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IX. WATERSHEDS: PROCESSES AND MODELING

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Fine Sediment and Fish: Indicators of Natural and Man-Induced Landscape Influences

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Abstract: Fine sediment (< 2 mm), spawning gravel substrates, and fish density and biomass varied greatly on a suite of streams in the White Mountains of east-central Arizona. Although fine sediment was not significantly different in streams on National Forest lands compared to those on the Fort Apache Indian Reservation, percentage of substrate spawning materials (4-16 mm) and fish density and biomass were significantly greater in Reservation streams. We hypothesize 1) that parent geology may be of equal or greater importance than fine sediment in effecting or limiting fish populations in streams and 2) that geologic substrates and processes may mask or override any negative influence of fine sediment that could result from multiple use land management activities.

INTRODUCTION

In streams emanating from forested watersheds, water quality is a critically important value since these streams and their riparian corridors are used for water supplies and provide habitat for wildlife. As human impacts increase across most landscapes, these streams will increase in importance as habitat and refugia for aquatic biota. For salmonid fish and aquatic organisms that form their food chain, fine sediments (<2 mm) can adversely affect their reproductive ability and survivability (Cordone and Kelley, 1961; Bjornn et al., 1977; Everest et al., 1987; and Chapman, 1988).

Sedimentation has long been the most obvious and important concern regarding water quality and aquatic organism habitat. Natural rates of geologic erosion in the USA average 0.6 to 15 Mg/ha/yr. Sediment yields from major river systems in the USA range from 0.03 Mg/ha/yr (St Lawrence River) to 3.8 Mg/ha/yr (Colorado River). Smaller rivers such as the Eel in California can range up to 30 Mg/ha/yr but don't approach the upper limits of sediment yield in the world (140 Mg/ha/yr, Huang Ho River, CHINA). The magnitude and size distribution of these yields reflect the climate, hydrology, geology, soils, vegetation, physiographic regions, and land use history of each basin. Natural rates of sediment yield from smaller, forested watersheds are normally low (<0.1 Mg/ha/yr) but can vary tremendously (up to 5 orders of magnitude; Neary and Hornbeck, 1994).

Except during catastrophic mass wasting events, floods, or where bedrock is naturally highly erosive, sediment is usually not an important problem in undisturbed forest ecosystems. Debris avalanches associated with road construction or tree harvesting can cause major sediment problems (Neary and Hornbeck, 1994). Harvesting can increase natural rates of erosion produced by debris avalanches and other processes by a factor of four, but roading can increase the rate to about 350 times that of undisturbed steepland forests (Platts et al., 1989).

Salmonid females generally construct spawning redds in streambed gravels (6-76 mm) and cobble (76-254 mm), modifying the substrate depending on the size of the fish and the substrate (Chapman, 1988). The construction process and geometry removes fines from the redd and assures sufficient intergravel flow velocities to adequately oxygenate developing embryos. Deposition of fine sediments after salmonid fish spawning clearly reduces survival-to-emergence (STE) of the developing fry (Stowell et al., 1983; Young et al., 1990). Fry STE rates of 80-90% when fine sediments constitute <10% of a redd drop to 15-55% when fines exceed 30%.

Fine sediments moving over alluvial streambeds can be stored for varying lengths of time depending on the relative size distribution of the suspended load and bed materials as well as the flow hydraulics at the point of storage (Jobson and Carey, 1989). Storage of fines can occur by foreset bed formation (resulting in fine bedload dunes), scour and fill processes, straining into the interstices of bedload gravels and cobble, or surface caking. Lisle (1989) found that although suspended sediment constituted 75-94% of the clastic load during 10 stormflow events studied on three different streams, bedload material <2 mm in diameter accounted for 70-78% of the fine sediment accumulated in streambed gravels. Also, he found that fine sediments from scour and fill processes often formed deeper deposits on bed surface materials than caking from deposited suspended fine sediments.

Changes in flows within channels (e.g. irrigation diversions, seasonal low flows, droughts, etc) without the addition of fine sediments usually results in greater amounts of fine sediment deposition due to size-dependent entrainment thresholds (Jackson and Beschta, 1982). Large woody debris can counter this by producing temporary increases in flow velocity and flushing of fine sediments on streambed surfaces.

Most of the literature on the interaction of fine sediment and salmonid fish focuses on the human-caused introduction of fines into streams. As Brown and Krygier (1971) pointed out, sediment yields and characteristics can vary widely between watersheds, years, stream sections, and at given flow volumes. Because of this, entire streams or sections thereof that are gravel and cobble limited will naturally have fine sediment >30%, and naturally have a reduced capability to provide suitable habitat for salmonid reproduction. Rinne (In press) noted distinct differences in the abundance of spawning gravels (8-32 mm) and Apache trout (Oncorhynchus apache) population sizes in streams within close proximity in the White Mountains of Arizona. Watersheds with un-glaciated basaltic bedrock (lava flows) had limited amounts of spawning gravels, higher amounts of fine sediments, and low trout numbers. Nearby streams with glaciated quartz latite geology had abundant spawning gravels, similar percentage fines, and abundant trout.

OBJECTIVES

Bedload of streams is a function of geology of the area, stream hydrographs and influences of land management activity. Over the past decade, data have been accumulated on fine sediment (< 2 mm), fish populations, and stream substrate composition in several dozen streams in the White Mountains. Ongoing research effort is focused on the effects of ungulate grazing on riparian-stream areas on a subset of these streams. Two components of this study are trout populations and fine sediment composition of stream substrates. A basic question is "How does one of the multiple land uses, grazing, affect fish habitat and fish populations?" Data are being collected both in the field and laboratory to address this question. Because data on fish density and biomass and fine sediment are available on a suite of additional streams in the White Mountain area, including the Fort Apache Indian Reservation, it is timely to put the specific study on grazing and land use in general in context of all streams in this area. The objectives of this paper are to: 1) delineate the variability of sediment fines in streams across the landscape; 2) define fish populations in these same streams; 3) estimate the gravel or optimum spawning component (4-16 mm) within streams; and 4) begin to describe the relationship of parent geology, substrate composition, and fish populations.

STUDY AREA

The area of study includes a suite of streams in the White Mountains of east-central Arizona. Streams lie on the Apache-Sitgreaves National Forest and Fort Apache Indian Reservation. Most are first or second order streams within the Black and Little Colorado River drainages (Tables 1, 2, 3). Most have modal, low flows of less than 0.14 m3/s (5 cfs). The Apache Sitgreaves Forest is influenced by standard multiple use management activities; grazing, timber harvest, and recreational hunting and fishing. The landscape encompassing the three streams on the Fort Apache Indian Reservation sustains timber harvest and ungulate (cattle, horses and elk) grazing and recreational (hunting and fishing) activity.

METHODS

Fishes: Fish densities and biomass estimates are based on three-pass DC electrofishing methodology. Stream sections are blocked with seines and sampled from down to upstream three times. Fish are enumerated, weighed (grams), and returned alive to the stream. Three primary species of fishes are variously included in density and biomass estimates; Apache trout (*Oncorhynchus apache*), brown trout (*Salmo trutta*) and brook trout (*Salvelinus fontinalis*). Fish sampled on National Forest streams were collected in 1989 during cooperative research on trout/habitat relationships. Samples from the Reservation were collected during stream renovation of Ord Creek in the late 1970s, during cooperative Forest, State Game and Fish and Tribal Fish and Wildlife GAWS (General Aquatic Wildlife System) surveys and monitoring, Rocky Mountain Station and Tribal cooperative studies in 1995, and National Forest and Research Station cooperative research and monitoring of the West Fork Grazing Allotment in 1993-94.

Substrate, sediment: Substrate composition and fine sediment content of substrates were estimated by a combination of: 1) passive sampling with Whitlock Vibert Boxes in 1988-89 (Wesche et al. 1989); 2) active shovel grab samples in 1994-95; and 3) pebble count methodology in 1995 (Bevenger and King 1995). Fine sediment in this study is defined as 2 mm or less in size. Sediment was washed from Whitlock boxes, dried at 100 C for 24 hours and weighed to provide an estimate of percentage by weight. All boxes contained clean gravel (4-16 mm) and were positioned in gravel substrate (4-32 mm) in streams, left for 6 months before retrieving and processing. Shovel grab samples were also taken in gravel substrates, placed in ziplock bags, transported to the lab, air dried and ultimately oven-dried at 100 C. Composition of samples was separated with 16, 8, 4, and 2 mm sieves. All substrate size classes were weighed after drying and expressed as a percentage of total sample. Pebble count methodology strictly followed Bevenger and King (1995). A minimum of 200 substrate "hits" were made for each stream sample (n = 17; Table 1).

RESULTS

Fishes: Fish density in 1989 ranged from 0.08 fish/m2 to 1.04 fish/m2 and averaged 0.42 fish/m2 on 11 National Forest (Forest) streams (Table 1). Biomass ranged from 0.80 to 16.4 g/m2 and averaged 7.8 g/m2. By comparison, both density and biomass were markedly greater on the three Fort Apache Reservation (Reservation) streams compared to the Forest streams. Intra-stream, linear estimates of fishes on Centerfire and Boggy creeks were markedly higher at upstream sites compared to downstream, meadow sites (Table 2).

Substrate, fine sediment: Fine sediment collected with Whitlock boxes ranged from 7 to 27 (mean = 17) percent by weight in the 11 Forest streams (Table 1). By comparison samples taken by shovel grab samples in 1995 from the same 11 streams ranged from 14 to 38%, averaged 22.1%. Estimates by the two methods, although highly correlated (r = 0.94), were significantly different (P = < 0.001, DF, 10) from each other. Fine sediment estimates made by pebble count ranged from 10 to 60 and averaged 32.2% by weight. Fines estimated by the three methods were highly correlated (Pearson's r = 0.77-0.94). Kruskal Wallis analyses of fines taken by grab samples in 1995 revealed a highly significant difference (P = < 0.0000) in fine sediment among 17 streams across the Forest. Results of Tukey's multiple range analyses are in Table 3. Comparison of estimates of fines in the 11 Forest streams with five sites in the three streams on the Reservation suggested no significant differences (means 22.1 vs 22.8; P = 0.89; DF, 14) in fine sediment. Fine sediment in Reservation streams ranged from 14 to 28 and averaged 22.7 (Rinne In press).

To determine the efficiency of shovel grab methodology, samples were taken in June 1994 during drought conditions and streambed drying in both Centerfire and Boggy creeks. Comparison of ten samples each taken at two sites in Centerfire revealed no significant differences (T = -0.37; DF, 18; T = -1.67; DF,18) between samples collected during surface flow and during drought with a lack of surface flow (19.6 vs 20.62; 14.8 vs 19.4, respectively). Similar comparisons in Boggy Creek also revealed no significant differences between samples collected with and without surface flow (T = -1.71; DF 18, means 21.6 vs 26.5; T = - 0.35; DF, 18; means = 25.6 vs 26.8, respectively).

Gravel substrate optimum for Apache trout spawning (4-16 mm; Harper 1978) and collected in Forest streams by shovel grab sample in 1995, ranged from 3.6 to 32% and averaged 12.8% by weight (Table 1). These substrates in the three Reservation streams ranged from 27 to 48% by weight and averaged 31.4%. Comparison of weights of 17 substrate samples each from the three Reservation streams with estimates from the 17 Forest streams revealed a highly significant difference (P = 0.000, DF, 64). Means for the three Reservation streams (33, 35, 44) were three to four times those on the Forest streams (12.8).

Fine sediment, substrate, fish relationships: Correlation analyses of fine sediment estimated by Whitlock boxes, shovel grab samples and pebble count methodology on fish density and biomass revealed no significant relationships. However, similar analyses using the estimated 4-16 mm substrate component as the independent variable and fish number and biomass as dependents, suggested significant correlations with fish density (P = 0.000) and biomass (P = 0.02), respectively. This substrate size is optimum for Apache trout spawning (Harper 1978) and probably for both brook and brown trout.

Table 1. Comparative substrate fine sediment (< 2 mm; estimated by pebble counts, Whitlock boxes [fines 2] and shovel grab [fines 3] samples), spawning substrate material (4 -16 mm), and fish density and biomass in 11 streams on the Apache Sitgreaves National Forest and three on the Fort Apache Indian Reservation.

Stream	Fines 1 (pebble count)	Fines 2 and 3 Box and (grab) sample	Substrate (4-16 mm)	Fish Density (n/m2)	Fish Biomass (g/m2)
Bear	51	20 (28)	3.6	.29	12.4
Beaver	35	15 (20)	11.6	.16	8.1
Conklin	10	8 (15)	16.0	.50	8.0
Corduroy	32	10 (14)	19.0	.80	9.6
Double Cienega	24	16 (14)	32.0	1.04	8.8
Fish	14	15 (17)	6.8	.08	2.8
K P Cienega	35	18 (24)	14.0	.71	16.4
Hannagan	18	7 (12)	5.5	.35	4.5
Mamie	60	27 (38)	13.6	.05	0.8
Nutrioso	43	25 (33)	6.5	.15	8.0
Paddy	35	26 (31)	12.5	.50	6.0
Ord	--	-- (23)	31.4	1.42*	41.9*
Pacheta	--	-- (19)	35.0	1.25	22.7
Reservation	--	-- (26)	44.0	- --	27.0

* Values from Rinne et al. 1981.

Intra-stream, linear fine sediment estimates in Centerfire and Boggy creeks displayed a slight increase from up- to downstream sites in 1994, however,the same pattern was not obvious in 1995 sampling (Table 2). Comparison of samples by analyses of variance suggest no significant differences (P = 0.07; DF, 45) in intra- stream estimates of fines in Centerfire Creek. However, fines at the three sites in Boggy were significantly different (P = 0.00; DF, 27) between sites in 1995.

Table 2. Comparison of percentage fine sediment (< 2 mm) and fish density (n/km) at up to downstream sites in within Centerfire and Boggy creeks, 1994.

Centerfire Creek				Boggy Creek			
Fish/km		% Fines		Fish/Km		% Fines	
1993	1994	1994	1995	1993	1994	1994	1995
240	218	13	17	330	106	12	--
--	158	13	14	--	160	17	20
7	90	21	20	4	35	26	12
0	25	22	28	0	20	21	26

Table 3. Homogenous groups of sediment samples (n = 10) from 17 Forest streams collected by shovel grab sample in 1995. Homogeneity of groups (produced from multiple range analyses) are indicated by letters.

Hayground	10.7 a*	Beaver	20.0 abc
Stinky	11.6 a	Campbell Blue	20.7 abc
Hannagan	11.7 a	KP Cienega	22.8 abcd
Corduroy	12.9 ab	Bear	27.4 bcde
Double Cienega	14.1 ab	Paddy	32.0 cde
Wildcat	14.3 ab	Nutrioso	32.8 cde
Conklin	14.8 ab	Mamie	37.0 de
Bear Wallow	14.9 ab	Coyote	41.4 e
Fish	16.8 ab		

*Means not followed by the same letter are significantly different at the 0.05 level.

DISCUSSION

Fishes

Fish populations estimated in 1989 for streams in the White Mountains varied widely. Such variations can be attributable to a number of factors. Location of study reaches (see Table 2) and specific habitat factors such as cover, volume, and amount and depth of water, and gradient (Rinne 1978, Marsh 1990) can affect these estimates. Upstream reaches of both Boggy and Centerfire creeks are higher gradient (2-3 %) than downstream, meadow reaches (1 %) with both a greater proportion of streamside alder and larger-sized (> 64 mm) substrate materials. Rinne (In press) demonstrated that significantly greater fish standing crops are associated with streamside vegetation. In addition, sample size (n = 3) and efficiency of 3-pass method can also influence population estimates (Fausch et al. 1988). Further, a standing crop estimate is only a point-in-time estimate of fish numbers and/or biomass with no reference to previous influences (e.g. floods and drought). Data at the same sites through time is necessary to establish the stability or fluctuation of population estimates through time. Nevertheless, fish density and biomass on the three Reservation streams were significantly greater than those on the 11 Forest streams. On a landscape scale, these streams are contiguous. In fact, Forest streams such as Fish, Bear and Conklin displayed low fish density compared to the Reservation streams (Table 1), yet lie adjacent to the Reservation. From a land management perspective, these streams sustain the same land use activities. It seems a paradox that such a difference in fish standing crops should exist on these two adjacent, similarly-managed landscapes.

Fine sediment and spawning substrates

Fine sediment estimates among Forest streams varied significantly with eight separate groupings of 17 streams (Table 3). Estimates made by Whitlock boxes were lowest and shovel grab samples were significantly higher. Estimates of fine sediment made by the pebble count method were the highest. Based on comparison of samples collected during a drought and Grost et al. (1991) the shovel grab sample technique is both efficient and effective in estimating substrate fine sediment. Samples taken by this technique in both streams on the Forest and the Reservation revealed near identical mean percentages of fine sediment composition. In contrast, the trout spawning component of substrate samples (4-16 mm) was highly significantly greater in the Reservation compared to the Forest streams.

Fine sediment, substrate, fish relationships

No relationships could be established between any of the fine sediment estimates and fish standing crops. This can be explained based on both temporal and spatial factors. In time, sediment and fish samples were not taken synchronously and in replication to better establish estimates. In space, variation can even occur linearly in streams as illustrated in Boggy and Centerfire creeks despite both sediment and fish samples being collected during 1993-95 (Table 2). Also, lower gradients in downstream meadow reaches of these two streams would facilitate greater deposition of suspended sediment in these reaches. Marsh (1990) found significant positive correlations between fish standing crop and stream gradient.

An equally important factor in dampening or removing any significant relationship between fish and sediment is that adult fish can survive in presence of elevated sediment levels. It is the spawning segment of the life cycle that is most critical and has been most studied. Two factors, fish age distribution and apparent movements in Boggy and Centerfire creeks, are further evidence to the influence of fine sediment and fish standing crop in these two creeks. In all fish sampling over two years only 5% of all trout collected were young-of-year. In addition, number of adult fish increased in downstream reaches between autumn 1993 to autumn 1994 (Table 2). Increased fish density downstream in 1994 we attribute to downstream migration during spring 1994 runoff by fish formerly residing in upstream reaches of these streams. Further, the influence of streamside vegetation which provides both thermal and hiding cover and stream gradient have to be considered (Rinne In press).

Finally, laboratory studies using artificially-created substrates with varying levels of fine sediment (< 2 mm) suggest, similar to studies with salmonids in the Pacific Northwest, that the threshold of fine sediment percentages negatively impacting STE of Apache trout lies somewhere between 20 and 30% by weight. Preliminary results of laboratory experiments suggest a 13-16 % reduction in emergence compared to controls at 10 and 15 % fine sediment. At 20 % fines, emergence is reduced by 24%. Finally, at 30% fines reduction of STE reached 78% compared to that in controls.

CONCLUSIONS

It has been established in Pacific Northwest streams that land management activities affect salmonid populations in streams (Meehan 1991). We should expect no divergence from this paradigm on upper elevation montane streams in the Southwest. However, evidence suggests that mean fine sediment estimates in streams in this region are below (i.e. < 30%) values critical or limiting to spawning. At the same time, greater availability of spawning gravels (4-16 mm) appears correlated with higher fish populations in streams on the Fort Apache Indian Reservation compared to those on the Forest. Amount of gravel material is controlled, in part, by parent geology. Gravel integrity may be modified and affect trout populations by increase in fine sediment resulting from land uses (Everest et al. 1987, Rinne 1990, Bevenger and King 1995). Stream hydrographs in this contiguous landscape must be similar and not a factor in effecting the significant differences in gravels in White Mountain streams; gravels that are optimum for spawning of Apache trout and most probably brook and brown trout. Geologic processes associated with multiple glaciation on Mt. Baldy and Ord on the Reservation in the middle and late Pleistocene (Melton 1961, Merrill 1970, Merril and Pewe 1971) may have resulted in increased gravel-sized

materials in Reservation streams. By comparison, with increasing distance from Baldy and Ord, both glacial activity and quartz latite intrusions decrease and stream channels reflect weathering of volcanic materials characteristic of the White Mountain Volcanic field. Accordingly, larger (64-256 mm) substrate material predominates in these streams relative to those on the Reservation.

Additional data are needed before it can be conclusively stated that elevated trout productivity results from greater availability of gravel resulting from geologic materials and processes. Intensified sampling of fine sediment, stream substrate characteristics via pebble counts, and fish population estimates are needed on streams flanking Mt. Baldy and Ord and lying intermediate to most of the Forest streams to the east (e.g. Lee Valley Creek, Thompson Creek, East and West Forks of the Little Colorado River) and on additional Reservation streams. Such an approach will provide a spectrum of more detailed data on fish, fine sediment and spawning gravels that will verify if natural, geological parent materials and processes effect trout populations to a greater extent than do land management activities such as grazing and timber harvest.

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SEDIMENT CONCENTRATION IN RELATION TO SURFACE AND SUBSURFACE HYDROLOGIC SOIL CONDITIONS

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Abstract

Soil detachment in headcut development and rilling is an important mode of soil erosion. Yet, little is known about soil and hydraulic conditions that are conducive to this process. Studies in progress attempt to determine soil hydraulic and hydrologic conditions that affect headcut and rill development. In this study, results of selected experiments with different soils are reported concerning the effect of seal development, seal stability, and seal breakdown (the precursor to headcuts) on sediment concentration during rainstorms and surface flow. The soils are a glauconitic sediment, the Ap horizon material of a Neshoba soil, and the Ap horizon material of a Grenada soil. Also, the effect of soil water pressures on sediment concentrations and surface flow rates is determined. The results of this study indicate that seal development and subsurface soil water pressure appreciably affect sediment concentrations. The results also indicate that subsurface pressure may be a critical factor in rill development.

INTRODUCTION

Soil erosion is a complex phenomenon involving many component processes. These processes are usually simultaneously operative during a rainstorm event. Their evaluation is difficult and can only be accomplished under carefully designed and controlled conditions. Even then, substantial difficulties must be overcome as soil removal changes the prevailing hydrodynamic and soil conditions.

Surface flow is probably the most significant factor of soil loss from field size areas. The commonly used concepts for estimating soil removal by surface flow are hydraulic shear (cf. Foster et al., 1977) and stream power (cf. Rose, et al., 1983). These concepts are extremely useful, but their values are temporally and spatially variant due to the rapidly changing flow regime and surface conditions.

In most situations soil erosion by surface flow manifests itself through the development and migration of headcuts which are the precursors to rilling. Yet, little is known about the severity and frequency of headcut development or of the soil conditions and properties that are conducive to headcut development. Therefore, research was undertaken to examine in greater detail critical soil and surface flow conditions for headcut development and subsequent rilling. The early stages of our research focused on surface seal development by rainfall and on subsequent seal breakdown (incipient rilling) by overland flow. Of particular interest were factors that impact these processes such as rainfall intensity, slope steepness, and soil type. In this paper some aspects of this ongoing research will be discussed and selected experimental findings will be reported. The objective is to present a general view of this research, its approaches, and preliminary findings.

EXPERIMENTAL APPROACH

Simulated rainfall and surface flow studies were conducted on a slope adjustable flume of 3.70 m x 0.61 m x 0.23 m packed with soil to a constant depth of either 0.165 m or 0.22 m. The flume was complemented with (1) a three-nozzle (nozzle spacing 1.64 m) multiple intensity rainfall simulator, similar in design and concept to the single nozzle, multiple intensity rainfall simulator described by Meyer and Harmon (1979); (2) a removable laser microreliefmeter (Römkens et al., 1988); (3) a fast response tensiometer system (cf. Römkens et al., 1990); and (4) a drainage system in which free water was aspirated to a flask placed on a balance. A schematic diagram of the experimental set-up with many of the indicated features is shown in Fig. 1.

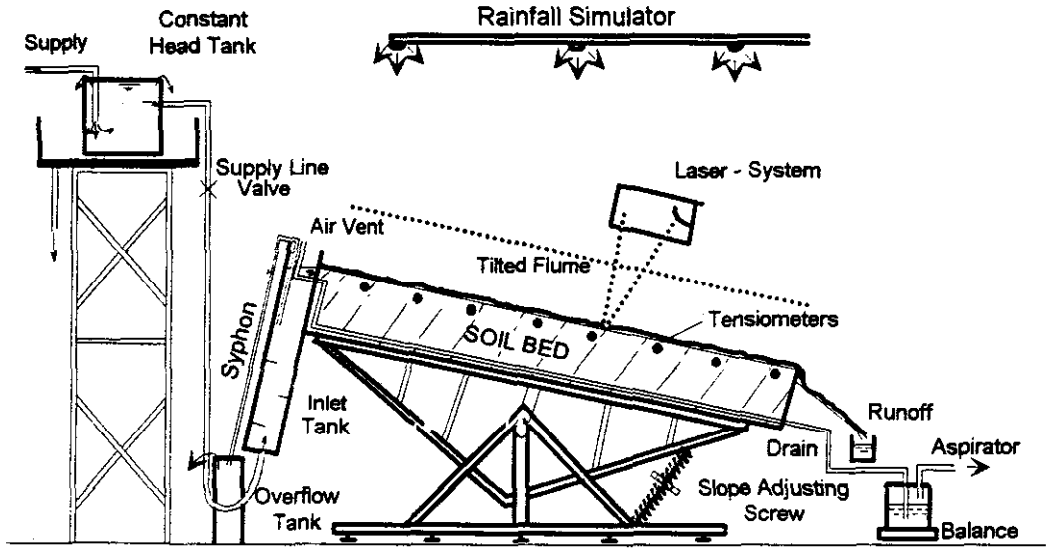

Figure 1. A schematic diagram of the adjustable flume with rainfall simulator, laser microreliefmeter, tensiometer system, and subsurface pneumatic pressure control.

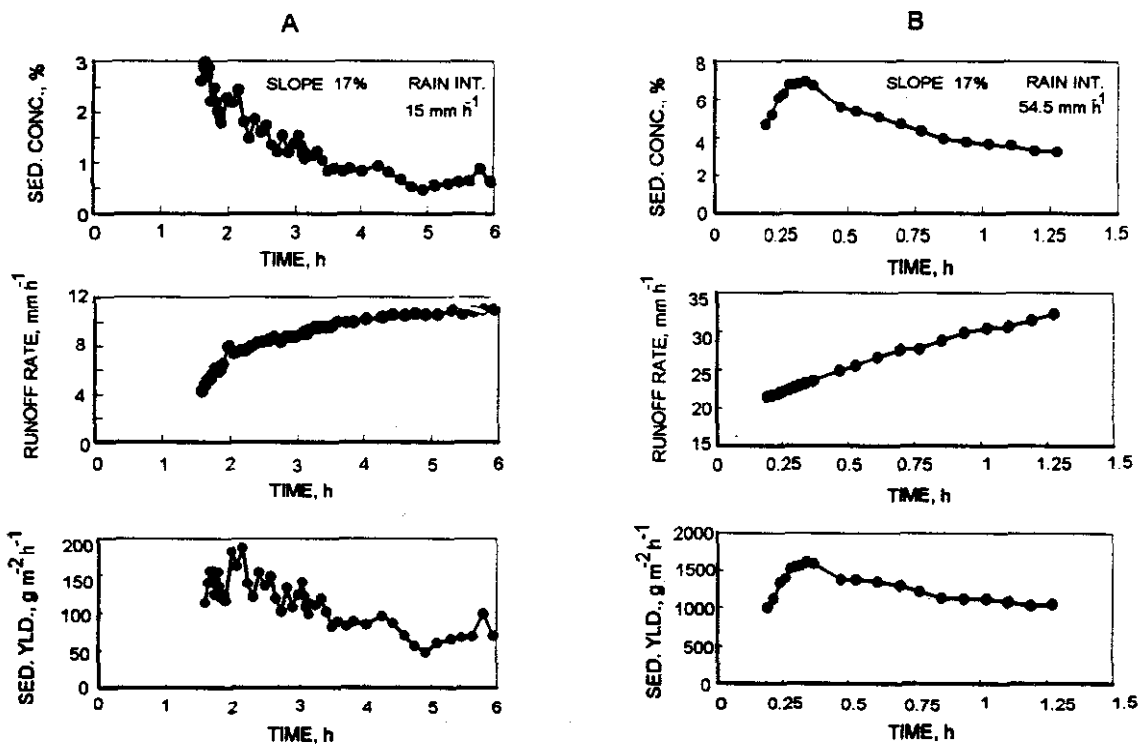

Figure 2. Sediment concentration, surface runoff rate, and sediment yield for the glauconitic sediment and Neshoba Ap material of 17 % slope steepness and rainfall intensities of 15 and 54.5 mm/h, respectively.

A : Glauconitic sediment ; B : Neshoba Ap

Rainstorm Characteristics: Depending on the specific objective of a given experiment, rainstorms applied were of constant intensities of either 15, 30, 45, or 60 mmh^{-1} and usually lasted from 0.5 to 3 hours. In experiments, involving several storms with different intensities, the total energy for each rainstorm was constant by adjusting the storm duration using the relationship

$$E_t = E_k \cdot I \cdot t = \text{constant}$$

where E_t is the total rainstorm energy, E_k is the rainstorm energy rate (0.027 kJm^{-2} per mm) I is the rainstorm intensity, and t is the rainstorm duration.

Surface Flow Regime: Water was delivered to an inlet tank attached to the upper end of the flume with a soil bed. Water was admitted to the soil bed over a level, baffled edge on the downstream side of the tank and regulated with different size valves in the supply line to the inlet tank and different size syphons draining the inlet tank. The maximum flow rate attainable was about 20 $m^3m^{-1}h^{-1}$ and the coefficient of variation for a given supply valve setting and syphon was about 0.25%.

Soils: Several soils were studied in various phases of this research. These are: (1) the parent material of a Ruston silt loam (fine loamy, siliceous, thermic, Typic Paleudult) taken at a depth of about 3 m (20.0% clay, 2.9% silt, 77.1% sand, <0.01% Org. C, pH 1:1 H_20 5.3, pH 1:1 1N KCl 4.0). This material is a marine deposit, consisting of glauconitic, fossilerous sand of which 40 to 60% of the pellets is unweathered (Nash et al., 1988). The material was chosen because of its sealing susceptibility (Römkens et al., 1995a) following addition of $Ca(OH)_2$ due to its appreciable iron content (2.9%, CDB-extractable) and its ready availability. This soil was taken at a depth of about 3 m from a borrow pit on the south side of Mississippi State Road 16, about 2.8 km west of the Administrative Offices of the Choctaw Indian Reservation in Neshoba County, Mississippi. (2) The Ap material of a Neshoba soil (clayey, mixed, thermic, Rhodic Paleudult) was taken from a forested site (> 20 year), west of St. Rd. 19 and about 12 km south of Philadelphia, Mississippi, (5.8% clay, 47.6% silt, 46.6% sand, 1.6% Org. C, pH 1:1 H_20 5.6, pH 1:1 1N KCl 4.4). (3) The Ap material of a Grenada silt loam (fine silty, mixed, thermic, Glossic Fagiudalf) was taken from the Mississippi Agricultural and Forestry Experiment Station at Holly Springs, Mississippi, (19.4% clay, 75.1% silt, 2.4% sand, 1.1% Org. C, pH 1:1 H_20 5.8, pH 1:1 1N KCl 5.5).

Soil Bed Preparation: Crushed, air dried soil was packed in incremental layers of about 25 to 40 mm thickness into the flume, first by uniform spreading followed by tamping to obtain a compacted bed with a density of about 1.4 to 1.5 Mgm^{-3}. The upper 50 mm of the soil bed consisted of soil material sieved to pass a 2 mm screen. For smooth surfaces, a scraper consisting of a straight-edged knife that narrowly fitted the width of the flume produced a flat soil surface in which variations in surface elevation over a cross section were less than 1 mm. Rough surfaces, simulating seedbed conditions, were obtained by placing in a random manner aggregates and clods on the soil bed prepared as before. Details of soil bed preparation and experimental procedures are given elsewhere (Römkens et al., 1995b; 1995c).

Studies: Several studies were conducted in which combinations and/or sequences of rainstorms and surface flow were applied to prepared soil beds. They include: (1) breakdown by overland flow of surface seals developed during rainstorms of different intensities; (2) the effect of slope steepness on surface seal breakdown by overland flow; (3) subsurface hydrologic influences on soil detachment; (4) rill development in relation to rainstorm regimes such as intensity, sequences of different storm intensities, roughness, etc. These studies were designed to focus on selected aspects of soil erosion, surface seal development, and rill formation. Only selected results will be presented and discussed.

RESULTS AND DISCUSSION

Surface Seal Development: The effect of surface seal formation on sediment concentration and sediment yield during rainstorms is not well understood. On one hand, surface sealing reduces infiltration, thereby, increasing runoff and thus the erosive power of runoff. On the other hand, seal formation due to drop impact imparts a degree of smoothness and compaction of the soil surface that tends to increase soil strength and promote the soil resistance

to detachment by flow. Which of these opposing effects dominates in a given situation probably depends on a combination of factors including soil type, antecedent conditions, and the prevailing hydrologic and hydraulic regimes. In most experiments that we have conducted on an initially dry compacted soil and a flat soil bed, the sediment concentration in runoff decreased with time, until a "breakdown" in the soil surface occurred. Then a sudden, at times sharp, increase in the sediment concentration was observed. Fig. 2 shows the sediment concentration, water runoff rate, and sediment yield relationships of runoff as a function of time for two of the soils studied: the glauconitic sediment and the Neshoba Ap horizon material. In both cases, the sediment concentration and yield decreased appreciably with time during a rainstorm following ponding even though water runoff rates increased. This indicates the decreased detachability of the soil as the rainstorm progressed even though the erosive power and transport capacity increased. The reduced detachability of the soil reflects the changing nature of the soil surface matrix, which is associated with surface seal development. The data also suggest that the two soils differ appreciably in the dynamics of surface sealing.

Surface Seal Stability: The effect of surface sealing on detachment by overland flow can be very substantial and can differ appreciably among soils. Fig. 3 shows runoff and sediment concentrations for 3 soils tested with various surface flow rates after an initial rainstorm on an air-dry soil bed. After a seal was formed during the rainstorm phase, the glauconitic sediment showed no detachable soil loss with flow rates of as much as 18 to 20 m^3h^{-1} per m following a 3-h rainstorm of 15.5 mmh^{-1} intensity on an initially dry soil bed of 16.5% slope steepness. The Neshoba surface soil showed extremely low sediment concentrations (0.03%) during a successive series of constant surface flow rates of 0.5 h duration each, following the application of a 2.5 h rainstorm of 54.4 mmh^{-1} intensity on a 16.5% slope steepness. On the other hand, appreciable sediment concentrations were measured in surface flow on the Grenada silt loam following a 3-h rainstorm of 15 mmh^{-1} intensity and 8% slope steepness. Only two 30 min. surface flow rates, the maximum flow rate being equivalent to 775 mmh^{-1} of rain, were needed to yield appreciable sediment concentration. This soil, however, showed evidence of incipient rilling during the rainstorm regime. The results of these tests show appreciable differences in seal stability among these soils and in their ability to resist breakdown by overland flow. We do not know what soil properties or lack of properties cause these differences in sediment yield. At this point, both physical (interlocking of grains) due to drop impact effects in the Neshoba Ap soil and physico-chemical effects (dispersed clay material in the void space between the compacted sand size particles in the glauconitic sediment are thought to be important factors. No specific explanation can be given for the response of the Grenada silt loam. Our tentative conclusion is that the greater the contrast in the structural and density characteristics between the sealing zone and the underlying substrate, the more severe erosion occurs once surface flow breaks through the surface seal.

Surface Seal Breakdown by Overland Flow: Circumstantial evidence indicates that the subsurface antecedent soil water content substantially affects the stability of soil surface seals. Fig. 4 shows the water runoff rate, expressed in mmh^{-1}, as a function of time during a 2.5-hour 55 mmh^{-1} rainstorm on the glauconitic parent material of the Ruston silt loam of 8.9% slope steepness. Experiment 1 was conducted on an initially air dry soil bed, while experiments 2 and 3 were conducted on a soil layer of which only the upper 30 to 40 mm was initially air dry and the remainder of the profile was partially wet. Whereas the surface seal retained its stability during most of the rainstorm in experiment 1, seal failure in experiments 2 and 3 occurred at much earlier times into the rainstorm. Similar experiences were obtained in experiments with slope steepness of 12.5%. Seal failure in these instances was associated with vents of escaping compressed air (increase in the pneumatic pressure potential), return flow, and the generally larger soil water pressure potential. Seal failure was reflected by sudden increases in the sediment concentration and by increased runoff rates. In these cases, as calculations would show, breakdown occurred when the wetting front in the initially dry soil in the upper 30 to 40 mm reached the wet substrate. The subsurface water pressures rapidly increased leading to a decrease in the infiltration rates, a breakdown of the developing seal and an increase in the sediment concentration. Breakdown on this soil was usually "catastrophic." That is sharp increases in sediment concentration occurred and incipient rilling leading to headcut development and growth were visible.

Subsurface Pressure Effects on Soil Detachment: In soil erosion studies, the effect of subsurface water pressures on soil detachment is usually ignored. Yet, subsurface conditions may appreciably affect the soil erosion processes. Fig. 5 shows the effect of subsurface pressure on sediment concentration and surface runoff for the Grenada silt

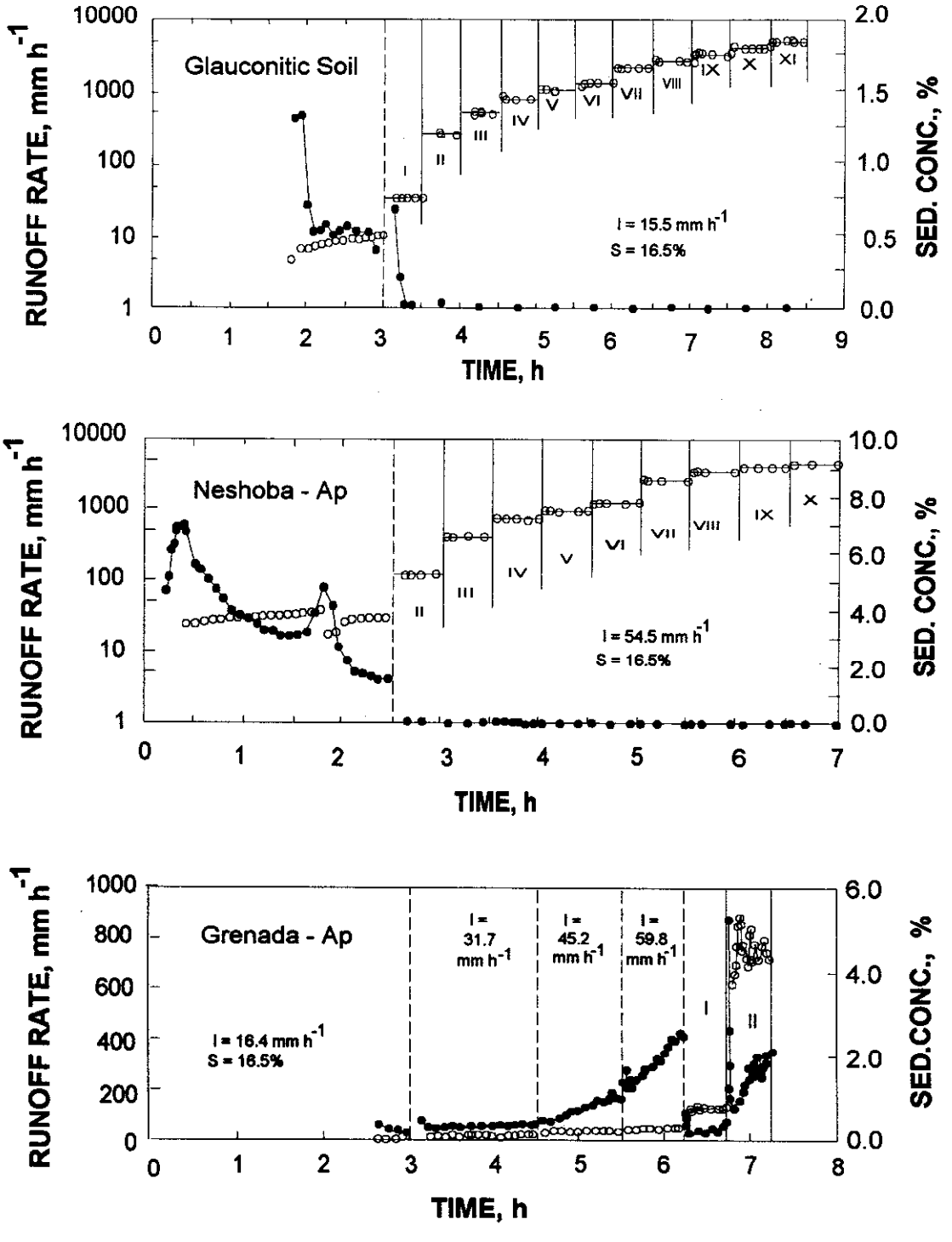

Figure 3. Sediment concentration and runoff rate for the Glauconitic sediment , Neshoba Ap - material, and the Grenada silt loam Ap - material, under different rainstorm intensities (= I), slope steepness (= S), and surface flow rates. The Roman numerals represent successive stages of surface flow rates. • represents sediment concentration, ○ represents runoff rate.

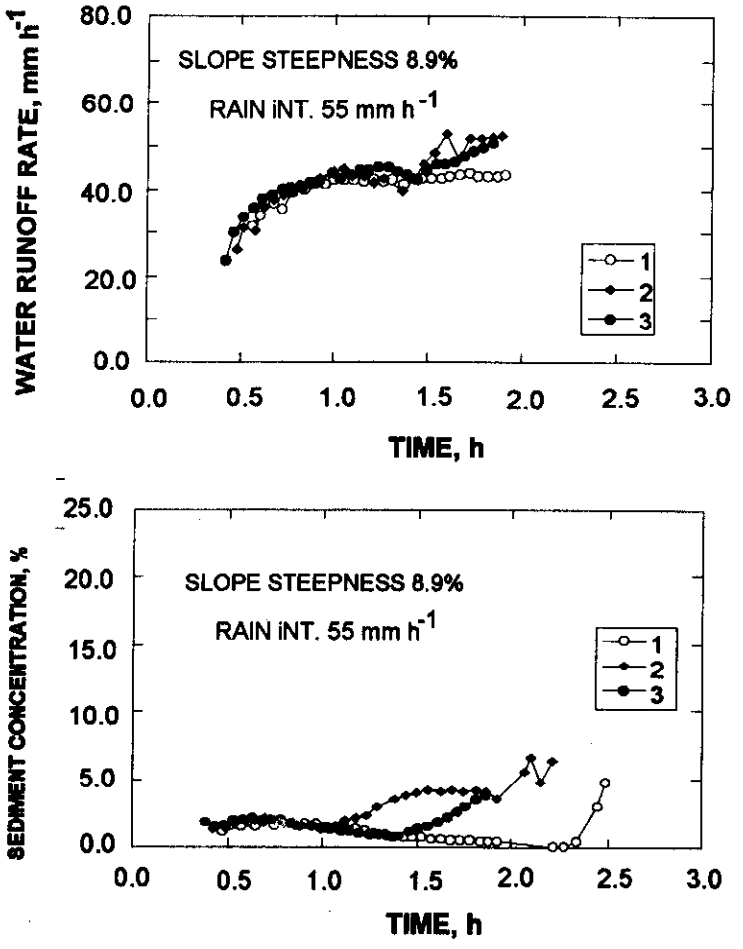

Figure 4. Sediment concentration and water runoff rate for a Glauconitic sediment at 8.9 % slope steepness during a 2 - h rainstorm of about 55 mm/h intensity. 1 : Initially dry soil, 2 : Upper 30 mm soil is initially dry, 3 : Upper 30 mm is initially dry and the bottom 30 mm is sand.

