within the watershed.

SEDIMENT FROM SURFACE EROSION

Management-induced sediment generated from surface erosion processes is modeled independently from management-induced mass erosion. Mass erosion processes are an acceleration over natural sediment rates, while surface erosion is created by management activities.

Basic surface erosion rates (Table 1) were derived from research data for new road construction, logging, and fire (Cline et. al., 1982). Basic erosion rates for road reconstruction and road management were estimated based on the relative amount of soil disturbance compared to new construction.

Heavy reconstruction means the entire existing road surface is completely disturbed, cut slopes receive significant disturbance, and fill slopes minor disturbance. Light reconstruction involves minor excavation and disturbance of cut and fill slopes. Heavy use is defined as more than five vehicles per day. Light use averages less than 5 vehicles per day. Closed roads are generally gated to prevent traffic and are not surface bladed annually. Obliterated roads have natural drainageways restored and are revegetated. Closures and obliterations are assumed to take place during the fourth year following disturbance.

Table 1. Basic surface erosion rates for standard practices in tons per square mile of disturbance per year.

	Years Since Activity Occurred						
PRACTICE	1	2	3	4	5	6	6+
Fire	550	120	25	5	0	0	0
Logging	340	180	140	90	40	20	0
New Road/Heavy Use	67,500	18,000	7,000	7,000	7,000	7,000	7,000
New Road/Light Use	67,500	18,000	5,000	5,000	5,000	5,000	5,000
New Road/Closed	67,500	18,000	5,000	3,000	2,000	1,250	1,250
New Road/Obliterated	67,500	18,000	5,000	1,000	500	250	250
Heavy Reconst/Heavy Use	18,000	10,000	7,000	7,000	7,000	7,000	7,000
Heavy Reconst/Light Use	18,000	5,000	5,000	5,000	5,000	5,000	5,000
Heavy Reconst/Closed	18,000	5,000	5,000	3,000	2,000	1,250	1,250
Heavy Reconst/Obliterated	18,000	5,000	5,000	1,000	500	250	250
Light Reconst/Heavy Use	9,000	7,000	7,000	7,000	7,000	7,000	7,000
Light Reconst/Light Use	9,000	5,000	5,000	5,000	5,000	5,000	5,000
Light Reconst/Closed	9,000	5,000	5,000	3,000	2,000	1,250	1,250
Light Reconst/Obliterated	9,000	5,000	5,000	1,000	500	250	250

When a proposed disturbance deviates from the standard practice used to define the basic rates, erosion rates are modified by multiplying by appropriate factors based on the deviation from the standard.

Road Construction

Computationally, total erosion from a uniform road segment within one landtype for any year is calculated as:

(BASIC ROAD EROSION RATE) times (DISTURBED AREA) times (GEOLOGIC EROSION FACTOR) times (ROAD GRADIENT FACTOR) times (MITIGATION FACTOR) times (SLOPE SEDIMENT DELIVERY FACTOR)

where:

BASIC ROAD EROSION RATE = erosion in tons per square mile of disturbed area per year (Table 1). The standard road is assumed to be a maintained, 16 foot wide, native material road with a sustained grade of 5 to 7 percent, constructed on grantic material on a 50 percent side slope.
DISTURBED AREA = the total area disturbed by road construction expressed in square miles. The disturbed area of the road prism includes road subgrade, cut and fill slopes, ditches, berms, turnouts, and any other construction features that may be present. Tables of geometry for low standard roads, such as those developed by Megahan (1976) are useful to determine total disturbed area.
GEOLOGIC EROSION FACTOR = a coefficient applied to management-induced surface erosion to account for the relative difference in erodability based on geologic parent material. On the Boise National Forest, weathered granitics are assigned a value of 1.0; basalts have a value of 0.42.
ROAD GRADIENT FACTOR = a coefficient use to correct for gradients other than the standard. Gradients from 5 to 9.9 percent are assigned a value of 1.0; gradients less than 5 percent are assigned 0.5; gradients 10 percent or greater are assigned a value of 1.5.
MITIGATION FACTOR = a coefficient used to express the percent reduction in erosion due to the application of erosion control practices. Included are vegetative measures, such as seeding and mulching of cut and fill slopes, as

well as physical measures, such as gravelling and the placement of filter windrows. Combinations of practices are commonly employed. The mitigation effectiveness of many road erosion control practices has been documented by Burroughs and King (1988).
SLOPE SEDIMENT DELIVERY FACTOR = a coefficient used to express the percent of on-site erosion which reaches active drainageways. A modification of a procedure developed by the Forest Service (U.S. Forest Service, 1980) is used. Variables include slope steepness, shape, dissection, and distance to active drainageways (Reinig, et. al., in preparation). Delivery efficiencies generally are less than 20 percent.