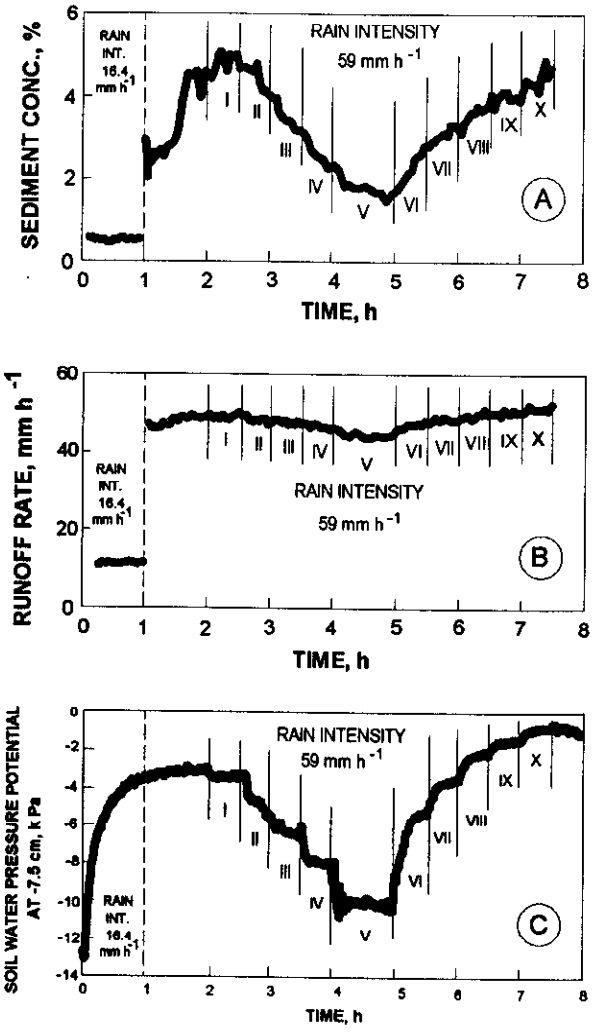

Figure 5. Sediment concentration (A), runoff rate (B), and soil water pressure potential (C), during a 7.5 - h rainstorm on an irregular topographic bed with rainstorm intensity of 16.4 mm/h (0 - 1 h) and 59.0 mm/h (1 - 7.5 h).

loam soil bed of 8.0% slope steepness. The initially wet soil bed previously used in a roughness study, was first subjected to a 1-h rainstorm of 16.4 mmh^{-1} to stabilize (quasi-state equilibrium) the soil bed and the degree of wetness, and then subjected for another 6.5 hours to a rainstorm of 59.0 mmh^{-1}. During the latter storm, the subsurface pressures were stepwise changed each 0.5 h by adjusting the pneumatic pressure, first by a series of decreases then by a series of increases until the initial subsurface pressure was re-established. The effect of changes in the pneumatic pressure on the matrix potential is shown in Fig. 5c for a tensiometer placed in the slope bed at about 7.5 cm below the soil surface. The matrix potential decreased from about -3.5 kPa at the beginning of the storm to about -10 kPa at the lowest subsurface pressure about 4 to 5 hours into the storm and then increases to about -0.75 kPa at the end of the storm. The effect of the subsurface pressure changes on soil detachment as measured in the sediment concentration is very dramatic as shown in Fig. 5a while the effect on the runoff rate as shown in Fig. 5b is minimal. This finding demonstrates that subsurface matrix potential may indeed substantially affect soil detachment during rainfall. Based on this finding and on those discussed in the previous section of this article, we postulate that headcut development and rilling are appreciably affected by the subsurface water potential regime. However, this hypothesis needs further study in focused experiments and needs to be explored in relation to different soil types, rainfall intensity regimes, surface flows, slope steepnesses, coupled with actual morphological observations of headcut development and migration.

SUMMARY

Laboratory research is in progress to determine the hydraulic and hydrologic influences on sediment concentration, headcut and rill development. Three soils with different sealing susceptibilities and stabilities were studied. The experimental approach consists of applying rainfall and surface flow to prepared soil beds in a tilted flume. Rainstorms and sequences of rainstorms of different intensities followed by surface flow regimes were used to determine seal development, stability, and conditions of seal failure. In a highly sealing susceptible soil, a glauconitic sediment with a well-structured substrate, sudden steep increases in the sediment concentration accompanied by headcut development and rilling were observed. In another soil with less structural difference between the sealing and subseal zones, the Neshoba soil, rilling did not occur. Subsurface matrix potential appreciable impacted the sediment concentration in runoff from a Grenada silt loam soil. It is postulated that subsurface pressures impact in a substantial way the development of headcuts and rills.

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USE OF LAND SURFACE EROSION TECHNIQUES WITH STREAM CHANNEL SEDIMENTATION MODELS

by

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Abstract: The objective of this paper is to present methods that can be used to estimate the quantity and gradation of sediment produced from a watershed. These values are necessary for mobile boundary hydraulic modeling and other sedimentation studies. These quantities are needed for designing flood control channels, estimating sediment deposition in reservoirs or navigation channels, and evaluating the sedimentation impacts of proposed projects or land use modifications. Considerable information is available for the estimation of sediment yield from a watershed. These methods use both empirical techniques and land surface erosion theory. The same is true for quantifying sediment transport and sorting processes in rivers. This paper focuses on procedures for using land surface erosion computations to develop the inflowing sediment load for a river sedimentation model, specifically, HEC-6.

Included herein are the results of an assessment of numerical models for the prediction of land surface erosion (HEC, 1995). It was concluded from this assessment that these models have not yet evolved from the experimental/developmental phase to routine engineering use. Therefore, this paper presents a suggested strategy for the use of several traditional methods of computation of land surface erosion to prepare inflowing sediment loads for the operation of HEC-6.

INTRODUCTION

Considerable information is available on estimating the sediment yield from a watershed using both empirical methods and land surface erosion theory (Haan et al., 1994, Barfield et al., 1981, Kirby and Morgan, 1980, and Tatum, 1963). The same is true for quantifying sediment transport and sorting processes in rivers.

Sediment production and transport in a watershed are influenced by a complex set of geomorphic processes that vary in time and space. Important erosion processes include soil detachment through raindrop impact and overland flow, rill erosion and transport, gully erosion, channel degradation and bank erosion, various types of surficial gravity erosion, and wind erosion. Other processes that can contribute to the total watershed sediment production may include channel bank and hillslope failures, landsliding, forest fires, and debris flows. Land use practices such as logging and clearing, grazing, road construction, agriculture, and urbanization activities also affect sediment production and delivery from a watershed. Sediment production may vary significantly with long-term cycles in drainage system development and rejuvenation, and zones of sediment production and/or deposition may shift in location with time (e.g. headward movement of nick points and/or channel migration and avulsions).

Spatial and temporal variations in physical and biological features of the watershed make estimation of sediment yield an extremely difficult and imprecise task. Important variables include soils and geology, relief, climate, vegetation, soil moisture, precipitation, drainage density, channel morphology, and human influences . Dominant processes within a watershed may be entirely different between physiographic or ecological provinces, and may change with time. The problem becomes even more complex when grain size distributions and sediment yield for particular events must be estimated for input to sedimentation models such as HEC-6 (HEC, 1993) and WES-SAM (WES, 1992). At the present time, there is no widely accepted procedure for computing basin sediment yield and grain size distribution directly from watershed characteristics without measured information.

REVIEW OF WATERSHED EROSION MODELS

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) is a simple mathematical expression which is the most widely used method for estimating total annual sediment discharge from land surfaces resulting from sheet and rill erosion. The Modified Universal Soil Loss Equation (MUSLE) (Williams 1975) is an altered form of the USLE for applications to single storm events. The USLE is an empirically based lumped parameter model which does not define separate hydrological processes such as rainfall, infiltration, and runoff, or fundamental erosional processes such as detachment by raindrop impact, detachment by flow, and sediment transport and depositional processes. The USLE also neglects channel and gully erosion.

Research in the field of land surface erosion has progressed to focus on the physical processes which influence sediment detachment and transport. Yalin (1963) formed a widely used equation which represents the transport capacity in an erosive model through combining rill and interrill flow. Continuing research on interrill erosive processes such as raindrop impact and sediment delivery by Palmer (1965), Young and Wiersma (1973), Mutchler and Young (1975), and Walker et al. (1977) among others indicated that conditions of interrill transport differ from fluvial transport in two areas: soil surfaces in interrill areas are generally more cohesive and finer grained than alluvial bed material, and transporting forces are supplied both by flow and raindrop impact in the interrill areas.

The rapid advancements in computer technology over the past 20 years has allowed for the widespread application of state-of-the-art erosion prediction technology. There are many hydrologic models available today that have the capability of simulating sediment discharge, transport, and deposition in a watershed. Combined sheet and rill erosion can be predicted through the use of empirically-based models or physically-based models. An indicator of physically-based models is the subdivision of the surface into rill and interrill areas of separate erosion processes.

Continuing research on the physics of rill and interrill sediment discharge has greatly augmented the understanding of watershed erosive processes. However, the application of physically-based models to large watersheds, for which sufficient sediment yield and runoff data are often unavailable, is not a common practice. Furthermore, the physically-based models contain equations with constants and exponents that must be determined for each watershed, and the subdivision of a large watershed into rill and interrill areas would require an enormous amount of time and effort. In contrast, empirical models require information on topography, soils, precipitation, and land use that can be estimated from maps and simple field surveys. In modeling decisions, care must be taken that the level of detail of the erosion processes represented by the numerical model and field data is commensurate with the objectives of the application. A summary of the models reviewed (HEC, 1995) is provided in Table 1.

ESTIMATING SEDIMENT SOURCES

Table 2 lists sediment yield estimation techniques that may be considered for particular applications. The table includes several empirical computation methods, two comparative methods (aerial photography and topographic surveys), and three regional relationship methods (Dendy and Bolton, 1976, Strand and Pemberton, 1982, and SCS Yield Rate Maps and local or regional soil loss/yield rate estimates from soil and water conservation agencies).

Table 1
Comparison of Land Surface Erosion Models

Model Characteristic / Model Name	SP	AGNPS	RUNOFF	WEPP	KINEROS	KYERMO
Proprietary	No	No	No	No	No	No
User's Manual available	Yes	Yes	Yes	Yes	Yes	--
Computer needs	PC	PC	PC	PC	PC	PC
Current version number	--	3.65	3.0	91.5	--	--
Most recent update	3/89	6/92	6/92	9/91	5/89	7/87
Single event yield analysis	Yes	Yes	Yes	Yes	Yes	Yes
Average annual yield analysis	No	No	No	Yes	No	No
Division of watershed into subbasins	No	Yes	Yes	Yes	Yes	Yes
Raindrop impact detachment	No	No	Yes	Yes	Yes	Yes
Rill and interrill erosion processes considered separately	No	No	No	Yes	Yes	Yes
Rill formation processes modeled	No	No	No	No	Yes	Yes
Channel transport/deposition	No	Yes	Yes	No	No	No

GENERAL PROCEDURE FOR ESTIMATING SEDIMENT YIELD

Potential methods for estimating sediment yield in ungaged catchments include: (1) application of regression equations based on detailed basin characteristics like rainfall intensities, soil properties, ground cover, etc., (2) use of regional relationships based on global basin characteristics like drainage area, altitude and slope-aspect ratio; (3) transposition of data from similar basins where reliable data are available; (4) integration of annual or single event yields from stream sediment rating curves and flow-duration curves or hydrographs; and (5) application of empirical methods. Any estimate should account for: (1) sheet, rill and interrill erosion from upland land surfaces; (2) gully erosion, stream bed and bank erosion; and (3) mass wasting processes in the basin. In practice, it may be necessary to apply more than one estimation procedure to account for all three. The following general steps are necessary to estimate basin sediment yield. Several of these steps may require iterative applications and adjustment in order to develop reasonable estimates.

(1) Perform field inspection and review of available data. Discuss observations and results from previous studies with local SCS field office, USGS field survey people, County flood control and channel maintenance personnel, and Corps of Engineers hydrology and hydraulics personnel.

(2) If little or no data are available, prepare a field sampling program to at least collect several bed material and bank material samples from sediment source areas and stream channel locations upstream and through the study area. Perform standard sieve analyses and settling tests on the samples.

(3) Examine published long-term daily discharge records and sediment gage records. The standard procedure used by the USGS is to plot the daily water discharge hydrograph and the daily sediment concentration graph, then integrate them as prescribed by Porterfield (1972). Results from this exercise are expressed in t/day. Before comparing sediment yields, the period-of-record data should be examined for homogeneity. Adjustments for

upstream reservoirs, hydrologic record, land use changes, and farming practices may be necessary before the correlation between sediment yield and water yield can be established.

Table 2
Sediment Source Estimation Techniques

Method	Sheet and Rill Erosion	Gully Erosion	Channel Bed and Bank Erosion	Mass Movemen t	Average Annual Yield	Single Event Yield
USLE					*	
MUSLE						*
RUSLE					*	
PSIAC					*	
Aerial Photography					*	*
Topographic Surveys					*	*
Thompson or SCS TR32					*	
Dendy and Bolton					*	
Strand and Pemberton, USBR					*	
SCS Yield Rate Map					*	

(4) Develop the daily water discharge - suspended sediment load rating curve from gage data. Integrate the flow duration curve with the measured sediment load - discharge rating curve to develop a good representation of the process-based average annual yield. (Details of how to prepare these curves and compute these values are summarized in (USACE, 1989).

(5) When no field measurements exist, and at least some are required to make dependable sediment yield estimates, a limited sediment sampling program is highly recommended early in the planning phases of the study. This level of short duration sampling is often referred to as "flood water sampling." Caution is necessary, however, because the short record data set will not necessarily provide a representative sample of watershed processes for the full range of possible hydrologic conditions. Therefore, these data are less dependable than the flow duration sediment discharge rating technique. The lack of large flood data may bias the yield results.

(6) Apply several regional analysis procedures (Tatum, 1963, Dendy and Bolton, 1976, and PSIAC, 1968) to estimate average annual yield. Compare the results to published information or reports obtained from other studies in the area. Compare the yields by plotting yield vs. effective drainage area. Attempt to establish upper and lower bounds on the yield - drainage area curve for low, average and high sediment production years (MacArthur et al., 1990). Use this range of yield values during sediment load sensitivity studies.

(7) Use one or more yield estimating equations to estimate the average annual and single event sediment yields for a range of events (e.g., USLE, RUSLE, PSIAC, MUSLE).

(8) Multiply your gross sediment yields by an appropriate sediment delivery ratio (SDR) if necessary to give the net sediment yield at the project location. For more information on how to estimate the sediment delivery ratio and when to apply it, refer to (USACE, 1989) and (Haan et al., 1994).

(9) A quick method for estimating single event sediment yields involves application of several reliable "annual yield" estimating methods to establish the average annual yield first. Then, assume that an equivalent amount of sediment to the average annual yield occurs during a 2-year event. Also assume that greater single event yields can be approximated by the linear extrapolation of the annual value by multiplying the annual yield by the ratio of the peak single event water flow to the 2-year flows.

$$\text{Yield}_i = \text{Yield}_{AvgAnn} * Q_i/Q_2$$

where Yield_i is the single event yield for an ith-year storm event and Q_i is the peak water discharge for the ith-year event.

This method is only recommended as a procedure for establishing rough estimates of single event yields and for cross-checking values developed by other methods.

(10) Another procedure for estimating single event and average annual yields is through the application of the MUSLE single event yield method. Use the MUSLE procedure to develop single event yield estimates for the 5-, 10-, 50- and 100-year events. Convert the single event sediment yields to an average annual value (if applicable) by integrating the sediment yield vs. probability curve. Compare this value with observed reservoir annual yield data and/or computed annual yield values. Select the most reliable value for annual yield. A detailed example is presented in (HEC, 1995).

(11) Decide whether gully, stream bank erosion or mass wasting processes are active in your study basin. Determine whether your selected annual and single event estimating procedures adequately account for these processes. No generalized analytical procedures are presently available to explicitly calculate these types of sediment production for the full range of possible events. Measured data are obviously the most reliable source to use; otherwise application of empirical relationships and the careful examination of pre- and post-flood event photographs are necessary.

When time, data, and budget permit, process-based erosion and yield models can be used to develop average annual and single event yields. Application of process-based erosion and yield models is generally complex and requires detailed data collection for development of model input parameters and calibration.

ESTIMATING SEDIMENT DISCHARGE CURVES AND GRAIN SIZE DISTRIBUTION RELATIONSHIPS FOR USE IN MOBILE BOUNDARY MODELS

The following sequence of study components was prepared from our experiences with HEC-6 applications and other types of sediment and river engineering investigations.

(1) Collect representative bed material sediment samples through the project reach (USGS, 1978). Develop grain size distribution curves for each bed and bank sample and plot the representative grain sizes (D_{50}, D_{84} and D_{10}) with distance from downstream to upstream.

(2) Develop a sediment gradation curve for the wash load using measured data or watershed soil surveys. If there are no data, apply Einstein's (1950) assumption that the largest representative size present in the wash load is approximately equivalent to the D_{10} of the bed material load. Using this assumption and soil survey data regarding the approximate percentages of sands, gravels, silts, and clays, develop an approximate grain size

distribution curve for the wash load fraction of the total load.

(3) Estimate the fraction of the total sediment load that travels as bed material load and the fraction that travels as wash load. One method involves using HEC-6 through an iterative procedure to synthesize its own inflowing bed material load and gradation from the grain size distribution curves measured in the field. Wash load is then computed as the difference of the total sediment yield volume or weight and the HEC-6 estimated bed material load. Another method develops the bed material load by starting with the estimated total sediment load from the computed basin yield. The approximate percentage of bed material load to total load is estimated from information and data measured in the study area. Because there are no established rules of thumb for the ratio of bed material load to total load, one assumes a value based on field observations or measured information and checks to see if that assumption is reasonable (see step number 6). If it is not, new percentages are assumed and checked until the estimated bed material load produces reliable results. Example computations are given in (HEC, 1995).

(4) Develop a composite total load gradation curve by combining the bed material gradation data and curves with the wash load gradation data and curves.

(5) Apply the Corps' SAM procedures (Thomas et al., 1992) to estimate bed form-dependent *n* values. Also utilize SAM to select the most appropriate transport function for a particular river type. Check to see if the river is capable of carrying the estimated single event sediment load using SAM or HEC-6. Determine whether the river through your study reach is "supply limited" during large events or "transport limited." If it is sediment supply limited, channel bed and bank erosion may be important. If it becomes transport limited during large events, sediment accumulation and possible channel avulsion may occur.

(6) Once the total inflowing load curve is complete and an appropriate transport function(s) is selected, use them in HEC-6 or other stream sedimentation models to determine if the estimated load and gradations are in balance with the stream hydraulics and basin yield estimates. If significant deposition or scour occurs in the first few upstream cross sections, then the inflowing load may require adjustment. Once the model performs properly and the computed HEC-6 results appear stable, compare the volumes of total load, bed material load and wash load to observed data. Make adjustments to the load, grain size distribution or transport function according to procedures outlined in the HEC-6 User's Manual, CPD-6, (HEC, 1993) and TD-13 (HEC, 1992).

(7) Perform model calibration and sensitivity studies according to guidelines provided in Chapters 3, 5 and 6 of CPD-6 (HEC, 1993) and Section 3.5 in TD-13 (HEC, 1992).

PREPARATION OF MODEL DATA

Calibration and Performance Testing: Following the development of the basin sediment yield estimates and the necessary model input data, conduct model calibration and application procedures according to Chapters 4 and 5 in TD-13 (HEC, 1992). Check model geometry data for accuracy and completeness, then check the model's ability to duplicate natural river hydraulic conditions for low flow, bank full flow, and high flow. Begin testing using fixed bed computations first and then proceed to movable bed conditions. Apply SAM (WES, 1992) procedures to (a) select the most appropriate transport function, (b) estimate natural channel *n* values linked to channel roughness and bed form. Use methods outlined above to develop the total inflowing sediment load curve and grain size distributions.

Once the total inflowing sediment load curve has been developed, it must be tested to see if the sediment load is compatible with hydraulic conditions of the channel (e.g., sediment transport capacity). If the mobile boundary model, (e.g., HEC-6) computes extreme amounts of scour or deposition at the upstream boundary then the inflowing load curve may not be in balance with the stream and adjustment is required. When this occurs, assume a different percentage for the bed material load, develop a new load curve for HEC-6, and test it again. Be sure the model is numerically stable before adjusting it. Attend to hydraulic problems starting at the downstream end and proceeding toward the upstream end of the model. Reverse the direction for sediment problems. Do not worry about computed scour or deposition problems at the downstream end of the study reach until the model is demonstrating proper behavior upstream from that point.

Check the boundary conditions to determine that the particle size classes in the inflowing load are representative or approximate observed data. Correct any inconsistencies in the load or gradation data and try another execution. If computed transport rates are too high, check the field data for gravel content and determine whether an armor layer is developing. If deposition or scour rates are too high or low, check bank elevations and ineffective flow limits to ensure that the model is not allowing too much overbank flow to create excess channel deposits. Finally, if none of these actions produce acceptable performance, adjust the ratio of inflowing bed material to total load and/or inflowing load curve. Attempt to match observed load data whenever possible.

Sensitivity Testing: During the course of a study it is advisable to perform a sensitivity test. Often, input data such as inflowing sediment load and gradation are not available. The estimating procedures outlined herein can be used to develop load and grain size distribution estimates, but it is important to assess the possible impacts of uncertainties in those values on model results. This simply requires modifying the suspected input data by +/- X% and re-running the simulation. If there is little change in the simulation results, the uncertainty in the estimated data is of no consequence. If large changes occur, however, the input data may require refinement and perhaps field verification (data collection).

CONCLUSION

This work was motivated by the need to provide engineers with tools to develop inflowing sediment load information for HEC-6. The methods suggested represent what we determined are useable and credible at this time. The determination of the size distribution of the sediment delivered to the stream needs more research. Many of the steps in preparation and use of data will continue to be necessary (such as calibration and sensitivity testing) as the technology for computing land surface erosion evolves. We foresee that precipitation-runoff and sediment washoff models will become coupled through the use of digital elevation models and geographic information systems; some systems are currently available that do so. Indeed, one of the components of HEC's NEXGEN software development project is to provide these tools for routine use in hydrologic engineering work.

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NOTES

NOTES

FREEZE/THAW EFFECTS ON RUNOFF AND SOIL LOSS IN THE NORTHWESTERN WHEAT AND RANGE REGION

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Abstract: Rain and snowmelt on frozen or thawing soil are important causes of runoff and soil loss from agricultural land in the Northwestern Wheat and Range Region. Quantifying effects of these factors is important for hydrologic model development and calibration, and for designing crop management systems to reduce runoff and erosion. An experiment with eight runoff plots (3.7 x 22.7 m) with replicated and varying crop management treatments was installed at the Palouse Conservation Field Station near Pullman, Washington in the fall of 1978; data were collected from natural events for 13 years. Soil frost, surface thaw and snow depths were measured on the plots regularly throughout the winter runoff seasons. Runoff and sediment samples were obtained from collection tanks on a daily or event basis. Data were analyzed and events grouped as having occurred with frozen soil, thawing soil or nonfrozen soil. Soil freezing condition and crop management had substantial effects on infiltration and runoff, but even more significant impacts on soil erosion. A continuous bare fallow plot produced 5 times as much runoff but 100 times as much soil loss as winter wheat following small grain. Runoff and soil loss on solidly frozen soil were about the same on all treatments, but were much less under thawing and nonfrozen soil for the winter wheat following small grain.

INTRODUCTION

Rain and snowmelt interact with frozen and thawing soil to create serious erosion problems in the Northwestern Wheat and Range Region (NWRR). Agriculture Handbook 537 (Wischmeier and Smith, 1978) indicates that as much as 90% of the erosion in parts of the region are caused by surface thaws and snowmelt. Zuzel and other researchers (Zuzel et al., 1982), during a five-year study in north-central Oregon, found that about 86% of the soil erosion on winter wheat following summer fallow was caused by snowmelt, rainfall or frost melt on thaw-weakened soil. There is lack of data to quantify these effects elsewhere in the region.

A comparison of crop management treatments was established at the Palouse Conservation Field Station in the late 1970's and runoff plots were installed. Treatments included continuous bare fallow (CBF), winter wheat following summer fallow, tilled (WW/SF-T) and winter wheat following small grain, tilled (WW/SG-T). The CBF is an index or control condition and the cropped treatments are typical of those in the intermediate and higher precipitation zone of the NWRR. This paper reports results of this 13-year study indicating the interaction of soil freeze/thaw activity with crop management and their combined effects on runoff and soil loss.

EXPERIMENTAL SETUP

The treatments were installed at the Palouse Conservation Field Station (PCFS), 3 km northwest of Pullman, WA, on a south-facing slope. Plots were of uniform profile but plot to plot steepness ranged from 15.6 to 25.7%. Soil on the site is a Palouse silt loam (fine silty, mixed Mesic Pachic, Ultic, Haploxeroll). Average annual precipitation at the station is 541 mm, 254 mm of which occurs during the December through March erosion season. Instrumentation at the plot site included standard and recording rain gages. Temperature and other climate data were collected at the PCFS weather station, about 0.3 km from the plots. Frost tubes (McCool and Molnau, 1984) were installed to determine frost depth and

neutron access tubes were used to determine soil moisture. Metal bordered runoff plots were rectangular, 45.9, 22.2 or 12.0 m long by 3.7 m wide. Except for the CBF treatment which was maintained year round, borders were installed each fall after seeding and removed each spring. The data include 13 winter erosion seasons from 1978/79 through 1990/91. A plot length study was included on some of the treatments from winter erosion season 1978/79 through 1986/87. Plot length was standardized at 22.2 m in 1987/88. Seeding direction was cross slope from 1978/79 through 1986/87, part cross slope and part up and downslope in 1987/88, and up and downslope from 1988/89 through 1990/91. Plot treatments and characteristics are given in Table 1.

EXPERIMENTAL PROCEDURE

Runoff volume for each plot was determined by measuring depth of runoff collected in a large tank and using a volume vs depth relationship. In general, runoff and sediment samples were collected daily and represented average composition of runoff for that day. For multiple day events when all plots produced runoff it was necessary to prioritize and empty first those tanks in danger of overflowing. Under these conditions not all tanks were emptied daily.

Runoff was pumped from the tanks after resuspending the settled sediment with a jet on a large pump. The water and sediment mixture passed through a splitting tee and a portion was collected in a smaller tank. Sediment in this tank was resuspended by stirring and two 1-L samples were collected for sediment analysis. Sediment concentration was determined by flocculating the sample, siphoning off the supernate and drying the remainder.

ANALYSIS

Runoff and soil loss were computed on an event basis; runoff events were separated into those with a) soil frozen at the surface, b) soil frozen but thawing from the surface and c) soil reconsolidated after a previous thaw or not frozen. Frost tube readings were used in conjunction with field notes to make an initial event classification. No further separation was used with the nonfrozen events. The remaining events were sorted by volume and sediment concentration. In general, if the runoff depth exceeded 5 mm and the sediment concentration was less than 2000 mg L^{-1}, it was assumed the bulk of the event occurred under frozen conditions. The remainder of the events were classified as thawing. Because of the complexity of the runoff events, no attempt was made to separate the events as to rain, snowmelt, or combination of the two. For those years and treatments with the plot length study, depth of runoff and soil loss per unit area were averaged to give an average annual result.

RESULTS AND DISCUSSION

Average annual runoff and soil loss are presented in Table 2 and Figure 1 and annual data for each of the three treatments are plotted in Figures 2-4. These data are averages from all plots with the given treatment. Separation of the event data into frozen, thawing or nonfrozen was difficult. Within any given day, the soil might change from solidly frozen to thawing at the surface; during extended events, the soil may thaw completely and reconsolidate. Identification of the frozen soil events on the CBF plots on the basis of a threshold sediment concentration alone was attempted. This approach did not appear promising. A more subjective approach based on the frost depth readings, surface condition notes, runoff depth and sediment concentration appeared to produce reasonable results.

Data from the CBF plots are shown in Figures 1 and 2. About 19% of the annual runoff but only 1% of the soil loss occurred from runoff events designated as occurring when the soil was frozen. For the WW/SF-T plots about 32% of the annual runoff and 4% of the soil loss occurred from the frozen soil condition (Figures 1 and 3), and for the WW/SG-T plots 73% of the annual runoff and 27% of the soil loss occurred under frozen soil conditions (Figures 1 and 4). Frozen soil is relatively resistant to detachment by either raindrops or sheet flow.

The thawing soil condition accounted for about 32% of the annual runoff and 39% of the soil loss from the CBF plots. Corresponding figures were 34% and 43%, respectively, for the WW/SF-T and 22% and 36% respectively, for the WW/SG-T.

Runoff events when the soil was not frozen accounted for 49% and 61% of the runoff and soil loss from CBF, 34% and 53% of the runoff and soil loss from WW/SF-T and 5% and 36% of the runoff and soil loss from WW/SG-T.

With the exception of the frozen soil events, both of the cropped treatments produced much less runoff and soil loss than the continuous bare fallow (CBF) treatment. The data indicate that improved cover and management has a substantial impact on runoff as compared to bare fallow. Runoff and soil loss from frozen soil events was less influenced by cover and management than that from thawing or nonfrozen events. Soil loss data from thawing or nonfrozen events showed even more impact of cover and management than did the runoff data; all categories of events were affected, but nonfrozen more so than the frozen or thawing categories. Another way of describing this is that good cover and management will withstand most nonfrozen events and will respond mainly to events when an impermeable frozen layer impedes infiltration. A field with pulverized soil and no cover might suffer about 50 to 60% of its runoff and about 40 to 50% of its soil loss from events when the soil contained an impermeable frost layer. A field with large clods and moderate residue cover might produce 90% of its runoff, and 60 to 70% of its soil loss from events that occurred when the soil had an impermable frost layer. These loses, however, would be much less than from the field with less protection.

SUMMARY

Runoff plots were installed on a number of treatments at the Palouse Conservation Field Station near Pullman, WA. The treatments included typical crop sequences for seeding winter wheat in the intermediate and higher precipitation zones of the Northwestern Wheat and Range Region. The project covered a 13-year period from winter erosion season 1978/79 through 1990/91.

Response to runoff opportunities varied with type of treatment. Treatments with poor cover and surface roughness respond to storms when infiltration is not impacted by an impermable frozen layer. When the soil was not frozen, infiltration rate for treatments with greater cover and roughness (conservation tillage) was higher than the rainfall rate for nearly all storms. Only when the infiltration rate was modified by a frost layer did runoff occur. Even when runoff occurred from these treatments, soil loss was reduced by cover and roughness. For an excessively tilled winter wheat following summer fallow treatment, only about 50 to 60% of its runoff and 40 to 50% of its soil loss would occur when soil frost influenced infiltration. For annual cropping with conservation management, these percentages might be as much as 90% and 70%, respectively.

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TABLE 1. TREATMENTS AND PLOT CHARACTERISTICS

Treatment	Period	Slope (%)	Number of Plots: Total	Row Direction: Contour	Row Direction: Up & Down Slope
Continuous Bare Fallow (CBF)	1978/79	15.6	1	NA	NA
	1979/80-1987/88	15.6, 21.5	2	NA	NA
	1988/89-1989/90	15.6, 21.5	2	0	2
	1990/91	15.6	1	0	1
Winter Wheat Following Summer Fallow (WW/SF-T)	1978/79-1986/87	22.3-25.7	3	3	0
	1987/88	22.3, 25.7	2	1	1
	1988/89-1990/91	22.3, 25.7	2	0	2
Winter Wheat Following Small Grain (WW/SG-T)	1978/79-1986/87	20.4-23.6	3	3	0
	1987/88	20.4, 23.6	2	1	1
	1988/89-1990/91	20.4, 23.6	2	0	2

TABLE 2. AVERAGE ANNUAL RUNOFF AND SOIL LOSS FROM A 13-YEAR STUDY AT THE PALOUSE CONSERVATION FIELD STATION, PULLMAN, WA

Treatment	Runoff (mm): Frozen	Thawing	Nonfrozen	Total	Soil Loss (t ha-1): Frozen	Thawing	Nonfrozen	Total
CBF	22.2	37.0	57.8	117.0	0.8	43.1	67.8	111.7
WW/SF-T	19.6	20.5	20.5	60.6	0.7	7.8	9.6	18.1
WW/SG-T	16.5	5.0	1.2	22.7	0.3	0.4	0.4	1.1
	Runoff (% of total)				Soil Loss (% of total)			
CBF	19	32	49		1	39	61	
WW/SF-T	32	34	34		4	43	53	
WW/SG-T	73	22	5		27	36	36	

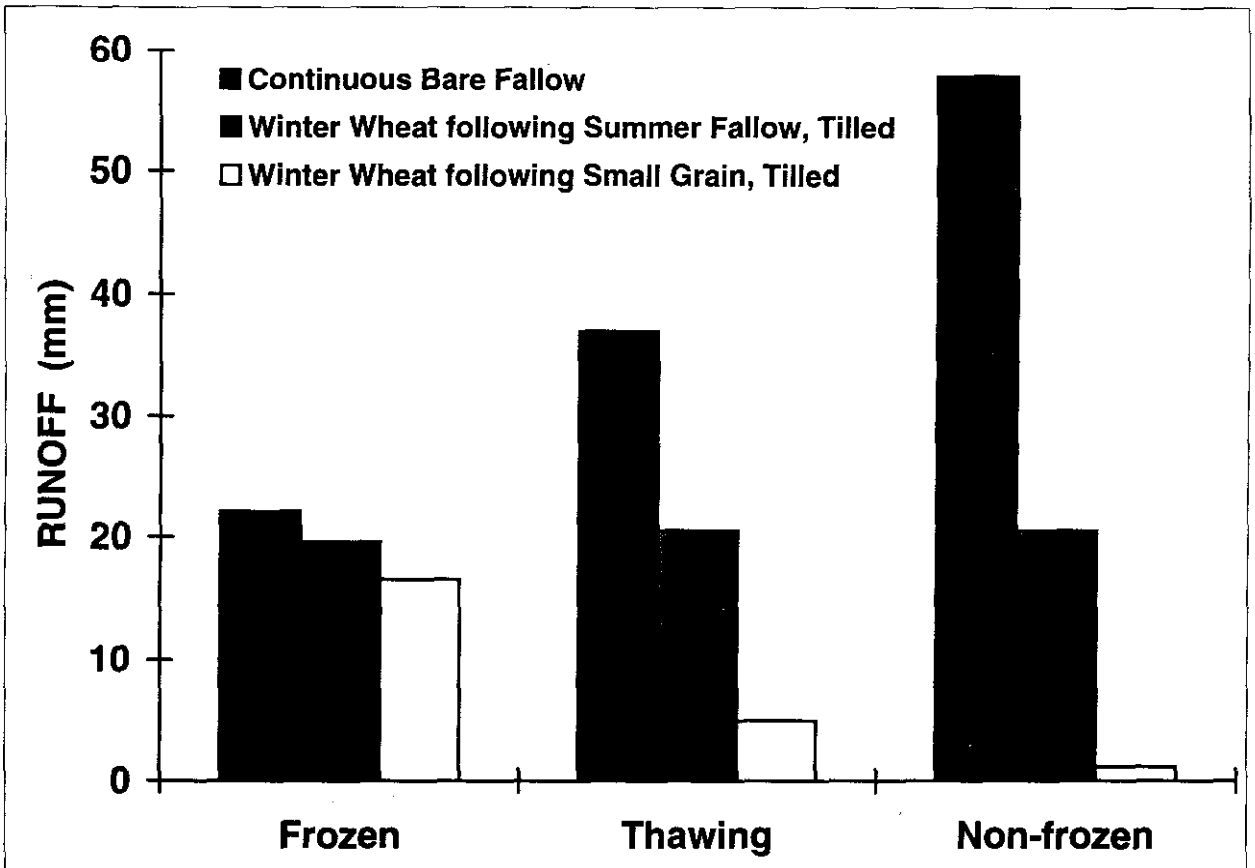

Figure 1A. Average Annual Runoff

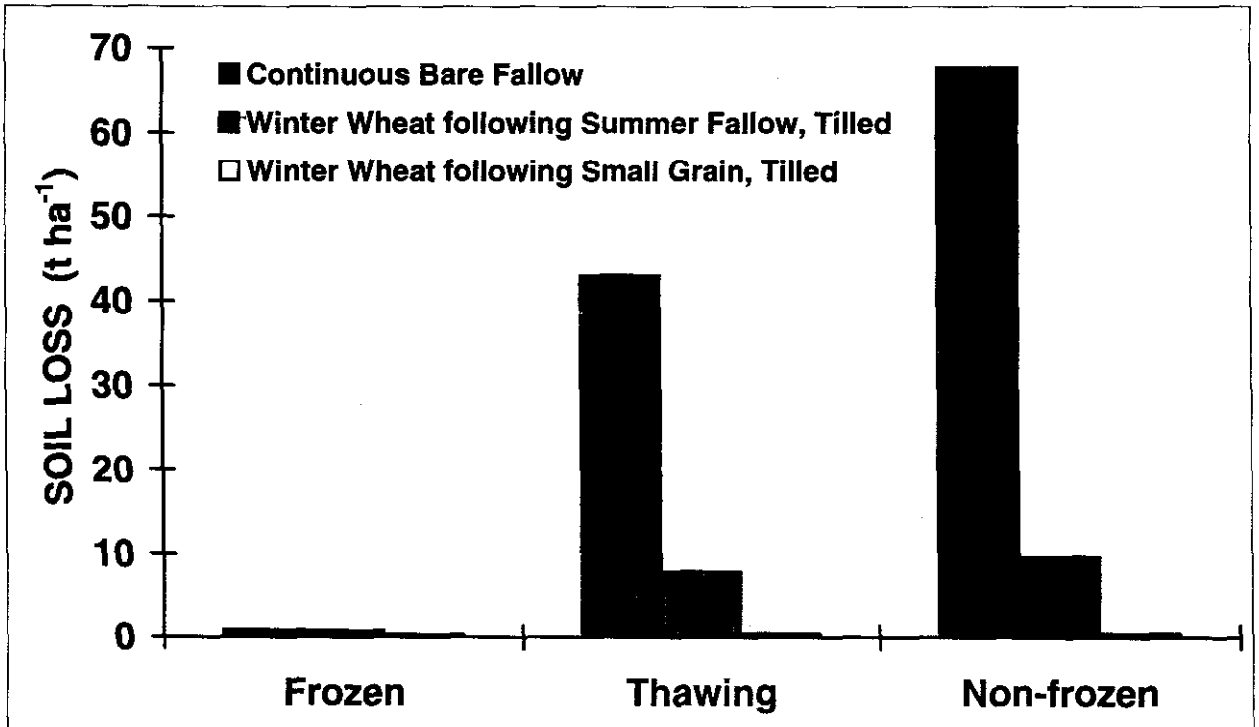

Figure 1B. Average Annual Soil Loss

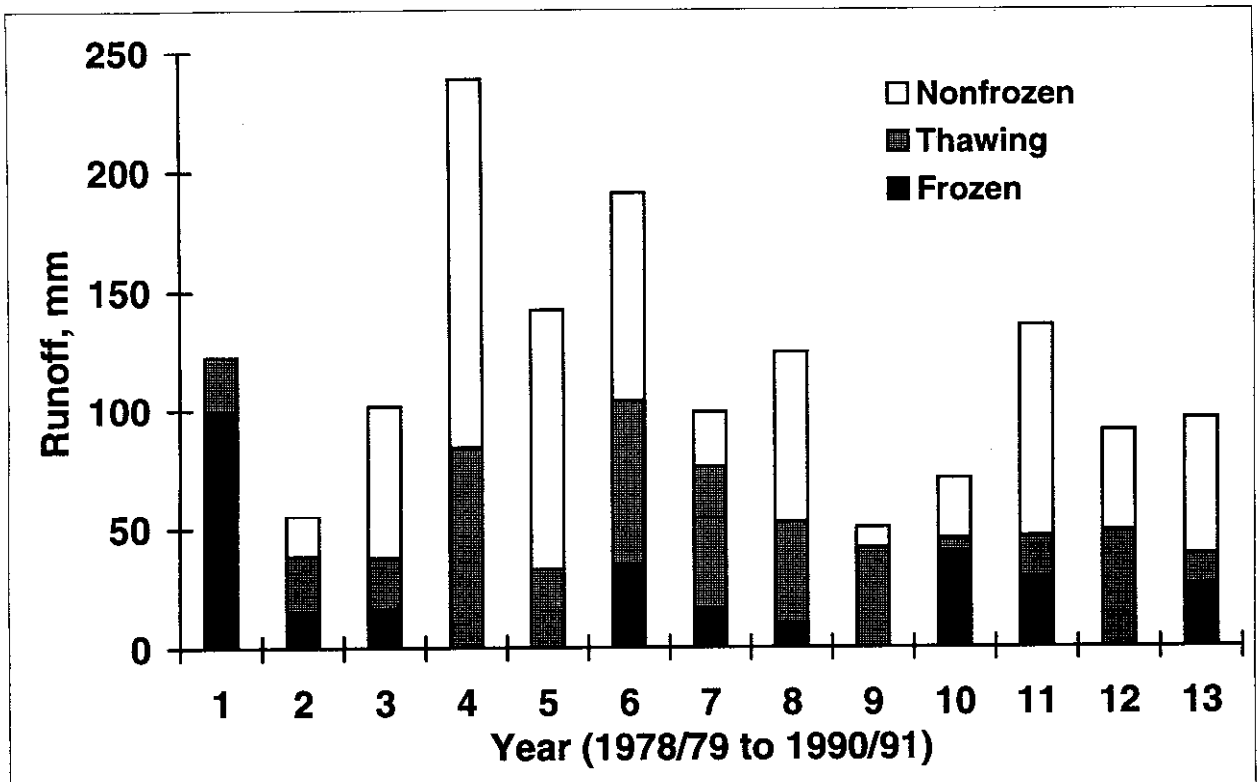

Figure 2A. Annual Runoff from Continuous Bare Fallow (CBF) plots

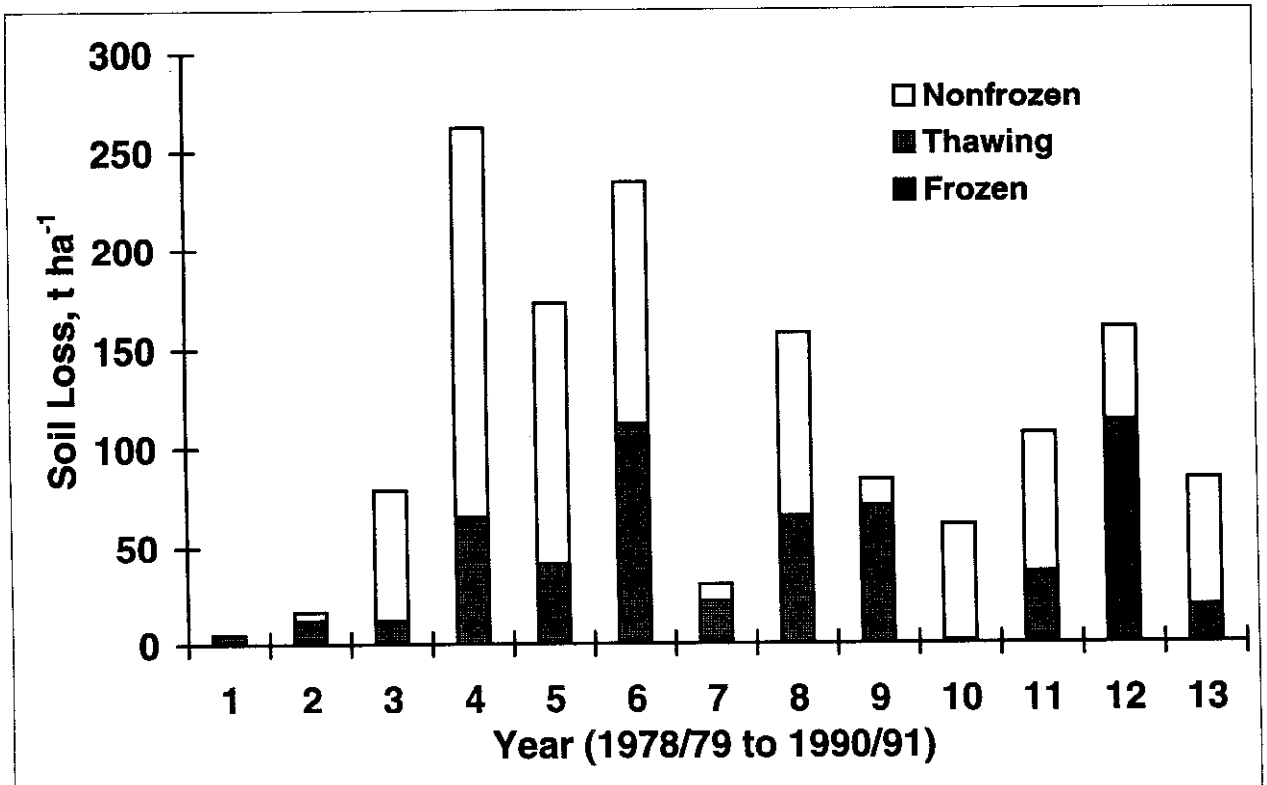

Figure 2B. Annual Soil Loss from Continuous Bare Fallow (CBF) plots

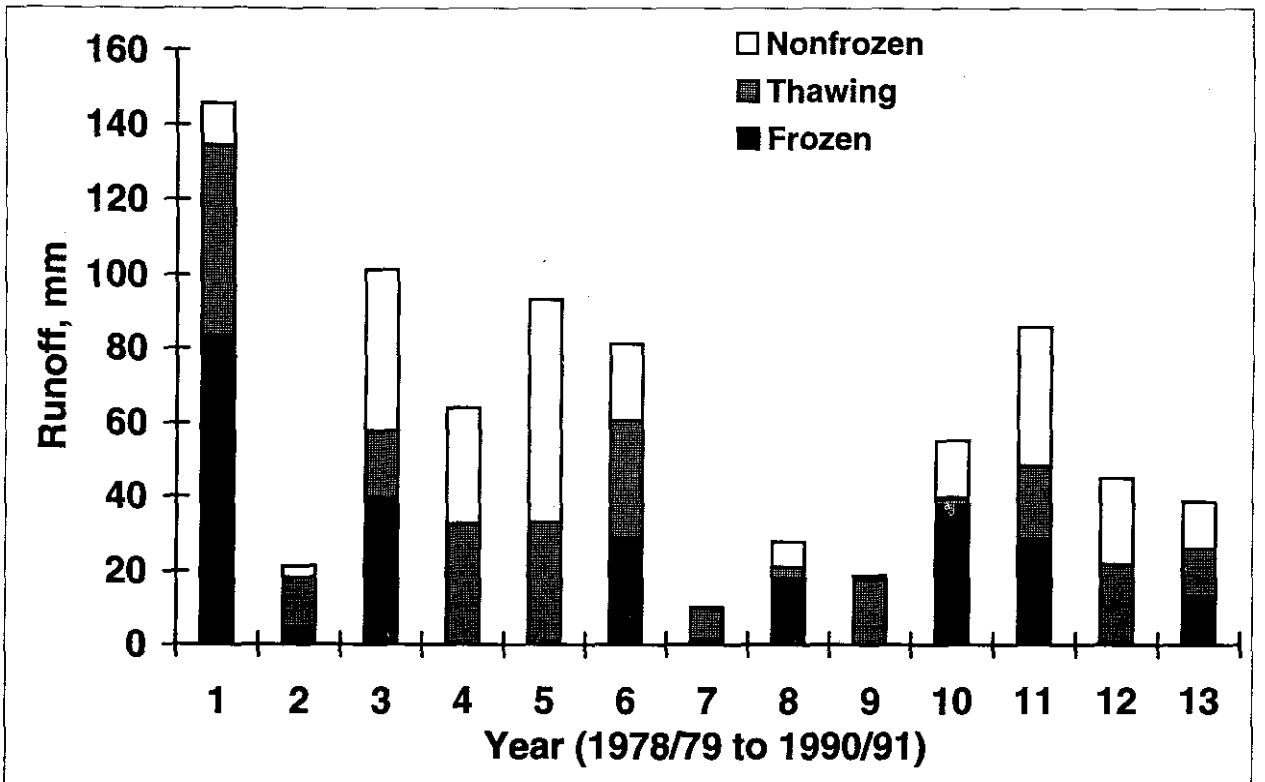

Figure 3A. Annual Runoff from Winter Wheat following Summer Fallow (WW/SF-T) plots

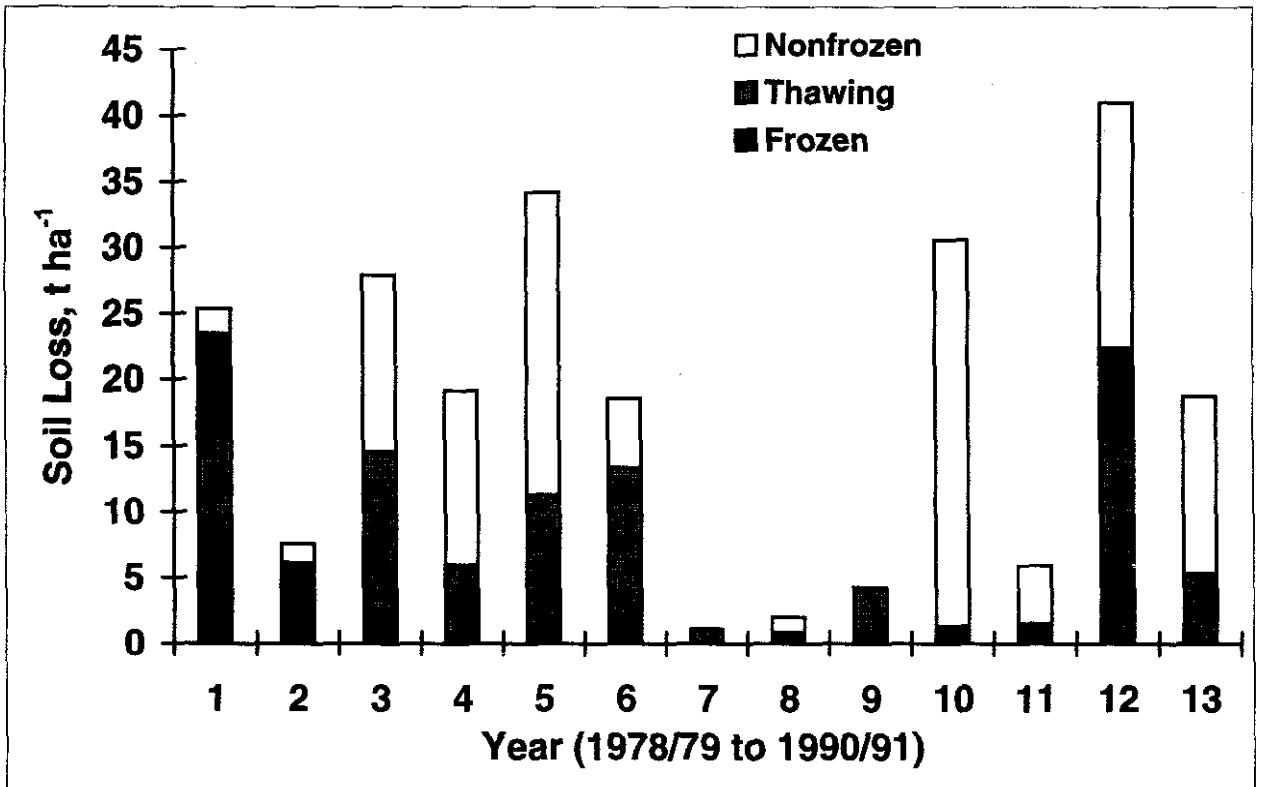

Figure 3B. Annual Soil Loss from Winter Wheat following Summer Fallow (WW/SF-T) plots

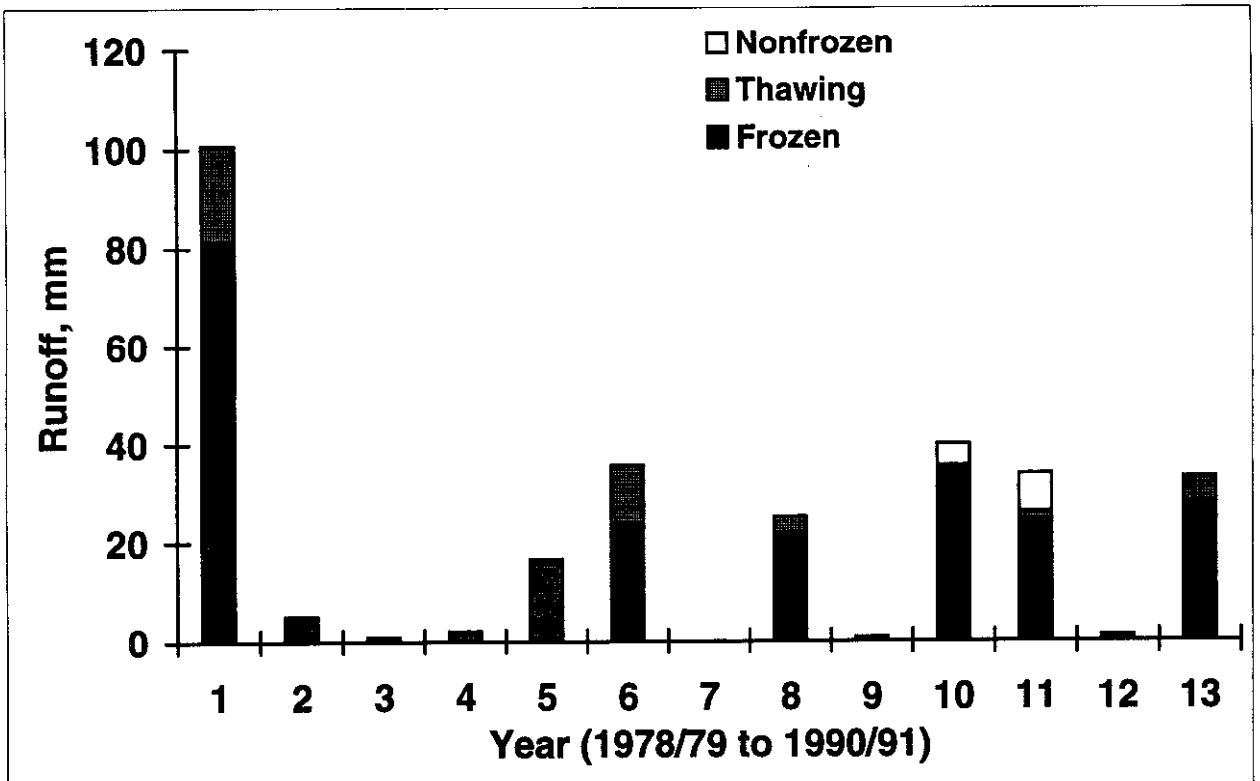

Figure 4A. Annual Runoff from Winter Wheat following Small Grain (WW/SG-T) plots

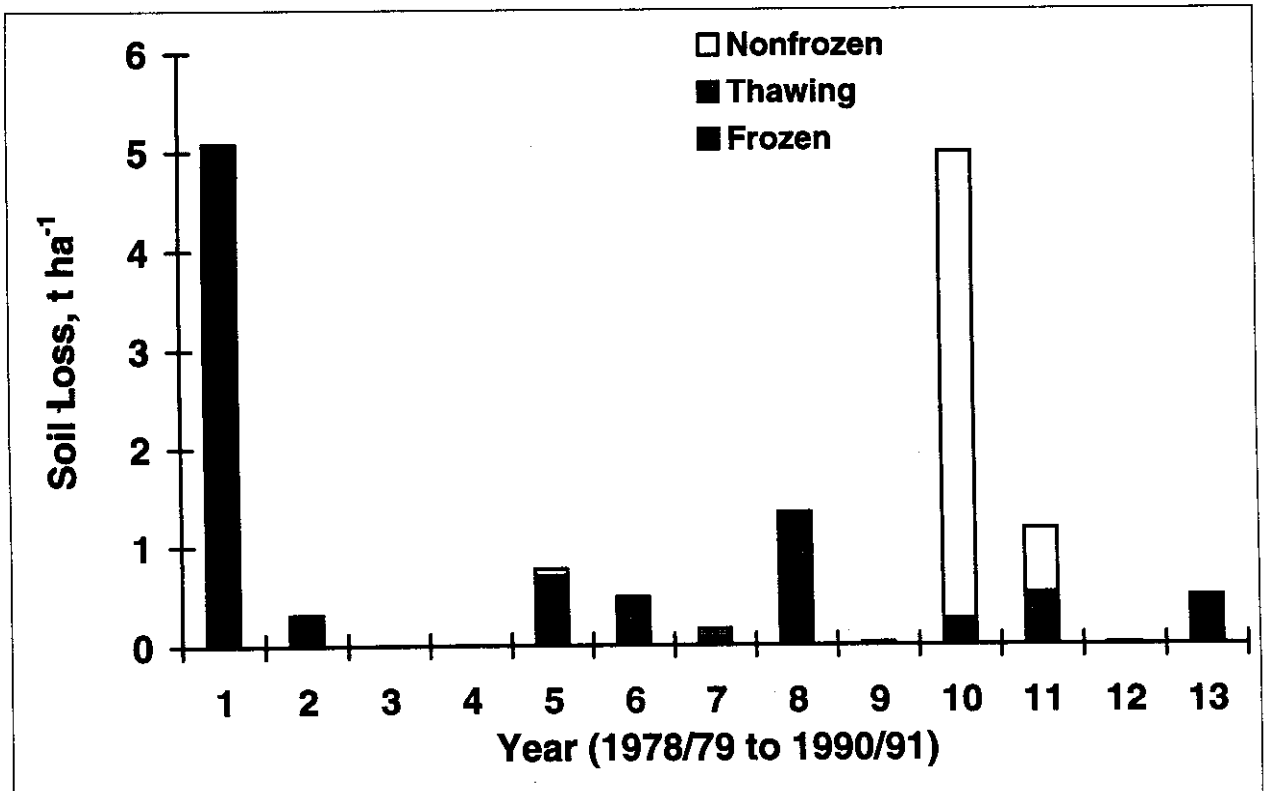

Figure 4B. Annual Soil Loss from Winter Wheat following Small Grain (WW/SG-T) plots

QUANTITATIVE GEOMORPHOLOGY AND SEDIMENTATION OF RILLS AND RUNNELS, UPPER MOSQUITO CREEK WATERSHED, WESTERN IOWA

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"Ephemeral gullies" recently have received increased attention in the analysis of erosion and sedimentation in agricultural watersheds. An "ephemeral gully" is geomorphically termed a tunnel (a rivulet, or a stream let, or the channel eroded by a small stream, as in Webster's and the AGI Glossary). Runnels typically occur in upland positions between topographically oppositional hillslopes, and are low-order channels that convey ephemeral or intermittent flow. Runnels are geomorphically distinct from rills because tunnels are fixed in position and can be used to obtain upland geomorphic parameters in the compositional analysis of watersheds.

Traditional methods of quantitative geomorphology of drainage networks were used to inventory and analyze rills and tunnels and to develop the pertinent interrelationships of drainage composition for six sample sub watersheds of upper Mosquito Creek, Shelby county, Iowa, and for the total watershed (79.2 square miles or 50,712 acres).

A representative first order tunnel in upper Mosquito Creek is 417 feet in length, has a drainage area of 4.0 acres, a gradient of 7.3%, a watershed length of 669 feet, a watershed slope of 12%, and terminates downstream on a foot slope or toeslope. Combined morphometric analysis of the sample areas and the total watershed indicates that 2,684 tunnels exist in upper Mosquito Creek. Data for second order tunnels are: number--220 length--627 feet area--21.8 acres and chattel gradient--3.2%.

The NRCS Ephemeral Gully Erosion Model (GEM) version 1.1 was used to estimate both single storm and average annual sediment eroded from representative tunnels. The average annual amount was calculated as 1.1 ton per watershed acre, compared to a field estimate of 0.75 tons per acre. Total EGEM runnel erosion in Upper Mosquito Creek was computed to be 57,342 tons per year.

Suggestions for improved methods of tunnel inventory and analysis for obtaining EGEM input data became apparent during the study, and include: 1) use of qualitative geomorphic methods to obtain network morphometric parameters 2) development of sediment delivery ratios for runnels, based on the identification and distinction of continuous and discontinuous drainage networks 3) use of field measurements of tunnel hydraulic geometry to better evaluate and predict channel flow and transport 4) development and use of sediment type/channel shape relationships to better evaluate and predict runnel shape and dimensions 5) use of existing knowledge of crop type, land use, farming practices, and related seasonal variations in runnels.

SCOUR OF CONTAMINATED SEDIMENTS IN THE ASHTABULA RIVER

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Abstract The Federal navigation project in the lower Ashtabula River at Ashtabula, OH, contains a break-water protected harbor in Lake Erie and a navigable, commercial waterway extending about 3.2 kilometers (2 miles) upstream. Dredging in the upper 2.4 kilometers (1.5 miles) was suspended in the 1970's, and the accumulated bed sediments are contaminated with heavy metals, chlorinated hydrocarbons (including, in some locations, toxic levels of polychlorinated byphenyls, PCB's), and polynuclear aromatic hydrocarbons. Limited dredging operations in this upper reach were conducted in 1993 to permit continued use of the waterway by recreational traffic. The most heavily polluted sediments are buried under relatively clean sediments. As part of a broader effort to evaluate the future of the waterway, the Waterways Experiment Station (WES) is conducting both field and numerical model investigations to determine the risk of scour through the relatively clean surficial sediments thus exposing and dispersing the underlying contaminants. This paper will discuss the methods used to determine this risk and significant findings from the ongoing study.

INTRODUCTION

The Ashtabula River flows north into Lake Erie at the city of Ashtabula in northeast Ohio. The Federal navigation project in the lower Ashtabula River contains a break-water protected harbor in Lake Erie and a navigable, commercial waterway extending about 3.2 kilometers (2 miles) upstream to the 24th Street Bridge (Figure 1). Sediments in the harbor and lower 0.6 kilometers (2000 feet) of the river are classified as suitable for open lake disposal whereas sediments upstream of the lower 0.6 kilometers to the 24th Street Bridge are classified as unsuitable for open lake disposal. In the upper 2.4 kilometers (1.5 miles) of the waterway, dredging operations required to permit commercial navigation were suspended in the 1970's and the accumulated bed sediments are contaminated with heavy metals, chlorinated hydrocarbons (including, in some locations, toxic levels of polychlorinated byphenyls, PCB's), and polynuclear aromatic hydrocarbons. The most heavily polluted sediments are buried under relatively clean sediments. Contaminant concentrations are generally greatest in the upper turning basin located between Fields and Strong Brooks, gradually decrease as one proceeds downstream through the lower turning basin near river mile 1 (RM 1), and rapidly decrease upstream of the turning basin. Limited dredging operations in this upper reach were conducted in 1993 to permit continued use of the waterway by recreational traffic.

The objective of the on-going study of sediment transport in the Ashtabula River is to determine the potential magnitude and extent of scour that may occur during a flood event or in response to rapid changes in Lake Erie stages potentially causing exposure and dispersal of contaminants buried in the channel bed sediments. This is to be accomplished by a combination of field data collection and analysis and numerical model studies.

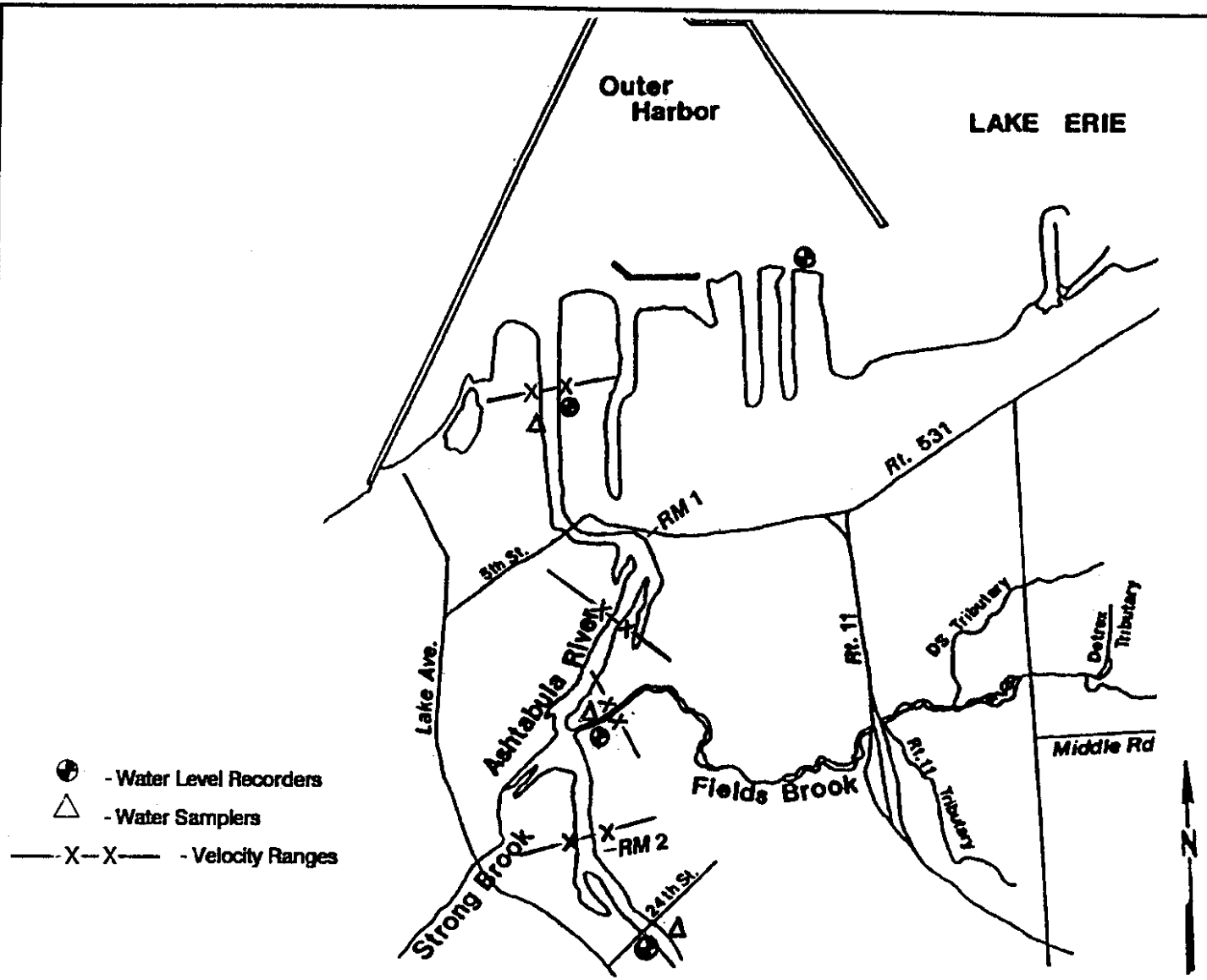

Figure 1. Ashtabula River Data Collection Locations

Approach

The purpose of field investigation was to identify and characterize significant hydraulic and sediment transport processes in the river and determine the physical properties of the bed sediments. The field investigation was initiated in June of 1994 and includes both long-term continuous monitoring of water levels and suspended sediment concentrations with automated data collection equipment and short-term efforts to collect bed material samples along with velocity and suspended sediment concentration profiles.

Laboratory analysis of the bed material consists of testing to determine physical and chemical properties, i.e., gradation, pH, cation exchange capacity, etc., and to estimate the critical shear stress(es) for erosion and erosion rate. The field and laboratory investigations provide critical data needed to properly direct the overall effort toward resolution of the problem under study and to estimate coefficients used in numerical model simulations of hydraulic and sediment transport in the river.

The numerical model study is being conducted using the TABS-MD modeling system, a family of numerical models which provide multi-dimensional solutions to open-channel flow and sediment transport problems (Thomas and McAnally 1985). RMA-2V, a two-dimensional, depth-averaged hydrodynamic numerical model is used to generate water levels and current patterns. RMA-2V employs finite element techniques to solve the Reynolds Form of the Naiver-Stokes equations for turbulent flows. Input data requirements for RMA-2V include a finite element mesh describing system geometry, Manning's roughness coefficients, turbulent exchange coefficients, and boundary conditions. STUDH, a two-dimensional sediment transport model which solves the convection-diffusion equation with bed source and sink terms may be used in combination with the hydraulic forces computed by RMA-2V and input describing bed sediment characteristics to simulate the erosion, transport, and deposition of sediment.

In addition to these investigations being conducted by the WES, the U.S. Army Cold Regions Research and Engineering Laboratory has conducted a field investigation to determine if ice processes in the river have a significant impact on channel scour (Wuebben and Gagnon), and the U.S. Army Corps of Engineers, Buffalo District, is conducting hydrologic studies to develop flood hydrographs for the Ashtabula River.

PRELIMINARY RESULTS

A preliminary investigation was conducted to determine whether the channel scour is highly probable, warranting a detailed study of sediment transport, or whether the erosion is so improbable as to eliminate or reduce the requirement of a thorough investigation of this phenomena. A report describing the results of the preliminary investigation is in preparation (Heath, et. al.).

The results of laboratory erosion tests showed that the critical shear stress for commencement of surface erosion was as low as 0.2 to 0.3 Pascal (0.004 to 0.006 psf). Continued erosion over a 30 minute duration was observed at higher shear stresses on the order of 0.5 to 0.6 Pa (0.010 to

0.013 psf). Estimated bed shear stress with a 100 year flood discharge may vary between 1 and 24 Pa (0.02 to 0.5 psf) over the region of buried contaminated sediment. If the high flood duration extends over a long period of time, there is a very high probability that the relatively clean surface layer of bed sediments covering the contaminated sediments may be completely eroded, thus exposing and eroding the contaminated sediment.

Based on the preliminary results, the potential exists for substantial erosion of channel sediments during a large flood event. This potential increases for floods coincident with relatively low lake levels. The magnitude of scour will be dependent on a number of as yet unquantified factors, including the shape of the flood hydrograph, the erodibility of subsurface bed material layers, and the sediment yield from the watershed.

Laboratory analysis of the surficial bed material indicated that compaction under the weight of subsequent deposits may occur. Thus, subsurface material may be more resistant to erosion. Resolution of this issue will require laboratory analysis of subsurface sediment samples which have been collected for this purpose.

ACKNOWLEDGMENTS

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SEDIMENT TRANSPORT FROM SMALL, STEEP-GRADIENT WATERSHEDS IN COLORADO AND WYOMING

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Abstract: Streamflow dynamics and sediment transport from high-elevation, subalpine watersheds of the central Rocky Mountains are driven more by melting snowpack than summer rainfall. Streamflow from small catchments on the Fraser Experimental Forest (FEF) has been monitored since 1941. Total sediment export, estimated annually from accumulations in stilling ponds associated with the gaging stations, has been measured since 1952. Earlier analysis indicated a strong correlation between total sediment accumulation and such flow parameters as duration (in days) of high-flow levels, annual peak, and to a lesser extent, total flow.

During the 1993 runoff season, suspended sediment and bedload samples were collected and sediment/discharge relationships developed for four of seven gaged watersheds at FEF and from two drainages on the Encampment river in Wyoming. The sediment rating curves were integrated with historical flow records to define effective discharge, and for "predicting" total sediment export for prior years. The flow-integrated estimate of total export was then compared with the measured load from the ponds, in order to evaluate the predictive merit of the sediment/discharge relationship. There was a strong correlation between the two estimates.

Although there is considerable unexplained variability in the comparisons, annual accumulations of sediments are reasonably well approximated by the integration of the flow regime and the sediment rating curve.

INTRODUCTION

Total annual sediment production from one or more of six of the gaged watersheds at the Fraser Experimental Forest (FEF) has been monitored since 1952. The watersheds range in size from 40 to 800 ha. Annual sediment production is estimated from measurement of material accumulated in the settling ponds associated with each of the stream gages. Each fall, following snowmelt runoff, the weir ponds on five of the watersheds are drained and the pond floor surveyed, the accumulated material is removed to a fixed level, and the survey repeated. The change in surface elevation is multiplied by the cross sectional area of the pond to determine the volume of material removed. Virtually all of the bedload and some portion of the suspended load being transported at the gagesite is deposited in the ponds (Leaf 1970). The sixth watershed, Fool Creek, has a separate pond; sediment accumulation is estimated as the difference in yearly surveys of the mean bed surface elevation.

Troendle and Olsen (1994) were able to demonstrate correlation between annual sediment accumulation from Fool Creek and several other FEF watersheds and both the duration of higher levels of flow and the peak discharge. They further note that sediment export, presumably from in-channel sources, also increased as a result of the increased flow following timber harvest on Deadhorse Creek. Although the estimates of total sediment obtained from accumulations in settling ponds have been quite useful for developing general relationships and for establishing sideboards on sediment transport volumes, these aggregate data are not useful in defining sediment transport process.

OBJECTIVES

In 1993, the opportunity arose to intensively sample both suspended sediment and bedload transport from the gaged watersheds at FEF, and Upper East Fork, and Coon Creek, two tributaries of the Encampment River in southern Wyoming (see Wilcox, et. al., this volume). The objectives were to: 1) define the sediment

transport/discharge relationships for each of the watersheds, during what was expected to be a well-above-average runoff year; 2) compare transport/discharge responses among differing basins as a function of flow, geology, and channel characteristics; and 3) determine if the discharges demonstrated to be most "effective" in transporting sediment were consistent with those flow parameters previously determined (Troendle and Olsen 1994) to be most highly correlated with the total annual export.,

METHODS

Uniform channel cross sections were selected above each stream gage for incremental sampling of both bedload and suspended sediment. Each cross section was permanently referenced. A metal tape stretched from left to right, looking downstream, was used to reference sampling locations during each visit. A cross section was also established on the wooden sill above the weir ponds at East St. Louis Creek on the FEF and the two streams in Wyoming. Discharge, suspended sediment, and bedload transport were measured almost daily during the period on either side of the peak, and then every 2 or 3 days until flow receded to the mean annual value.

Discharge: Discharge was measured at each visit using standard USGS practices (Buchanan and Somers 1965). The cross section was divided into as many as 20 equally spaced verticals. At each vertical, depth (D) and velocity at 0.6D were measured for at least 40 seconds using either a Price AA or a mini (pygmy) meter, depending on velocity and depth. The Price AA meter was preferred and used whenever velocity exceeded 1 $m \cdot s^{-1}$ and depth allowed its use. The same verticals were sampled at each visit, with additional verticals added or eliminated as the wetted channel width changed. Discharge for the cross section was estimated by summing the discharges represented by individual subsections. Since each of the streams is also gaged, gaged discharge was documented at the beginning and end of the sampling period as a check on, and calibration of, the measured discharge. Because runoff is snowmelt driven, the streams demonstrate a strong diel cycle, peaking in the late afternoon to early evening. To minimize sample bias, the sampling order was rotated such that, over time, all streams were sampled early and late in the day, on the rise and fall of the diel fluctuation, and at or near the daily peak.

Suspended Sediment: Suspended sediment was sampled using a US DH-48 depth integrating sampler (Brakensiek et al., 1979). A 300 ml (approximate) water sample was collected and refrigerated until it could be measured volumetrically and passed through a 0.45 micron filter. The pre-weighed filter was then oven dried and weighed to determine sediment (organic and inorganic) weight. The suspended sediment sample represents a cross section composite, as approximately a third of the volume was collected at each of three equally spaced verticals. The same verticals were sampled on each visit.

Bedload: Bedload was sampled at each of the cross sections using a 76 mm Helley-Smith bedload sampler (Helley and Smith 1971). Each cross section was sampled between 24 and 44 times during the 1993 flow season. Sample points or verticals were located at regular intervals across each section (approximately 10) and the same vertical was sampled for a 2-minute period each time, with additional verticals added or deleted as the channel-wetted width changed. Bedload collected was bagged and analyzed for each vertical in the cross section. The bedload samples were: 1) dried, 2) large organic debris removed and later weighed, and 3) split and sieved into 21 size classes using a mechanical shaker. Each sieved fraction less than 4.0 mm was weighed, placed in a muffle furnace to burn the fine organics, and then reweighed to get the inorganic component. The bedload samples were composited with the other verticals to get total transport for the cross section.

RESULTS

Discharge: In Wyoming and Colorado, 1993 was an above-average water year. The return interval for the maximum mean daily flow from East St. Louis Creek, for example, was 2.5 years. East St. Louis Creek has one of the longest discharge records and one that encompasses all the watersheds sampled. The 1993 return interval and length of record for other catchments is shown in table 1. The above-average peak was also associated with a longer duration of higher flows (see example for East St. Louis Creek, figure 1). The runoff season was characterized by an early melt, a false peak followed by a cool-period recession, and then a normal melt regime. Timing of the peak was consistent with the long-term average. Field sampling of discharge, suspended sediment,

and bedload was well distributed as evidenced by East St. Louis Creek (figure 1), typical of all the catchments sampled. Sample size varied from a low of 24 on Lexen creek, the smallest watershed, to 44 on East St. Louis Creek (table 2).

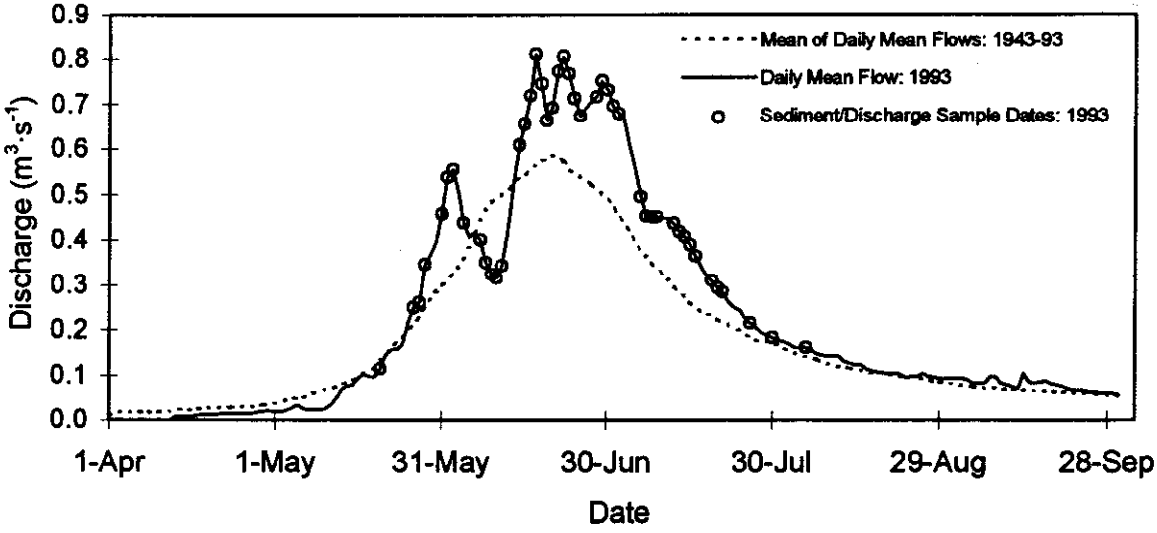

Figure 1. East St. Louis Creek average mean daily flow hydrograph for the period of record plotted against 1993 mean daily flow with 1993 sample dates identified.

Table 1. Summary of watershed characteristics.

Watershed Name	Area (ha)	Period of Record	1993 Peak Daily Mean Flow ($m^3 \cdot s^{-1}$)	1993 Peak Return Interval (years)	1993 Seasonal Flow (mm)
Lexen Creek	124	1955-Present	0.19	5.6	686
Deadhorse Creek	270	1956-Present	0.29	6.7	414
Fool Creek	289	1941-Present	0.32	2.7	254
East St. Louis Creek	803	1943-Present	0.81	2.5	432
East Fork Encampment	911	1982-Present	1.50	3.0	498
Coon Creek	1613	1982-Present	2.82	4.0	566

Table 2. Sample size and sediment rating equations for the study watersheds.

Watershed Name	Number of Samples*	Bedload Rating Equation ($kg \cdot s^{-1}$)	Bedload R^2	Bedload SE ($kg \cdot s^{-1}$)	Suspended Sediment Rating Equation ($mg \cdot L^{-1}$)	Suspended Sediment R^2	Suspended Sediment SE ($kg \cdot s^{-1}$)
Lexen Creek	24	-0.001+0.165Q	0.35	0.001	-1.393+67.94Q	0.26	4.80
Deadhorse Creek	33	-0.001+0.013Q	0.18	0.002	$22.9-318.9Q+1281.7Q^2$	0.57	8.60
Fool Creek	37	-0.004+0.040Q	0.54	0.003	-9.89+124.6Q	0.26	18.80
East St. Louis Creek	44	-0.006+0.021Q	0.40	0.005	6.0	**	0.92
East Fork Encampment	35	-0.023+0.052Q	0.54	0.024	$7.9-25.6Q+20.8Q^2$	0.59	8.60
Coon Creek	35	$0.02-0.06Q+0.03Q^2$	0.91	0.029	$10.5-21.9Q+9.6Q^2$	0.81	9.60

Q = Discharge in $m^3 \cdot s^{-1}$

* Difference of sample size determined by length of runoff season for a given watershed.

** The mean value (i.e. a constant).

Sediment/Discharge Relationships: Suspended sediment samples were processed with no attempt to partition particle sizes or separate organic and inorganic fractions. The sample content or concentration was expressed in $mg \cdot L^{-1}$ for the cross section, and then flow weighted to estimate total suspended load. Bedload samples were collected and analyzed by vertical. Once sieved and burned, the inorganic fractions for each vertical were aggregated to get total cross-section transport. Bedload transport was quite variable relative to flow, as typified by Fool Creek on FEF (figure 2). The same variability was expressed throughout the range of particle size classes transported, although the entrainment of the largest particles appeared to occur at higher flows than the smallest particle class. In all cases, increasing flow increased bedload transport. As will be discussed in more detail below, there was little difference in sediment transport rates between the rising and recession limbs of the hydrograph.

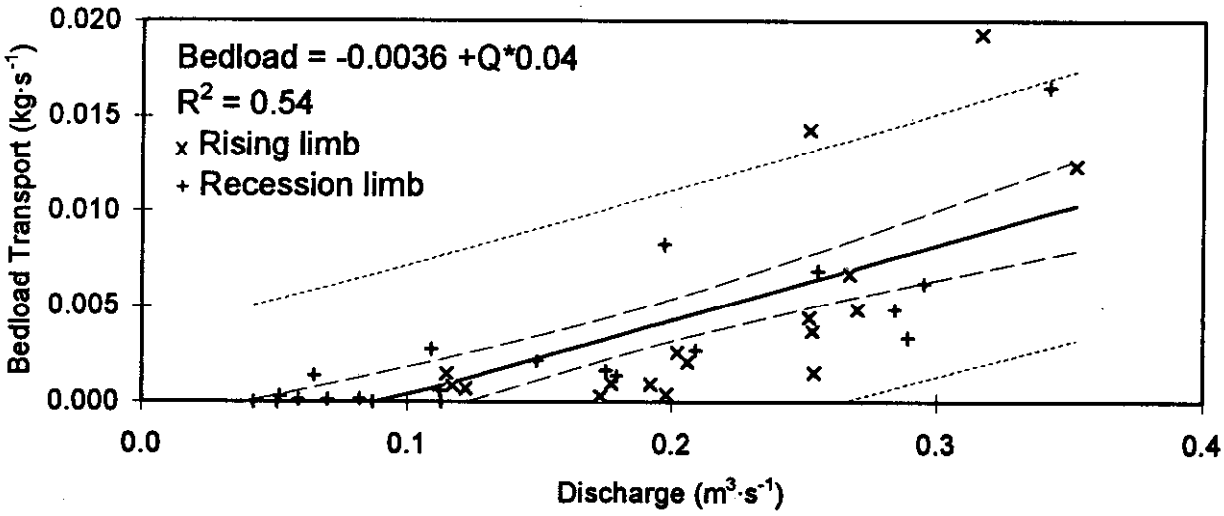

Figure 2. Fool Creek bedload rating curve for 1993. The solid line indicates the predicted value, dashed lines indicate 95% confidence intervals about the mean, and dotted lines the 95% confidence interval on the prediction.

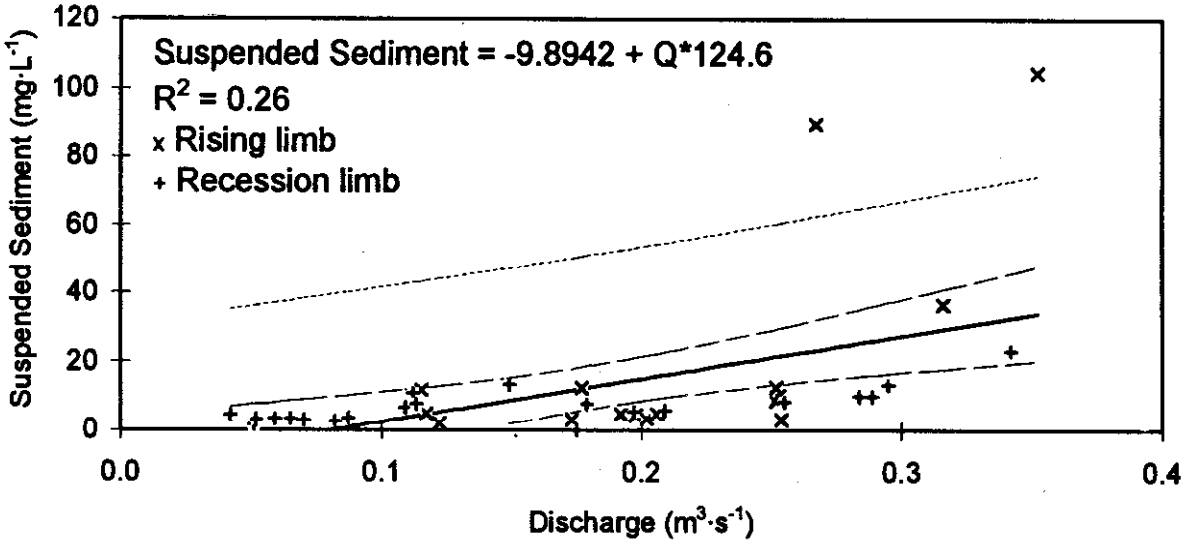

Figure 3. Fool Creek suspended sediment rating curve for 1993. The solid line indicates the predicted value, dashed lines indicate 95% confidence intervals about the mean, and dotted lines the 95% confidence interval on the prediction.

Sediment rating curves, or the equation describing sediment transport as a function of flow, were developed for both suspended sediment and bedload. No a priori decision had been made on the form these equations should

take, and the SAS statistical package (SAS Institute 1990) was used to arrive at the best form and fit. We found the strongest model for our data was either a linear or a second degree polynomial equation of sediment (Y) regressed against flow (Q) (table 2). Statistical anaysis indicated that nonlinear forms, such as power functions, did not significantly improve predictive capability, therefore we chose to use the simplest model.

As with bedload (figure 2), the variability in suspended sediment was also quite large as exemplified for Fool Creek (figure 3). The goodness of fit (R-square) varies between watershed and type of transport (table 2). No attempt was made to improve the models by adding parameters other than flow. In a separate analysis, samples collected on the rising and recession portions of the hydrograph were partitioned and models fit to both components. In every case, a single equation for suspended sediment or bedload described both limbs of the hydrograph. Also, to evaluate the adequacy of the sample size, a "power analysis" was performed (Guenther 1977) to evaluate the number of samples necessary to detect a relationship, of a specified strength, between transport rate and flow. Computations using the PASS program (Hintze 1991) indicated the sample size obtained in this study was almost double that needed to detect the correlations observed in the watersheds, assuming a Type I error of α = .05 and a Type II error of β = . 01.