Logging

Computationally, total erosion due to logging on a landtype for any year is calculated as:

(BASIC LOGGING EROSION RATE) times (GEOLOGIC EROSION FACTOR) times (DISTURBED AREA) times (LOGGING SYSTEM FACTOR) times (LAND UNIT SLOPE FACTOR) times (SLOPE SEDIMENT DELIVERY FACTOR)

where (factors not previously defined):

BASIC LOGGING EROSION RATE = Erosion in tons per square mile per year for the standard logging system which is clearcut with tractor yarding (Table 1). Temporary roads and skid trails within the harvest area and which have erosion control practices employed are assumed to be part of the standard practice.
DISTURBED AREA = the total area harvested.
LOGGING SYSTEM FACTOR = a coefficient used to express relative erodability of various logging systems and silvicultural prescriptions based on the amount of bare soil exposed (Table 2)

Table 2. Logging system factors for alternative logging systems and silvicultural prescriptions.

	LOGGING YARDING SYSTEM			
SILVICULTURAL PRESCRIPTION	Tractor	Cable	Skyline	Aerial
Clearcutting	1.00	0.62	0.33	0.19
Selection	0.71	0.43	0.29	0.14

LAND UNIT SLOPE FACTOR = a coefficient used to increase or decrease erosion for slopes other than 45 percent. The factor is adapted from the slope factor relationship of the Universal Soil Loss Equation scaled so that slopes of 45 have a factor of 1.0, slopes of 75 percent have a factor of 2.0, and flat surfaces have a factor of 0.5.

Fire

Computationally, total erosion due to fire on a landtype for any year is calculated as:

(BASIC FIRE EROSION RATE) times (GEOLOGIC EROSION FACTOR) times (DISTURBED AREA) times (FIRE INTENSITY FACTOR) times (LAND UNIT SLOPE FACTOR) times (SLOPE SEDIMENT DELIVERY FACTOR) where (factors not previously defined):

BASIC FIRE EROSION RATE = Erosion in tons per square mile per year for the standard fire which is assumed to have burned at high intensity on a side slope of 45 percent consuming at least 40 percent of standing vegetation (Table 1).
DISTURBED AREA = the total area actually burned.
FIRE INTENSITY FACTOR = a coefficient used to express relative erodability assigned to low, medium, and high fire intensity classes as defined in the Forest Service Burned-Area Emergency Rehabilitation Handbook (FSH 2509.13). High equals 1.0, medium equals 0.5, and low equals 0.2

SEDIMENT FROM MASS EROSION

Debris avalanche-debris slide slope failures are the major categories of mass erosion occurring on the Boise National Forest based on published and unpublished data from a landslide inventory conducted in Idaho (Megahan, et. al., 1978; Unpublished data, Intermountain Research Station, Boise, Idaho). The frequency of these slope failures in various parts of the world average about 140 times greater per unit area of road than undisturbed slopes, whereas clearcutting increases slope failure frequency an average of only 7 times (Megahan and King, 1985). Studies consistently indicate that debris avalanche-debris slide slope failures are limited to slopes greater than 45 percent with a maximum frequency of occurrence at about 70 percent. For these reasons, only new road construction on landtypes with average slopes greater than or equal to 45 percent are assumed to accelerate mass erosion processes. Provisions are made to exclude landtypes on steep slopes known to be unstable and landtypes on gentler slopes known to be susceptible to slope failure due to other factors.

Using the inventory data cited, total mass erosion during a 20 year period was tabulated and then divided by the total miles of road construction during the same time period and by the average natural sediment yield for the study area to yield an acceleration factor as a function of natural sediment yield. A cumulative frequency curve of age versus slide frequency was constructed to derive acceleration factors for individual years (Table 3).

Table 3. On-site Mass Erosion Acceleration Factors.

Road Age (years)	Accel. Factor	Road Age (years)	Accel. Factor	Road Age (years)	Accel. Factor	Road Age (years)	Accel. Factor
1	44	6	51	11	25	16	6
2	76	7	44	12	19	17	6
3	82	8	38	13	13	18	6
4	63	9	32	14	13	19	3
5	63	10	25	15	13	20+	3

Since the data used to derive acceleration factors represents on-site erosion, a delivery factor had to be developed for each landtype. Because mass erosion delivery processes are inherently different from surface erosion delivery processes, a mass erosion delivery ratio patterned after a graphical relationship found in the WRENSS Handbook (U.S. Forest Service, 1980) for debris avalanche-debris flows was used.