Although the catchments at FEF have similar geology and glacial history (Retzer 1958), each catchment has its own transport "signature" (figure 4). All drainages demonstrate increased transport with increasing flow, but the threshold for entrainment as well as the slope of the transport rate varies among catchments (figure 4).

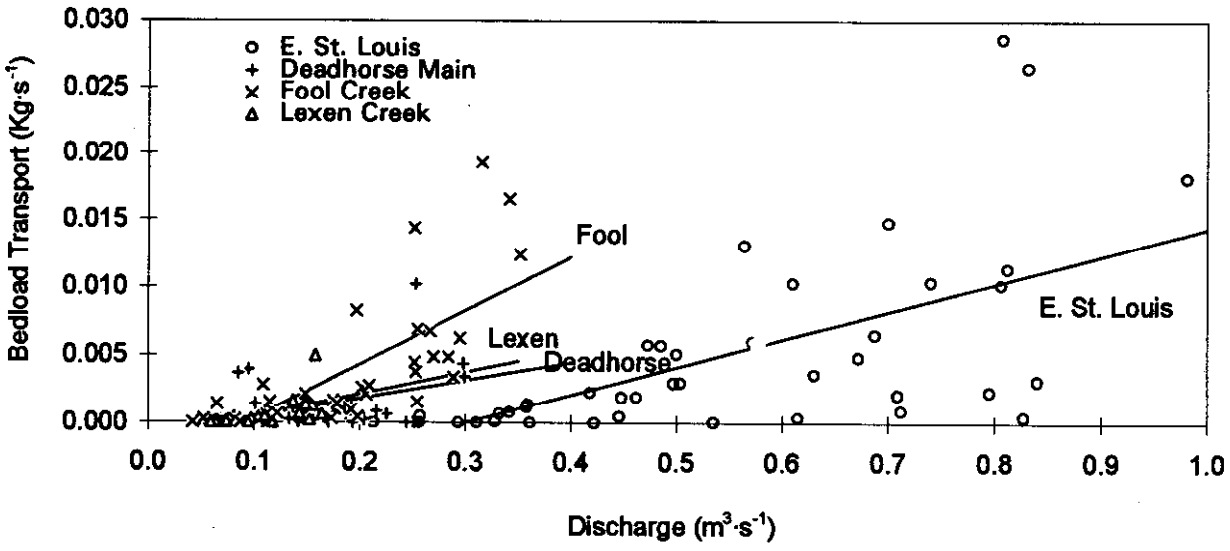

Figure 4. Bedload transport data for 4 FEF streams in 1993. Solid lines indicate the predicted value of the individual rating curves.

Effective Discharge: One application of the sediment rating curve is that it can be integrated with long-term flow records to define "effective discharge", or that portion of the flow regime which, over time, transports the largest component of sediment (Wolman and Miller 1960). This is one of the intended applications of the sediment transport models developed above. Prior to evaluating that application, however, the appropriateness of those models in predicting sediment transport, over time, was evaluated. As noted earlier, an estimate of total annual sediment export, based on accumulations in settling ponds, is available for many of the years of flow record from each of the watersheds at FEF. For those years, we integrated the sediment rating curves (both bedload and suspended) with the mean daily flow record to estimate or "model" seasonal sediment export. Since the measured seasonal flows usually began and ended well below the threshold for sediment movement, we assumed the simulated export would approximate the measured export.

In general, the correlation between the measured and simulated seem somewhat comparable, with the exception of Fool Creek (table 3). In contrast to the other watersheds, Fool Creek has a separate pond above the streamgage in

which the sediment is trapped. That pond is not cleaned annually. Instead, sediment accumulation is estimated by annual changes in the elevation of the pond floor, and thus is more susceptible to the effect of settling, organic decomposition, etc. The relationship between simulated and measured export for East St. Louis Creek (figure 5) is typical of the other three watersheds at FEF and the two in Wyoming. Using the 1:1 line as a base for comparison, we found combining the suspended and bedload components usually overestimated the measured material far more than did bedload curves alone, suggesting poor pond efficiency in trapping suspended material (table 3; also see Wilcox, et. al., this volume).

Table 3. Relationship between predicted and measured sediment transport and return interval of effective discharge

Watershed Name	Mean Annual Measured Sediment m^3	Mean Annual Predicted Bedload m^3 (R^2)	Predicted Bedload plus Suspended Load m^3 (R^2)	Return Interval of Effective Discharge (yr)
Lexen Creek	1.4	1.1 (0.43)	13.8 (0.35)	1.6
Deadhorse Creek	5.1	2.3 (0.57)	43.7 (0.73)	1.4
Fool Creek	19.4	7.0 (0.03)	32.1 (0.03)	1.7
E. St. Louis Creek	5.8	9.0 (0.66)	19.7 (0.66)	1.4

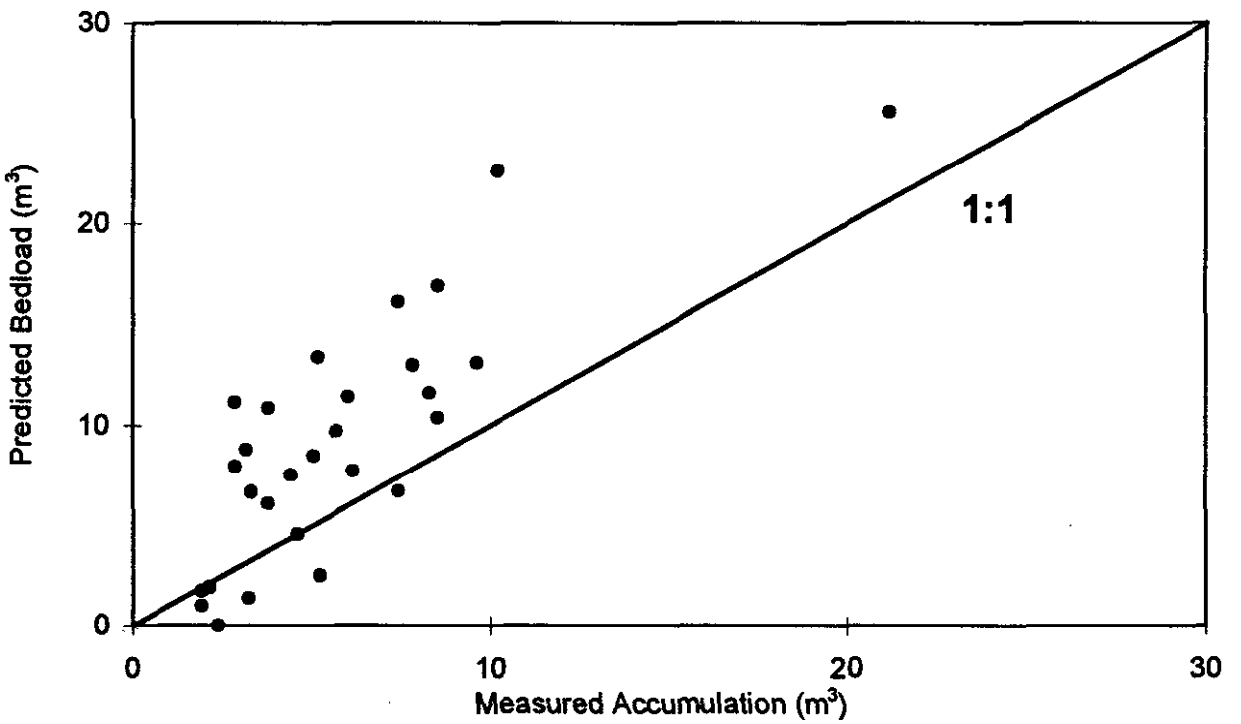

Figure 5. Predicted annual bedload transport versus measured sediment accumulation in the weir pond for East St. Louis Creek, 1965-93.

Effective discharge was determined in a manner similar to that proposed by Wolman and Miller (1960). The procedure used here differs in that the entire seasonal flow record (approximately April 15 to October 15 each year) was used, not just that portion which lies above the sediment transport threshold as Wolman and Miller suggested. For each of the FEF watersheds, mean daily flows were arrayed and placed in bins, each representing 5 percent increments of the range of observed flows for the period of record. For each bin, the bedload transport for each individual daily flow was calculated and then aggregated to get the bin total, or the total sediment transport, for all flows occurring within the range of the bin. The general relationship between discharge, sediment transport, and effective discharge proposed by Wolman and Miller (1960) appears to hold for East St. Louis Creek (figure 6) as

well as the other three drainages (table 3). It is apparent in figure 6 that a significant portion of the total seasonal flow occurs at levels well below the threshold for sediment movement (an aspect not addressed by Wolman and Miller 1960). The return interval for the mean value of the mean daily flows in the bin that moves the most sediment, over time, ranges from 1.4 to 1.7 years (table 3). In the case of East St. Louis Creek, the most effective discharge has an average return interval of 1.4 years. Troendle and Olsen (1994) concluded the duration of flows approaching the 1.5 year flow were most consistently best correlated with annual sediment export. Our calculation of effective discharge for FEF watersheds confirms that earlier conclusion.

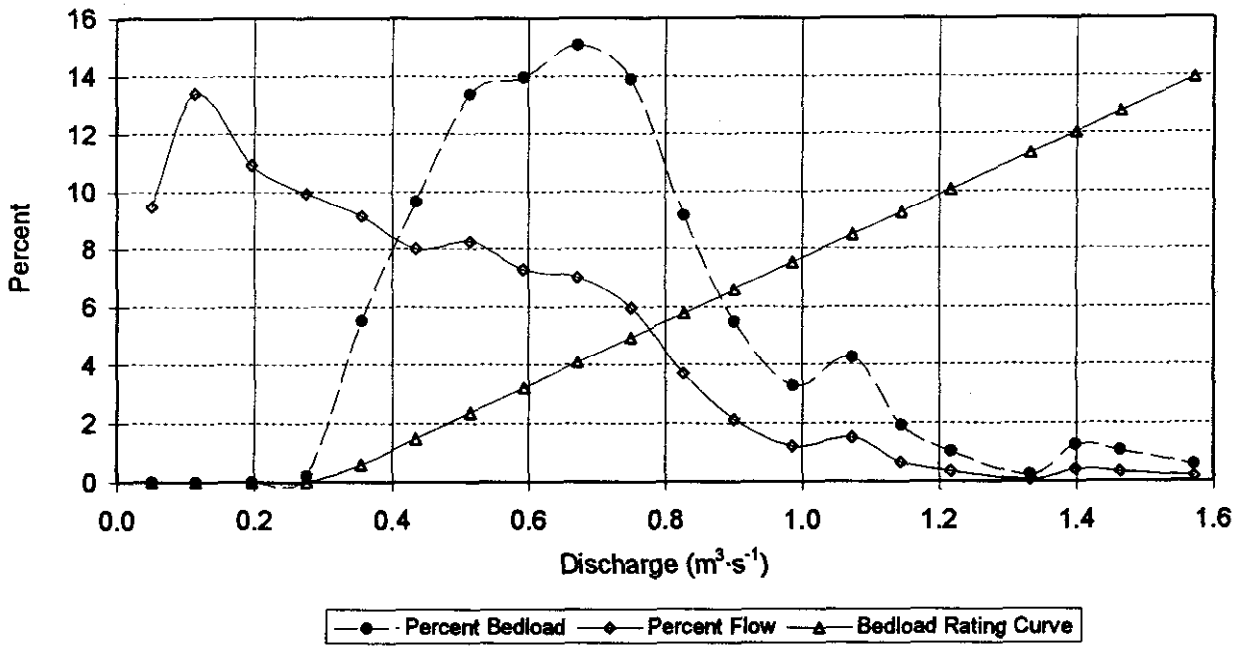

Figure 6. Wolman-Miller model showing the magnitude and frequency of streamflow and sediment transport at East St. Louis Creek.

DISCUSSION

Individually, the study catchments range in size from 125 to nearly 1700 ha, and differ greatly in the total annual yield and discharge rates for both water and sediment. Measured annual sediment export varies both in time and by watershed (Troendle and Olsen 1994). Sediment transport is also quite variable from day to day, even at the same flow level (figure 4). In most cases only a small, but significant, portion of the variation in either suspended or bedload transport rates can be explained by discharge alone. However, the average condition, whether expressed as the average annual export based on accumulations in the settling ponds, or mean annual production predicted from the integration of the sediment rating curve and the seasonal hydrograph, appears to approximate the mean transport rate over time. In this study, 24 to 44 suspended and bedload sediment samples uniformly distributed over an above average runoff season have characterized the sediment transport relationship reasonably well. A separate analysis indicates fewer samples, equally well distributed, would have been as good in defining the transport equation, implying that sample bias was minimal or at least random. Transport rate also appears to have a random or stochastic component. These inferences are drawn because systematically altering sample size through a wide range did not alter the estimate of the mean response or the estimation of its confidence. The models seem to be a reasonable approximation of mean response, at least based on comparison with historic measured responses.

As inferred by others (Wolman and Miller 1960, Leopold et al., 1964, Dunne and Leopold 1978, Andrews 1980, etc.), calculations of effective discharge indicate the more frequently occurring discharges (those around the 1.5-year mean daily flow) are more influential in moving sediment than those of less frequency, but higher magnitude. This is a conclusion arrived at by Troendle and Olsen (1994) for the same basins using a separate analysis.

A second observation is that, in spite of the range in catchment sizes, differences in flow regimes and water balances, and the unique nature of each "transport signature", the effective discharge region appears to have a similar return interval for all the watersheds monitored.

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Predicting Sedimentation from Timber Harvest Areas with the WEPP Model

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ABSTRACT

Disturbed forest lands are prone to increased erosion. Predicting the effects of forest operations on surface hydrology and erosion is difficult. Hydrologic models have been developed for agricultural conditions, but they may not be valid in forests. The WEPP model, a process-based erosion model under development, may have limitations in modeling erosion in forest areas. Field research has shown that timber harvest area soil properties may vary widely. Validation studies with the Watershed Version of the WEPP model show that as observed, snow melt dominates the runoff processes in the Northern Rockies, and that disturbed areas generally have a greater influence on runoff and erosion that do undisturbed areas. The model overpredicted snow melt rate, and did not allow snow to accumulate, but rather melted any accumulation on the first day above freezing following a snow event. It may be necessary to reduce hydraulic conductivities from those observed on small field plots to obtain runoff. A model that better describes the attributes of this region's snowmelt processes and upland hydrology is needed. Additional research is also needed for modeling the large spatial variability observed in timber harvest areas. Research is ongoing with this research unit to address all of these forest-specific problems.

INTRODUCTION

The USDA Forest Service's mission "is to achieve quality land management under the sustainable multiple-use management concept to meet the diverse needs of people." One aspect of this mission is minimizing the offsite impacts of any forest operation.

Sediment can harm critical fish spawning areas, and can generally degrade upland stream habitats. Determining the sources of upland sediment, and methods to reduce erosion, have been a major management concern and research activity.

The Water Erosion Prediction Project (WEPP) soil erosion model is being developed by an interagency group of scientists including the U. S. Department of Agriculture's Forest Service, Agriculture Research Service, and Natural Resource Conservation Service, and the Department of Interior's Bureau of Land Management and U. S. Geological Survey. Over 100 scientists from these agencies, and from universities throughout the United States and abroad have been working since 1985 to develop WEPP. It may replace the Universal Soil Loss Equation (USLE) now commonly used to predict soil erosion.

The WEPP model is physically based, so it is more easily transferred to a wider range of conditions than are empirical models like USLE. One of the research problems we study is determining the suitability of the WEPP model to predict erosion on disturbed forest areas. Field experiments are being carried out to provide calibration and validation data for the WEPP model. This paper presents some results of the field work and validation studies, and indicates the

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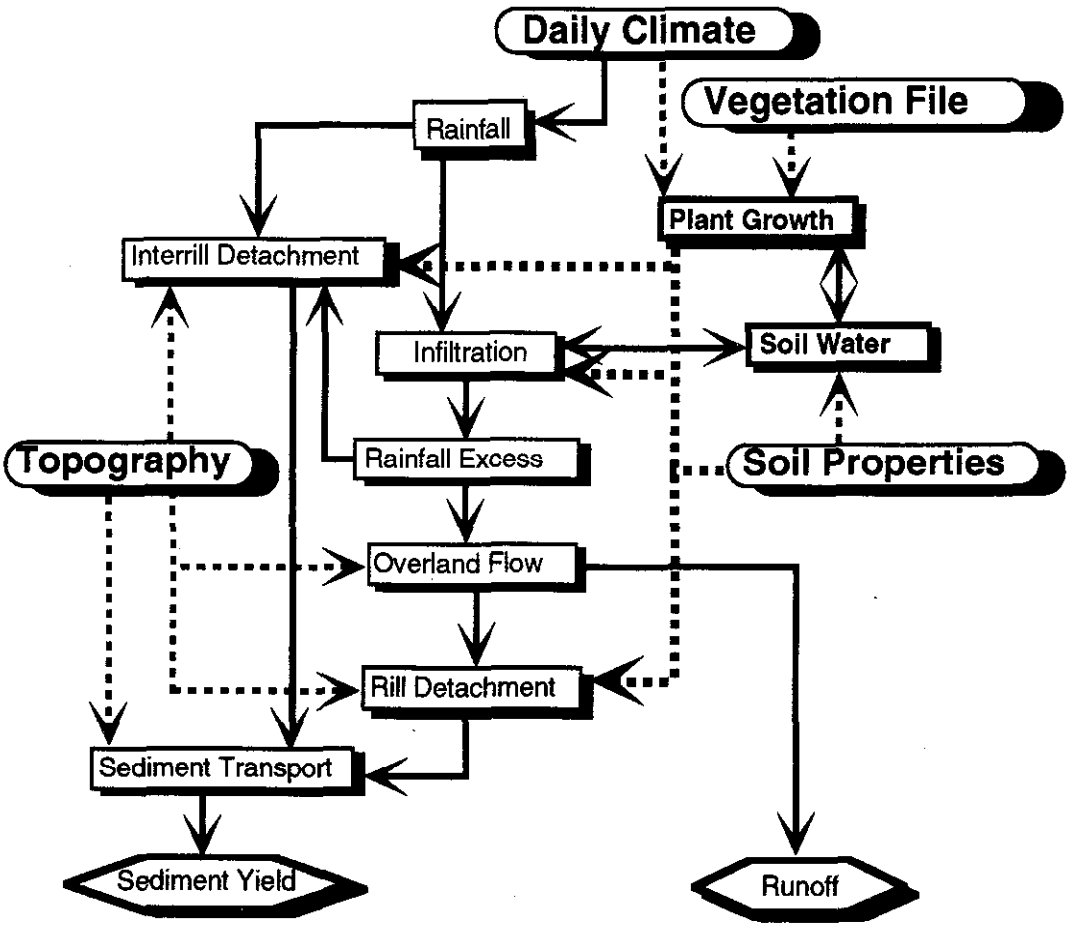

Figure 1. Outline of WEPP Model

direction of future research in modeling soil erosion and hydrology in disturbed forest environments.

The WEPP Model

The WEPP model is a complex computer program that describes the processes that influence erosion (Figure 1). These processes include infiltration and runoff; soil detachment, transport, and deposition; and plant growth, senescence, and residue decomposition. The model has a daily time step to calculate soil water content in multiple soil layers and daily plant growth and decomposition (Laflen et al., 1991). One of the major benefits of a process-based model is that sediment yield can more readily be predicted. This is important for predicting the effects of erosion on water quality. In addition, the model can more easily be applied to areas where soils, climate, and vegetation may vary widely from traditional research plots. The WEPP model was released in 1989 for scientists to begin validation studies. In 1991 a version was released incorporating numerous improvements, correcting errors in earlier code, and including a file builder. In 1994, a recoded version was released for a year of validation and field testing by scientists before the model's release to the public in August, 1995. All of these releases were a "Hillslope" version, which restricted the user to modeling topographies that could be described by a hillslope profile. The Hillslope Version also allows the user to describe different vegetation and soil conditions along a hillslope as different "overland flow elements" or OFEs. A "Watershed" version which links hillslope elements, channel elements, and impoundment elements was also released in August, 1995, which allows the user to combine hillslope elements with channel and structural elements (such as culverts and silt fences) (Ascough II et al., 1994).

Harvest Area Practices

Forest managers are using an ecosystem approach to manage their resources. Ecosystem management:

> "... ensures that stewardship of lands and resources is accomplished in an environmentally sensitive, socially responsive, and scientifically sound manner. It enables resource managers to view natural resources from a landscape or whole system perspective. It integrates the human, biological and physical dimensions of natural resource management to promote healthy, productive, and sustainable forest and rangeland ecosystems." (USDA Forest Service, 1994)

Ecosystem management may mean converting intensively managed stands to more natural conditions. Practices to accomplish ecosystem management may include increased use of partial cuttings, where only a portion of the trees are removed. Some past management activities, such as fire suppression, increased the risk of catastrophic fires. Prescribed fires now play a significant role in maintaining a healthy forest, while meeting management objectives (Reinhardt et al., 1994). Burning post-harvest residue is a common method of fire hazard reduction and site preparation. Burning is conducted alone, and in combination with other treatments, to dispose of slash, reduce the risk of insects and fire hazards, prepare seedbeds, and suppress plant competition for both natural and artificial regeneration.

Harvest Area Hydrology

Forest practices can have significant effects on local hydrology. Understanding the relationship between rainfall, runoff, and erosion is essential in developing models for any natural system. Dunne (1978) describes two processes creating overland flow: Horton overland flow and saturation overland flow. Either process may potentially occur in forest harvest areas.

Horton overland flow occurs when the rainfall intensity is greater than the infiltration capacity of the soil. Horton overland flow seldom occurs in undisturbed forests. Soil disturbance by forest practices may reduce infiltration capacities, allowing Horton overland flow to occur under high intensity precipitation. These practices include removing the organic forest floor layer by fire and compacting the soil surface by harvesting equipment.

Disturbances within forest harvest areas are generally patchy, making it difficult to model Horton overland flow processes. Springer and Cundy (1988) describe how high spatial variability of infiltration capacity can affect runoff and erosion. Compacted areas or severely burned areas may produce runoff through the Horton overland flow mechanism, but often they drain to less disturbed areas having high infiltration capacities where the surface flow ceases. Input files to the WEPP model do not readily describe the variation in forest hillslope hydrologic properties. Consequently, the effective or aggregate behavior of a hillslope as an homogenous unit or a series of homogenous overland flow elements must be determined before the WEPP model can be used.

Saturation overland flow occurs when precipitation falls on soils saturated by lateral subsurface flow. Water seeping back to the surface and direct precipitation onto the saturated soils become overland flow. Saturation overland flow is most often a result of steep local topography and long-duration, low-intensity precipitation or sustained snowmelt. Saturation overland flow can occur on soils with high infiltration capacities due to hillslope geometries that concentrate water, such as hillslope draws. Saturation overland flow is the most common process producing overland flow in undisturbed forest areas. Reducing the soil's ability to carry subsurface water downslope by removing the forest floor and compacting the soil can increase saturation overland flow. When considering the overall behavior of a hillslope in a forest harvest area, saturation overland flow should be considered.

The WEPP model does not model saturation overland flow processes. It will predict increased runoff due to increased soil water content using the Green-Ampt infiltration model, increasing

Table 1. Summary of soil physical properties and calculated parameters from the rainfall simulator experiments near McCall, Idaho.

Operation	Conductivity mm/hr	Interrill Erodibility kg s/m^4 x 10^6
Undisturbed	75 - 85	0.1 - 0.2
Burned	11 - 75	0.1 - 3.6
Unbladed Skid Trail	22 - 85	0.2 - 1.2
Bladed Skid Trail	12 - 65	0.4 - 1.8
Access Road	4 - 11	1.1 - 1.8

infiltration to the maximum saturated hydraulic conductivity in the profile under saturated conditions. The planar hillslope geometry used by the WEPP model will not allow the conditions leading to saturation overland flow to be described accurately. Identifying circumstances where the WEPP model may or may not work for estimating sediment production from harvest areas is important. This requires determining whether Horton or saturation overland flow dominates the erosion process for an area.

Differences in the climates of the Southeastern United States and the Northern Rockies provides an example of how climate can determine dominant runoff behavior. Storms in the Southeast include strong wet flows from the Gulf of Mexico, delivering frequent, high-intensity precipitation. Storms in the Northern Rockies are typically of low-intensity but long-duration. Snow melt events also tend to be of long duration and low intensity, with intensities seldom greater than a few mm/h. One would expect Horton overland flow to play a more important role in runoff in the Southeast than in the Northern Rockies. In a study comparing WEPP predictions for two typical climates, Elliot et al. (1995) found that the WEPP model apparently predicted the general trends observed in the Southeast and the Northern Rockies. This paper summarizes further validation work to compare predictions from the WEPP Watershed Version to data collected from a small harvested watershed in Central Idaho.

FIELD STUDIES

Several studies have been completed and others are ongoing to determine the parameters values needed to model runoff and sediment production from forest operations. These studies address different harvesting methods, fire severity, and spatial variability associated with these treatments. Simulated rainfall events were used to determine infiltration and erodibility parameters. Natural rainfall on both large hillslope plots and small watersheds is being used to validate the erosion parameters and the model's overall performance for forest conditions.

For this study, a 2-ha watershed was located in the Payette National Forest, between Riggins and McCall, in Central Idaho. The site was harvested several years prior to the study, and was covered in regrowth up to 1 m high prior to burning. Interrill erodibility and infiltration rates were measured on small undisturbed plots prior to a prescribed burn, and on plots with low and high severity burns after the prescribed burn as well as access roads, and skid trails. The site naturally converged to a channel at the bottom. The runoff was diverted through a sediment trap and a calibrated weir to measure runoff rates. The soil was a fine loamy Typic Crychrept derived from basalt, with a surface horizon sand content of 35 percent, silt of 40 percent, and clay of 25 percent. Table 1 shows the range of observed hydraulic conductivities and interrill erodibility values. This variation is attributed to differences in surface conditions throughout the timber harvest unit (due to management activities) and to natural variation in soil characteristics.

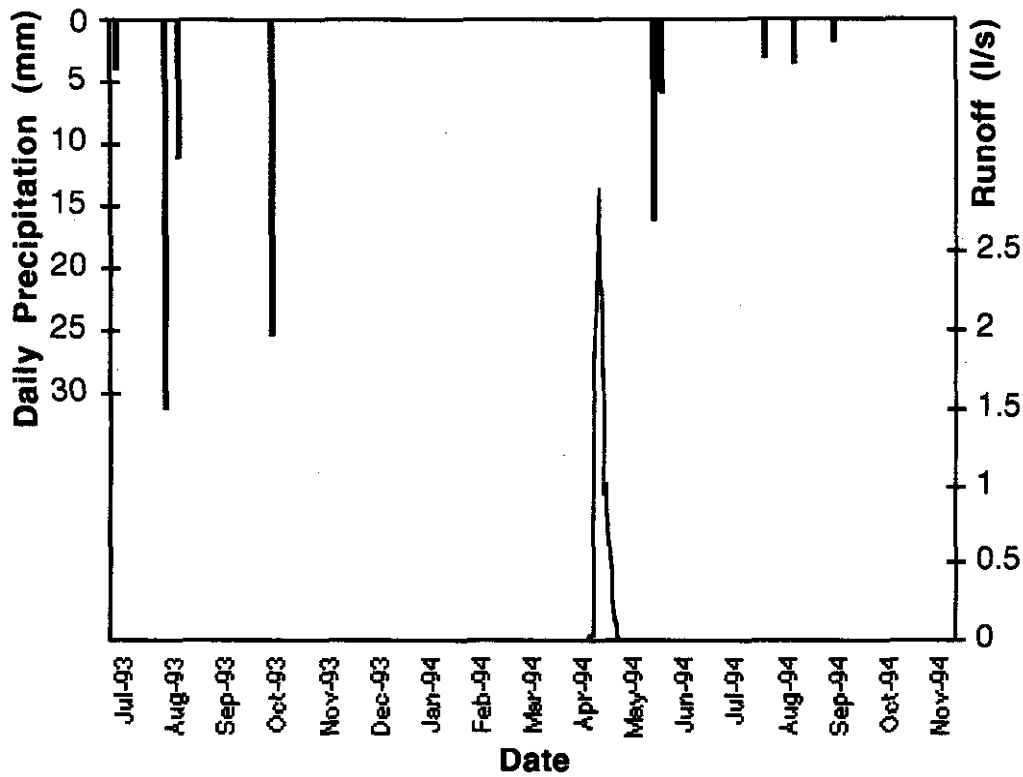

Figure 2. Distribution of storms with 1 minute intensities greater than 25 mm/hr and Runoff on Idaho watershed.

In the small plot studies, simulated rainfall events were applied to hydrologically undisturbed timber harvest sites on 1-m^2 plots with a USDA Forest Service oscillating nozzle rainfall simulator. Each plot received three 30-min rainfall events. Event 1 was conducted at the existing soil water condition. The plot was then covered with a plastic tarp. Event 2 was conducted the following day. Event 3 was conducted about 30 minutes after Event 2. The maximum intensity of the rainfall simulator was 85 - 95 mm/hr, so it is possible that some plots may have had hydraulic conductivities in excess of the 85 mm/hr maximum that was measured. Timed runoff samples were collected, weighed, and oven-dried to develop hydrographs, sedigraphs, total runoff volumes, and sediment yields. Hydrographs were analyzed using the methods of Luce and Cundy (1994) to obtain infiltration parameter values. Interrill erodibility parameters were calculated from a modified version of Laflen et al.'s (1991) sediment delivery equation, as a function of applied rainfall, rainfall excess, canopy cover, ground cover, and slope adjustment factors. There are limitations to small plots in that any hydrologic observations on the plots will have a much greater variation in properties than will larger plots where such variation tends to be averaged. Generally, our observations show that the conductivities observed on small plots are greater in both magnitude and variation than on larger plots.

Rainfall and runoff observations for 16 months from the small watershed are presented in Figure 2. The daily precipitation depth is plotted only for days with one-min rainfall intensities greater than 25 mm/h, which was the median observed saturated hydraulic conductivity of bladed skid roads, the disturbance yielding the lowest infiltration capacity. The most noticeable aspect of these data is that all of the runoff is during the spring snowmelt period. No runoff is recorded from the high-intensity summer thunderstorms. Snowmelt intensity rarely exceeds 10 mm/hr, and should be less on this north-facing watershed. The surface hydrology and erosion of this system appears to be driven by saturation overland flow. About 120 kg of sediment were trapped from the one

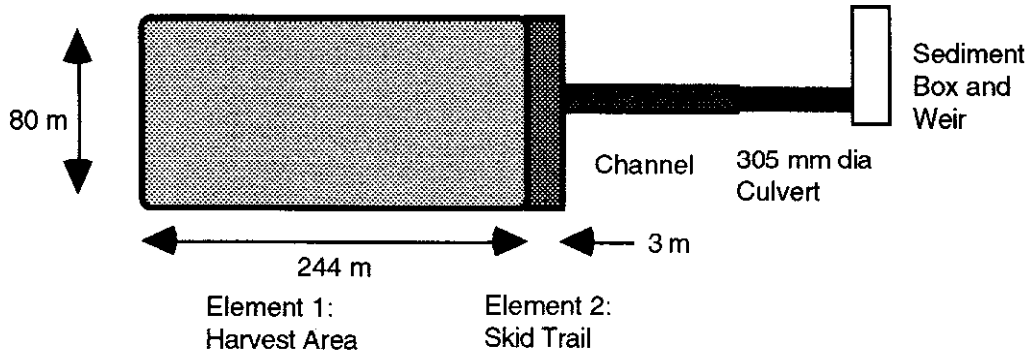

Figure 3. Schematic of McCall Watershed.

runoff period before the sediment trap was filled, which was about three days into the two-week runoff period. The total sediment yield is estimated to be between 500 and 1000 kg, and the total runoff was nearly 1500 m^3 or a depth of 76 mm on the 2 ha watershed.

On such large plot studies, several years of data are necessary to evaluate a model, because of the variability of the natural climate. Data collection from this watershed, and six others, will be ongoing to obtain a range of validation conditions.

WEPP PREDICTIONS

The WEPP Watershed model was set to describe the McCall watershed conditions as shown in Figure 3. The harvest area and skid trail were defined as a single hillslope element with two OFEs. The harvest area had a slope of 44.7 percent, and the skid trail, which was approximately on the contour, had a downslope steepness of about 9 percent. The hillslope drained into a channel with a 44.7 percent gradient, which led to a culvert with a slope of 70%. The observed climate was available for one winter season, and was formatted for the WEPP model. Vegetation was described as a regenerating forest (Elliot et al., 1995).

Previous validation studies have shown the importance of ensuring that the conductivity is correct, so a number of WEPP scenarios were developed. The soil profile was based on a typical forest soil found nearby and site observations. To determine the relative importance of the range of observed hydraulic conductivities and soil variation, a range of values were run with the WEPP model. In the lower soil layers, hydraulic conductivity is determined by the clay content, and calculated internally (Flanagan et al., 1995). A summary of the runoff and erosion rates for different conductivities is presented in Table 2.

From the simulation results in Table 2, it appears that their is a threshold conductivity for the harvest area between 40 and 80 mm/h. For harvest area conductivities greater than 40 mm/h, there is no runoff from the harvest area and for conductivities below 40 mm/h, there is combined runoff from the skid trail and the harvest area.

All of the observed runoff and erosion in Table 2 occurred from snow melt during several days in early April as shown in Figure 2. The predicted runoff, however, occurred in a single day of snow melt in mid-December. It appears that the WEPP model is overpredicting the rate of snow melt so that the large observed snowfalls in early December (over 120 mm) are predicted to melt as soon as the temperature rises above freezing, and there is insufficient snow remaining to melt and cause runoff for the warm weather observed in early April.

The importance of the clay content in the subsoil is also apparent in Table 2. Frequently, the depth and texture of a forest subsoil is not well known because of the limited detail available from forest soil surveys. Such a lack of information may restrict the application of WEPP to areas lacking detailed forest soil surveys. As discussed previously, in forest conditions, the subsurface soil water may play a major role in determining surface runoff and it appears that WEPP is able to

Table 2. Summary of total runoff and erosion predicted by the WEPP model for the McCall watershed for the range of observed soil hydraulic conductivity properties.

Hydraulic Conductivity mm/h Harvest Area	Skid Trail	Runoff cubic meters	Sediment Yield Mg
Observed			
15 - 80	15 - 65	1486	0.5 - 1.0 *
Predicted			
Subsoil Clay = 20 %		Sand = 30 %	
80	60	0	0
	30	4	0
	15	4	0
40	30	150	1.3
	15	150	1.3
20	15	150	1.3
Subsoil Clay = 40 %		Sand = 10 %	
80	60	0	0
	30	10	0
	15	10	0
40 **	**30 ****	**617**	**11.1**
	15	617	11.1
20	15	617	11.1
Subsoil Clay = 60 %		Sand = 5 %	
80	60	0	0
	30	12	0
	15	12	0
40	30	764	14.6
	15	767	14.7
20	15	767	14.8

* Estimated
** Median of values observed on the site

account for part of this process. In the very steep hillslopes in forest conditions, however, additional consideration may be necessary to determine whether the subsurface flow from the top of the hillslope is accumulating at the base of the hillslope to cause less infiltration and greater runoff from this part of the slope. The current input and output options from the WEPP model make it difficult to determine subsurface flow influences, and further work is required to fully evaluate WEPP's performance under such high infiltration, steep slope conditions.

The sediment yield is over-estimated, so some additional consideration needs to be given to paramaterizing forest soil rill and channel erodibility and ground cover factors. The high sediment yield is also due to the very high runoff rates predicted on December 10, causing considerable upland erosion, with some channel deposition. Table 3 shows that there was predicted rill erosion, with channel deposition. Site observations indicated little rilling, but apparent channel downcutting. In almost every scenario, the runoff occurred during a single day, and not two

Table 3. Summary of the distribution of total runoff and erosion predicted by the WEPP model for the McCall watershed

Location	Runoff (m^3)	Sediment Yield (Mg)
Hillslope bottom	622	34
Channel Outlet	623	18
Culvert outlet	628	10

weeks as was observed. This is likely due to the lack of any subsurface flow consideration in the hydrology routines to give an extended runoff period. If the modeling of the snow melt and near-surface runoff can be improved, then the predicted sediment yields may decline significantly, because of the reduced surface and subsurface runoff rates.

CONCLUSIONS

The WEPP model shows promise as a tool to help forest managers predict the onsite erosion and offsite sedimentation due to timber harvest. Additional validation with small watershed, natural rainfall and snowmelt field data is necessary to determine the accuracy of the predicted erosion. Further research is needed in modeling snow melt effects on runoff, in modeling saturated overland flow, and in determining the equivalent hydraulic conductivities of hydrologically complex watersheds. This work unit is currently researching all of these areas to improve future model performance.

Acknowledgments

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THE SEDIMOT III - MODEL OF WATERSHED HYDROLOGY AND SEDIMENTOLOGY

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Abstract: A description of the new SEDIMOT III model is given along with example predictions. The new model is a major revision of SEDIMOT II with dramatically improved procedures for hydraulic and sediment routing and new routines for predicting erosion in ephemeral gullies and small channels. In addition to the standard drop inlet spillway algorithms available in SEDIMOT II, procedures are included to effectiveness of rock-fill outlets, culverts, slotted risers, open channels and emergency spillways, straw bales, filter fence, and brush barriers.

INTRODUCTION

SEDIMOT II and its derivatives have been widely used to predict the hydrology and sedimentology of small watersheds where channel erosion was not assumed to be significant. Included in SEDIMOT II was the ability to predict sediment deposition in vegetative filter strips and in structures that impounded water. Impoundments were limited to reservoirs where density currents were not a problem, and to check dams formed by porous rock fill. The hydraulics component of the rock fill was suspect and not experimentally validated. Sedimentation procedures in the rock fill, reservoirs and vegetative filter models were dramatically different. Although SEDIMOT II and its derivatives have been widely used, there has been a continuing need to extend the hydraulics component to different types of structures and to utilize consistent principles of sedimentation.

An additional problem with SEDIMOT II was the instability which occurred with small structures when outflow rates approached inflow rates. There was a need to improve the routing procedure and make it more robust. In addition, the model was routinely being used where concentrated flow erosion could be a problem. Since the routine did not consider channel erosion, there was a probability of significant error associated with the predictions. Finally, the user was allowed to model erosion with either a Modified Universal Soil Loss type relationship or use a process based model of erosion and deposition known as SLOSS. There was a need for a consistent procedure.

To solve these three problems, SEDIMOT II has been dramatically modified to develop SEDIMOT III, Version 1. The four enhancements are: (1) Replacement of the Puls reservoir routing method with an adaptive time step numerical routing procedure. (2) Development of algorithms to predict stage-discharge relationships for a variety of outlet structures. (3) Incorporation of an erosion/deposition model that allows calculation of erosion/deposition in channels throughout the watershed. (4) Modification of the impoundment elements to allow consistent sedimentation procedures.

In addition, the erosion-sediment-transport component was modified to only allow use of SLOSS to route sediment through all channels and watersheds.

DETAILS OF RESERVOIR HYDRAULICS

Introduction

The hydraulics portion of SEDIMOT III is a modification of the WEPP Surface Impoundment Element (WEPPSIE) developed for the Water Erosion Prediction Project watershed model (Lindley et al., 1992, 1993). The WEPPSIE model includes five sections: a front end interface, daily input, hydraulic simulation, sedimentation simulation, and daily output. The hydraulic simulation and front end interface are modified and used in SEDIMOT III.

Within the front end interface, the coefficients of continuous stage-discharge relationships are determined from information entered by the user, describing each outflow structure present in a given impoundment. The user can enter information on one or more of the following possible structures.

1. Drop spillway (circular or rectangular)
2. Perforated riser.
3. Two sets of identical culverts.
4. Emergency spillway or open channel.

5. Rock-fill check dam.
6. Filter fence or a straw bale check dam.

The user also has the option of entering a discrete stage-discharge-relationship. The model then uses nonlinear regression to develop coefficients that fit a polynomial to the discrete data. For structures that are too hydraulically complex to allow for a direct solution of outflow for a given stage, the coefficients for continuous, directly solvable equations are also developed the nonlinear regression procedure. The coefficients for continuous stage-area and stage-length equations are also developed in the front end interface. By using continuous flow functions, the error associated with linear interpolation between discrete data points is eliminated.

Hydraulic Routing

The hydraulic simulation section of the impoundment element performs a direct numerical integration of the continuity equation. An adaptive time step is utilized which increases the time step when the inflow and outflow rates are relatively constant. The hydraulic component of SEDIMOT III functions on the five types of impoundments described earlier. The outflow, Q_o, in the continuity equation depends upon the type of outlet structure, and its dimensions. Given the type and size of the outlet structure, the outflow, Q_o, is functionally related to the difference between water surface stage and the inlet stage of the outlet structure, called the driving head, or:

$$Q_o = f_{Q_o}(h) \tag{1}$$

In some impoundments, more than one outlet structure is utilized, as in the case of a traditional reservoir with a drop-inlet spillway and an emergency spillway. In this case, the functional relationship in equation 1 takes one form when there is flow only through the drop spillway, and another form when there is also flow through the emergency spillway. In the model, an outflow regime is defined as the range of water surface stages in which the functional relationship in equation 1 takes on a certain form. When the functional relationship in equation 1 changes form, as in the case when flow changes from flowing only through a drop-inlet to flowing through both a drop-inlet spillway and an emergency spillway, the flow is said to have transitioned from one outflow regime to another.

The reservoir area, A, is also related to the stage of the water surface, depending upon the topography of the impoundment, or

$$A = f_A(h) \tag{2}$$

Using equation 1 and 2 in a continuity relationship, the change in head becomes:

$$\frac{dh}{dt} = \frac{Q - f_{q_o}(h)}{f_A(h)} \tag{3}$$

where Q is the inflow rate and dh/dt is the rate of change of stage with time. The continuity expression given in equation 3 shows that the change in stage over time is uniquely related to the inflow rate and stage. To integrate the continuity expression given in equation 3, a classical fourth-order Runge-Kutta numerical integration is employed which has been adapted from Press et al. (1986). This approach gives an error term on the order of Δt^5.

To increase the speed of the Runge-Kutta numerical integration procedure, an adaptive ste size has also been incorporated from Press et al. (1986). This adaptive step size procedure increases or decreases the time step, Δt, based on the rate at which the outflow and inflow rates are changing.

Stage-Discharge Relationships

Stage-discharge relationships are developed from information the user enters about each outflow structure incorporated into a given impoundment. To save time, the front end interface is utilized to develop coefficients for directly solvable continuous outflow functions for each possible outflow structure. For structures such as drop-inlet spillways, culverts, rock fill check

dams, filter fence, and straw bale check dams; explicit stage-discharge functions can be developed directly from the dimensions of the outflow structure entered by the user. For structures with more complex stage-discharge relationships that require iterative solutions for the discharge for a given stage, regression equations are utilized as stage-discharge relationships.

Drop-Inlet Spillway

A drop-inlet spillway is a common outflow structure used in farm ponds and sediment detention basins. It consists of a vertical riser connected to a horizontal or near horizontal barrel. The drop spillway has two possible outflow regimes; no flow and flow. If the water surface stage is below the stage of the riser opening, the outflow is zero. Flow through a drop spillway occurs when the water surface stage is above the riser inlet. The outflow rate is determined by assuming weir flow, orifice flow, and pipe flow control. The outflow rate is the minimum of the three possible controlling flows.

Perforated Riser

Perforated risers are often used as outlet structures for small impoundments and terrace outlet systems. A perforated riser is similar to a drop inlet in that both employ a riser that empties into a subsurface conduit. The perforated riser includes slots along the riser to allow complete drainage of the terrace. A bottom orifice plate is sometimes included to limit flow to the subsurface conduit located below the slots.

The perforated riser has three possible outflow regimes; no flow, flow through the side slots, and flow submerging the perforated riser. If the water surface stage is below the stage of the bottom of the slots, the outflow is zero. When the water surface stage moves above the stage at the bottom of the slots, water begins to flow through the riser. Flow can be controlled by either the slot (slot flow), the orifice plate located below the slots (orifice flow), or by the subsurface conduit flowing in full pipe flow (pipe flow). The outflow rate is determined by computing the slot flow, orifice flow, and the pipe flow and taking the minimum controlling flow. Procedures for calculating flow through the slotted riser were adopted from McInroe et al. (1988).

Culverts

Culverts and trickle tube spillways, can be used as outlet structures for sediment basins. Culverts are also used to control flows under roadways, often resulting in an impoundment from ponding upstream of the culvert. The determination of outflow through the culvert is based upon the FHA (1985) report on culvert hydraulics. The outflow through the culvert is determined by computing the outflow if the inlet is unsubmerged, and if the culvert is flowing under full pipe flow. The outflow is the minimum controlling flow.

In practice it is common for engineers to use two or more identical culverts to route channels under roadways. It is also possible for engineers to utilize two culverts of different shapes, sizes, or at different elevations. To accommodate these situations, the impoundment element allows the user to specify two different sets of any number of identical culverts.

Emergency Spillways and Open Channels

In many reservoirs and sedimentation basins, emergency spillways are used to route the excess runoff from very large storm events that cannot be routed through the principle spillways. This keeps flow during rare events from over topping and breaching an earthen dam. Sometimes an open channel forms the only outlet structure.

Emergency spillways and open channel outlet structures have two possible flow regimes; either no flow or flow. If the water surface stage is below the stage of the open channel inlet, the outflow is zero. For computational efficiency, flow through an open channel is determined with a fourth-order polynomial expression:

$$Q_{open\ channel} = A + Bh + Ch^2 + Dh^3 + Eh^4 \qquad (4)$$

where h is the driving head (water surface stage - stage of the open channel inlet) and A, B, C, D, and E are coefficients unique to the user defined open channel outlet. A stage-discharge relationship computed with the steady-state standard step method (Fogle and Barfield, 1992; Chow, 1959) is utilized with regression routines in the front-end interface to compute the coefficients A, B, C. D, and E for a given user defined open channel outlet.

Rock Fill Check Dams

Construction, mining, and silviculture operations need inexpensive temporary sediment traps. Porous rock-fill check dams provide an inexpensive, easily constructed solution. A porous rock-fill check dam is simply a pile of rocks obstructing the free flow of sediment laden water. Frequently a rock-fill check dam is constructed with a coarse sand or fine gravel core in order to trap the most sediment and covered by a larger rip-rap used to prevent washout.

A porous rock-fill check dam has four possible outflow regimes: no flow, flow through the rock, or flow overtopping the structure plus flow through the fill. If the water surface stage is below the stage of the rock-fill inlet the outflow is zero.

Flow begins when the water surface stage rises above the stage of the rock fill inlet. Flow through the rock-fill is determined using a numerical adaptation of the graphical method developed by Haan et al. (1994), or:

$$h_{rock\ fill} = wd_{rf}\left(\frac{dh}{a\ dl}\right)^{1/b} \tag{5}$$

where wd_{rf} is the width of the rock-fill, dh is the head loss through the rock-fill, dl is the length of the rock-fill, and a and b are coefficients. Regression equations were developed for the constants a and b using the Haan et al. (1994) graphs. When flow overtops the rock-fill, the flow over the rock-fill is modeled as a broad crested weir and added to the flow through the rock-fill.

Filter Fence and Straw Bale Check Dams

Check dams can also be constructed with straw bales or filter fence. Both straw bale and filter fence check dams provide inexpensive, easily constructed sediment trapping structures. Discharge through a filter fence or straw bale check dam is dependent upon the porosity of the check dam, the flow stage, the cross-sectional flow area, and the size distribution and concentration of incoming sediment. A filter fence or straw bale check dam has three possible outflow regimes: no flow, flow through the filter, or flow overtopping the structure and flow through it. *Although SEDIMOT III will compute flow overtopping a filter fence or a straw bale check dam, in reality most filter fence or straw bale check dams will wash out under such large flows.* If the water surface stage is below the stage of the filter fence or straw bale inlet the outflow is zero. The slurry flow rate can be utilized to compute the flow through a straw bale or a filter fence check dam by assuming a rectangular cross section.

When the flow overtops a filter fence or a straw bale check dam, the structure will probably wash out. Filter fence and straw bale check dams are designed to filter low flows and should not see water surface stages greater than 0.2 to 0.4 m. It is assumed that proper maintenance is utilized to promptly repair any damaged check dam. When choosing slurry flow rates the user should consider the effects of sediment laden water and clogging which usually result in lower slurry flow rates as compared to clear water.

User-Defined Stage-Discharge Relationship

A user-defined stage discharge relationship is utilized when a structure is encountered that is not included in the user interface. When using a user-defined stage-discharge relationship, two flow regimes are possible. When the water surface stage is below the user-defined stage at which flow starts, the outflow is zero. When the water surface stage is above the stage at which flow starts, flow is computed according to the fourth-order polynomial give in equation 4.

To determine the coefficients of equation 4, the user enters as many stage-discharge points as possible (at least 15). Regression routines (Press et al., 1986) are then utilized to determine the coefficients in equation 4.

Overall Outflow Expression

The total outflow is simply the summation of the outflow contribution of every possible structure making it possible to have any combination of the possible outflow structures on a given impoundment. The total outflow is determined by summing the contributions of each possible outlet structure considering the relationship of the stage to the transition stages for each of the possible outlet structures. The total outflow is determined with the following expression:

$$Q_{total} = Q_{drop\ spillway} + Q_{perforated\ riser} + Q_{culvert\ set\ 1} + Q_{culvert\ set\ 2}$$
$$+ Q_{emergency\ spillway,\ open\ channel,\ user\ defined} + Q_{rock\ fill} + Q_{filter\ fence,\ straw\ bale} \quad (6)$$

tage-Area Relationship

The stage-area relationship, $f_A(h)$, utilized in the continuity expression, equation 3, is in the form of a power function as recommended by Laflen (1972) and Haan and Johnson (1967). The functional relationship between area and stage is given in the following expression:

$$A = f_A(h) = a + bh^C \quad (7)$$

where h is the stage and a, b, and c are coefficients. To determine the coefficients in equation 7, the user enters as many stage-area points as possible (at least 10), and regression routines (Press et al., 1986) are used to determine the coefficients a, b, and c.

CONCENTRATED FLOW EROSION MODEL

Introduction to Channel Erosion and Foster and Lane Model

Concentrated flow channels develop from the concentration of overland flow, where interrill and rill sediment is transported and eroded material detached from within the channel itself. Soil detachment in concentrated flow channels results from excessive shear forces produced by concentrated flow, sidewall sloughing, and head cut advancement. Head cut advancement, due to its complexity and the lack of available physically based models, is neglected in SEDIMOT III. Vertical sidewall sloughing is assumed to occur on rectangular channels during lateral expansion. Rectangular channel cross sections are assumed in order to incorporate the Foster and Lane channel erosion model (Foster, 1982). The basic structure of the model is that of DYRT (Storm et al., 1990).

Foster and Lane Model Development

The Foster and Lane channel erosion model (Foster and Lane, 1983) was originally incorporated into CREAMS for describing ephemeral gully growth in a tilled agricultural field. The model assumes a steady state flow rate, separating channel development into two distinct stages. During the initial stage, the channel bottom erodes uniformly downward at a width dependent upon flow rate and soil properties. If flow conditions remain constant, an equilibrium width is achieved. During the second stage of development when the channel bottom reaches a non-erodible layer, the channel expands laterally causing sidewall sloughing. This lateral expansion continues until a final width is reached, after which soil detachment ceases. Their model estimates the maximum potential erosion; therefore, the effects of sediment load and transport capacity must be accounted for.

Detachment Rate

The rate of potential channel detachment is assumed to be based on shear excess, written as (Foster, 1982):

$$D_{rc} = K_r\ (\tau - \tau_c) \quad (8)$$

where D_{rc} is the maximum potential channel detachment rate per unit channel length and width, K_r is a soil erodibility factor for channel flow, τ is the shear stress acting a point along the channel boundary, and τ_c is the critical tractive force.

Equilibrium Channel Characteristics

For a constant flow rate, the channel is assumed to have a rectangular cross section with an equilibrium width. Prior to reaching a non-erodible layer, the channel bottom is assumed to have a parabolic shape, which is assumed to move vertically

downward at a uniform rate, thereby implying that the vertical erosion vector is constant along the channel bottom. Using this assumption and a symmetrical shear distribution, Foster and Lane (1980) developed normalized relationships for the channel equilibrium characteristics which predicts channel width as a function of flow rate and density, slope roughness, and critical tractive force.

The Foster and Lane model assumes steady state flow conditions. Therefore, during flow rate changes their steady state erosion model is not applicable. To reconcile this problem, a procedure was developed to represent channel geometry and detachment rates during this transitional phase using the DYRT model of Storm et al. (1990).

Sediment Load and Transport Capacity Interactions

Meyer and Monke (1965) observed that in equation 8, the potential detachment rate does not describe actual detachment since it neglects the interaction between sediment and transport capacity. Foster and Meyer (1975) proposed that rill detachment and deposition are proportional to the difference between transport capacity of the flow and sediment load;

$$D_r = D_{rc}\left[1 - \frac{q_s/W}{T_C}\right] \tag{9}$$

where D_r is actual detachment, D_{rc} is potential detachment, q_s is sediment load, W is channel width, and T_c is transport capacity.

Transport Limiting Case: Deposition Effects

For transport limiting flow, deposition of eroded sediment has a major impact on sediment yield. Deposition occurs when the flow does not contain sufficient energy to transport eroded sediment. This can result from either a decrease in transport capacity or an influx of additional sediment. The deposition rate per unit length of channel, E_r is calculated from

$$E_r = \frac{V_S X}{q}\,(T_c - q_s/W)\,\frac{W}{L} \tag{10}$$

where L is the total channel length, and V_sX/q represents the fraction of deposited sediment at a distance X downstream.

Transport Capacity

Most current sediment transport theory was developed for stream flow conditions. However, Alonso et al. (1981) found that the Yalin equation (1977) was appropriate to use on the transport of light materials in stream flow, and a range of particle sizes and densities in shallow flow typically encountered in field conditions. Therefore, the Yalin transport equation was selected to evaluate the transport capacity of channel flow.

APPLICATIONS

An illustration of the application of Sedimot III was made on two construction watersheds using impoundments with a variety of outlet structures. A summary of watershed characteristics are given in Table 1. The impoundments utilized are summarized in Table 2. A 24 hour NRCS Type 2 storm of six inches was used as model input.

A variety of impoundments were applied to the watersheds to illustrate some of the computational capability of Sedimot III. Characteristics of the impoundments are shown in Table 2. The output of different types of impoundments should not be compared directly. This exercise is simply to illustrate some of the kinds of structures that can be evaluated.

Table 1. Characteristics of Example Watersheds							
Watershed	Area (ac)	Curve No	Soil Erodibility	Slope (%)	Peak Discharge (cfs)	Peak TSS (mg/L)	Peak Settleable Solids (mL/L)
Small	10	85	0.3	10	8.7	201,120	114
Large	200	85	0.3	10	100.0	243,496	120

Table 2. Characteristics of Impoundments					
Code	Description	Watershd	Code	Description	Watershd
DI,1.25,2A	1.25 ft drop inlet, pond area 2A.	Large	RK,0.2,2A	20 ft wide rock spillway, 0.2 ft dia, 5 ft thick, 4 ft high, pond area 2 A	Large
DI,1.25,4A	1.25 ft drop inltet, pond area 4A .	Large	RK,0.2,4A	20 ft wide rock spillway, 0.2 ft fia, 5 ft thick, 4 ft high, pond area is 4 A	Large
DI, 2.0,4A	2.00 ft drop inltet, pond area 4A	Large	SB	Straw bale dike, 20 ft wide, 1.5 ft high.	Small
DI,3.0,4A	3.00 ft drop inltet, pond area 4A	Large			

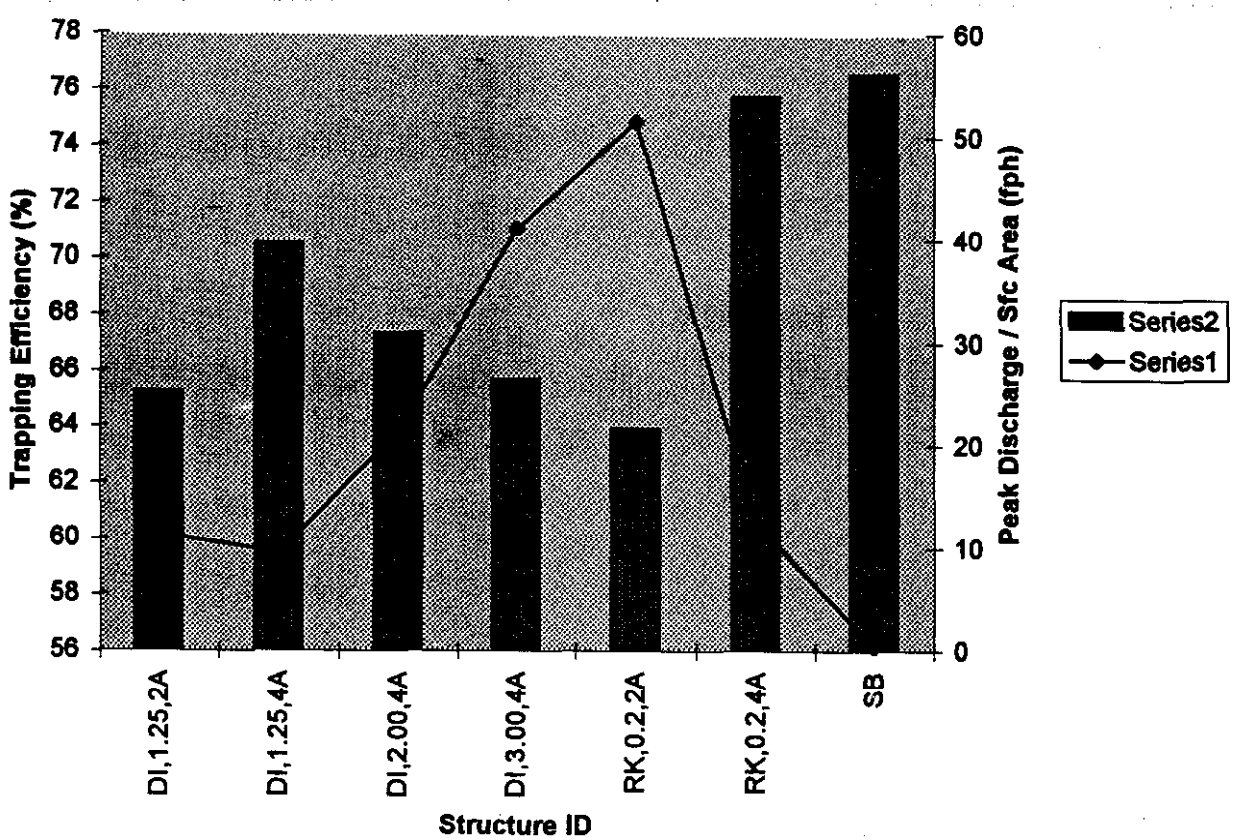

Figure 1. Trapping efficiency predictions for the structures described in Table 2.

Results

Example results are shown in Figure 1 where trapping efficiency is plotted as the bar chart for each structure type and the ratio of peak discharge to surface area (modified overflow rate) is the solid line. Trends follow whatone would expect, with trapping efficiency decreasing for a given reservoir as the modified overflow rate increases. In interpreting the results, it should be remembered that the watershed for the structure with the straw bale outlet is only 10 ac compared to 200 ac for the larger watershed.

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ERODED PARTICLE SIZE DISTRIBUTIONS FOR DESIGN OF SEDIMENT CONTROLS

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Abstract: Engineering design of sediment control systems usually involves computer modeling or extensive calculations. These methods require input such as rainfall, soil, cover, topography, and information about management practices. For the prediction of sediment transport and deposition, it is important to obtain an eroded particle size distribution. This size distribution is used in detachment and transport equations and in determining trapping efficiencies of structures. Currently recommended procedures for estimating eroded sizes often revert to simplistic rule of thumb methods because of the lack of an accepted method. This occurs even though the impact of an error in the eroded sizes probably has more impact on design of a sediment control structure than any other single design component.

One currently used method for obtaining eroded size is based on equations used in the CREAMS model. These equations estimate amounts of sand, silt, clay, and large and small aggregates based on primary particle size distributions. Percentages of each component are then used to estimate the eroded size distribution. This paper compares results from the CREAMS-equation method with eroded particle size distributions obtained from 17 topsoils and 17 subsoils resulting from rainfall simulation. The soil textures of these 17 soils were outside of the range of soil textures that were used to develop the CREAMS equations. Since the equations were developed primarily from high clay content topsoils in the midwest, there was concern that the statistically-based CREAMS equations would not adequately predict distributions for topsoils and subsoils having high sand content such as in the Southeastern U.S.

Results from the work indicate that the CREAMS equations can only provide a rough estimate but may be appropriate because of their availability and ease of use. However, results indicate that for major projects, particularly in sensitive areas, there is no substitute for analyzing a field sample. Analysis of a local sample for primary particle size distribution and input into the CREAMS equations provides some improvement, while analysis using rainfall simulation often provides better estimates of the size distribution.

INTRODUCTION

Sediment is a major byproduct of construction sites, agriculture, mining operations, and other disturbed soil operations. These are defined as nonpoint sources of pollution. Recently, a great deal of attention has been given to controlling sediment input into water sources. Water quality laws require more control at the sources and put pressure on engineers to accurately predict sediment runoff from sites and the efficiencies of control devices. One such law is the South Carolina Storm Water Management and Sediment Reduction Act of 1991, which requires a full sediment control plan before any construction starts (South Carolina Land Resources Commission, 1992).

Evaluation of sediment control systems usually involves modeling programs. For the prediction of sediment transport and deposition, it is important to obtain an eroded size distribution (ESD). The ESD is used in detachment equations and in determining sediment pond efficiencies.

Size is important in calculation of settling velocities of individual soil particles. After settling velocity is found, it can be used to estimate whether a specified size particle will be removed by a sediment pond. Computer models use these equations to determine the amount of detention time required for particles to settle.

One method for determining ESD involves the use of data collected by the U.S.D.A. Soil Conservation Service and equations used in the CREAMS model to estimate the eroded percentages of sand, silt, clay, and large and small aggregates. These equations will be referred to as the CREAMS equations herein. The CREAMS equations use dispersed particle size data and estimate the non-dispersed particle size distribution.

Impacts of Different ESD: The most important portion of ESD's for designing sediment controls is in the range of 0.031 to 0.002 mm. This is because smaller particles are more difficult to remove by settling. If the sediment is 0.031 mm, the time for settling a 1 m depth would be approximately 4 hours, assuming a specific gravity equal to 2.65 and a spherical shape. However, if the diameter is 0.002 mm, settling time approaches 140 hours. This increase of thirty-five times shows the importance of ESD in sizing settling ponds. Particles less than 0.002 mm are generally considered to be too small to be trapped without flocculation.

Methods of Obtaining ESD: Much research has been done regarding primary particle size distributions (i.e., percentage of sand, silt, and clay). The basic process by which primary particles are found is by taking a sample of soil and mixing a solution of sodium hexametaphosphate and water to disperse the aggregates into primary particles. This dispersion method is done because the resulting distributions are more consistent, and the results can be used to explain much about the chemical and physical behavior of the soil. However, primary particle distributions are not what is needed for estimating sediment detachment, transport and deposition because aggregates are naturally present in sediment laden runoff.

Many researchers have suggested using original soil matrix texture data. This is probably because county soil surveys produced by the Soil Conservation Service contain data that are easily converted to textural data (percentage of sand, silt and clay). Also, soil survey data is readily available. One method of predicting the ESD was produced by a review of 21 soils (Young, 1980). Young divided the 21 soils into three categories and produced equations for each. The three categories were high sand, clay and silt. These equations provided one of the first methods of predicting ESD. An important aspect of soil is the aggregate content because density also affects fall velocities.

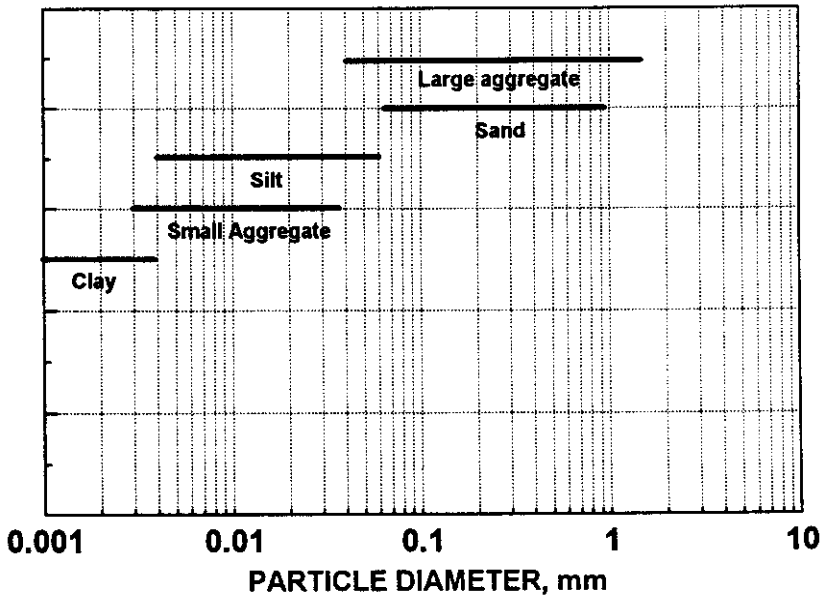

Figure 1. Size ranges of the different collections of sand, silt, clay, and small and large aggregates.

Soil is composed of individual particles and combinations of individual particles called aggregates. Aggregates typically have a lower density because of void spaces. A set of ESD equations was developed using Young's data to predict percentages of sand, silt, clay, and small aggregate and large aggregate in the sediment (Foster et al., 1981). These equations were revised by Foster et al. (1985) based upon additional data. The revised equations have been used recently in a number of process-based erosion models.

The divisions of sand, silt, clay, and large and small aggregates can be further manipulated to form cumulative distribution curves. In 1992, personnel at the South Carolina Land Resources Conservation Commission developed a program to calculate these five divisions from the CREAMS equations using soil survey data and then estimate an ESD using linearly interpolated percentages of the particle size ranges. The soil survey data used are percentages of high and low clay and percentages of high and low sand. The calculations involved in producing the distribution curve use a linear interpolation of the particle size ranges for sand, silt, clay, and small and large aggregates. The size ranges of eroded soil shown in Figure 1 were estimated from several studies (Young, 1980). For instance, if one of the points on the desired curve was 0.031 mm diameter, then all particle types (i.e., small aggregate, silt and clay) that exist on Figure 1 below 0.031 mm diameter need to be included. The 0.031 mm particle size intersects the small aggregate and silt ranges in Figure 1.

Size of fraction for any of the five divisions can be calculated by the following equation

$$Size\ Fraction = \frac{D_i - D_{min}}{D_{max} - D_{min}}. \tag{1}$$

where D_i, D_{min}, and D_{max} are the diameter of interest, minimum diameter, and maximum diameter, respectively. For example if we use 0.038 mm as the diameter of interest, a fraction of silt (Fsi), all of the small aggregates (Fsg), and all of the clay (Fcl) should be included. In this case when we are concerned with the silt,, D_{min} is 0.004 mm, and D_{max} is 0.06 mm. The resulting silt fraction less than 0.038 mm is 0.6. The equation for cumulative percent finer at diameter 0.038 mm (i.e., for small aggregates, silt and clay) then becomes

$$Fraction\ Finer_{0.038} = Fcl + 0.6\,Fsi + Fsg \tag{2}$$

Equations similar to equation 2 can be determined for any sizes of interest. Equations for twelve diameters are shown in Table 1. From the ESD curves generated, representative diameters are selected as desired.

MATERIALS AND PROCEDURES

The following sections describe the materials and methods used to complete this project. Each soil was located using the Soil Conservation Service county soil surveys. The soils were selected by finding dominant soils in the major land resource areas of the state. At each sampling location, surface vegetation was removed, and the intersection of topsoil and subsoil was defined by an abrupt change in color, such as brown to red, and usually more clay content was observed. Once the depth was determined and recorded, a shovel and a posthole digger were used to remove each soil sample. At the laboratory the samples were tested using a rainfall simulator to gather sediment-laden runoff from which an eroded particle size distribution was estimated.

Rainfall Simulation: The rainfall simulation used a 25 x 30 cm pan with a retaining grate and metal plate inserted inside. This pan was placed at a slight angle 3 m below a nozzle. The nozzle was a Spraying Systems 80150 nozzle with a flow regulator.

Water was supplied to the flow regulator at 137 kPa until rain gages on each side of the pan were filled to 12.7 cm to simulate a design rainfall in South Carolina. The runoff was directed onto sieves within a bucket. The runoff was filtered through 3 sieves and collected in an 18 L bucket. The three sieves had openings of 2, 1, and 0.5 mm.

Sieve Analysis: During the simulation, the sieves were occasionally shaken to prevent blockage which would cause the runoff to overflow the sieves. After the rain gages were filled to 12.7 cm, the bucket with the sieves was removed from the simulator. Another bucket was used along with a stand for holding the sieves in the bucket.

The procedure consisted of placing the stand and sieves in the second bucket, stirring the first and pouring the mixed solution over the sieves. This procedure was repeated 3 times, then the second set of sieves, sizes 0.250, 0.125 and 0.063 mm, were placed in one of the buckets and the runoff passed through them 3 times each. The depth of the runoff in the bucket was measured in order to determine the volume. The runoff water was then poured into a container in preparation for pipet analysis. Approximately 1.2 L was used for each pipette analysis.

The sieves containing captured soil were then placed in a drying oven at 105 °C for at least 12 hours. Then they were weighed. The sieves measured size ranges between 2 mm and 0.063 mm.

Pipet Analysis: The sediment/water effluent from the rainfall simulation was then pipetted. This method was used to obtain the size distribution ranges between 0.063 mm and 0.002 mm. This procedure is similar to that in Brakensiek et al. (1979) except there is no dispersing agent added.

Little quantitative information is available to evaluate the accuracy of the methods. Limited information is available from three tillage treatments with three replications by Holbrook et al. (1986) on a South Carolina soil. Runoff from the plots were subjected to the sieve/pipet analyses previously described. The rainfall simulator technique produced eroded size distributions that were close to the measured values for diameters less than 0.1 mm. Since these sizes are of most concern in designing sediment control structures and better information is not available, the sieve/pipet (S/P) results are considered to be accurate.

COMPARISONS

The next three sections describe current methods of estimating ESD and two variants examined in an attempt to improve ESD prediction. One method is used in simulation programs. The other two are performed to match the sieve and pipet results.

Current Estimated ESD: Soils data from the Soil Conservation Service were used with a previously developed BASIC program developed by the South Carolina Land Resources Commission to calculate eroded particle size distributions based on the CREAMS equations. The program estimates percent finer for the diameters of 1.4, 1.0, 0.063, 0.044, 0.038, 0.004, 0.003 and 0.001 mm. The percent finers and diameters will be referred to as eight sample points herein. Available soil series data have depth ranges associated with it. Some soils have only one data set per depth range while others have two or more. For example, Lakeland soil series has two depth ranges 0 to 43 in. and one for 43 to 80 inches. Hiwassee has three depths for 0 - 7, one for 7 - 61, and one for 61 - 70 in. This project used the first available range (0 to ...) listed. To estimate the subsoil layer, the first depth range that did not start at 0 inches was used. Equivalent values of eroded particle size percent finer were obtained by semi-log interpolation to enable a comparison with field data.

Matching Sieve and Pipet Diameters: The second interpolation of the eroded size distributions was done according to the procedure described previously. The same particle sizes were used as in the sieve/pipet testing (i.e., 4, 2, 1, 0.5, 0.25, 0.125, 0.062, 0.031, 0.016, 0.008, 0.004, and 0.002 mm). These results are referred to as the twelve sample points. An equation for each size was calculated using a linear interpolation on the particle size ranges. This produced the twelve equations shown in Table 1.

Alternative Interpolation: *The third method of predictions was done similarly to the second except the* interpolations were logarithmic. This means that logarithms of all the particle sizes were first obtained before using the equations. This technique was believed to more closely represent a "typical" ESD.

Soil Survey Data: The USDA Soil Conservation Service soil surveys contain dispersed particle size data in the engineering section. These data had to be converted in order to be used in the CREAMS equations. This data had a high and low percent clay and percent sand (percent passing through sieve number 200). Personnel at the South Carolina Land Resources Commission produced a BASIC program to estimate ESD from soil survey data. The BASIC program takes an average of the high and low percentages of clay and sand and then calculates the amount of silt. This soil texture data are used as inputs for the previously described CREAMS equations and

values are then interpolated for ESD. The soil survey data were run through the previously described BASIC program modified for 12 data points and that of the original 8 data points. A data point represents a specific particle size of interest.

Hydrometer: A hydrometer test was also done on each of the soils sampled in this project. This test was done according to the procedures in Brakensiek et al. (1979). However, exploratory work indicated that subsoils had very

little organic matter. Therefore, organic matter was determined only for topsoils, but not for subsoils. ESD were calculated for this data in much the same way as for the soil survey data, except the texture is a direct product of the hydrometer testing.

Table 1. Equations for estimation distribution curves derived by linear interpolation.

Size, mm	Equation for Percent Finer[a]
4	100
2	(fcl + fsi + fsg + fsa + flg)*100
1	(fcl + fsi + fsg + fsa + 0.7 * flg)*100
0.5	(fcl + fsi + fsg + 0.46 * fsa + 0.34 * flg)*100
0.25	(fcl + fsi + fsg + 0.20 * fsa + 0.15 * flg)*100
0.125	(fcl + fsi + fsg + 0.07 * fsa + 0.06 * flg)*100
0.062	(fcl + fsi + fsg + 0.20 * fsa + 0.15 * flg)*100
0.031	(fcl + 0.45 * fsi + 0.80 * fsg)*100
0.016	(fcl + 0.20 * fsi + 0.37 * fsg)*100
0.008	(fcl + 0.07 * fsi + 0.14 * fsg)*100
0.004	(fcl + 0.03 * fsi)*100
0.002	(0.33 * fcl)*100

*fcl = %clay, fsi = %silt, fsg = %small aggregate, fsa = %sand, flg = %large aggregate

Repeated Test: Since little data is available on testing the same soil several times for ESD, one soil series was replicated ten times using rainfall simulations. Appling topsoil was used for this test because duplicate samples were readily attainable. A large sample was taken from the field and mixed together. Then, using procedures previously outlined for the rainfall simulation and sieve and pipet analysis, ten samples were analyzed.

RESULTS

Five different interpolations of the CREAMS particle sizes were used to estimate the ESD for all soil samples. An explanation of the five different tests follows:

1. Hydrometer original (H8) used 8 diameters in the distribution equations, then a log-linear interpolation was performed to get the equivalent of the sieve-pipette test.
2. Hydrometer 12 points (H12) used twelve diameters in the distribution equations so no interpolations were necessary except for obtaining the distribution equations.
3. Hydrometer log (HL) used a log interpolation to obtain the distribution equations.
4. Soil survey original (ss8) was the same as the H8 except the soil survey data was used as input.
5. Soil survey 12 point (ss12) used the same procedure as H12, but the soil survey data was used as input.

The ranges below the 0.063 mm level tended to be larger between the estimates and the measured S/P values because the estimates stayed approximately the same percent finer through three sizes: 0.031, 0.016 and 0.008 mm of the same soil. In fact, 9 of the 17 topsoils did not change over this range of sizes in the hydrometer method. Five did not change in the soil survey method. Only one subsoil changed in the H8 method, and two subsoils changed in the SS8 method. In an extreme case, Lakeland soil series had a D_{50} size range of 0.062 to 0.6 mm. The D_{35} sizes ranged from 0.03 to 0.52 mm.

For illustration purposes, graphs of the results are shown for one soil series. Wedmalaw topsoil is a black sandy loam, and the subsoil is a grayish sandy clay loam (USDA SCS, 1977). Figure 2 represents the comparison between two different estimations of distributions H8 and H12. The interpolations yielded substantial differences. The repeated test shown in Figure 3 represents some variation in ESD for one soil series (Appling) for the sieve/pipet method, but the resulting variations are considered to be reasonable for this type of analysis. While there is some variation, a common shape to all of the trials performed is shown. Figure 4 compares results using soil survey data compared with hydrometer test data for both 8 or 12 points. Each pair has a similar shape, particularly the subsoil curves, but variations are evident. Figure 5 represents comparisons between sieve-pipette, H12 and HL tests. Substantial differences are shown between each procedure and soil. Results for the other sixteen soils exhibited similar results to each of these figures.

Table 2. Topsoil estimated d_{15} diameters from the S/P, ss12, HL, and H12.

Topsoil Names	Diameter at 15 percent finer than, mm			
	S/P	ss12	HL	H12
Appling	0.009	0.046	0.043	0.028
Madison	0.018	0.017	0.014	0.021
Hiwassee	0.008	0.018	0.049	0.090
Cecil	0.006	0.022	0.014	0.024
Coxville	0.009	0.013	0.016	0.029
Norfolk	0.012	0.044	0.021	0.034
Varina	0.012	0.041	0.021	0.031
Rembert	0.005	0.011	0.022	0.031
Fuquay	0.034	0.054	0.075	0.149
Dothan	0.013	0.066	0.039	0.060
Blanton	0.085	0.115	0.074	0.134
Lakeland	0.057	0.157	0.073	0.137
Pelion	0.018	0.029	0.069	0.130
Johnson	0.006	0.013	0.056	0.092
Valcluse	0.003	0.064	0.068	0.134
Wedmalaw	0.004	0.035	0.011	0.022
Yonges	0.011	0.019	0.043	0.038

To determine the extent that the methods were conservative, a d_{15} estimate was calculated from each of the four methods of S/P, ss12, HL, and H12. Based on previous work, the S/P method's d_{15} was assumed to be closest to the actual d_{15}. The results are shown in Table 2. The results show the ss12 and HL methods both had eight soils for which the d_{15} was the most conservative for topsoil. For topsoil, the S/P method had the smallest diameters except for two soils. For subsoil, eight of the 17 soils had the smallest diameters (more conservative) using the S/P method. For most of the estimation methods, d_{15} was larger (less conservative) than those from the S/P method. The H12 method was not conservative for all soils except one topsoil.

CONCLUSIONS

The main objective of this section was to compare the ESD estimated using CREAMS-based equations compared with distributions obtained using a simple rainfall simulation technique for soils commonly found in South Carolina. There are six distinct conclusions that can be made.

1. Determining ESD from soil textures through the CREAMS equations and then interpolating is not adequate.
2. The sieve and pipet method were noticeably different from the CREAMS equations methods.
3. The ESD's using the CREAMS equations have more difficulty predicting subsoil than topsoil distributions, with less than half of either predicted closely.
4. The best estimator varied by method of interpolation and by particle size.
5. The repeated tests showed that there may be significant experimental error even for the same soil type.

If runoff analysis for ESD has been done in a similar location, this probably provides the best estimate of ESD. If not, the interpolated CREAMS equations for ESD are the best current method for obtaining a first estimate of ESD based on the fact that they are the only method that is generally used.

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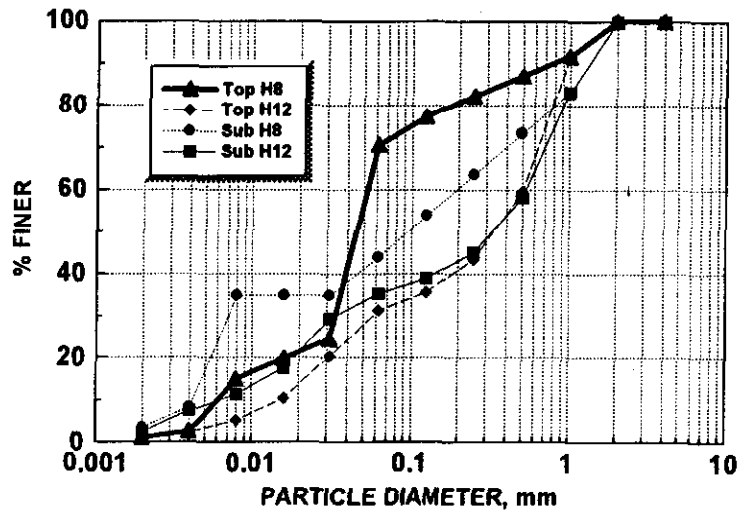

Figure 2. H8 versus H12 method for Wedmalaw soil series.

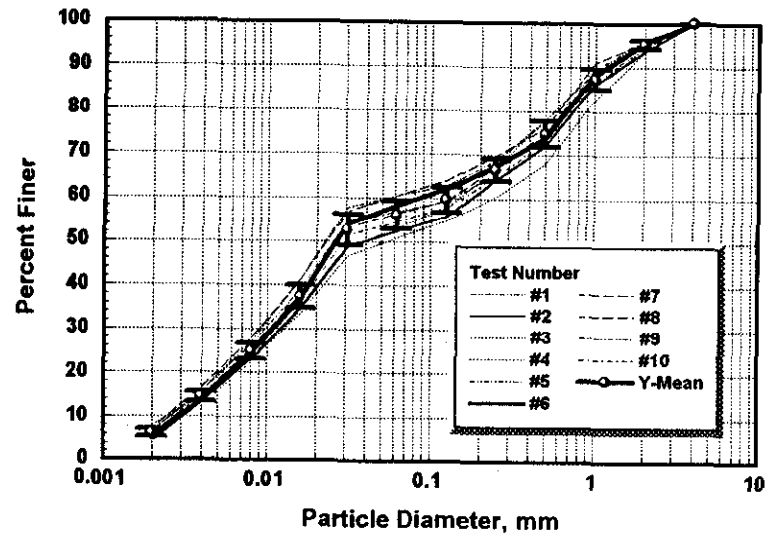

Figure 3. Replicated results from ten runs of Appling topsoil.

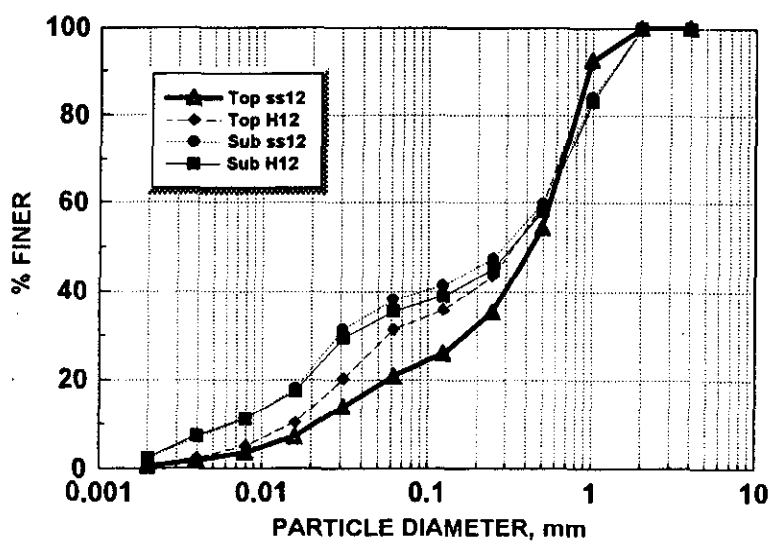

Figure 4. Soil survey versus the hydrometer test with 12 points for Wedmalaw soil series.

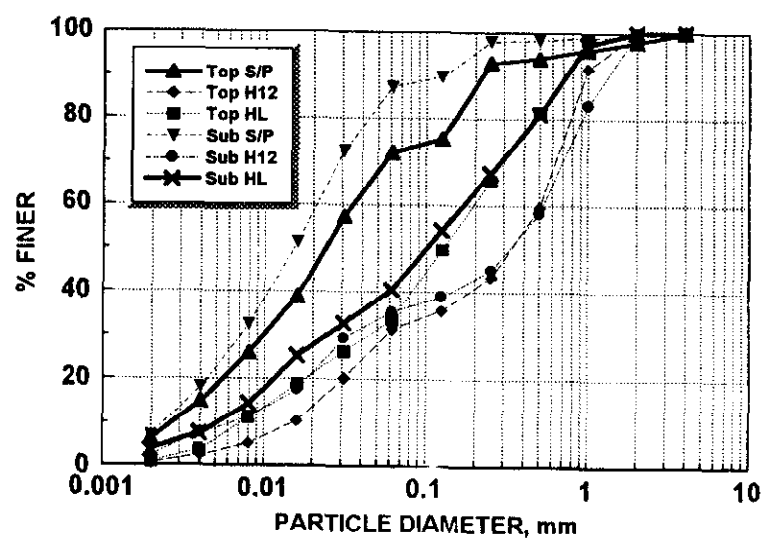

Figure 5. H12 versus HL and S/P methods comparisons for Wedmalaw soil series.

ENGINEERING DESIGN AIDS FOR CONTROL OF SEDIMENT[1]

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INTRODUCTION

Simulations using a modified version of SEDIMOT II estimated the effectiveness of structures for sediment control in four different physiographic regions of South Carolina. For the purposes of this work, we separated the state into four (4) major land resource areas - piedmont, sand hills, coastal plain, and tidal area. Treatments also included multiple watershed sizes, land uses, and soil textures in each land resource area. The evaluation included a wide range of slope lengths, slopes, pond dimensions, watershed shapes, as well as other factors that are required for specific structures. Impacts of various controls on downstream sediment load were evaluated using generated hydrographs and sedimentgraphs from watersheds. Design aids in the form of graphs were developed to simplify design for typical conditions and avoid simple rule-of-thumb design estimates. These design aids are a compromise between detailed simulations and simple rules-of-thumb.

BACKGROUND

Recently regulations have been instituted that require control of stormwater runoff and sediment discharge. Standard techniques are recommended for runoff, but methods for designing structures for sediment control are lacking.

The described work is part of a more inclusive project that includes estimation of performance of sediment ponds, filter fences, and rock ditch checks. The performance of each control was simulated using a modified version of SEDIMOT II (Wilson et al., 1982) with South Carolina's specific conditions and compared with existing regulations in the state. From these simulations, design aids were developed that are consistent with the sediment performance standards required by the state regulations.

Effectiveness of control is commonly determined by either a water quality design standard or a performance standard. For sediment control, a water quality performance standard dictates a maximum acceptable level of sediment in the effluent. The control is designed such that this concentration is not exceeded. On the other hand, a water quality design standard establishes a standard pond design based on a given drainage area or similar criterion. There are obvious benefits associated with each method. Performance standards offer site specific water quality control, but require considerable on-site collection of information for design purposes and are more difficult to review. Structures designed for performance standards have a higher design cost than structures designed for water quality design standards since estimation of effluent concentration is difficult and requires complex calculations. However construction costs tend to be considerably less, since design standards are inherently conservative. Design standards, on the other hand, are more easily employed and regulated. A preferable alternative to these methods is to provide a design procedure that meets a performance criteria without requiring excessive design costs. To achieve this, the design is typically expected to be slightly conservative, but considerably less conservative than if developed from a design standard.

A typical approach under the performance philosophy is to size a control to meet a water quality standard such as a total suspended solids (TSS) or settleable solids (SS) standard. Trapping efficiency can also be used, but this fails

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[1]The Design Aids are provided "As Is" without warranty of any kind, either expressed or implied. In no event shall the authors be liable for any damages (incidental, consequential, or other), lost profits, or lost savings arising from the use or inability to use the methods presented.