Computationally, management-induced mass erosion for new roads constructed on landtypes with average slopes of 45 percent or greater is calculated as:

MASS EROSION (new roads) = (NATURAL SEDIMENT YIELD) times (DISTURBED AREA) times (MASS EROSION DELIVERY FACTOR) times (ON-SITE MASS EROSION ACCELERATION FACTOR)

where:

NATURAL SEDIMENT YIELD = the sediment yield from an undisturbed landtype expressed in tons per square mile per year.
DISTURBED AREA = the total area disturbed by road construction as previously defined.
MASS EROSION DELIVERY FACTOR = a decimal fraction expressing the percentage of on-site mass erosion material delivered to the nearest first or higher order drainage.
ON-SITE MASS EROSION ACCELERATION FACTOR = a dimensionless multiplier from Table 3.

PROCEDURE APPLICATION

By varying either the amount, location, anmd timing of management activities or the application of erosion mitigation practices, the mix of activities which keeps sediment impacts within acceptable limits can be identified. This is normally done during the environmental assessment phase of project level planning to provide the decisionmaker and public with a reasonable assessment of probable impacts.

Sediment yield outputs from the model are normally expressed as a percent increase over the natural condition. An example of a typical application of the model to a 7 square mile watershed is shown in Figure 1.

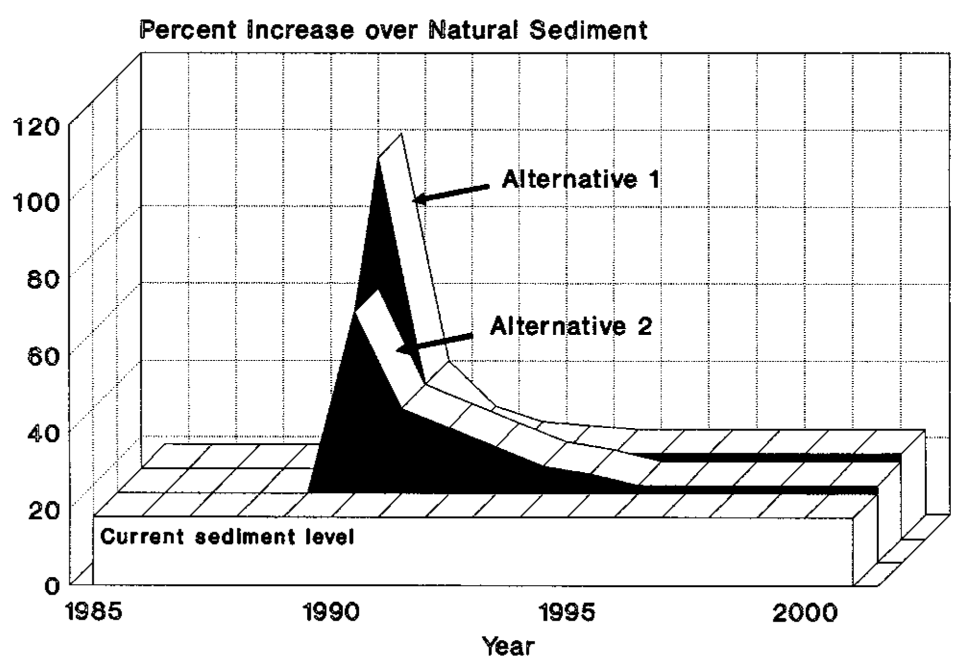

Figure 1. Example of a typical application of the procedure.

The example assumes 9 miles of existing road which produces the current 18 percent increase over natural followed by alternatives which construct 5 miles of new road in 1990 and harvest 450 acres of timber by selection methods in 1991. The time dependence of sediment response to these activities is readily apparent. Alternative 1 assumes all construction takes place in one year followed by timber harvest the next year. Sediment yield peaks at 100 percent over natural. Alternative 2 employs a higher degree of erosion mitigation and defers some road construction into 1991. Peak sediment yield is reduced to 65 percent over natural and remains high for a slightly longer period of years. Sediment yields in both alternatives do not return to predisturbance conditions due to long term surface erosion from added roads. Based on reduced peak and long term sediment yields, Alternative 2 is clearly the environmentally preferred alternative.