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to account for incoming sediment concentration. Specific requirements for permanent stormwater management and sediment control plan approval shown in the S.C. Stormwater Management and Sediment Reduction Regulations (S.C. D.H.E.C., 1995) include discharge rates and hydrographs for stormwater runoff. Additionally, sediment basins or other practices must be designed to meet a removal efficiency of 80 percent suspended solids or 0.5 ml/l peak settleable solids concentration from a 10-yr, 24-hr design storm.

POTENTIAL BENEFITS

The intent of this work was to develop area specific design methods that give reasonable assurance that effluent meets desired sediment performance standards without the lengthy design process typically associated with designs developed to meet a performance standard. This approach benefits regulatory agencies and developers because the time required for design of controls for "typical" situations would be straightforward and minimized. Plan reviewers do not have to labor through detailed calculations. The use of area specific design methods provides a means of achieving sediment control without the steep learning curve associated with simulation techniques. This allows engineers to gradually gain experience and expertise in design of sediment controls. As reviewers and planners become more experienced with the procedures, they may move to modeling techniques or other methods. (For large scale developments or in sensitive areas, it is still anticipated that site specific data and other procedures such as modeling be used for detailed evaluation of sediment controls.) Adoption of area specific design techniques among state and local agencies helps to standardize use of the practices, reduce confusion, and promote adoption of design techniques.

METHODOLOGY

The project began with site visits at numerous locations in each of the land resource areas of the state in order to see innovative methods, as well as areas needing improvement. Evaluation of existing modeling capabilities led to major revisions in the SEDIMOT II model to allow evaluation of a wide range of sediment control technologies in a seamless manner. Input data bases were generated for all major land resource regions and results from almost half a million runs of the model were used to develop simple design aids for sediment ponds, rock ditch checks, and filter fences.

The tour of South Carolina construction sites revealed that channel erosion was a significant problem in many watersheds, indicating a need for adding a channel erosion component to the model since the existing routine in SEDIMOT II allows only for deposition in channels.

After investigating possibilities for modifying existing routines in SEDIMOT II, it was determined that the inaccuracies in hydraulic routing when the pond routine is used for small structures and the lack of adequate sedimentation routines in the check dam routine meant that a major program modification was necessary. Because of the availability of a new hydraulic routine that is accurate over a wide range of structural sizes and types, it seemed prudent to make such a modification. The process used was to:

- Develop a common model for reservoir routing which utilizes continuous functions for discharge and stage storage rather than discrete stage points.
- Develop physically based and tested methodologies for predicting stage discharge relationships for commonly used sediment control structures.
- Combine these routines with the CSTRS routines used in SEDIMOT II.
- Modify the model to include channel erosion.

After each of these tasks was accomplished, graphs of trapping efficiency versus ratios that contain parameters involved in hydrology and sedimentology were plotted. Numerous ratios were compared in these preliminary graphs. For example in the development of the pond design aids, ratios included volume of storage at the riser, maximum or average elevation compared to volume of runoff; peak outflow rate divided by areas at the riser, maximum or average elevation and divided by reference settling velocities for D_{15}, D_{35}, or D_{50}; detention time; and riser, maximum or average surface areas. A ratio was sought that utilized inputs that could be readily obtained and

that provided a grouping of data points so that a curve could be drawn that would represent a conservative estimate of the trapping efficiency. Two of the preliminary graphs are shown as Figures 1 and 2. These figuress show data for two soil conditions having substantially different D_{15}'s. The Piedmont fine condition and the Sandhill coarse were used in the preliminary analysis because they represent the extremes in soils data and because it was desired to have a reduced data set for the initial investigations. The ratio used in Figure 1 was not deemed adequate for use in a design aid because there is little variation in trapping efficiency for a wide range of ratios for one soil and a wide range in trapping efficiencies for the same ratio for the other soil. In Figure 2, the trapping efficiencies are grouped much closer as a function of the ratio for the two soils. Additionally, the terms required to calculate the ratio are obtainable. Many more alternative graphs were produced before the final ratios were selected. Prior to analyzing the data, we anticipated that it would be necessary to have a for each soil condition in each land resource area (i.e., twelve graphs would be required). However after the data was plotted and overlays were developed, it became apparent that all conditions except the high water table condition in the tidal area could share the same line. This finding greatly simplified the construction and use of the design aids.

The selected ratios led to graphs that can be used as an aid for designing sediment control structures that are described in subsequent sections. It should be recognized that aids such as these are developed for typical conditions ***in South Carolina***. Other methods should be used if the situation is environmentally sensitive or hazardous. In all cases, good engineering judgement should be considered as an essential ingredient in design.

POND DESIGN AIDS

The design aids will be briefly described and then examples will be used to demonstrate their use in realistic problems. A common feature of each of the design aids is that a characteristic settling velocity for the eroded soil must be obtained. The characteristic settling velocity corresponds to an eroded particle diameter that is referred to as D_{15}. This diameter corresponds to a point on the eroded particle size distribution curve such that 15% of the particles (by weight) are equal to or smaller than this size. Estimated eroded size distributions for South Carolina soils using an adaptation of the method described by Foster et al. (1985) have been previously developed. The procedure uses the primary particle size information reported by the USDA Soil Conservation Service as part of county soil surveys. The information is now available from the South Carolina Department of Health and Environmental Control. By plotting "fraction finer than" versus "diameter," D_{15} can be read. If D_{15} is less than 0.01 mm, then settling velocity based upon a simplified form of Stokes law is

$$V_s = 2.81d^2 \tag{1}$$

where V_s is settling velocity in ft/sec and d is diameter in mm. If D_{15} is greater than, or equal to, 0.01 mm, then settling velocity should be found using

$$\log_{10}V_s = -0.34246\,(\log_{10}d)^2 + 0.98912\log_{10}d - 0.33801 \tag{2}$$

where V_s is settling velocity in ft/sec and d is particle diameter in mm (Wilson et al., 1982).

Eroded size distributions used in sediment control design are frequently quite different from primary size distributions that are often determined for other construction purposes. The user should note that D_{15} is often smaller for coarse textured (more sandy) because of the reduced clay content and the lack of aggregation.

Figures 3 and 4 plot the ratio q_{po}/AV_{15} versus percentage of trapping efficiency. For ponds, the ratio is defined by

$$Ratio = \frac{q_{po}}{AV_{15}} \tag{3}$$

where q_{po} is peak outflow rate from the pond in cfs, A is the surface area of the pond at the riser crest in acres, and V_{15} is settling velocity, in fps, of the characteristic eroded particle corresponding to D_{15}.

Two curves are presented. Figure 3 is for soils including Piedmont, Sandhill, Coastal, and Tidal area soils, except as noted subsequently. For the Piedmont, Coastal, and Tidal areas, soils are classed as either coarse (sandy loam), medium (silt loam), or fine (clay loam). Sandhill soils include coarse (sand), medium (sandy loam), and fine (silt loam) because of the prevalent textures in this region. These classifications are summarized in Table 1. Figure 4 is for tidal soils (sands and sandy loams that are classified in hydrologic soil group D because of high water table). The ratio should be less than or equal to the curve value at any given trapping efficiency. For example at 80% trapping efficiency, the ratio is equal to 2.2E5 for most soils as shown in Figure 3. If the ratio q_{po}/AV_{15} intersects the curve at a point having a trapping efficiency less than the desired value, the design is inadequate and must be revised. Upper limits on site conditions for ponds are included with Figure 3. **Ratios above the design curves are not recommended for any of the design aids.**

Table 1. Soil Textures by Group for Each Land Resource Area.

Land Resource Region	Coarse	Medium	Fine
Piedmont, Coastal and Tidal	Sandy Loam	Silt Loam	Clay Loam
Sand Hills	Sand	Sandy Loam	Silt Loam
Tidal (High Water Table)	Sandy Loam	Silt Loam	Clay Loam

EXAMPLE PROBLEMS

The example problems serve to illustrate the use of the design aids for calculation of trapping efficiency for various types of structures. Basic soils, hydrologic, and hydraulic information are combined. Methods as required by Standards for Stormwater Management and Sediment Reduction (72-300) may be used to estimate the peak flows. Site specific soils information can generally be found from county soil surveys. Hydraulic information is obtained by combining site and structural information.

In all cases, a ratio is calculated. The ratio is used to locate the point on a turning line for the specified conditions and structure. Trapping efficiency is then found by turning to the x-axis and estimating trapping efficiency. The design aids are intended to be slightly conservative, but use of the design aids should not override use of good engineering judgement. Questionable results should be investigated by the engineer. In addition, the engineer should consider installation and maintenance of all structures. For example, it may be appropriate to add baffling to a pond in order to prevent short circuiting between the inflow and outflow locations.

The user should recognize that the intent of the design aids is to provide an estimate of trapping efficiencies for "typical" structures. Extreme or critical situations necessitate that more detailed analyses be conducted. For example, sensitive areas in steep terrain would be an example of an extreme situation. Additionally, it is not the intent of this document to present detailed descriptions of hydrologic or hydraulic methods.

Design techniques can best be illustrated by following the steps shown in the following examples.

Example Problem 1 - Sediment Pond: A sediment pond is to be constructed on a 30-acre commercial site in Richland County, SC. The following information is available for the site based on soil, hydrologic, and hydraulic conditions.

> The eroded size distribution is for a coarse soil (Pelion and Fuquay mix) with D_{15} set equal to 0.024 mm because this is the smaller D_{15} (Pelion soil).
> Peak outflow from the pond cannot exceed 11.2 cfs.
> Allowable surface area of the pond at the riser crest is 1.67 ac.

Determine whether the sediment pond is adequately sized for satisfactory trapping.

Solution:

1. With D_{15} = 0.024 mm, determine settling velocity V_{15} = 0.0014 fps.
2. Calculate the ratio q_{po}/AV_{15}= 11.2/(1.67)(0.0014) = 4650 = 4.6E3
3. Enter Figure 3 on y-axis with ratio = 4.6E3, go to line and turn to x-axis to read trapping efficiency.
4. Trapping efficiency is approximately equal to 93%, therefore okay.

Example Problem 2 - Sediment Pond: A sediment pond is to be constructed in a tidal area having a high water table. The following information is available for the site near the coast.

The eroded size distribution is for a coarse soil with D_{15} equal to 0.05 mm.
Peak outflow from the pond is 10 cfs.
Allowable surface area of the pond is 0.25 ac.

Determine whether the structure will provide at least 80% trapping.

Solution:

1. With D_{15} = 0.05 mm, determine settling velocity V_{15} = 0.006 fps.
2. Calculate the ratio q_{po}/AV_{15}= 10/(0.25)(0.006) = 6667 = 6.7E3
3. Enter Figure 4 (since high water table) on y-axis with ratio = 6.7E3, go to line and turn to x-axis to read trapping efficiency.
4. Trapping efficiency is approximately equal to 78%, therefore a larger pond is required if it is desired to have a trapping efficiency of at least 80%.
5. Assume that surface area can be increased to 0.67 ac, calculate the ratio q_{po}/AV_{15}= 10/(0.67)(0.006) =2490 = 2.5E3.
6. Reading the trapping efficiency from Figure 4 using this value yields a trapping efficiency of 82%, which is okay. (Note: If there had been no high water table, Figure 3 would be used, and the smaller pond area would be sufficient.)

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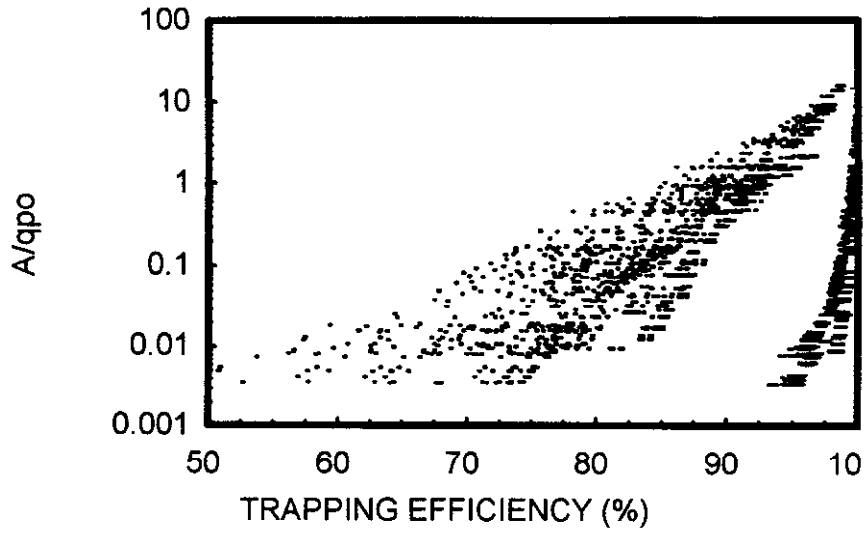

Figure 1. Trapping efficiency related to ratio of pond area and peak outflow rate with data for piedmont fine and sandhill coarse conditions.

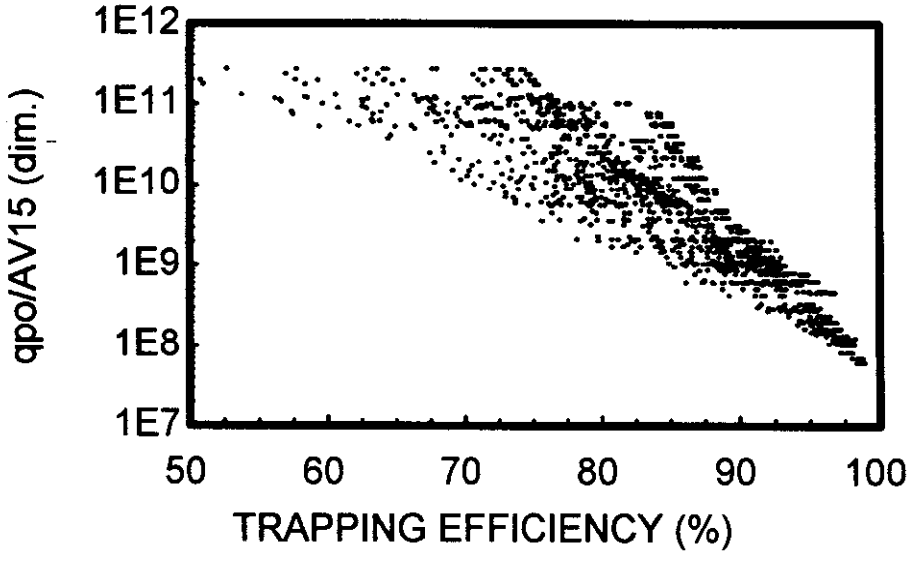

Figure 2. Trapping efficiency related to ratio containing peak outflow rate, pond area, and settling velocity with data for piedmont fine and sandhill coarse conditions.

Table 2. Limits on values for ponds.
watershed area ≤ 30 acres
overland slope ≤ 20%
outlet diameter ≤ 6 ft

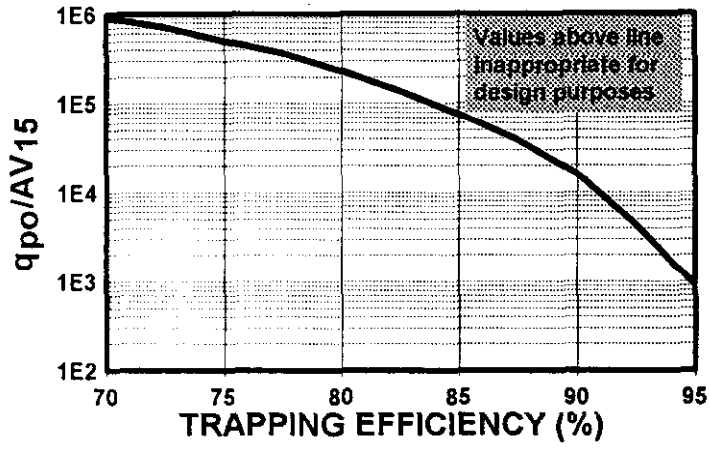

Figure 3. Design aid for trapping efficiency of ponds **not** located in low-lying areas with high water tables.

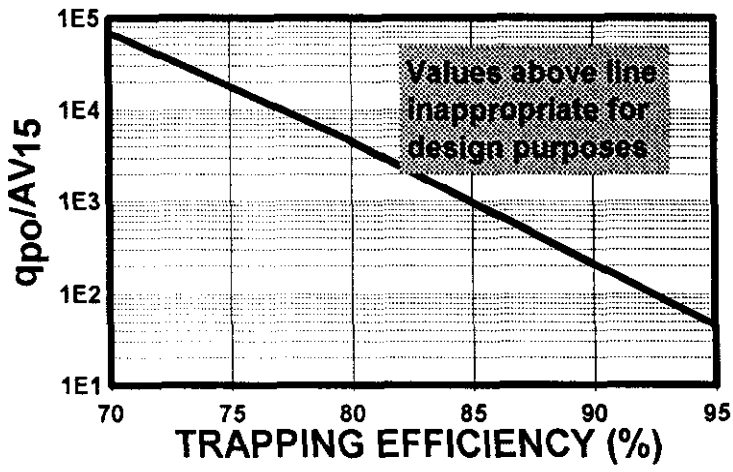

Figure 4. Design aid for estimating trapping efficiency of ponds located in low-lying areas having high water tables (Hydrologic Soil Group D).

ON MODEL OF SMALL WATERSHED MANAGEMENT IN CHINA

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ABSTRACT The Chinese people have long since fount against soil erosion and accumulated valuable experiences. The history of watershed management can be traced back as early as in West Zhou dynasty(about 1,000-771 BC). Since 1949, the severity of soil erosion has been recognized by various levels of government in China,and since then,tremendous efforts have been put into soil erosion control. Especially since 1980,the comprehensive watershed management of integrating agriculture,forestry,animal husbandry,fishery,sideline production,water conservancy facilities and road construction etc. in a small watershed to attain integrated benefits of erosion control and development of natural resources of watershed area on a sustainable basis has been widely carried out and has proved to be effective and successful in China. Although the model of small watershed management may be varied depending upon the local watershed conditions,need of local people and technologies available etc., the basic principles are common. This paper have reviewed and studied the history of small watershed management, basic principles of model of small watershed management such as comprehensive management with small watershed as basic unit,construction of basic farmland,unified planning and overall management,intensive, continuous and comprehensive management,investment policy of relying on farmers themselves and small watershed economy have been studied and described in this paper.

In addition,farmer's participation in watershed management is increasingly becoming a subject for public concern,the success of any integrated watershed management project lies on farmer's active participation. The households based contract responsibility system is very successful in promoting farmer's participation in China. The principles,ways and operation of the system are discussed and studied too in this paper.

Key words: Soil erosion, Comprehensive watershed management,Farmer's participation, Contract responsibility system, small watershed economy

INTRODUCTION

China is a country with numerous mountains, the mountainous area accounts for two thirds of the total territory. The influence of natural conditions of topography,geology, morphology and climate etc. and the influence of human activities, have resulted in serious loss of soil and water in China. According to the survey made by the Remote Sensing Center of Ministry of Water Resources in 1990, the total eroded area in China was 3.484 million sq.km,in which, the area eroded by water was 1.794 million sq.km, the area eroded by wind was 1.69 million sq.km. The total eroded area represents 38% of the total territory.

Since the founding of people's republic of China in 1949, the tremendous efforts have been put into combating soil erosion and thus a lot of experiences have been accumulated. Especially, since 1980, the soil and water conservation work has entered a new stage of rapid and stable development by advocating the comprehensive watershed management of integrating agriculture,forestry, animal husbandry,sideline production,water conservancy facilities and road construction etc. in a small watershed as basic unit to attain integrated benefits of erosion

control and development of natural resources in watershed area,the basic model of small watershed management was thus formed. Although the model of small watershed management may be varied depending upon the local watershed conditions,need of local people and technologies available etc., the basic principles are common. It can be generally summarized as follows.

COMPREHENSIVE MANAGEMENT WITH SMALL WATERSHED AS BASIC UNIT

Before 1980, the soil and water conservation work was implemented without unified planning,the erosion control measures were scattered distributed in different watersheds without any integration, the standard of erosion control was very low, the economic benefits and sediment reduction effects were not obvious. In 1980, in order to sum up the experiences and lessons of watershed management in the past,the Ministry of Water Resources convened the National Conference of Comprehensive Management of Watershed attended by representatives from 13 provinces,autonomous regions and municipalities. During the conference, the experience of Shanxi small watershed management was introduced and the importance of comprehensive management with small watershed as basic unit was emphasized. and subsequently the Ministry formulated the << Provisional specification of comprehensive management for small watershed>>. Since then, a large scale of comprehensive management with small watershed as basic unit has been widely carried out in 26 provinces, autonomous regions and municipalities.

Concept of Small Watershed Management in China is to integrate agriculture,forestry, animal husbandry,fishery, sideline production,water conservancy facilities and road construction in a naturally closed region covering an area of 5-30 sq.km as basic unit to attain integrated benefits of erosion control and development of natural resources in watershed area on a sustainable basis. The unit is possible to combine the engineering measures with vegetative measures and tillage conservation practices as well, and is also favor of the settlement of the contradictions between upstream and downstream, between the right and left banks and between the localities and the community. Meanwhile, as relatively independent economic unit, the small watershed facilitates overall managements of materials and manpower and comparison and appraisal. At present, 846 small watersheds with area of 34,040 sq.km are now enlisted as key watersheds for comprehensive management at state level, among them, 80 small watersheds in an area of 4,000 sq.km are selected as pilot projects for demonstration. According to present statistics,so far, more than 7,000 small watersheds are now under comprehensive conservation. Observations in key small watershed show obvious economic and ecological benefits. Usually,the economic benefits and sediment reduction effects of small watershed management begin to be effective in the first 3-5 years and the total investment can be returned in the 6th to 7th year and the whole project can be completed in the 10th year. In places with favorable conditions, the project term of small watershed management could be shortened to 4-5 years. The comprehensive management of small watershed in a national wide scale has proven to be successful and effectively.

Unified Planning and Overall Management It lasted a long period from scattered and individual watershed management to the overall management with unified planning. The individual and scattered management in the past could not form a whole system to effectively protect farmland and control erosion and flood. Since 1980, after systematic summarization of past experiences and lessons, the unified planning and overall management have been recognized as a must to implement in

watershed management. Based on the present status of soil erosion and the local natural and socio-economic conditions, the unified planning of short-term(at district and county level even township and village level) and long-term planning(at national and regional level covering a large areas) should be worked out in accordance with rational adjustment of land use structure in agriculture,forestry animal husbandry, sideline production fishery,road etc. and rational disposition of engineering measures,vegetative measures,conservation tillage and farming practices with maximum economic benefits as ultimate objective. After unified planning, the overall management should be carried out in large areas following up the management of pilot project,because only overall watershed management in large area or region can the scale management be possible,the economic benefits be obvious,the integrated erosion control system be formed and the various control measures be promoted and protected each other.

Intensive,Continuous and Comprehensive Management Watershed management work requires heavy investments of labor and cash. China, has the severe financial constraints as other most developing countries. Therefore, the limited funds,manpower and materials will be first used for key projects of serious soil erosion,high potential of land exploitation and available strong committed local government and farmer's organization.

The practice of soil and water conservation work has also proven that the continuous management of watershed is highly costeffectiveness because it is favor of forming the integrated protection system quickly and satisfies the design standard of erosion control. Otherwise, the management alternating with standstill will repeat the past lessons,for which, the previous completed control measures will be destroyed in case of heavy rainstorms because of no protection from other combined control measures.

Comprehensive management is in order to maximize erosion control effects by combining engineering measures,vegetative measures and conservation tillage and farming practices,because any watershed management project if depending on single erosion control measures can not be effective in controlling erosion. The comprehensive small watershed management in China generally includes the slopeland management of mainly constructing bench terrace,strip terrace etc. with support of implementation of tillage conservation and farming practices;barren land management of mainly planting soil conservation forest,growing grasses,fodders with support of closing off mountains and gully management of mainly constructing various check dams, ponds, small reservoir and sediment barriers with support of other projects of gully protection and gully stabilization.

To Conserve and Optimize Natural Resources in Space For instance, in mountainous area of Shanxi province, the typical model of comprehensive management is to plant forest for soil and water conservation and grasses on mountain top for controlling splashing erosion and conserving soil; to plant fruit trees,economic trees and fodder grasses in the medium of hilly slope for the consideration of farmer's economic benefit; to construct basic farmland in the form of bench terrace, strip terrace and intermittent terrace for self-sufficient grain production of local farmers and to construct check dam,water storage ponds and small sediment basin for the purpose of sediment interception, flood control and land reclamation. Meanwhile, the water storage ponds can be used for agriculture,irrigation and aquatic production. In addition, the terrace ridge can be used for growing cash crops,which function both protecting farmland and increasing economic benefits. In this way, the comprehensive management of

watershed integrates erosion control with poverty eradication while integrates long-term benefits with medium-term and short-term ones.

Stress on Construction of Basic Farmland China, as one of the developing countries, in which, survival is at stake. The food self-sufficiency for the 1.2 billion people in China is a pressing problem for concern. Hence, the construction of basic farmland in the solution of food problem for the population is listed in soil and water conservation planning as a must in eroded area. Wherever the local conditions are favorable as thick top soil layer,large and unbroken tracts of land,slope flatter than 25 etc.,the slopeland should be transformed into terraced farmland in an orderly way as basic farmland. At the same time, the basic farmland can be also developed by trapping fertile soil with check dam. For instance,the loess plateau contains many gullies-hilly regions that have the highest erosion rate ranging from 10,000 to 30,000 tons annually in China. Heavy soil erosion has deprived this region of good top soil land together with meager precipitation, has led to low agricultural unitary yield. Thus, the key socio-economic problem in this region used to be lack of adequate food production. In striving to produce enough food to sustain life, local farmers used to cultivate extensively on the slope at low unitary yield. In so doing, erosion of the watershed was increased because whatever ground vegetation existing was damaged. Increased loss of good top soil resulted decreasing unitary yield which in turn promoted the farmers to enlarge their cultivation on the even steep slope, disregarding conservation requirements. To break this bicious circle, one must first to construct basic farmland like transformation of low unitary yield slopeland into high unitary yield terraced farmland and construction of check dams to silted land on gully floor by intercepting fertile soil from upper watershed. After the food problem is settled , the steep slopeland can be further transformed into grassland and forestland for the purpose of conservation and exploitation.

Stress on Small Watershed Economy Development As the soil erosion usually occurs in the poor mountainous area, the production is often highly emphasized. In China, any projects of soil and water conservation aiming only at erosion control will hardly induce farmer's initiative and get government's support either. This situation ever happened in 1950s' and 1960s, farmers were reluctant but had to contribute their labour for the implementation of conservation project of only stressing on sediment reduction without concern on farmer's interest in some eroded region. The results was poor quality of project and waste of funds,materials and manpower. Therefore, any soil conservation project should be designed to achieve multi-purpose,usually to include in the projects some production goals such as cash crop,fruit,water and power production. The resources of small watershed should be utilized rationally and integratedly for promoting small watershed management toward development of both economy and ecology. The practice in China has shown that it is only by stressing on economic development of watershed, can the farmer's income be increased significantly,farmer's initiative be mobilized, the quality of watershed management be improved and the rate of management progress be speeded up and the achievement of watershed management be ensured. At present,the following principles are applied into project management for achieving good economic benefit.

(1) to implement concentrated erosion control in large area; to conduct management in a proper scale,multi-purpose development,professionalized production and to emphasize the development of fist-product.

(2) on the foot of natural resources of small watershed, to rational adjust land use structure,industrial structure;to study the developing product of market demand and to form the integration of planting,breeding and processing and the streamline in production,supply and sale; to transform the superiority of resources into product superiority and finally into commercial superiority.
(3) to exploitate the resources of watershed and to process the raw products of watershed for increasing the commercial value of resources; to vigorously introduce new technology and new product.
(4) to develop circulation and industrial commercial production;to seek for way out of product in domestic and foreign markets.

INVESTMENT POLICY OF STANDING ON THE FOOT OF FARMERS THEMSELVES WITH GOVERNMENT'S SUPPORT AS SUBSIDIARY

The area of soil erosion in China is very large, the required input of erosion control is also marvelous. It is very difficult for the Chinese government to cover all of the investment of erosion control. Therefore, the small watershed management in China has to stand on the foot of farmer's own potential while with the support of state investment. At present, central government's investment is only a subsidiary, which accounts for 20% of the total, the local government' investment for 10-20%. The main source of input, about 60-70% is from farmers themselves,which is mainly in the form of labour contribution. Normally, the state investment for watershed management mainly costs to engineering measures by providing tools,powders and materials, and to vegetative measures by providing seeds,seedlings,fertilizers etc. and to maintenance and operation. Vegetative measures usually cost about 40% of the total investment while engineering measures 60%.

In addition, the investment from enterprises,factory, and organs and groups etc is also an important source. Especially the financial support from UN organizations is helpful to soil and water conservation projects.

Meanwhile,the introduction of competition mechanism in investment policy of watershed management is very effective to motivate local government' and farmer's initiative in participation. In the area with active participation of farmers and strong committed local government ,watershed management projects will be highly supported, contrarily it will be less supported. In those areas with good economic benefits, the projects will have priority to get financial support. The sock system,leasing contract and imposing tax of benefit etc. are also useful to attract the investments from all circles of society.

STIMULATING FARMER'S PARTICIPATION IN SMALL WATERSHED MANAGEMENT

Farmer's active participation is small watershed management is the key to the success of any watershed programme or project. The problem confronting us is how do we induce farmers to participate? On the one hand, to induce farmers to participate willingly in a watershed management program requires good extension. Unless farmers understand well that soil conservation will do them good in the long run, they may not maintain the conservation practices even after they did the work. For this case, before we start on the overall planning,a small pilot watershed is usually selected for planning in order to train staff and farmers. Meanwhile, the Department of Soil and Water Conservation at different government levels in China is responsible for the education and propaganda of farmers in forms of video tap,TV programme, slides, slogans, pictures,broadcasting,drama etc. sometime, the rural open market and project site are also used for

propaganda. The practical examples of good soil conservation and propaganda of hazard of soil and water loss enable farmers to understand the relationship between soil erosion and its control with their immediate interest and thus arise their awareness of suffering and participation. On the other hand,the Department of Soil and Water Conservation will energetically help and guide farmer's implementation of watershed management project to obtain maximum economic benefits. From the practice, the key to stimulate farmer's participation in watershed management is closely related to farmer's economic return. Hence, the Department of Soil and Water Conservation must help farmers to formulate planning of soil and water conservation, so that farmers know their goal and economic benefits to be achieved after their hard work, and also helps farmers to implement their planning of soil conservation and provides seeds,powders, technical assistance ,tools and other services. In the planning, the immediate benefits should be the main concern while in combination with long-term benefits. The experience of the past watershed management work shows that the project with good economic benefit attains farmer's active participation. Meanwhile, since 1980, a series of preferential soil conservation policies have been adopted to attract farmer' participation in watershed management in China. The household based contract responsibility system, as the main policy of stimulating farmer's participation in watershed management enables farmers to attain the right of land use and make unity of responsibility,right and interest possible. This system centers the principle on "who owns the right of mountain land use, who is responsible for management and is to be benefitted from it". It is executed by contracting with the households. the contractor may be (1) individual household,(2)a group of households,(3) Household(s) with sub-contractor of household(s),(4) household(s) with specific specialties,(5) special team of village or township. The system is based on households,those land fitted for household management will be contracted to households firstly. Only those land which is difficult to handle can be contracted to special team of village or township. The Department of Soil and Water Conservation at county level will be in agreement upon all the requirements of tasks,standards,quality,workplan and subsidies,low-interest bank loans etc. expressed in the contract. Some other preferential policies and incentives such as the technical assistance, supply of seeds,seedings,tax exemption, tax deduction and marketing services etc. are also provided for the contractors upon request. The contractors may also purchase the right of land use within a period of 30-50 years, even 100 years. The gains of project management can be inherited and transferred in terms of money. The new reclaimed land through erosion control can exempt from agricultural tax for 5 years. The products of the watershed are freely to deal with. All of the above-mentioned articles are guarantee by the Law of Soil and Water Conservation,People's Republic of China. Thus, the farmers can be released from their anxieties of policy changing and be fully supportive and enthusiastic in watershed management.

In the early of 1994, the household based contract responsibility system was further developed, any groups, organs,and individuals or farmers are encouraged to participate in watershed management by adopting auction off barren land. At present the auction is mainly in the following forms:

(1)Bidding auction
(2)Stock auction
(3)Mortgage auction
(4)Agreement auction

Besides, some preferential policies are also provided for purchasing barren land. This reform will further motivated enthusiasm of various circles of society in participating watershed management.

CONCLUSION

(1) The comprehensive watershed management of integrating agriculture,forestry,animal husbandry,fishery, sideline production, water conservancy facilities and road construction in a natura' closed region of 5-30 sq.km should be considered as a fundamental way dealing .ith erosion problem in eroded area at present.

(2) In China, until 1970s,local people's participation in watershed management was sought mainly for the implementation of a project. They had to simply contributes their labour as directed and often without their willingness to do so. Later on, in the 1980s, people's participation could not limited in the implementation phase only. Their participation was considered equally essential at all levels of project activities,such as decision-making,implementation,monitories,evaluating and benefit sharing. The household based contract responsibility system is satisfied with farmer's requirements in decision-making,implementation, monitoring,benefit sharing, and land tenure and thus,has greatly motivated farmer's enthusiasm of participating in watershed management.

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PREDICTION OF SEDIMENTATION RATES

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INTRODUCTION

Simulation models are often use to project the impact of changes in land use and management scenarios on reservoir sedimentation rates. These models must: (1) be continuous in time to project years into the future; (2) simulate large basins that drain into reservoirs that contain multiple soils, land use, and management; and (3) be capable of simulating alternate management scenarios including cropping systems, tillage, and irrigation. The existing model, SWAT (Soil and Water Assessment Tool) (Arnold, et al., 1993; Srinivasan and Arnold, 1994) is intended to fill these requirements. To date SWAT has been validated for two watersheds for which conventionally derived sedimentation data was available. Further validation case studies within a specific geomorphic province for a range of watershed sizes would be useful. In addition, management practices instituted over the last 10 years have not been adequately tested due to the cessation of many sediment survey efforts across the country in this same time period. We intend to fill this gap in validation data collected using a new acoustic sediment survey system in a collaboration with Baylor University.

THE SWAT MODEL

SWAT was developed to predict the impact of management on water, sediment, and agricultural chemical yields in large ungaged basins. To satisfy this objective, the model (1) is physically based (as calibration is not possible on ungaged basins), (2) uses readily available inputs, (3) is computationally efficient enough to analyze large basins in a reasonable time, and (4) is continuous time and capable of simulating long periods and the effects of management changes. For each subbasin, components for weather, hydrology, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management are simulated each day. Subbasin sediment yields are estimated with the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977). Water and sediment leaving the subbasin outlets are routed through channel reaches and impoundments until reaching the reservoir. The channel sediment routing model consists of two components operating simultaneously (deposition and degradation). The deposition component is based on Bagnold's stream power concept (Arnold, et

al., 1995). Inflow sediment yield to the reservoir is computed by routing and adding the subbasin yields to the reservoir. Sediment outflow is calculated as the product of the outflow volume and sediment concentration. Outflow concentration is estimated using a simple continuity equation based on volumes and concentrations of inflow, outflow, and storage. Initial concentration is input. Between storms the concentration decreases as a function of time and median particle size of inflow sediment.

SWAT has been applied to several reservoir sedimentation studies including White Rock Lake and Stamford Lake in Texas (Arnold, et al, 1987). The dam impounding White Rock Lake was completed in 1910 to provide water for the city of Dallas. Since then, land use on the watershed has changed from entirely rural to over 77 percent urban. Model results showed that if urbanization had not occurred, the annual sediment yield would have been 0.3 t/ha higher (4.4 t/ha rather than 4.1 t/ha). The weather generator in SWAT was utilized in Dallas, Texas to estimate the loss of reservoir capacity for three different land use management scenarios. The Stamford Lake was surveyed by the Soil Conservation Service in May 1966 and September 1982. Measured annual sediment loading was 6.1 t/ha compared to 5.3 t/ha simulated by SWAT. An unusually intense storm (greater than the 100-year storm) occurred on the Stamford Lake watershed on August 3-4, 1978. Simulation results show 21-26 percent of the sediment deposited in the reservoir from 1966 to 1982 occurred during the August 1978 storm.

SEDIMENT SURVEY SYSTEM FOR SWAT MODEL VALIDATION

Further testing and calibration of the SWAT model will require more cases studies involving watersheds with different bedrock geology, land use, management scenarios and numbers of secondary impoundments, such as flood water retention structures. However, the required data on sedimentation rates in both reservoirs and secondary impoundments is generally not available due to the large cost of sediment surveys. Also, due to time and budgetary constraints, traditional sediment surveys cannot effectively sample large areas of the watershed for evidence of "event related" sedimentation episodes as on Lake Stamford. Such information is most cost effectively gathered using acoustic subbottom profiling methods, which allow rapid mapping of the thickness of sediment accumulation (LeBlanc, 1992). In a May, 1995 project funded by Baylor University we test one of these systems, the EG&G Mini-Star Subbottom System, in Lake Waco, Waco Texas. The system performed well, recording clear reflections from the lake bottom and the buried 1965 lake floor, about one meter below (Figure 1). The sediment fill averages 0.75 meters thick over the length of 9 km of subbottom profiles collected in the reservoir. Assuming this average thickness applies to the reservoir as a whole suggests a volume

loss of approximately 12 percent over its 30 year life. This closely agrees with the 0.38 percent/yr volume loss rate found by the U.S. Army Corps of Engineers from 1965 to 1970. However, it exceeds by more than a factor of three, the volume loss rate of 0.12 percent/yr, estimated from the apparent change in bathymetry from 1970 to 19 5 (Sullivan et al., 1995). Although the subbottom profiling system we tested performed well, such a system would be too bulky to deploy from the small craft normally used in to survey flood water retention structures. In addition, because precision fathometers are vessel mounted and subbottom profilers are mounted on a remote tow fish, there is no way to collect both kinds of data at the same bottom locations.

In a development project funded by the Advanced Technology Program of the Texas Higher Education Coordinating Board, we will build a new acoustic survey system designed for simultaneous reservoir bathymetry and sediment surveying (Figure 2). The goal is to develop a system that integrates DGPS navigation, a precision fathometer, and a subbottom profiler into a suitcase size unit plus tow fish . The system will be built by Specialty Devices, Inc. of, Plano Texas (SDI), which is a marine instrument company that currently manufactures a briefcase size integrated fathometer-DGPS system. The new system will be based on SDI's existing product, but will include an integrated subbottom profiler. The fathometer in the new system will be mounted on the subbottom tow fish to acquire bathymetry and subbottom data simultaneously at the same bottom locations. Water depth will be measured using the combination of "upward looking" 200 kHz and "downward looking" 400 kHz sonars to measure both the depth of the tow fish below the surface and its distance above the bottom. The subbottom acoustic source will consist of a bank of four narrow-band transducers with resonance frequencies between 3.5 kHz and 24 kHz. The recording system with be composed of a standard PC with a large enough hard drive to store a weeks worth of field data and a 96 kHz analog-to-digital conversion board.

The initial development of the new reservoir survey system will be carried out during the winter and spring of 1996. Field testing will begin in the summer of 1996. To assess the new systems performance and provide data for further SWAT validation case studies we will conduct surveys for a shallow (12 m) shale floored reservoir, Lake Waco, Waco, Texas , and a deep (35 m) limestone floored reservoir, Lake Belton, near Belton, Texas. These reservoirs are 30 to 40 years old and contain significant sediment accumulation on top of different types of original lake floor. To contrast these older structures, we will also survey Lake Aquilla, Aquilla Creek, Texas, which is five years old and contains limited sediment accumulation on a sandy shale floor. In addition, we will survey a series of upstream flood water retention structures within both shale and limestone watersheds.

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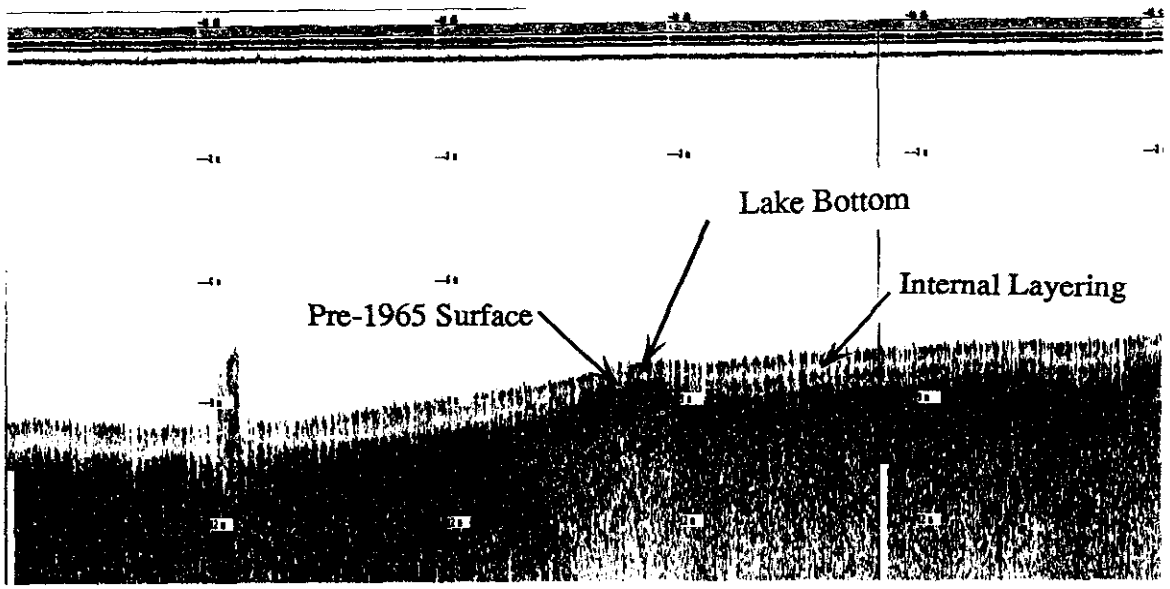

Figure 1. Example of acoustic subbottom profile collected in Lake Waco, Waco Texas, in May 1995. The vertical axis is in meters, converted from travel time using the speed of sound in water. Vertical "ticks" are three meters apart. A one meter thick layer of soft sediment fill, that has accumulated since 1965, is visible (light gray layer) on top of the original reservoir floor (dark surface). An internal stratigraphic surface is also visible within the sediment layer.

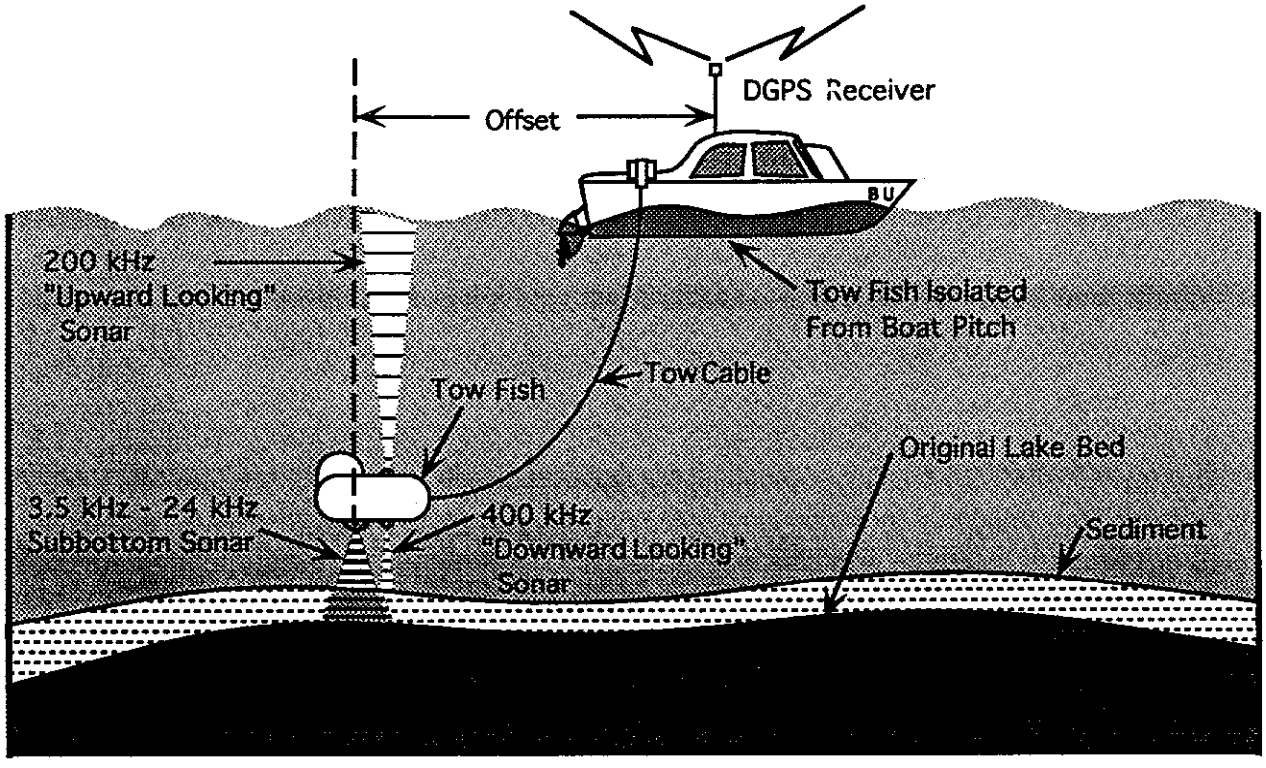

Figure 2. Planned reservoir sediment survey system. Sediment thickness is measured by subbottom profiling. Water depth is measured at the same bottom location by a combination of "upward looking" and "downward looking" sonars. Tow fish offset from the differential Global Positioning System (DGPS) receiver is estimated from the known tow fish depth, cable length, and boat speed.

WEPP-THE NEW GENERATION OF WATER EROSION PREDICTION TECHNOLOGY

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Abstract

WEPP (Water Erosion Prediction Project) is the fundamentally based erosion prediction technology developed by the federal agencies for use on the nations lands. WEPP is a daily simulation model that every day computes the physical and biological status of a field. If runoff occurs due to rainfall, irrigation or snowmelt, sediment detachment and deposition on a hillslope are computed, as is delivery to a channel. If desired, WEPP computes the delivery from multiple hillslopes through a channel system (which can include most common impoundments) to an outlet from the watershed. WEPP is intended to be used on small watersheds that do not include erosion from classical gullies or continuous streams. WEPP must be a component of any models that purport to estimate sediment delivery from large areas because of the superior estimation of sediment delivery (not soil loss) to channels and streams, and because it considers erosion from all sources. Because it is a dynamic model that realistically predicts the status of fields on a daily basis, it is a critical model for estimating realistic frequency distributions. WEPP has performed well in tests in the United States and foreign countries. WEPP is available on the internet, along with supporting materials. Federal user agencies have initiated evaluation and implementation of WEPP.

INTRODUCTION

The WEPP model was developed by federal agencies to replace the Universal Soil Loss Equation (Wischmeier and Smith, 1978) for predicting soil erosion on the nations lands (Foster and Lane, 1987). The agencies include the USDA's Agricultural Research Service (ARS), the Natural Resource Conservation Service (NRCS), the Forest Service (FS), and the Department of Interior's Bureau of Land Management (BLM). The WEPP model has been released for public use, and the WEPP project is entering the implementation phase.

Erosion prediction technology is used for many purposes. The heaviest user historically has been NRCS. Other users have included the construction industry, consultants, and various natural resource professionals. As our society becomes more complex, and as critical issues related to natural resource management arise, additional demands will be placed on erosion prediction technology. WEPP is intended to meet these demands for the foreseeable future.

Issues related to natural resource management will be much broader than just soil erosion, and erosion prediction will be one of several considerations in natural resource management. Soil erosion prediction will be a part of a family of tools for making natural resource management decisions. Other tools may be related to air and water quality, production of food and fiber, economics, and fisheries and wildlife.

DESCRIPTION OF WEPP

WEPP is a daily simulation model that computes the conditions of the soil and plant system that are important in runoff and soil erosion. If rainfall occurs, WEPP computes surface runoff. If surface runoff occurs, WEPP computes the soil that is detached and deposited down a hillslope and the amount delivered to a channel at the foot of a slope. These are all computed in the hillslope version of WEPP (Nearing and Lane, 1989). The watershed version is used to compute the erosion, deposition and delivery of sediment through the channel system on the field, ranch or farm. A grid version is being developed, but is not yet complete.

WEPP represents the area where sheet and rill erosion occurs as a series of overland flow elements (OFE) beginning at the top of the slope and ending at a field boundary or a channel at the end of a slope. Each OFE is homogeneous with regard to ecosystem, soil, and management.

Within an OFE, sediment detachment and transport occurs on rill and interrill areas. On interrill areas, detachment is caused by water drop impact, transport is in very shallow flows impacted by water drops. Detached and transported soil on an interrill area is delivered to a rill. Sediment detachment in a rill is due to the hydraulic shear of the flow and is not affected by water drops. Sediment deposition occurs in a rill if sediment load exceeds the transport capacity of the flow.

WEPP contains a plant growth and residue decomposition component, a hydrologic component, a winter component and an erosion component. The plant growth routine is derived from EPIC (Williams, 1983). Residue decomposition is estimated using a decomposition day concept (Stroo et al, 1986). Infiltration is estimated using the Green-Ampt approach (Chu, 1978), with evapotranspiration estimated using a modified Ritchie model (Ritchie, 1972). The winter component deals with winter hydrology-snow accumulation and melt, frost and thaw. The erosion model is a steady state erosion model, that is, erosion occurs only at one rate over a period of time sufficient to generate a runoff volume that matches the predicted runoff volume.

The watershed version deals with detachment, transport and deposition in channels and impoundments. These channels and impoundments receive runoff water and sediment from one or more hillslopes. A very wide range of common channels and impoundments are modeled with WEPP. Channel transmission losses are estimated in the watershed version.

WEPP is described fully in the WEPP technical documentation (Flanagan, 1995).

WEPP USE AND APPLICATIONS

WEPP will apply to all land uses in the United States, and because of its fundamental nature, should be usable all over the globe for applications where appropriate parameters can be developed to represent conditions where sheet and rill erosion occur. WEPP does not model erosion from stream processes or from classical gullies, but erosion and deposition on the landscape, including channel erosion for small watersheds, are well represented. WEPP has been best evaluated for cropland and rangeland conditions in the US, but it has been applied to

disturbed forest conditions in the US, mine tailings in Canada, and fallow and cropped conditions in China, Italy, Portugal, Russia, Ukraine and Austria.

WEPP is a model easy to use. A user friendly interface has been developed that selects and/or builds appropriate data files for a WEPP run, and then controls model output and output display. The interface is an evolving piece of work, and will likely move to a windowing environment in the near future.

There are a number of WEPP output options, including graphical display of many variables. WEPP output gives location of detachment and deposition for various periods-storm, monthly or average annual. Values of many variables are available also, including hydrologic, biologic and physical conditions.

WEPP requires 5 input files. These input files are a climate file, a soil file, a topographic file, a management file and a watershed file (if the watershed routines are used).

Climate file

The climate file used by WEPP contains daily values of rainfall amount, rainfall duration, time within the duration where peak rainfall intensity occurs, the ratio of peak intensity to average intensity, maximum temperature, minimum temperature, solar radiation, daily average wind velocity, wind direction for that day, and dew point temperature.

The climate file is generated by CLIGEN (Nicks and Lane, 1989). CLIGEN can be operated independently of WEPP, or from the WEPP interface. CLIGEN is supported by a database of climate parameters for about 1000 locations in the continental United States. Climate parameters for CLIGEN can be supplied on an as needed basis for most areas of the earth.

CLIGEN was evaluated by a joint ARS-NRCS team and was found to be quite satisfactory for generating a climate data base for erosion prediction. The WEPP interface contains an averaging technique to assist in generating climate parameters for most locations in the US.

In the watershed version, a different climate file can be used for each hillslope. This makes it possible to analyze conditions where different rainfall amounts are received for different hillslopes. Applications such as this would include irrigated conditions where irrigation waters are not applied to the entire watershed on the same day.

Soils file

A WEPP soils file is available for most rangeland and cropland soils in the United States. These files were generated from the 1992 NRCS Soils 5 data base. A soil file contains texture, organic matter and CEC for each soil layer, as well as the albedo, erodibilities, critical hydraulic shear and effective conductivity for the uppermost layer. The soils file can be modified or constructed using the soil file builder incorporated in the WEPP Interface allowing the user to construct a file

for particular soils. The soil file builder is also used when a hillslope is represented by more than one overland flow element, since each OFE has a unique soil description.

The relationships used to compute soil erodibility values are the result of a study on many cropland soils (Elliot et al., 1989; Laflen et al., 1991) and rangeland soils (Simanton et al., 1987).

Hillslope Topography file

The hillslope topographic file represents the surface on which rill and interrill erosion occurs. A typical hillslope file contains one or more overland flow elements (OFE), each OFE is represented as a length, with the slope of the land surface at the upper and lower end of the OFE and at other user selected points along this length. The topographic file also includes the width of the surface and its aspect, both important in computing snow melt and snow drifting. The hillslope begins at the watershed boundary and continues to a channel. The information for the topographic file can be taken from a contour map or measured in the field. Efforts are underway to use remotely sensed data.

One of the strengths of WEPP is its ability to compute soil erosion and deposition down a slope. To fully capture the power of WEPP, a good topographic database is required. In the past, we have used mostly uniform slopes for soil erosion estimation, even though the USLE could have used more complex information. Improved erosion prediction requires the use of a good topographic database that represents the topography as it occurs in nature.

Management file

The management file is used to represent the conditions to be evaluated. This file can be developed using the management file builder that is part of the interface for WEPP. The management file builder can be used for rangeland or cropland.

The management file is supported by a plant and ecosystem database and a field operations database. For most crops, a plant database development tool is available for developing an appropriate WEPP plant file (Deer-Ascough et al., 1993). A field operations database is also available for most field operations. The operations database is quite extensive for cropland, but is much less developed for rangeland. However, the management file builder allows the construction of a field operation database for any tool used on rangelands.

The management file for rangelands specifies the vegetation growing on a hillslope, and how the hillslope is managed in terms of grazing dates (when animals are let onto and removed from a hillslope), grazing intensity (animals/unit of land), size of animals, fraction of biomass produced that can be grazed, supplemental feeding, and information about if and when various operations are performed on the land. The plant and ecosystem database that supports the management file gives data needed to compute the biomass production, the fraction that can be grazed, canopy cover and height and decomposition of roots and plant material on the surface.

For most users, a management file will need to be developed only once, and used on other sites. In most regions, there are a limited number of potential ecosystems and managements to be evaluated for specific sites. A specialist, may develop several appropriate management files and then others will use these working directly with farmers and ranchers. Consultants could use the interface to develop management files for specific applications.

A users guide helps users select or develop management databases that represent appropriate ecosystems that best describe the situation a user is facing. These databases are quite extensive and should greatly assist in the use of WEPP on all lands.

Watershed file

If the watershed version is used, an additional file is required that describes the channel and impoundments on the watershed. The watershed file describes what hillslope discharges into which channel or impoundment. The watershed file is constructed using a program accessed within the interface. It is expected that as software and remote sensing capabilities are further developed, watershed files can be constructed using these capabilities.

WEPP TESTING

WEPP has been widely tested. These tests range from sensitivity analyses to actual comparisons of measured and predicted values of runoff and soil loss from plots, fields and watersheds in and outside the United States.

An early sensitivity analysis by Nearing et al. (1990) indicated that the WEPP model was more sensitive to factors related to rill erosion than to interrill erosion. More recent studies by Deer-Ascough (1995) have extended these analyses.

Zhang et al., (1995) evaluated WEPP runoff and soil loss predictions using natural runoff plot data from eight sites in the eastern US. The sites, soils, crops and managements varied widely. Cropping systems included fallow, no-till corn and beans rotations, potatoes, grass and legumes, cotton and small grains. Records used were as early as 1931 and as late as 1980. For the most part, WEPP performed well in estimating both runoff and soil erosion.

WEPP has been tested on small watersheds and plots in Italy for fallow, vineyard and olive grove managements. In Portugal, WEPP performed well on fallow plots. WEPP has been applied on mine tailings in Canada with some success. In China, on the Loess Plateau, WEPP performed especially well on fallow plots with very steep slopes and a wide range of slope lengths.

One of the major international tests has been conducted by A. Klik et al., (1995) in Austria. Two sets of natural runoff and erosion plots were designed and established in the Mistelbach and Pyhra regions for evaluating and/or calibrating WEPP for Austrian conditions. The Mistelbach site was about 50 km northeast of Vienna in the so called "Wine Quarter", one of the warmest but driest parts of Austria, with mean annual precipitation of 540 mm with rainfall during the growing season (April to October) of about 360 mm. The Pyhra region is about 80 km west of

Vienna in the foothills of the Alps. Slopes ranged from gentle to steep, and long term annual rainfall is about 725 mm. At Mistelbach, the soil was a moderately well drained silt loam while in Pyhra, the sandy loam soil is underlain by a clayey till that is nearly impermeable. While storm numbers were limited, and some calibration was required for soil erodibility at the Mistelbach site, results were promising, and the studies continue (see paper by Savabi et al. at this session).

WEPP AVAILABILITY

WEPP is available on the internet following the procedures given as an addendum to this paper. Materials available include many databases, interface, documentation, users manual and other information. Also available is a electronic bulletin board with commonly asked questions and answers, a newsletter, information about program glitches and other helpful information.

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ADDENDUM-WEPP ELECTRONIC RETRIEVAL

WORLD-WIDE-WEB ACCESS: Using your WWW browser, connect to location URL:

http://soils.ecn.purdue.edu:20002/~wepp/nserl.html

Main home page for the National Soil Erosion Research Laboratory. From there, you can link to other pages to transfer most recent public version of WEPP, check for information on model bugs and fixes, and read Frequently Asked Questions and answers. Also can link to WEPP CD-ROM training materials, which contain the model documentation and tutorials on using the WEPP model and interfaces.

ANONYMOUS FTP ACCESS:

The most current WEPP news, model, documentation, and databases can be accessed through connection to the NSERL file server via the Internet.

1 Using the FTP program, connect by typing: ftp soils.ecn.purdue.edu
2 Logon as ftp or anonymous. Enter your name as the password.
   Name: ftp OR anonymous
   Password: yourname
3 Set the transfer type to binary by typing: binary
4 Set for noninteractive transfer by typing: prompt
5 Move to the directory of choice:
   cd pub/wepp/wepp.957 * (for the DOS executable WEPP programs)
   cd pub/wepp/document (for the current WEPP documentation)
   cd pub/wepp/cligen (for CLIGEN program or state files)
   cd pub/wepp/cligen/maps (for climate file builder map files)
   cd pub/cpids (for CPIDS programs and database)
6 Get the desired file(s) using the GET or MGET commands by typing:
   mget *.* OR get cligen.exe (for example)

* - directory containing the most recent WEPP version may be different from this. See on-line README files for help.

ASSESSING SOIL EROSION OF AUSTRIAN FARMLANDS WITH THE WEPP MODEL

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Abstract: Soil erosion is a serious problem in Austria because of the steep slopes where agriculture is practiced, the highly erodible soils and intense, infrequent rainfall. Conservation tillage is not commonly practiced and farmers are just beginning to use no-till for erosion control. The USDA-Water Erosion Prediction Project (WEPP) hillslope computer model was used to investigate the relative effect of different farming practices on soil and water losses from three farmland watersheds in Austria. The three watersheds are located in the Mistelbach, Kuffern and Feldbach regions. At the Mistelbach watershed, erosion plots were established in 1993 and monitored in 1994 to measure soil and water losses under conventional, conservation, and no-till farming. The WEPP computer model was calibrated and tested given the data from Mistelbach plots. The calibrated model was then used to assess the effect of different management practices on soil erosion of the three watersheds under one hour rainstorms of 10, 50, and 100 year return periods. The results indicate that the WEPP computer model does an acceptable job predicting the effect of various farming practices on storm runoff and soil erosion under severe erosive events in Austria.

INTRODUCTION

Many changes in the Austrian agricultural landscape during the last 30 years have increased the susceptibility to erosion. These changes include the enlargement of fields, the removal of field boundaries, changes in rotation of crops, land use, drainage patterns and tillage practices. Under the pedologic and climatic conditions in the eastern part of Austria where most of the cropland is situated, the amount of soil erosion can reach more than 80 tons per hectare per year (AEPA, 1988). This continuous loss of productive soil by water erosion leads to ecological as well as economical problems for the farmers and the public. Until now, soil erosion protection measures have been done primarily in vineyards. Most of these vineyards are situated on south facing hillside slopes where the climate is better suited to the production of high quality grapes. The incline of these slopes sometimes exceeds 50%. In the last few years, farmers have considered soil erosion also a problem for cropland. As European farming conditions (farm size, field size) differ from those in the United States, some erosion control measures must be adapted to these conditions.

Evaluating the impact of different land management practices on the hydrologic and erosion regime of a site is easily feasible using a hydro-erosion computer model. Since measurements of runoff and erosion from every site with given soil-climate-management conditions is expensive and time consuming, if not impossible, a hydro-erosion computer model is needed to evaluate the effect of various farming practices on soil and water losses in Austrian watersheds. However, application of any hydro-erosion model to Austrian farmlands requires hydrometeorological, topography and soil parameters which may not be readily available. In order to adapt and use the USDA-Water Erosion Prediction Project (WEPP) hillslope computer model (USDA, 1989) for Austrian farmlands, natural erosion and runoff plots were designed and established in the Mistelbach watershed. The objective of this study was to assess soil erosion and storm runoff of Austrian farm watersheds under various agricultural systems with the USDA-WEPP computer model.

MATERIALS AND METHODS

Watershed Descriptions: Three watersheds at Mistelbach, Kuffern and Feldbach were selected for this study. The Mistelbach watershed was selected for measuring the storm runoff and soil erosion to calibrate the model for

Austrian conditions. The Mistelbach watershed is situated 50 km northeast of Vienna in the so called "Wine Quarter." This region is undulating and is one of the warmest but also driest parts of Austria. The mean annual precipitation is 539 mm (1985-1994), while the rainfall during the growing season (April to October) reaches 363 mm. Compared to hot and dry summers, the winters are cold. The mean annual temperature is 9.1°C (Table 1).

Table 1. Mean monthly and annual precipitation (mm) and temperature values (°C) for Mistelbach watershed.

	Months of the year												
	J	F	M	A	M	J	J	A	S	O	N	D	Year
Mistelbach (1985-1994)													
P (mm)	26	33	34	39	59	72	62	53	47	31	46	39	539
T (°C)	-2.9	-0.9	3.2	12.9	8.2	16.0	18.0	17.6	14.0	8.8	2.8	-1.1	9.1
Precipitation 1994	17.0	6.4	30.9	50.0	114.6	164.2	81.5	50.2	15.0	44.0	38.4	35.6	647.8

The soil in Mistelbach was surveyed and classified as a fine-loamy, mixed, mesic Typic Argiudoll (USDA-SCS, 1979). In Mistelbach, the soil is moderately well drained. Crop rotation (corn and small grains) is anticipated for the future crop, however, in 1994 all plots were seeded to corn. During the winter period, a mixture of legumes (phacelia, a.s.o.) protected the soil on the conservation tillage and no-till plots.

The plots were subjected to three different tillage systems: conventional, conservation, and no-till. To measure erosion and surface runoff from each site, runoff plots were installed after planting on each location. The inclination of the hillslopes was about 13 percent and the plot sizes were 3 by 15m. Each plot was isolated by vertical boards set 15 cm into the ground to prevent external runoff from entering the plots. Runoff and sediment were collected after every erosive storm event and measured.

WEPP required soil, climate, slope and management input files to be made using the gathered information at each site. Saturated hydraulic conductivity, Ks, was measured in the laboratory using a method given by Black et al. (1965). The Ks values were adjusted internally by WEPP to account for the effect of tillage, soil surface sealing and macroporosity (Savabi et al., 1989).

The Mistelbach and Kuffern watersheds have similar soil types, that are deep, well drained and have a mollic epipedon with textures of loam and silt loam; the subsoils occasionally have higher clay contents than the surface layer, contain some carbonates, and sometimes have Kansan till substrata. Most of the soils have, according to the Austrian Soil Survey Reports (Oesterreichische Bodenkartierung, 1995), "moderate" saturated hydraulic conductivity. In Mistelbach, eight different soil types can be classified, while in Kuffern and Feldbach there are only seven and five soil types, respectively. The soils in the Feldbach watershed are free of carbonates, they too have mollic epipedons, some have strong argillic horizons with low water transmission rates, others lack argillic horizons and have "high" saturated hydraulic conductivity. As soil input parameters for the WEPP program, all soil data was derived from the Austrian Soil Survey Reports (Oesterreichische Bodenkartierung, 1995). The erosion parameters for the Kuffern and Feldbach watersheds were calculated with the WEPP recommended formulas (Table 2). However, for the Mistelbach watershed, only the erosion parameter values that produced the best predictions were used in the WEPP model.

Four scenarios were simulated: 1) conventional tillage and management in the whole watershed, 2) conventional tillage and a filter strip at the bottom of the watershed, 3) conservation tillage, and 4) conservation tillage and a filter strip. At each site the entire watershed was represented by one slope profile along the longest runoff pathway.

This slope profile was subdivided into overland flow elements considering soils and crops. Plant parameters were taken from the WEPP data bank, and supplemented by using data from Brouwer (1972), Boguslawski (1981), Brown (1988), and Geisler (1980).

Table 1. Size, slope, length, mean annual precipitation, and daily maximum precipitation.

	Mistelbach	Kuffern	Feldbach
Size (ha)	37.46	38.95	31.14
Average slope (%)	7.8	9.6	18.1
Max. length (m)	900	690	1009
Mean annual precip (mm)	539	695	744
One hour max. precip (10 years, mm)	31	31	37
One Hour max. precip (50 years, mm)	41	41	49
One hour max. precip (1000 years, mm)	49	49	59

Table 2. Soil physical and chemical properties of the watersheds.

Watershed	Sand (%)	Clay (%)	Org. Matter (%)	Ki ($kg.s.m^{-4}$)	Kr ($s.m^{-1}$)	τc (Pa)	Ks ($mm.h^{-1}$)
Mistelbach	11	21	1.8	4886.570	0.0091	3.5	5.7
Kuffern	18	26	2.2	4608.250	0.0081	3.5	9.2
Feldbach	38	17	2.2	6555.220	0.0087	2.64	10.4

Three plant stages (high, low and medium) were considered: 1) seedbed, 2) middle of the growing season (max. LAI), and 3) after harvest with plant residues at the soil surface and before tillage. The initial saturation was estimated to be 70%, 40% and 50% for spring, summer and fall, respectively.

The single storm mode of the WEPP model was used for simulations. Erosion was simulated for different storm events and different plant stages. Storm events with 60 minutes duration and frequencies of 10, 50 and 100 years were used.

WEPP Model Description: WEPP is a new technology based on the fundamentals of hydrology, soil science, plant science, hydraulics, and erosion mechanics. The WEPP model provides several major advantages over existing hydrologic and erosion models, because it considers the effects of soil surface conditions due to agricultural, range and forestry practices on storm runoff and erosion. Furthermore, it models spatial and temporal variability of the factors affecting the watershed hydrology and erosion regime. The WEPP computer model (Fig. 1) can be divided into six conceptual components: climate generation, hydrology, plant growth, soils, management, and erosion (USDA, 1989). A brief description of each component is given here.

Climate Data Generation Component: The meteorological data required by the WEPP model can be generated, if not available, by a separate computer model called CLIGEN (Nicks and Lane 1989). Based on long-term statistics from historical climate data, the CLIGEN model generates daily values for precipitation amount, duration, maximum intensity, time to peak intensity, maximum and minimum temperature, solar radiation, dew point temperature, wind speed and direction for a station near the desired simulation location. Precipitation may be either in the form of rain or snow, depending upon the temperature. Rainfall is disaggregated into a time-rainfall intensity format for use by the infiltration and erosion components. If meteorological data for a location is available, the user can create the climate file using the observed climate and may also enter breakpoint precipitation information.

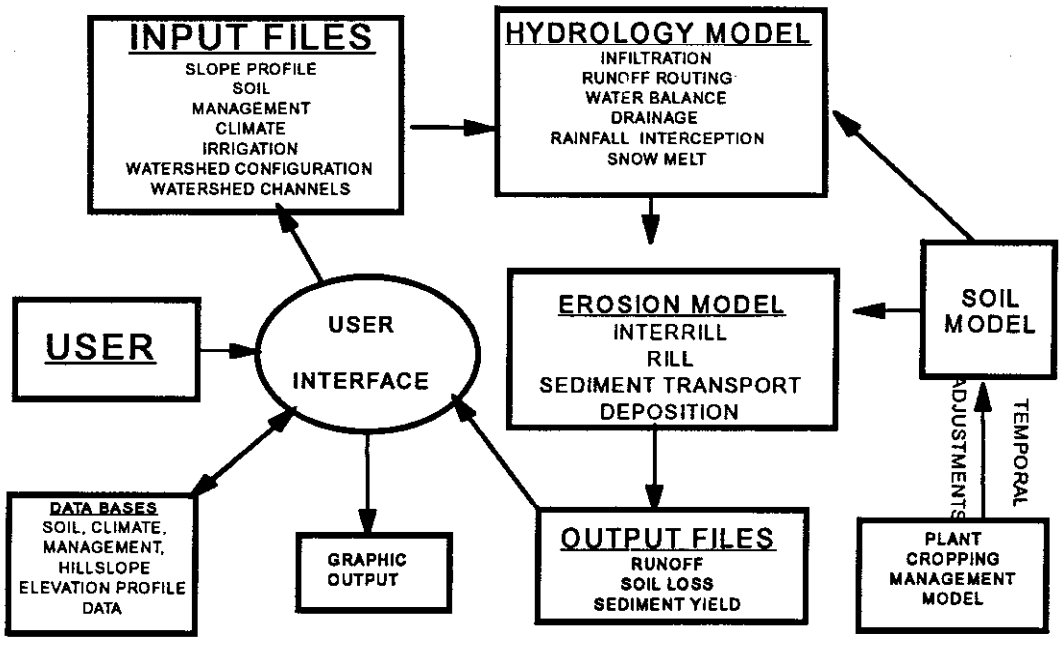

Fig. 1 - Schematic representation of WEPP hillslope computer model.

Hydrology Component: The hydrology component includes simulation of storm runoff, snow melt, soil evaporation, plant transpiration, percolation, irrigation, and subsurface flow (Savabi et al., 1989). Excess rainfall is calculated as the difference between rainfall rate and infiltration rate. Infiltration rate is calculated using the Green and Ampt equation (Green and Ampt, 1911) for unsteady rainfall as presented by Chu (1978). The spatial and temporal variability of factors affecting the infiltration rate is simulated by adjusting the effective hydraulic conductivity of the soil for human disturbances such as tillage and natural phenomena such as soil surface sealing and plant roots. Excess rainfall is routed down slope to estimate the overland flow hydrograph using a kinematic wave approach (USDA, 1989). The effect of surface depressional storage on surface runoff is simulated in WEPP. Peak runoff and runoff duration are used in calculating flow shear stress, sediment transport capacity, and rill erosion. The WEPP winter component predicts frost and thaw layer development, snow accumulation and snow melt. Adjustments to infiltration and erodibility parameters are made based on the soil frost and thaw status. Rill erosion due to the snow melt runoff is also calculated. Irrigation routines accommodate solid-set, side-roll and hand-move sprinkler systems, as well as furrow irrigation systems. The subsurface drainage component simulates water flow to subsurface tile drains and/or drainage ditches (Savabi, 1993).

Plant Growth Component: The plant growth model in WEPP assumes phenological crop development based on daily accumulated heat units, and a harvest index for partitioning grain yield. The Monteith approach is used to determine potential biomass and water and temperature stress adjustments (Monteith, 1977). Rangeland plant growth routines are capable of simulating herbaceous as well as shrub plant growth.

Soils Component: Many of the soil parameters used within the WEPP model change with time as a result of field operations, freezing, thawing, and weathering. The soil component simulates the temporal variability of soil properties such as bulk density, hydraulic conductivity, surface roughness, and rill and interrill erodibility parameters (USDA, 1989).

Management Component: The effect of various land management practices on hydrology and erosion for a site can be simulated with the WEPP model. The management component uses the data contained in the management input file to determine changes in soil physical properties and surface roughness and cover conditions due to practices such as tillage, crop harvest, grazing, and various residue management options (USDA, 1989).

Erosion Component: The erosion component uses a steady-state sediment continuity equation as the basis for the erosion computations. Soil detachment in the interrill areas is calculated using the equation

$$D_i = K_i I_e^2 C_e G_e \left(\frac{R_s}{w} \right) \tag{1}$$

where, K_i is baseline interrill erodibility (kg s^{-1} m^{-4}), I is effective rainfall intensity (m s^{-1}), C is the effect of canopy on interrill erosion (0-1), G is the effect of ground cover on interrill erosion (0-1), R is the spacing of rills (m), and w is the computed rill width (w). Soil detachment in the rills is predicted to occur if the flow hydraulic shear stress is greater than critical shear and the flow sediment load is below transport capacity

$$D_c = K_r(\tau_f - \tau_c) \tag{2}$$

where, D_c is detachment capacity by rill flow (kg s^{-1} m^{-2}), K_r is rill erodibility (s m^{-1}), τ_f is flow shear stress acting on the soil particles (Pa), and τ_c is the rill detachment threshold parameter (Pa). Deposition in the rills is computed when the sediment load is greater than the capacity of the flow to transport it (USDA, 1989)

$$D_f = D_c(1 - \frac{G}{T_c}) \tag{3}$$

where, D_f is net detachment (kg s^{-1} m^{-2}), G is sediment load (kg s^{-1} m^{-2}), and T_c is sediment transport capacity (kg s^{-1} m^{-2}).

WEPP Model Parameters: The WEPP hillslope profile erosion model requires a minimum of four input data files: climate, soil, slope, and plant/management (USDA, 1989, Fig. 1). Climate input files include daily precipitation amount, duration of storm, maximum intensity of storm, time to maximum storm intensity, maximum and minimum temperatures, solar radiation, wind speed and direction, and dew point temperature. Soil input files include such soil parameters as albedo, initial soil water content, soil textures, effective hydraulic conductivity, rock content, percent organic matter in the soil, and soil cation exchange capacity (CEC). The slope input file includes physical features such as slope length, slope steepness, and profile aspect. The plant/management file requires land use (agriculture, range, or forest) to be identified by users. For each land use, information about the specific plants present and management practices used is needed. For instance for cropland, information about the crop plant growth (such as planting and harvest dates), type and dates of tillage, and type and dates of residue management is required. Additional input files are needed if the user wishes to simulate irrigation water applications.

RESULTS AND DISCUSSIONS

Model Calibration: During the growing season in 1994 three erosive storm events occurred at the Mistelbach site. The total rainfall of these three erosive events was 219.4 mm, which was 60% of the total precipitation in Mistelbach during the growing season. The first heavy rainstorm was recorded on May 26 with 51.7 mm of rainfall three weeks after planting. The following period, almost until the end of June, was extremely dry. The next erosive storm occurred on June 30 with an amount of 115.6 mm in 2.5 hours that represents about 21% of the total mean annual precipitation. One additional rainstorm was measured on July 19 with 52.1 mm of rainfall. Figure 2 shows the comparison between measured and WEPP simulated storm runoff for Mistelbach plots.

The model was calibrated for erosion parameters such as rill erodibility (K_r), interrill erodibility (K_i) and critical shear stress (τ_c) using the measured erosion from each plot. The first rainfall event was used for calibration. Comparison of model simulated and measured soil erosion for Mistelbach is presented in Figure 2. The K_i, K_r and τ_c which produced the best prediction were used in WEPP for Mistelbach site (Table 2).

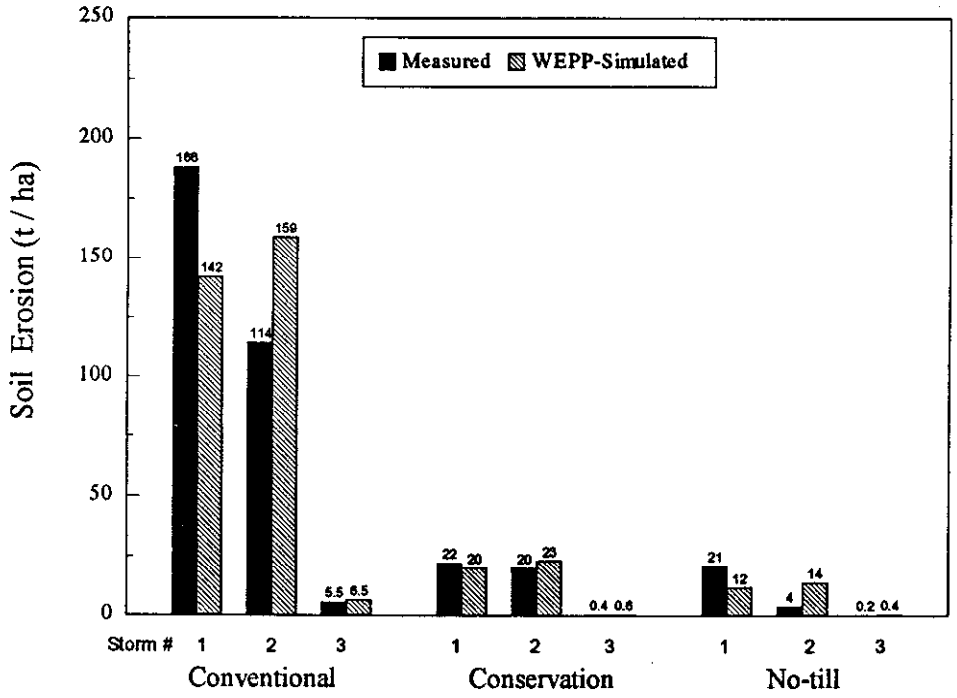

Figure 2. Comparison of WEPP simulated and measured soil erosion for the three storms in 1994 on Mistelbach site. Note that the first storm was used for calibrating the model.

Watershed Simulation: The steeper slopes of the Kuffern watershed compared to Mistelbach resulted in higher erosion in spite of the smaller surface runoff (Tables 3 and 4). By adding a 12 m wide filter strip at the bottom the eroded material leaving the watershed can be reduced significantly. This practice was more effective in Mistelbach than in Kuffern. Conservation tillage and a combination of conservation tillage and filter strips were equally effective in reducing erosion for both watersheds. Extremely high rates of erosion were calculated for the Feldbach watershed. For the ten year 37 mm daily rainfall, the soil losses for conventional tillage range between 40 and 50 metric tons per ha. The values presented in Table 4 are for the entire watershed. For certain locations along the hillslope the soil losses are substantially higher. The Feldbach watershed is a striking example of the severity of erosion hazard of some agriculturally used lands in Austria (Table 4).

SUMMARY AND CONCLUSIONS

Soil erosion is a serious problem in Austria because of the steep slopes where agriculture is practiced, the highly erodible soils and intense, infrequent rainfall. Application of a hydro-erosion model to predict soil erosion from Austrian farmlands requires hydrometeorological, topography and soil parameters which may not be readily available. The USDA-Water Erosion Prediction Project computer model was used to assess the relative effectiveness of improved methods for soil and water management and conservation on the three different agricultural watersheds in Austria. The model was first calibrated using measured runoff and erosion at the Mistelbatch watershed. The model was then used to predict surface runoff and soil erosion that may result from three watersheds with different soil and agro-management practices under one hour rainstorms with 10, 50, and 100 year return periods.

It is recognized that a definite conclusion cannot be drawn from this preliminary study concerning the applicability of the WEPP model for Austrian conditions. However, these results do indicate that the WEPP model is a powerful

tool to determine the effect of different agro-management strategies on soil and water conservation of Austrian farm watersheds under severe erosive events.

Table 3: WEPP simulated runoff (mm) for one hour heavy rainstorms of 10, 50 and 100 year return periods.

One hour precip with return period of:	10 years			50 years			100 years		
	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall
Mistelbach Watershed									
conventional	9.9	6.2	7.3	17.7	12.8	14.2	24.5	19.1	20.6
conv.+filter	5.2	1.3	2.4	13.1	8.2	9.6	19.7	14.4	15.7
conservation	3.1	0.1	0.4	9.3	5.7	6.1	16.0	10.5	12.1
cons.+filter	2.0	0.0	0.2	8.1	4.4	4.9	14.7	9.3	10.8
Kuffern Watershed									
conventional	9.3	4.8	6.1	16.8	11.8	13.3	23.3	17.5	19.1
conv.+filter	6.9	2.5	3.7	14.3	9.3	10.8	20.8	15.1	16.7
conservation	1.4	0.0	0.0	8.8	3.6	5.1	15.4	9.6	11.3
cons.+filter	0.5	0.0	0.0	7.6	5.6	3.9	14.1	8.4	10.0
Feldbach Watershed									
conventional	15.7	12.0	13.2	25.4	20.7	22.0	34.1	29.0	30.4
conv.+filter	14.6	10.5	11.7	24.6	19.9	21.3	33.2	28.1	29.6
conservation	14.2	9.7	10.9	23.9	19.2	20.5	32.6	27.4	28.9
cons.+filter	12.7	8.6	9.8	22.7	18.0	19.3	31.1	26.2	27.7

Table 4: WEPP simulated soil erosion (tons per hectare) for one hour heavy rainstorms of 10, 50 and 100 year return periods .

One hour precip with return period of:	10 years			50 years			100 years		
	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall
Mistelbach Watershed									
conventional	12.0	7.1	9.9	23.7	18.5	21.9	37.8	28.6	32.5
conv.+filter	1.0	0.2	0.4	3.3	1.8	2.3	6.7	3.7	4.5
conservation	1.5	0.2	0.2	6.5	3.5	4.6	13.2	7.7	10.7
cons.+filter	0.2	0	0	1.3	0.7	0.9	3.4	1.4	1.9
Kuffern Wateshed									
conventional	13.3	7.3	6.8	27.8	20.2	16.6	42.3	33.2	26.4
conv.+filter	4.1	0.9	1.7	11.2	6.1	7.3	18.9	12.1	13.3
conservation	0.6	0	0	8.6	1.9*	3.1	16.3	7.8	7.7
cons.+filter	0.1	0	0	7.3	0.6	1.3	9.8	4.9	6.3
Feldbach Watershed									
conventional	50.7	38.2	41.3	78.0	65.4	69.1	100.2	87.7	91.4
conv.+filter	25.1	14.4	15.3	52.0	37.4	35.8	75.8	59.5	55.0
conservation	31.0	11.6	18.5	49.8	25.3	33.6	65.1	38.0	46.2
cons.+filter	16.3	8.5	9.7	35.3	24.1	24.4	52.9	39.8	39.3

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SEDIMENT IMPACTS ON HYDROPOWER RESERVOIRS

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Abstract: Sediment impacts are discussed on loss of storage, aggredation in backwater region of reservoir, effect of sediment from a tributary, and sediment abrasion. Hydraulic methods of sediment flushing are summarized. Provision of bottom outlets, proper mode of operation, surplus water and topography of reservoir are essential for preservation of storage.

INTRODUCTION

The problem of reservoir sedimentation seems one of the most worrying engineers who have to deal with. Problems caused by sedimentation in hydropower reservoirs include loss of storage, turbine abrasion, sediment effects in upstream reaches on navigation, agriculture and industry, and environmental issues. Hydroelectric facilities cannot be operated as sustainable sources of energy unless the problems caused by sediment accumulation in reservoirs are solved with sediment management. Advanced project planning and careful on-site operation and management can greatly reduce the adverse impacts of sedimentation and can insure the sustainable ultilization of hydroelectric facilities with preservation of reservoir storage capacity.

Water impounding results in sediment accumulation in backwater area. and along the reservoir and before the dam. The deposition process and distribution of deposits depends on the amount of inflow sediment, storage capacity of the reservoir, reservoir topography, discharge capacity, location of outlet structures for releasing flood and sediment, etc. A schematic diagram is shown in Fig. 1, where different wedge-shaped deposits resulted from progressive and backwater deposition.

SEDIMENT IMPACTS

The high sediment loads produce rapid rates of reservoir sedimentation. and the infilling of hydropower reservoirs with sediment has presented a variety of obstacles to the operation of sustainable hydropower resources in China, as in the Sanmenxia Project with a storage capacity of 6.94 billion m3, and the Liujiaxia Hydropower Plant, 5.72 billion m3. Although sediment yield from rivers in the United States is lower than in China, reservoirs will face problems similar to those which have already been faced at reservoirs in China. Already there are smaller hydropower reservoirs in the United States where sediment accumulation is impacting hydropower production.

Loss of storage capacity: Depletion of storage capacity is the most difficult to deal with. In China some power plants suffered from serious deposition as shown in Table 1.

Table 1. Rate of siltation in some hydropower plants in China

Reservoir	Drainage area (km^2)	Storage capacity (10^9 m^3)	Duration	Amount of deposit (10^9 m^3)	Loss of storage (%)
Liujiaxia	181,700	5.72	1968-1986	1.078	18.85
Tianjiao	338,000	0.068	1976-1982	0.034	49.1
Sanmenxia	668,421	9.64	1960-1981	5.518	57.24
Shuicaozhi	1,233	0.0096	1958-1981	0.0082	85
Bikou	26,000	0.521	1976-1986	0.218	41.84
Yangouxia	182,700	0.216	1961-1968	0.168	77.7
Qingdongxia	285,000	0.606	1967-1971	0.527	87

In mountainous regions in the former USSR depletion of hydropower reservoirs have been very serious, some hydropower station lost about 70-80% of storage capacity after operation of less than ten years (Vorobyev,

1981). In USA according to statistics of the reservoirs built before 1935 in the areas of soil erosion, 10 % of reservoirs were silted up, 14 % of reservoirs lost 1/2 to 2/3 of storage, and 23 % lost 1/4 to 1/2 of storage (Task Com. on Sediment Manual, 1965).

The Yangouxia is the first hydropower station operated on the Yellow river in China, installed with a total capacity of 352 MW of 8 units, of which the maximum discharge is 140 m3/s each (Fig. 2). It started constructing in 1958 and operated to impounding before completion of the upstream hydropower station Liujiaxia, serious siltation occurred because no bottom outlets were installed below the power intakes, where inflow sediment was released from the overflow spillway and power intakes. The reservoir reached an equilibrium state by 1966, when the loss of storage was 74.6%, the trap efficiency of the reservoir in 1966 was only 1.1%. It is not possible to lower the water level to flush sediment except inflowing water enters power intakes (Yang et al, 1985).

The Qingdongxia project is a low head barrage for irrigation and power generation on the Yellow River, It is a pier type power station, installed with 272 MW and provided a discharge 550 m3/s for irrigation. It is a daily regulating hydropower station, having a storage capacity of 735 x 10^6 m3. The power station in the river channel has 8 units, 34 MW each, of which the intake sill is at elev. 1130.15 m, alternating with 7 overflow spillways at elev. 1149.2 m. Below the 7 power intakes there installed 14 sluiceways at elev. 1124 m. During the initial impounding period the sediment siltation was serious. During 4/1967 through 9/1971, a volume of 533 x 10^6 m3, was replaced by sediment, equivalent to 74 % of the initial storage. In order to reduce the rate of sedimentation, the operation mode was changed from impounding to flood flushing from 1972 flood season, that is, by lowering water level during flood season for sediment flushing. Measurements showed that by impounding the storage left was 79 x 10^6 m3 at 1971, and after flood season drawdown flushing, the storage was 74 to 91 x 10^6 m3 during 1972-1976. The operation mode was further changed from drawdown flushing during flood season into drawdown flushing during flood events for the purpose of producing much more hydropower, because of the higher water level during flood season, resulting in further siltation, the storage capacity was reduced to 60.3x10^6 to 41.5x10^6 m3 during 1977-1980.