A geomorphic threshold, or the point at which channel equilibrium is observably altered as evidenced by accelerated deposition of bed materials, loss of channel capacity, and changes in substrate particle size distribution, serves as one reference point for interpreting levels of acceptable change. Data from 65 watersheds on the Clearwater National Forest (Wilson, et. al., 1982) indicates these changes in sediment yield increase to range from 50 to 350 percent over natural, with 150 percent being a rough average. It is generally recognized that sediment increases which result in observable changes in stream characteristiscs are deterimental to fisheries. The development of relationships between sediment yield increases and effects on fish habitat and fish populations, however, have met with limited success (Chapman and McLeod, 1987). Based on this, the Boise National Forest employed a more pragmatic empirical approach to establishing sediment yield increase thresholds. Sediment producing activities from the early 1900's to the present were modeled for 51 watersheds to estimate the magnitude of past sediment yield increases. In general, maximum sediment yield increases occurred 25 to 30 years ago between 1960 and 1965. Maximum average annual increases averaged about 200 percent over natural and ranged as high as 715 percent. Assuming that current fisheries habitat conditions and fish populations are a direct result of past average increases in sediment of up to 200 percent, a 50 percent reduction, or a threshold of 100 percent over natural was selected as the maximum allowable sediment yield increase on the Boise National Forest for future land-disturbing activities. By reducing the magnitude of future impacts compared to the past, improvement to fish habitat and water quality are expected to occur. The procedures described in this paper will be used to define acceptable levels of activities and specific on-site erosion mitigation practices to achieve these goals.

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VEGETATION MANAGEMENT EFFECTS ON SEDIMENT YIELDS

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Abstract

Sediment is a key water quality issue in southern national forests. A regional analysis presented here studied 27 watersheds for cumulative effects of vegetation management (fire, mechanical, herbicides, manual, and biological) on sediment yield. The watersheds represent all relevant landtypes, range in size from 1,416 to 22,257 ha, and have an array of private lands (forest, pasture, cropland). The vegetation management alternative that could potentially disturb the most soil was evaluated. Natural sediment yield in these landtypes ranges from .004 to .022 Mg/ha/yr (metric tons/ha/yr). Increases above natural rates in the 27 watersheds are expected to be 7% or less due to intensive vegetation management. Roads and cropland are the major sediment sources. The low sediment yield due to vegetation management could be sharply reduced by favoring more herbicides and moderate prescribed fire over intensive mechanical and severe fire methods.

Introduction

The USDA Forest Service manages 34 national forests and two national grasslands in the 14 southern states from Virginia to Texas. These lands total 5.1 million ha, many of which make up the headwaters of the region's watersheds. As such, they are a source of much of the South's high-quality water. Streams on these lands usually have the lowest concentrations of sediment, chemicals, and bacteria in a given area, and meet water quality standards nearly all the time. By contrast, 6.5 million ha of cropland in the region have erosion rates which exceed the soil loss tolerance (Larson, et al. 1983). Erosion rates on these lands range from 5 to 12.5 Mg/ha/yr.

From 1986 to 1990, the Forest Service studied environmental effects of vegetation management on southern national forests and grasslands. The activities studies were fuel reduction; maintenance of trails, roads, utility lines, mountain balds, and recreation sites; improvement of range forage and wildlife habitat; and site preparation and stand improvements for timber. Prescribed fire, herbicides, mechanical, manual, and biological (livestock grazing) methods were studied. Environmental effects assessed included human health and safety, vegetation, wildlife, threatened and endangered species, soil, and water and aquatic life.

Three environmental impact statements (EISs) were prepared from these studies (USDA Forest Service 1989a, 1989b, 1990). The EISs covered three physiographic divisions to account for variations in management and environmental response among them. These divisions are groups of physiographic provinces:

Coastal Lowlands, including the Coastal Plain (rather flat terrain on young marine and alluvial sediments) and Piedmont (rolling terrain on ancient, weathered, metamorphic and igneous rocks);

Appalachian Highlands, including the Blue Ridge Mountains (rugged, deeply incised mountains on ancient metamorphic and igneous rocks), Ridge and Valley Province (parallel ridges and valleys on old, folded, and faulted sedimentary rocks), and Appalachian Plateaus (smooth mountain uplands on youthful, flat, sedimentary rocks);

Interior Highlands, including the Ozark Plateaus (broad, deeply incised uplands on flat sedimentary rocks) and Ouachita Mountains (parallel ridges and valleys on youthful, folded, and faulted sedimentary rocks).

In the EISs, the effect of each vegetation management method on erosion and sediment yield was modeled. These results were used to analyze cumulative effects on sediment yield in 27 watersheds and gage the contribution of Forest Service vegetation management to their total sediment budgets.

Methods

Erosion was modeled for each vegetation management method, roads, timber, pasture, and cropland. Sediment included channel erosion plus the portion of surface erosion delivered to streams. Cumulative effects were analyzed by integrating sediment yields for all actions in each watershed.

Erosion

Surface erosion was modeled by the Universal Soil Loss Equation (USLE). USLE computes potential erosion to increase with greater rainfall energy, soil erodibility, slope length and steepness, and to decrease with greater ground cover (Dissmeyer and Foster 1984). The USLE equation is: $A = RKLSCP * .3671$; where A is computed soil loss (Mg/ha/yr; metric tons/ha/yr); R is a rainfall energy factor; K is a soil erodibility factor; LS is a slope length-steepness factor; CP is a cover factor based on amount and quality of ground cover; and .3671 is the metric conversion factor. Average RKLS values for landtypes on federal lands in the South are shown in section IV.F.1 of the EIS's (USDA Forest Service 1989a, 1989b, 1990).

For roads, typical erosion rates for bare soil roads were taken from Dissmeyer and Stump (1978). Studies by Swift (1984) and Kochenderfer and Helvey (1985) in the Appalachian Highlands were used to adjust erosion rates for gravel and paved roads. Existing roads are permanent and erode every year. New timber access roads are opened temporarily and were modeled to erode for only 1 year.

Rainfall energy (R) ranges from 150 in the Cumberland Mountains to 500 in the Gulf flatwoods. Soil erodibility (K) varies from 0.17 in Coastal Plain sand ridges to 0.37 in loess uplands of the Mississippi Delta region. The slope length steepness factor (LS) is lowest in the Mississippi Valley (0.13) and highest in the Blue Ridge Mountains (12.70) (Dissmeyer and Stump 1978).

Potential erosion at any site depends on degree of soil disturbance and length of recovery period. Dissmeyer and Stump (1978) measured CP factors on many sites covering all landtypes on federal lands in the South. This factor was revised in some cases by reviewing specific erosion studies. The EISs cite 20 such studies in section IV.F (USDA Forest Service 1989a, 1989b, 1990). Revised CP factors for vegetation management were estimated to be: Zero- light prescribed fires, mowing, ripping, scarifying, selective herbicide treatments, and manual methods; most ground cover intact (or increased, surface storage); no suppression of plant regrowth; 0.002- timber harvest, moderate prescribed fires, broadcast herbicide treatments, and light grazing; minimal bare soil exposed; 1-year recovery; 0.003- chopping, shearing, piling, and moderate grazing; little bare soil exposed; 1-year recovery; 0.006- disking; nearly all soil exposed and tilled; 3-year recovery; 0.015- severe prescribed fires, raking, and bedding; much bare soil exposed; 3-year recovery; 0.060- disking (exposes and tills nearly all the soil); 3-year recovery.

On private land, CP factors were estimated to be 0.003 for pasture, 0.005 for timber harvest, and 0.020 for cropland (Dissmeyer and Stump 1978). Cropland and pasture are annually disturbed and were modeled to erode each year. Timber harvest is a temporary disturbance and was modeled to provide erosion for only 1 year.

Sediment from Channel Erosion

Channel erosion occurs even in pristine areas, increases with peak flow, and is all delivered to streams. Data isolating channel from surface erosion are scarce. The EISs cite 11 studies in section IV.G that either show effects of vegetation management on peak flow or suggest that channel erosion increases in proportion to mean peak flow (USDA Forest Service 1989a, 1989b, 1990). Based on these studies, increases in mean peak flow and channel erosion were modeled to be: 0%- light prescribed fires, mowing, ripping, scarifying, selective herbicide treatments, and manual methods; 40%- timber harvest, moderate prescribed fires, chopping, shearing, piling, bedding, broadcast herbicide treatments, and light to moderate grazing, with recovery taking 1 year; 200%- severe prescribed fires, raking, disking, and heavy grazing, with recovery taking 3 years.

On private lands, increases in mean peak flow and channel erosion are estimated to be 40% for pasture and 200% for cropland. It was assumed that recovery does not occur because these uses are continuous.

Sediment from Surface Erosion

Surface erosion is minimal in pristine areas, is caused by soil exposure and tillage, and is partly delivered to streams. The portion of eroded soil making it to streams is the sediment delivery ratio (SDR). Soil eroded from ridges and upper slopes rarely reaches a stream. The sediment source zone is a streamside area with a variable extent dependent upon drainage density and slope steepness.