The Sanmenxia Reservoir is one which suffered serious deposition during first 4 years and recovered a long-term storage capacity after reconstruction for enlarging discharge capacity of outlets with a change in operation mode.

Aggredation in backwater region of reservoir: Deposition occurs at the head of reservoir where the suspended load and bed load enter the backwater region. About 50 % of inflow sediments deposited in these regions, as in the Guanting reservoir in China. In Lake Texoma above Denison Dam, 49.5 % of the deposition between 1940 and 1948 occurred in the delta area (Harrison 1953). This kind of deposition forms a delta and raises the level of the river bed, creating several problems.

Difficulties in flood protection: The raising of a river bed causes channel slope to decrease, and deposition within the channel reduces the stream cross-section. Both factors can result in a higher flood stage and may require the heightening of protective flood levees. In some cases the channel bed became higher than the floodplain outside both river banks.

Rising of groundwater table: Rising of water level in the backwater region due to siltation can elevate the groundwater table in riparian areas; even causing extensive salinization.

Navigation: If river harbors are situated in the backwater region, as the Three Gorges Project in China, harbor siltation can also become a serious problem. When the navigation channel in the backwater region at the head of a reservoir had been filled with sediments not deep enough for navigation, the reservoir level may be lowered to flush deposits until the channel was scoured deep enough for navigation (Fan & Morris. 1992a) Heavy sediment depositon occurred in approach channel entrances and in blind canals due to density current, although the concentration in the river was only around 1 kg/m^3, as observed in the Gezhouba Project in China.

Effect of sediment deposition from a tributary: In Liujiaxia Reservoir a sand bar created across the Yellow River at the confluence was formed by density current deposition from the tributary, Tao River, 1.6 km from the Dam, where the density current from the tributary entered the impounded main river extending both upstream and downstream (Fig. 3).For example, in mid June 1980 the power plant needed to suddenly increase its output,

but the sandbar temporarily prevented from providing water, resulting in a lowering water level of 0.98 m before the dam. Although this event did not influence power production, it was decided to undertake drawdown flushing in 1981 in order to lower the top elevation of the sandbar. Before the flood season, drawdown flushing was undertaken for seven days with a lowering of 7.2 m at an outflow discharge 2150 m3/s, a net eroded volume of deposits of 3.09x10^6 tons was released from the reservoir, in which the eroded volume in the sandbar reach was 1.1x10^6 m3. The sandbar was on average lowered by 4.8 m with a maximum eroded depth of 5.5 m. Several drawdown flushings have been carried out since then.

Sediment entering power intakes and bottom outlets: With advance of the delta toward the dam the possibility of sediment slumping down and blocking the entrance to the bottom outlet tunnels is increased. As in the Sautet reservoir in France the bottom outlet was almost completely blocked during the period of operation of 1935-1938, therefore it was decided to open a new sluice. Also the Chambon dam's bottom outlets were found to be entirely blocked by sediment in 1955 after 20 years of dam completion, then a new bottom outlet was opened, 15 m higher than the original bottom outlet. The original bottom outlet was reopened in 1981 (Millet 1983).

Sediments which enter the power intake abrade the turbines, gate recess, and outlet tunnel by high velocity of water flow of high sediment concentration. In Yangouxia Reservoir, because no bottom outlet was installed, the sediment concentration passing through the intakes was greater than the mean outflow concentration, as showned in Fig. 4, it made serious abrasion of turbine blades. After five years operation the sediment amount passing through the power intake No. 4 increased from 0.446x10^6 tons (1962) to 2.753x10^6 tons (1966), while the particle size also increased from 0.0086 mm (1962) to 0.03-0.056 mm in the period of 1966-1978. Consequently the water turbines suffered heavy abrasion, resulting in reduction of efficiency of 2-5 %. Frequent major overhauling of the eroded turbine runners caused a long outage time of the machines. The unit No. 4, as an example, has had overhauling ten times during the operation period of 20 years, about 1.57 tons of stainless steel welding rods were used for each overhauling as recorded during 1970-1980. Similar serious abrasion of turbine blades were found in the Liujiaxia Hydropower Plant, the annual amount of sediment at 11.6-11.9x10^6 t/yr passing through the power unit No. 2 reached its peak in 1978-1979, during which the top elevation of sand bar was rising abruptly. This turbine was damaged so that it had to overhaul for a period of 125 days, comsuming welding rods of 3.5 tons.

HYDRAULIC METHODS OF SEDIMENT FLUSHING

Hydraulic methods to minimize reservoir sedimentation or to preserve storage capacity can be classified as follows: (1) Sediment routing during floods or flood flushing, (2) Drawdown flushing, (3) Emptying and flushing, (4) Emptying with lateral erosion, (5) Venting density current, (6) Siphon dredging, (7) Dredging. Some are discussed below.

Sediment routing during flood, or flood flushing: The purpose of regulating the flow by lowering the reservoir level during flood seasons is to release as much sediments as possible from the reservoirs to take advantage of the silt carrying capacity of the flood. Ideally the reservoir should be almost fully draw down using large bottom gates which minimize both backwater effects and hydraulic detention time. The larger transport capacity provided by flood discharge reduces sediment deposition in riverbed downstream of the dam.

The Sanmenxia reservoir was completed in 1960, and because of the limited discharge capacity of deep outlets at higher level, serious siltation occurred during 1960-1962 even after the mode of operation was changed from impounding to detention by opening all of twelve outlets during floods. Extra outlets to increase the sluicing capacity were reconstructed from 1965 through 1973. The extra outlets consisted of two tunnels, conversion of four penstocks into sluiceways, and reopening 8 diversion outlets that had been used during construction. During 1965-1973 the reservoir was operated similar to a detention reservoir, where retrogressive erosion developed over a length of more than one hundred kilometers, and a long-term storage capacity was maintained when the sediment outflow-inflow ratio was nearly adjusted to about 100 %, i.e., to a yearly or several years balance between sediment deposition and erosion (Long and Zhang 1981, Fan 1985), Fig. 5 illustrates the time variation in thalweg during erosion processes after 1964 heavy deposition.

Drawdown flushing: Table 2 lists some examples of partial drawdown flushing with water discharge mainly

passed through an overflow spillway. The flushing efficiency are lower.

Table 2. Overflow drawdown flushing (Fan, 1995)

Reservoir	Outflow situation	Years of operation	Q (m^3/s)	Duration	Flushing efficiency* (%)
Guernsey USA	Overflow spillway	1960-1962	56.6-198	10-18 days	0.017
Warsak Pakistan	Overflow spillway	1976-1979 5 flushings	1410	Total 490.5 hr	0.169
Liujiaxia China	Overflow and outlets water level lowered = 4.4-7.8 m	1981, 1984, 1985, 1988	1660-2090	103-177 hr	0.23-0.71
Shuicaozi China	Overflow spillway	1965, 1966 1974, 1978 1980, 1981	21.4-230	3-4 days	1.2-4.3

* Flushing efficiency is defined as the ratio between the volume of sediment deposits eroded and the water volume used for flushing.

Emptying and flushing: Drawing down the pool level in a reservoir to induce erosion of previously deposited sediment to recover storage capacity is a method often used in hydropower stations. This method has been particularly useful at small reservoirs, where a large fraction of the useful storage capacity is near the dam and sediment deposits may be scoured if the outlet gates remain open for a period of time, several days or weeks. Physical modeling is helpful in designing outlet arrangement and estimating flushing efficiency. The flushing efficiency of some hydropower plants is listed in Table 3.

Table 3. Flushing efficiency of emptied flushing (Fan, 1995)

Reservoir	Years of operation	Q m^3/s	Duration of flushing	Flushing effeciency, %
Gebidem, Switzerland	1969-1994	35	35 hr / year	4.8-6.0
Barenburg, Switzerland	1985	90	20 hours	6
Ferrera, Switzerland	1985			2.6
Gen-shan-pei, China	1958-1983		53 days/year	8.97
Santo Domingo, Venzuela	1978	8-10		9-13
Donfanghong, China	1984	51		5.6-8.3
Sefid-Rud, Iran	1980-1987		61-157 days	2.2-6.7
Zemo-Afchar, USSR	1939-1966	72-688	13-76 hours	1.5-9.6
Chirurt, USSR	1968	400-500	5 days	4

Based on the erosion pattern of emptying and flushing obtained from laboratory tests and prototype measurements, the effectiveness of flushing depends upon the inflow flow discharge and sediment transport, grain size of suspended load and bed load and that of bed samples taken on the original river bed and deposited sediment on the reservoir bed, original river slope and deposit slope of the channel, topography of the reservoir, water level lowered and its rate of lowering by drawdown flushing, duration of flushing operation, the dimension

and position of outlets provided, and their discharge capacity, etc.

Density current venting: The venting of density currents has long been considered an ecomonical and effective means of reducing the rate of reservoir silting in impounding reservoirs. An approximate method of computing density current venting from a reservoir was developed based on criteria for formation of density current and the condition required to maintain a density current that will reach the dam (Fan 1986). With this method, whether a density current might reach the dam or fade away on the way to the dam may be roughly estimated. The venting efficiency of a density current for a flood event can be 10 % to more than 50 % for different topography of reservoir, inflow flow and sediment discharge. Venting efficiency measured from various reservoirs are shown in Fan 1995.

Conditions to be satisfied in preserving storage capacity: To maintain a long-term storage capacity for a specific reservoir is feasible, if the following conditions are satisfied:

Provision of bottom outlets: Large capacity bottom outlets have capability to release relatively big flood during which a great part of inflow sediment transporting into the reservoir. For flood release, bottom outlets may be operated for under-sluicing floods of longer time period to avoid the high water level higher than the top of the dam for a longer time, while surface spillway is used for releasing flood with short duration . A bottom outlet has to be considered as a structure which contributes substantially to the overall safety of a storage scheme (ICOLD 1987), it may be used for draining the reservoir under emergency conditions when lowering the reservoir water level is urgently needed in a short period of time.

For sediment release, bottom outlets at low elevation may be used for venting density current during impounding, they may be used for sluicing sediment deposits (silts, sands and gravels) by drawdowning reservoir water level, and they may be operated by impounding to release finer particles passing through the intake, and to minimize coarse particles entering the power intake and thereby minimizing turbine abrasion. In the case of sediment regulation to release turbid flood and store clear water, or emptying flushing with outlets at low elevation, retrogressive erosion during water level drawdown would develop, yielding a long-term storage capacity.

The Bikou hydropower station has a total installed capacity of 300 MW. The bottom outlet, 4.4 m in diameter, was placed at an elevation 25 m lower than the power intakes, and 59 m lower than the normal pool level. An local erosion funnel zone was created before the dam by flood flushing, as shown in Fig. 6, from which the power intakes can locate within the funnel zone, so that no significant sediment concentration entered the intakes, and no serious abrasion of turbine blades was observed.

To investigate the role of bottom outlets in reducing turbine abrasion, experiments were made in 1991 in the Sanmenxia Reservoir. Flow regimes of stratified and non-stratified concentration profiles were measured. Under stratified sediment concentration profiles, the ratio between the sediment concentrations passing through outlets at elev. 280 m and at elev. 290 m, being equal to 2.4, are shown in Fig. 7. Under the nonstratified concentration profiles, as measured in 1970's, the ratio was 1.3, as shown in Fig. 8, in which the ratio of median diameter was also plotted.

Appropriate mode of operation: For the purpose of sediment regulation to minimize deposition and also for flood control, it is necessary to lower pool level before flood season to create a storage space for the following floods, so that during flood flushing the inflow sediment discharge may be transported and released out and previous deposited sediments may be eroded out. Such mode of operation is called "releasing the turbid and storing the clear", that is, to release flood water with high concentration during flood season and to store clear water after flood season, and has been successively used in many reservoirs for preserving storage capacity. The premise is that bottom outlets of enough discharge capacity are provided.

Lots of reservoirs in China in the 1960's were initially operated by storing water, resulting in heavy siltation, then the mode of operation had to change to venting density current, or to drawdown water level for evacuating previous deposits from reservoirs if low-level bottom outlets were available, or to construct new bottom outlet or reopen the original bottom outlet for sediment flushing. The Sanmenxia Reservoir seems a typical example of changing the mode of operation first but failed to achieve a yearly equilibrium between inflow and outflow

sediment transport, owing to the higher elevation of the deep outlets and their limited discharge capacity. An equilibrium of sediment transport between inflow and outflow has been achieved until two extra tunnels were opened and 8 bottom outlets which were used as diversion sluices during construction were reopened. From which one may find that to change the mode of operation from impounding to drawdown flushing during flood season might get ideal results of minimizing sediment deposition, if appropriate bottom outlet facilities were provided with necessary excess water to be utilized for flushing.

However, there were some reservoirs which were well designed and operated, for the purpose of minimizing sediment deposition in reservoirs. In China since the 1970's the Fengjiashan reservoir, the Bikou Hydropower plant and the Tianqiao Hydropower plant and others have well designed and operated by water and sediment regulation, providing bottom outlets of considerable discharge capacity and designing an appropriate operation scheme.

Surplus water for flushing: It is often that the reservoir water pool is lowered before the flood season to give a space for flood detention, and during flood season, water level was lowered for sediment flushing including erosin of previous deposits to minimize sedimentation. If not enough water is available, density current venting may be adopted during impounding, and flood flushing may be undertaken every several years, or other measures taken to reduce reservoir sedimentation.

Topography of reservoir: If the reservoir reach has an excess silt carrying capacity after dam construction, an equilibrium between sediment inflow and outflow can be obtained when large bottom outlets at low level having enough discharge capacity are provided and when an appropriate mode of operation for sediment management is adopted. Then a sustainable storage capacity can be maintained.

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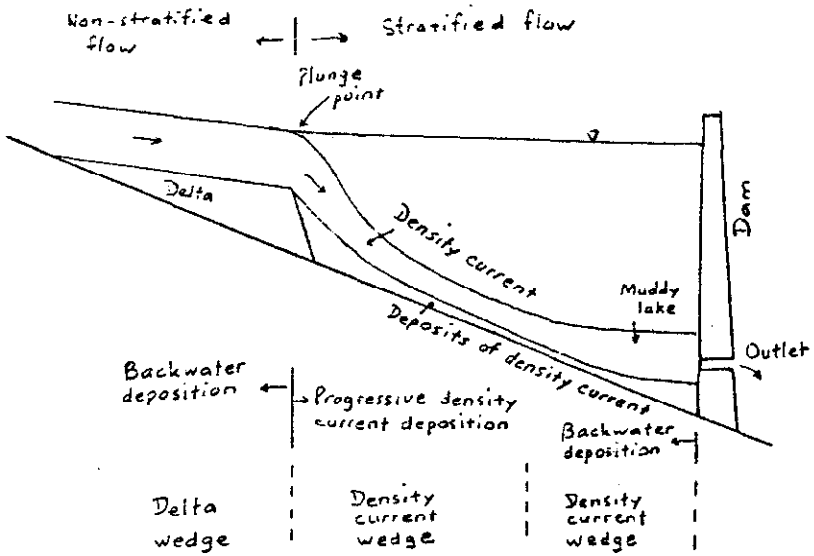

Fig. 1. Schematic diagram of wedge shaped deposits in an impounding reservoir

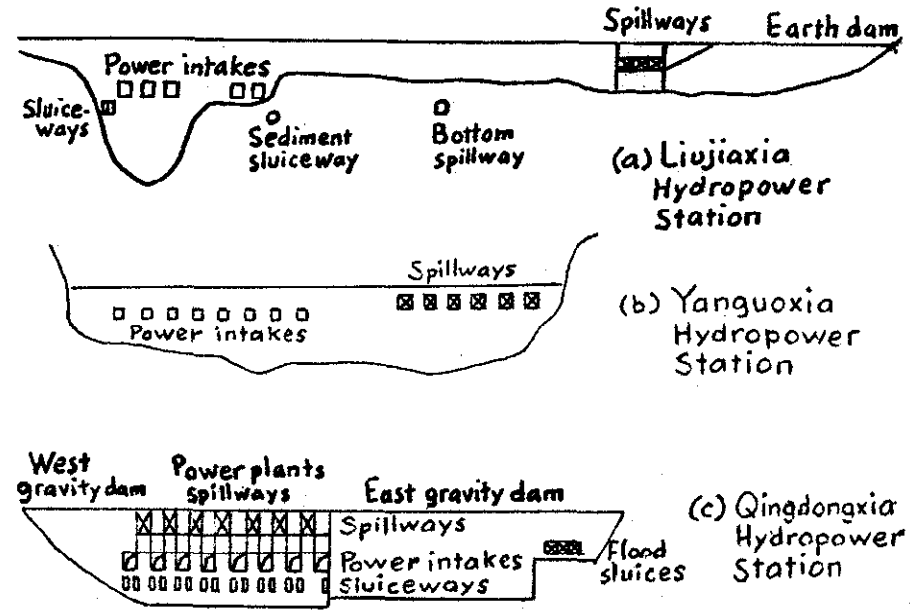

Fig. 2 Upstream views of Liujiaxia, Yanguoxia and Qingdongxia Hydropower Stations

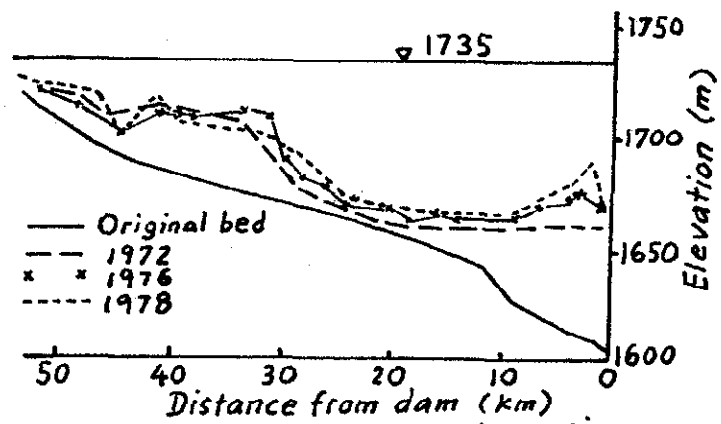

Fig.3 Sediment deposition along Yellow River, Liujiaxia Hydropower Station

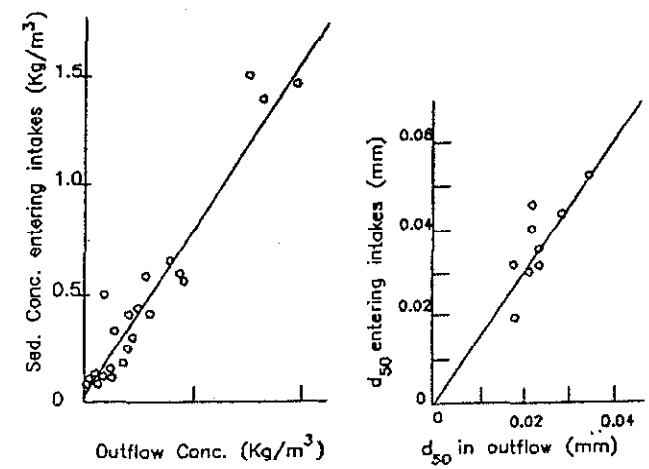

FIG. 4 Sediment concentration and particle diameter entering intakes versus that of outflow. Yangouxia Hydropower Station.

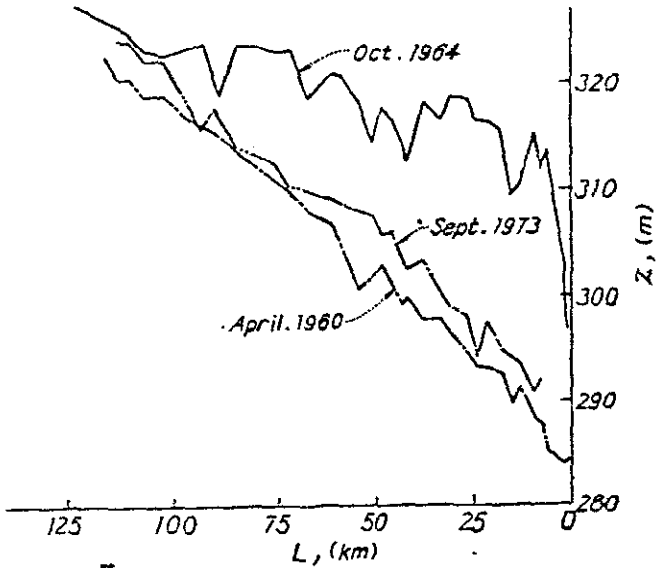

Figure 5 Profiles of thalwag in Sanmenxia Reservoir

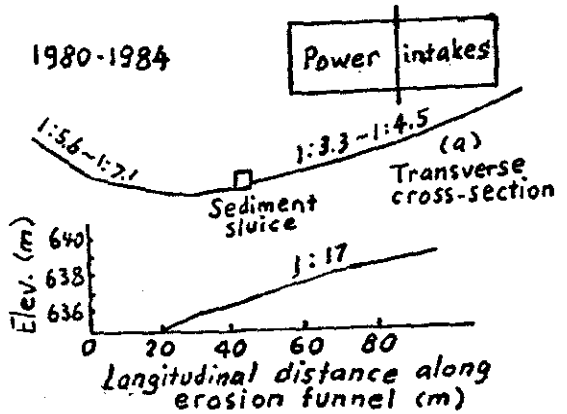

Fig. 6 Longitudinal and transverse cross sections in erosion funnel, Bikou Hydropower Station

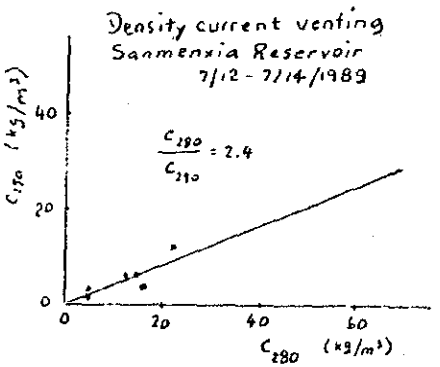

Fig. 7. Outflow sediment concentration from 280 m and 290 m outlets under density current venting

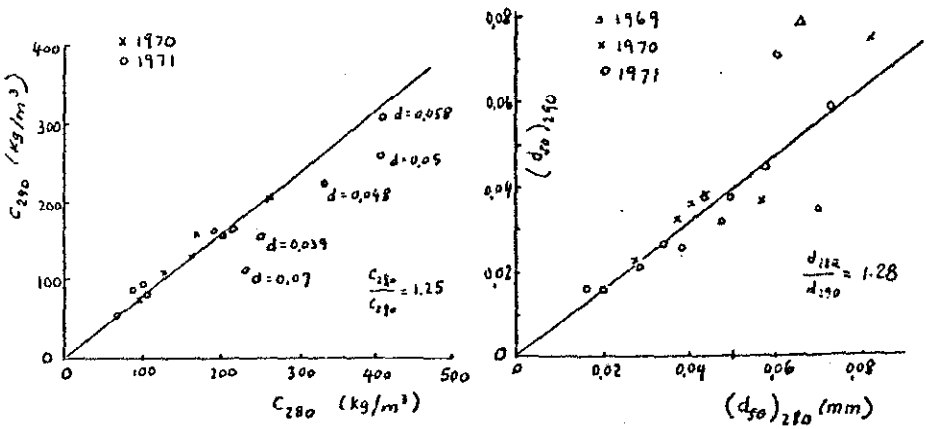

Fig. 8. Sediment concentration and median grain size of outflow passing through 280 m and 290 m outlets under non-stratified concentration profiles before dam

EFFICIENT MEASUREMENT AND ANALYSIS OF RAINDROP SIZE DISTRIBUTION

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Abstract : Knowledge of rainfall characteristics is important for the accurate estimation of kinetic energy and the prediction of soil erosion. In this study, an efficient method was developed to measure and analyze the natural raindrop data. The probability distributions of the natural raindrops were also analyzed. Based on the Kolmogorov-Smirnov test, it was found that the beta distribution gave a fairly good description on the probability distributions of the raindrops by number for the three subtropical stations investigated.

INTRODUCTION

Raindrop size distribution is an important factor for the estimation of kinetic energy and the prediction of soil erosion for a natural storm. Natural rainfall consists of a wide distribution and varies with both space and time. It is difficult to collect rainfall data for natural storms with short duration and high intensity. Ample sample of raindrop data has to analyzed to determine the variability of raindrop size distribution at a given location. It is, therefore, needed to develop an efficient data collection and analyzing system. The dyed filter paper method and the flour pellet method were two of the most widely used methods for collecting the raindrop data (e.g. Laws and Parson, 1943 ; Carter and Greer, 1974). Chang (1990) used an image capture system (including CCD camera, personal computer, and monitor) with 64 grayscales. Chang et al. (1993) also used an image process procedure to analyze the raindrop data. The raindrop stains of the filter paper had to be darkened by a pen manually before the data analysis for both Chang (1990) and Chang et al.'s (1993) methods. The main objective of this study was to develop an efficient method to measure and analyze the natural raindrop data.

METHODS AND PROCEDURES

Raindrop Collectors : Two raindrop collectors were designed and used in this study. The exposure time of the dyed filter paper was controlled by a timer with a resolution of 1/100 sec for the first collector (Wu and Lu, 1993). For the second raindrop collector, three A4 dyed filter paper were used to collect the raindrop samples simultaneously, and the exposure time was controlled manually depending on the rainfall intensity. The rainfall intensity was measured simultaneously with a simple rain gauge (Ma, 1995).

Color Image Scanning System : An EPSON GT-6000 color image scanner with 256

grayscales and 297 × 216mm scanning area was selected in this study. The gamma correction and color correction factors were used to properly adjust the contrast and color for the raindrop stains. An IBM 386 (or higher level) compatible personal computer with at least 100 MB HD, 640K RAM, VGA card, color monitor and a mouse was needed. A computer program in C Language was written by a computer specialist for scanning the raindrop stains.

There were four layers, including application layer, protocol layer, acquisition layer and device layer for the skeleton analysis of the scanner (Wu and Lu, 1993) . During the operation of the scanner, the contrast between the stains and background (seven intensity levels), the resolution (100 ~ 300dpi), and the grayscale had to be selected. The system had capability to find out the overlapped stains and displayed them on the monitor. The operator may either cut or delete part of the overlapped stains.

Raindrop Size Distributions : Three stations in central and northern Taiwan (Taichung city, Lien-Hua Chi in Nan-Tou, and Yang-Ming Mountain in Taipei) were selected for the collection of raindrop samples. The average annual rainfalls for these three stations were 1620mm, 1920mm and 4510mm, respectively ; and the numbers of sample analyzed were 128, 41 and 76, respectively. All three stations belong to the subtropical region. Four probability distributions, including normal, lognormal, gamma and beta distributions were chosed to describe the raindrop size distributions. The probability density function of the beta distribution can be expressed as :

$$P_x(x)=\frac{1}{B(\alpha,\beta)}\frac{(x-a)^{\alpha-1}(b-x)^{\beta-1}}{(b-a)^{\alpha+\beta-1}} \quad , a \le x \le b \qquad (1)$$

in which $B(\alpha,\beta)=\frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha+\beta)}$ and Γ is the gamma function

a , b=lower and upper limits, respectively.

α , β=parameters

The Kolmogorov-Smirnov test was used for goodness of fit test for both the raindrop size distributions by number and those by volume.

RESULTS

Color Image Scanning System : Table 1 is a comparison of the measuring features of three different image processing systems for analyzing the raindrop samples. The CCD camera image capture system was similar to that reported by Chang (1990) except that the system had 256 grayscales, instead of 64 grayscales. The image process system which used AutoCAD (trademark of AUTODESK, Inc.) was that reported by Chang et al. (1993) . The required data acquisition time and analysis time for an A4-size paper for the color image scanning system were estimated based on an IBM 386-33 compatible personal

computer. Both the acquisition time and the analysis time can be shortened if a better computer (e.g. IBM 486-66) is used. Also, the raindrop stains on the dyed filter paper did not need to be darkened by hand before scanning for the color image scanning system. In general, among the three systems compared, the color image scanning system developed in this study was the most efficient system for analyzing raindrop data.

Table 1 Comparison of measuring features for different image processing systems

Item \ Equipment	CCD Camera Image Capture System	Image Process with AutoCAD System	Color Image Scanning System
grayscales	256	256	256
resolution	521*480	512*480	512*480
maximum area to be analyzed (cm^2)	110*145	297*216	297*216
darken the stains before scanning	Yes	Yes	Yes
data aquisition time (A4)	Approx. 1 min	Approx. 30 sec with 486	Approx. 30 sec with 386-33
analysis time (A4)	depending on experience	Approx. 4~5 min. with 486	Approx. 1 min. with 386-33
calibration with known area	Yes	Yes	No
adjustment of contrast for stains	by adjusting monitor and CCD Camera	by adjusting brightness of monitor	offers 7 levels of brightness
zoom option	No	Yes	Yes

Fig.1 is a comparison of the areas obtained by the scanning system and the actual areas for circles with diameters varied from 0.9cm to 3.3cm. Table 2 are the results of precision tests for different irregular block figures as shown in Fig. 2. The mean percentage error was 0.33 %. Fig. 3 is a comparison of the areas estimated by the color image scanning system, planimeter (Ushikata, X-PLAN 360) , and geographic information system (GIS, NUMONICS 2210) using figures with different shapes as shown in the graph. Three samples were used for each test. It has to be mentioned that the areas for the scanning system included the areas of the border lines of the figures. The areas for the planimeter and GIS, however, included only half of the areas of the border lines of the figures. The results imply that the scanning system is a fairly accurate method.

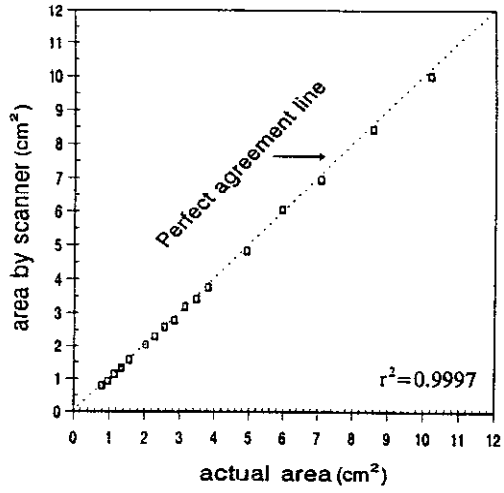

Figure 1 Comparison of areas by scanning system and the actual areas for circles with various diameters

Table 2 Precision tests for different irregular block figures

Figure No.	Area of Block Figure (cm^2)	Area by Color Image Scanning System (cm^2)	Percentage Error (%)
1	4.68	4.67	0.21 (-)
2	8.3	8.32	0.24 (-)
3	13.61	13.67	0.43 (+)
4	13.40	13.46	0.44 (-)

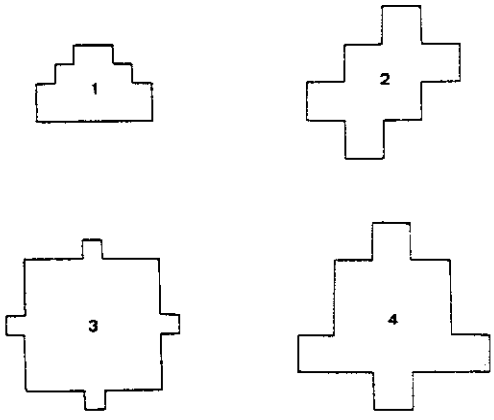

Figure 2 Irregular block figures with different shapes

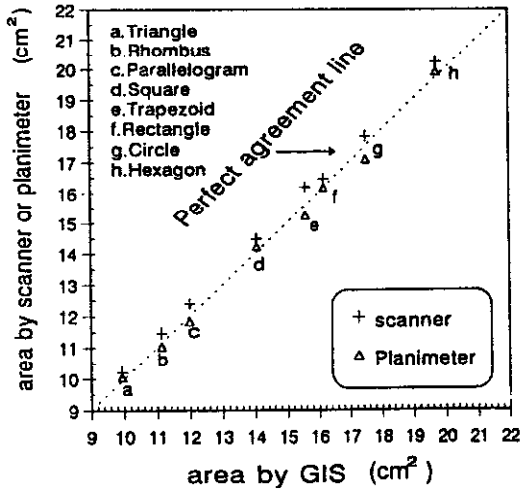

Figure 3 Comparison of the areas estimated by the color image scanning system, planimeter and GIS

Raindrop Size Distributions : **Fig.4 is the relationship between the median volume drop diameter and the rainfall intensity for Taichung area. Fig.5 is a comparison of the similar curves for different areas, including the curve measured by Laws and Parsons (1943) in Washington D.C. The curve for Taichung was fairly close to that for Washington D.C. However, the curves for the other two stations, Lien-Hua Chi and Taipei were quite different from that measured in Washington D.C. More data with higher rainfall intensities need to be collected for Taipei area in the near future.**

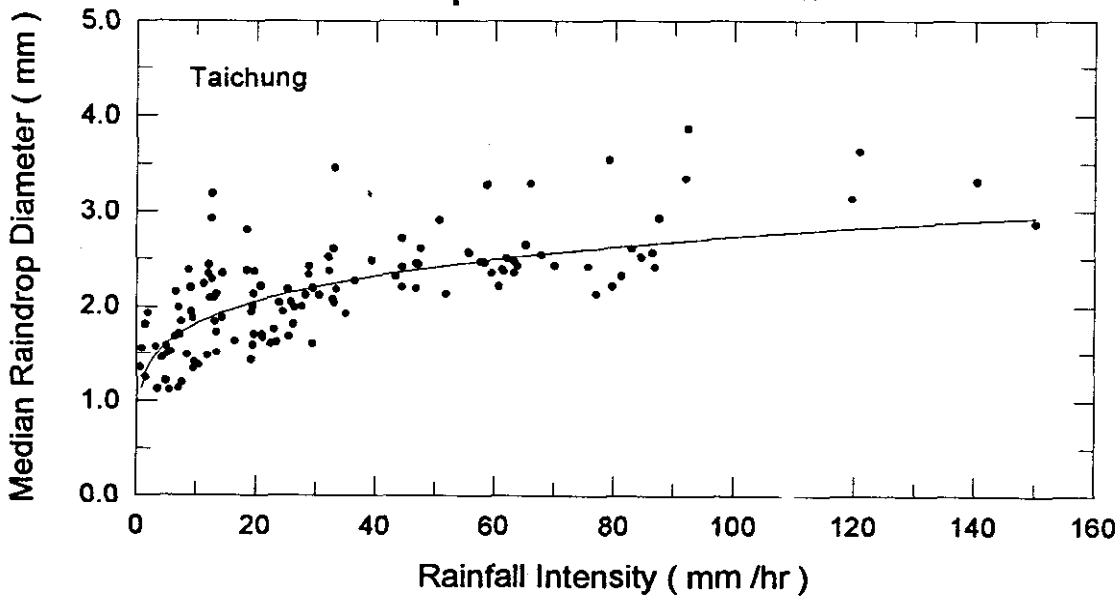

Figure 4 Relationship between median volume raindrop diameter and rainfall intensity for Taichung area

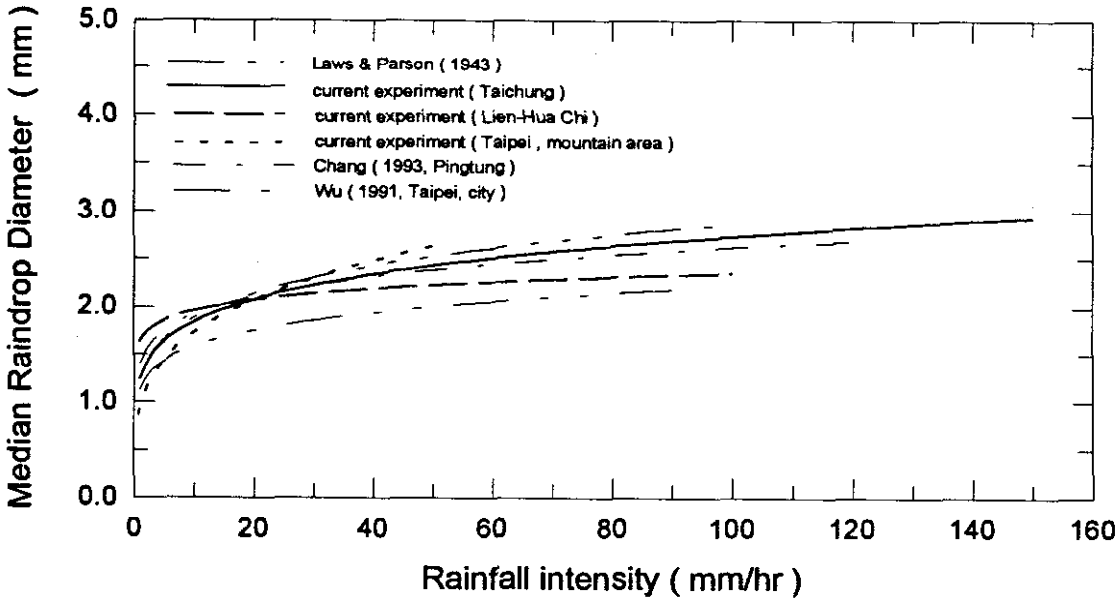

Figure 5 Comparison of median volume raindrop diameter-rainfall intensity curves for different areas

Fig.6(a) is a comparison of the measured raindrop size distribution by number and the four fitted theoretical probability distributions for a set of data collected in Taichung city. Fig .6(b) is a similar comparison except that the raindrop size distribution is calculated by raindrop volume. Fig.6, which is a typical result, shows that the raindrop size distribution by number tends to be skewed to the right ; and the raindrop size distribution by volume is closer to a symmetric distribution.

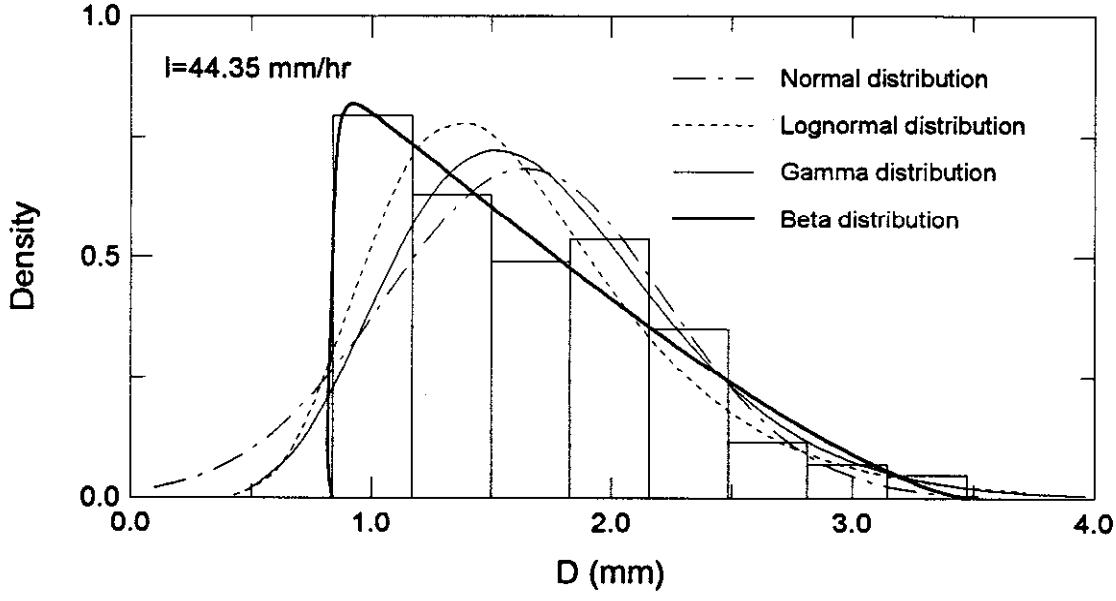

Figure 6(a) Comparison of measured raindrop size distribution by number and four fitted probability distribution , Taichung area

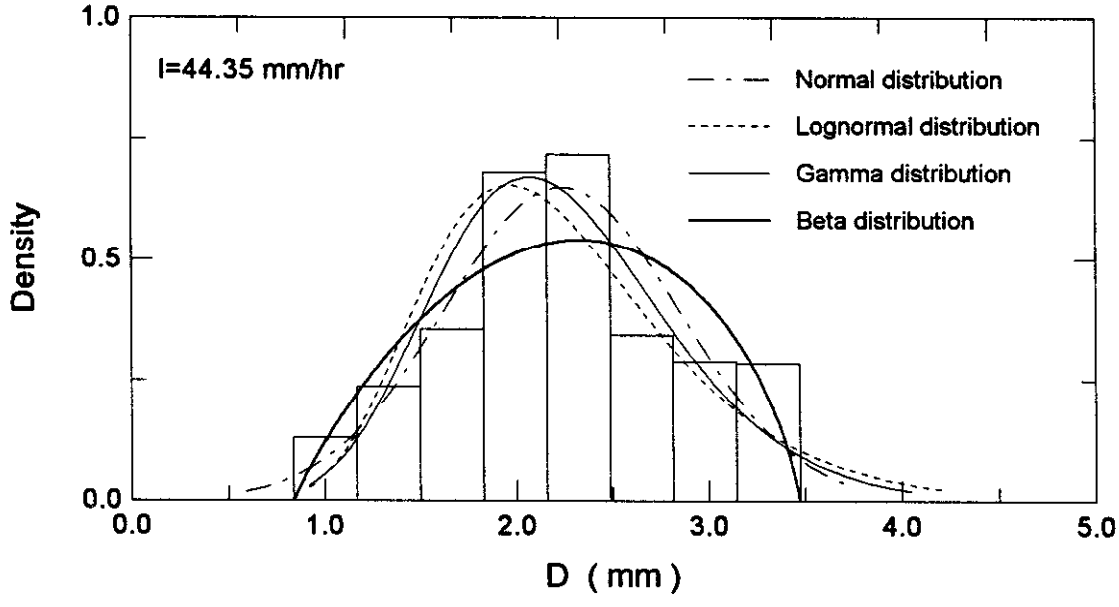

Figure 6(b) Comparison of measured raindrop size distribution by volume and four fitted probability distribution , Taichung area

The percentages of samples that passed Kolmogorov-Smirnov test for four different distributions and 3 stations are summarized in Table 3. For the raindrop size distributions calculated by number, it was found that both the beta and lognormal distributions gave fairly good fit. This result was consistent with Quimpo et al.'s (1986) finding that among the exponential, normal, upper limit lognormal, and lognormal distributions tested, the lognormal distribution fitted the data best. For the raindrop size distributions calculated by volume, Table 3 indicates that the distribution tends to be more or less symmetric and the normal distribution fits the data reasonably well.

Table 3 Percentages of samples passed Kolmogorov-Smirnov test ($\alpha = 0.05$) for different probability distributions

Station	Sample No.	Model	drop distribution by number	drop distribution by volume
Taichung	128	Normal	49.2 %	82.0 %
		Lognormal	79.7 %	75.8 %
		Gamma	76.6 %	84.4 %
		Beta	90.6 %	78.1 %
Lien Hua Chi	41	Normal	39.0 %	75.6 %
		Lognormal	61.0 %	46.3 %
		Gamma	56.1 %	68.3 %
		Beta	80.5 %	68.3 %
Yang-Min Mountain in Taipei	76	Normal	60.5 %	82.9 %
		Lognormal	86.8 %	85.5 %
		Gamma	84.2 %	84.2 %
		Beta	88.2 %	86.8 %

CONCLUSIONS

An efficient method using a color image scanning system was developed to measure and analyze the raindrop data. The results of the precision tests using figures of various shapes indicate that the scanning system is a very accurate method. Based on the Kolmogorov-Smirnov test, it was found that the beta distribution fitted the raindrop data reasonably well for the three subtropical stations investigated.

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