Drainage density (kilometers of stream per square kilometer of watershed) was measured on topographic maps and adjusted by field surveys. Adjusted mean values were 1.9 for landtypes with 1-3% mean slopes, 3.7 for landtypes with 5% mean slopes, and 6.2 for landtypes with 10%+ mean slopes. About half the channel network is perennial and intermittent streams. These are protected by buffers on Forest Service land, so the effective drainage density for sediment delivery consists of ephemeral streams only and was modeled to be 0.95, 1.9, and 3.1, respectively (Maxwell 1988).

Swift (1986) found the width of sediment source zone, in meters, to be 12.20 + (0.43 x slope %) for surfaced roads with grassed fills. This zone was used to estimate SDR for areal disturbances such as timber harvest and vegetation management where sheet erosion prevails. Swift found the width of sediment source zone to be 15.24 + (0.91 x slope %) for bare soil roads with unvegetated fills. This zone was used to estimate SDR for roads.

Not all soil eroded from the sediment source zone reaches a stream. Sediment delivery drops with distance from stream. It was assumed that 95% is delivered from the nearest 10% of the zone, and 5% from the farthest 10% of the zone for an average of 50%. Typical SDRs by landtype were thus estimated to be: (1) Lower Coastal Plain; clay flatlands- 0.01; (2) Oak savannahs; rolling uplands- 0.03; (3) Upper hills; loess uplands- 0.05; (4) Piedmont- 0.06; and (5) Mountains- 0.08.

Cumulative Effects

Cumulative effects are the effects of vegetation management plus all other actions in a watershed. In the EISs, one large (9,600+ ha) watershed per physiographic province and one small (1400-4,000 ha) watershed per landtype were studied (Table 1). The landtypes vary in geology, landform, and runoff-erosion response. The studied watersheds cover the full range of probable effects from a wide array of land uses. In each watershed, man-caused sediment was compared with natural sediment yield.

Sediment yield in undisturbed watersheds with good hydrologic condition occurs only from channel erosion. The EISs cite 25 studies in section IV.G.6 that report values of natural sediment yield for various landtypes (USDA Forest Service 1989a, 1989b, 1990). Based on these studies, typical mean annual values of natural sediment yield are: (1) 0.022 Mg/ha in the lower Coastal Plain, Ozark Plateaus, and Ouachita Mountains; (2) 0.034 Mg/ha in the Appalachian Plateaus; (3) 0.045 Mg/ha in the upper and middle Coastal Plain, Piedmont, and Ridge and Valley Province; (4) 0.112 Mg/ha in the Blue Ridge Mountains; and (5) 0.134 Mg/ha in the loess uplands along the Mississippi River.

Man-caused increases in channel erosion and surface-eroded sediment were added to natural sediment yield to derive total sediment yield in each watershed. Channel erosion was computed by multiplying acres treated by the proper increase rate for each practice (above). Surface-eroded sediment was computed by integrating area treated with the proper erosion rate and SDR for each practice.

High timber harvest rates and the vegetation management alternative disturbing the most soil were modeled to show a maximum effect. Major skid trails were assumed to cover 5 and 10% of timber harvest acres on Forest Service and private

Table 1. Land use data for typical watersheds in the Appalachian Mountains, Coastal Plain, Piedmont, and Ozark/Ouachita Mountains of the southern region.

Watershed	Landtype	National forest	Total area	Federal area	Private area			
					Timber	Crop	Pasture	Other
			ha					
Appalachian Mountains								
Davidson	Blue Ridge	Pisgah	10,465	10,465	0	0	0	0
Otter	Narrow Ridge	Washington	2,549	2,197	344	8	0	0
Avery	Blue Ridge Mtn	Pisgah	1,635	1,635	0	0	0	0
North	Unaka Mtn	Cherokee	2,954	2,954	0	0	0	0
Dry	Ridge & valley	Washington	16,422	14,204	2,218	0	0	0
Skidmore	Folded highlands	Washington	4,006	3,925	81	0	0	0
Hillabee	Faulted lowlands	Talladega	2,898	2,622	276	0	0	0
Indian 1	Plateau	Boone	10,117	7,345	2,469	0	287	16 [1]
Barron	Kentucky basin	Boone	2,711	2,509	158	0	44	0
Stony	Cumberland Mtn	Jefferson	2,752	2,331	421	0	0	0
Brushy 1	Table plateaus	Bankhead	3,108	2,849	259	0	0	0
Coastal Plain/Piedmont								
Brushy 2	Coastal Plain	Homochitto	9,656	6,572	2,792	118	174	0
Upper hills	Talladega	3,193	3,161	32	0	0	0	
Cottonwood	Oak savannah	LBJ	3,440	2,064	69	32	1,275	0
Hager	Rolling uplands	Crockett	2,104	1,457	437	20	190	0
Red Prong	Loess uplands	Homochitto	1,902	1,481	385	0	36	0
Buck	Clay lowlands	Bienville	3,282	2,841	311	65	65	0
Ninemile	Sand ridges	Ocala	1,781	1,696	85	0	0	0
Two Barrell	Flatwoods	Apalachicola	1,862	1,829	33	0	0	0
Indian 2	Piedmont	Sumter	22,096	12,465	5,779	1,926	1,926	0
	Midland plateau	Sumter	2,590	2,226	243	81	40	0
Ozark/Ouachita Mountains								
Brock	Ozark plat	Ozark	11,325	9,160	1,056	0	57	1052 [2]
Upper Brock	Boston Mtn	Ozark	3,164	2,962	52	0	4	146 [2]
Goose	Springfield Plat	Ozark	1,428	1,185	0	0	77	166 [2]
So. Ouachita	Ouachita Mtn	Ouachita	11,644	8,481	635	0	1,788	740 [2]
N. Ouachita	Ouachita Mtn	Ouachita	1,849	1,715	0	0	134	0
Little Bigger	Arkansas Valley	Ozark	1,647	1,611	0	0	16	20 [2]

[1] Mine
[2] No management

land, respectively. Site preparation on private forest land was assumed to be all disking. For computing SDRs, filter strips were assigned along perennial and intermittent streams on Forest Service land, perennial streams only on private forest land and nowhere on farmland.

Results and Discussion

Erosion and sediment yield vary a great deal among vegetation management methods in a given landtype. Chopping, shearing, and piling produce about 50% more erosion and sediment than moderate prescribed fires and broadcast herbicide applications; severe prescribed fires and raking produce about 7.5 times more; and disking produces about 30 times more. Table 2 shows potential erosion from some key landtypes in the Coastal Plain and Piedmont.

Table 2. Potential erosion for key landtypes in the Coastal Plain and Piedmont

Landtype	Moderate fire/ broadcast herbicide	Chop/shear/pile	Severe fire/ rake/bed	Disk
	---------- Mg/ha ----------			
Coastal Plain				
Upper hills	0.090	0.134	0.672	2.691
Rolling uplands	0.040	0.061	0.303	1.211
Loess uplands	0.133	0.296	0.999	3.994
Atlantic flatwoods	0.010	0.015	0.074	0.296
Florida sand ridges	0.017	0.025	0.123	0.492
Piedmont	0.165	0.247	1.237	4.949

Erosion and sediment also vary greatly among landtypes for the same vegetation management method. Erosion averages 50-60 times greater in the steep Blue Ridge Mountains than in the level Atlantic flatwoods. Surface-eroded sediment yield due to higher drainage densities and SDRs average 450 times greater. Cumulative 10-year sediment yields also vary widely among the 27 watersheds (Tables 3, 4, 5). Man-caused increases above natural sediment yield range from 5 to 487%. Some patterns noted are:

· In watersheds with over 20% private land, 70-90% of the man-caused sediment comes from private land. The only exception is a watershed in the Ouachita Mountains with a dense road network.

· In most mountain watersheds, forestry practices produce 2-20% of the man-caused sediment. The exceptions are four Appalachian watersheds with large amounts of intensively managed timber land. In these watersheds, roads produce 70-97% of the man-caused sediment. The exceptions are two Appalachian watersheds with large amounts of intensively managed timber land.

· In Coastal Plain and Piedmont watersheds, roads produce < 40% of the man-caused sediment. In watersheds with minimal farmland, forestry practices produce 45-65% except in the flat lower Coastal Plain. In watersheds with only 2-9% cropland, half of the increased sediment comes from cropland.

· In 21 watersheds, intensive vegetation management produces <1-7% of the man-caused sediment. In six watersheds, other activities are limited and produce little sediment, so the vegetation management share is greater. In no case does intensive vegetation management increase sediment yield by more than 7% above natural rates or materially affect a watershed's total sediment budget.

Table 3. Cumulative 10-year sediment yields from typical watersheds in the Coastal Plain and Piedmont.

Source	Brushy 2 [1]	Payne	Cottonwood	Hager	Red Prong	Buck	Nine mile	Two Barrel	Indian 2	Patterson
	Mg									
Natural	12,987 [2]	1,432	1,542	944	2,558	736	399	417	9,907	1,161
USFS										
Roads	96	34	13	33	79	15	8	6	4264	396
Harvest	244	19	209	28	38	4	4	4	266	32
Veg mgt	375	24	9	68	58	9	7	8	494	59
Private										
Roads	385	11	15	83	22	5	1	2	2012	131
Forest	3175	46	25	88	442	6	3	2	8169	343
Crops	1333	0	71	47	0	53	0	0	25,354	1,065
Pasture	611	0	659	139	128	17	0	0	7,676	161
Total increase	6,219	134	1,001	486	767	109	23	22	48,223	2,187
% increase	48	9	65	51	30	15	6	5	487	188
Veg mgt % increase	3	2	1	7	2	1	2	2	5	5

[1] See Table 1 for land use
[2] Mg is metric tons, 0.907 short tons (English units)

Table 4. Cumulative 10-year sediment yields from typical watersheds in the Appalachian Mountains.

Source	Davidson [1]	Otter	Avery	North	Dry	Skidmore	Hillabee	Indian 1	Stony	Barren	Brushy 1
	Mg										
Natural	11,730 [2]	2,858	1,833	3,311	7,363	1,796	1,299	3,402	925	912	1,045
USFS											
Roads	4,215	649	764	2,578	2,155	1,391	257	1,081	859	425	290
Harvest	198	51	40	54	292	54	68	182	72	43	36
Veg mgt	15	3	3	26	28	4	78	88	2	21	30
Private											
Roads	610	684	— [3]	—	785	171	146	1309	361	291	—
Forest	—	168	—	—	816	93	134	913	174	58	50
Crops	—	98	—	—	—	—	—	—	—	—	—
Pasture	—	—	—	—	—	—	—	1139 [4]	—	125	—
Total increase	5,038	1,653	807	2,658	4,076	1,713	683	4,712	1,468	963	406
% increase	43	58	44	80	55	95	53	139	159	106	39
Veg mgt % increase	<1	<1	<1	1	<1	<1	6	3	<1	2	3

[1] See Table 1 for land use
[2] Mg is metric tons, 0.907 short tons (English units)
[3] Land use not present in this watershed
[4] Includes 334 Mg from mined lands

Table 5. Cumulative 10-year sediment yields from typical watersheds in the Ozark/Ouachita Mountains.

Source	Brock[1]	Upper Brock	Goose	So. Ouachita	N. Ouachita	Little Bigger
	Mg					
Natural	2,540 [2]	709	320	2,614	415	369
USFS						
Roads	3,381	807	343	2,605	285	143
Harvest	134	33	21	258	53	31
Veg mgt	83	21	5	53	14	24
Private						
Roads	591	--[3]	19	1,295	191	—
Forest	403	21	—	228	—	—
Crops	—	—	—	—	—	—
Pasture	30	2	34	1047	78	9
Total increase	4,622	884	422	5486	621	207
% increase	182	125	132	210	150	56
Veg mgt % increase	3	3	2	2	3	7

[1] See Table 1 for land use
[2] Mg is metric tons, 0.907 short tons (English units)
[3] *Land use not present in this watershed*

Summary and Conclusions

Several vegetation management methods produce little or no erosion and sediment. Light to moderate prescribed fire, herbicide and manual treatments, and moving, ripping and scarifying offer a wide array of practices that are fully effective in meeting all vegetation management objectives. Applied using the mitigation measures mandated in section II.E of the EISs (USDA Forest Service 1989a, 1989b, 1990), these practices pose minimal risk to soil and water quality.

The factors most affecting erosion and sediment are topography and type of land use. In the South, slope length-steepness (LS) varies 98-fold between the coastal flatwoods and the mountains, and SDR varies eightfold. In contrast, rainfall energy (R) varies only threefold, and soil erodibility (K) varies only twofold. Amount and quality of ground cover (CP) which is based on type of land use, varies 30-fold between 0.002 for moderate prescribed fires or broadcast herbicides and 0.060 for disking.

Effects of intensive vegetation management on sediment yield in the 27 watersheds are minimal. The major sediment sources are agriculture and roads. Forestry practices on federal land, which are usually less intensive than on private land, have minor overall effects. Sediment yield can be reduced further by using less intensive vegetation management methods. Replacing intensive mechanical and severe prescribed fire methods with herbicides, moderate fire, and manual methods would sharply reduce erosion and sediment.

Alternatives selected in the individual EISs did shift the mix of vegetation management methods to less intensive techniques. Sediment yield from these alternatives was only 20-25% of that from the intensive alternatives that were analyzed for cumulative effects. With these alternatives, vegetation management would likely produce < 2% of the man-caused sediment, and increase sediment yield by < 2% above natural rates in the 27 watersheds.

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