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APPENDIX C

CORPS OF ENGINEERS METHODS FOR PREDICTING SEDIMENT YIELDS 1973

Section I. Introduction

C-1. Introduction. The methods used by the Corps of Engineers for predicting sediment yields are, in general, based upon empirical relationships, but vary in scope and procedure depending upon the complexity of the individual water resource project plan or design. Because of the diverse nature of these projects, both in design magnitude and geographic location, a standard method for design application is not employed throughout the Corps. Instead, the individual district offices make a sensitivity appraisal to evaluate the impact of all sedimentation influences on a specific project plan. From this first approximation analysis, the scope of the sedimentation problem is defined. This definition then becomes the basis for selecting methods to be used in establishing the true magnitude of the problem components and design solution criteria. Where it is apparent that modification of a method might be practical to produce an improvement in design evaluation, such modification is encouraged. For this reason, a variety of procedures is developed and employed throughout the Corps, but they all relate closely to one of the three basic empirical approaches for predicting sediment yield, namely, (1) measuring the yield rate directly by sediment sampling or reservoir surveys, (2) extrapolation of such measured data to unmeasured drainages by various correlation and probability techniques, or (3) establishment of identifiable physiographic watershed or stream flow characteristics that permit development of predictive equations. Theoretical approaches to the prediction of sediment yields have been occasionally employed for special circumstances where empirical relationships were weak or confidence lacking, but such procedures are not common.

C-2. History of Prediction Methods. Sediment sampling in the United States dates back to 1838, when the Corps of Engineers was engaged in navigation channel work on the lower Mississippi River. During the next 100 years, the need for sediment predictions related almost entirely to river navigation and estuary maintenance work. It was not until after passage of the Flood Control Acts of 1928 and 1936, when the Corps started to plan, design, and construct multiple-purpose reservoirs, that the need for sediment yield predictions developed. Typical of this initial phase of sediment yield investigations was Straub's work, which is well documented in the 1933 Missouri River Basin report of the Chief of Engineers in response to House Document No. 308, 69th Congress. His development of the sediment rating curve method was later amplified by Campbell and Bauder in the 1940's, and Miller in the 1950's, into the popular flow-duration sediment-discharge rating curve method. After Straub's work the emphasis on documenting sediment yield rates shifted in the 1940's to reservoir survey measurements and the relation of sediment yield to contributing drainage areas, reservoir capacities, stream density or slope, and runoff. The early work of Brown and Gottschalk is typical of this period. But this work, like Straub's, was considered professionally weak because it related sediment yield to only a few of the many contributing factors. Next, during the early 1950's, efforts were concentrated on the expansion of

Musgrave's definition of quantitative factors for small land units to the drainage increments of large river control projects. These evaluations attempted, without much success, to relate many of Musgrave's factors on a regional or annual basis in lieu of local or seasonal definitions. During this same period, sediment sampling and reservoir survey measurement techniques were enhanced. Long term basin runoff characteristics were also identified to improve confidence in the sediment rating curve - flow duration method. However, by the late 1950's, project planning had shifted to smaller drainage areas. The definition of local drainage controls and urban runoff assumed greater importance; the "big dam" criteria for yield predictions was no longer vogue. This change required a downward extrapolation toward the upper limits of Soil Conservation Service criteria. To meet this need the number of sediment discharge gaging stations in the Missouri River Division of the Corps of Engineers was doubled, plans were implemented to document urban runoff characteristics and correlation techniques concentrated on qualifying the adequacy of short term records. As the environmental issues of the late 1960's developed their impetus, design criteria and needs mushroomed into the broad fields of water quality control, biological reproduction, eutrophication acceleration and most recently wastewater management. Adequate methods for predicting the impact of sediment yield on the food chain and habitat of aquatic species and on wastewater disposal have not been developed yet.

Section II. Methods Involving Extrapolation of Measured Records

C-3. Sediment Load Measurements. The first category involves the extrapolation of measured records and is divided into three major measurement classifications: sediment loads, reservoir surveys, and reconnaissance inspections. Relevant methods for each are described below.

a. Sediment Rating Curve Method. This basic, older method is usually associated with a flow-duration analysis, but occasionally special circumstances still require its use. An example would involve instantaneous units of flow and concentration rather than mean daily values. These applications usually relate to a near constant or limited range of flows, such as for seasonal or monthly variations between run-of-river reservoirs within a large system. In such instances the minor incremental flow and sediment contributions including their duration and frequency, are usually obscured by the large base flow. The method involves the plotting of measured suspended sediment load values versus equivalent units of discharge for desired time periods and defining the mean curve. An example is shown in Figure C-1. This method was originally developed for the 1933 Missouri River Basin 308 report with further enhancement by Campbell and Bauder [12].

b. Sediment Rating Curve-Flow Duration Method. This popular method combines the sediment discharge rating curve with a flow-duration curve from the measured mean daily water discharges to develop a percent exceedance curve for the sediment discharge. Sediment yield is the area under that curve. The method is illustrated in Chapter 3 of this manual. For more complete details, including an evaluation of the techniques of this method, see [42].

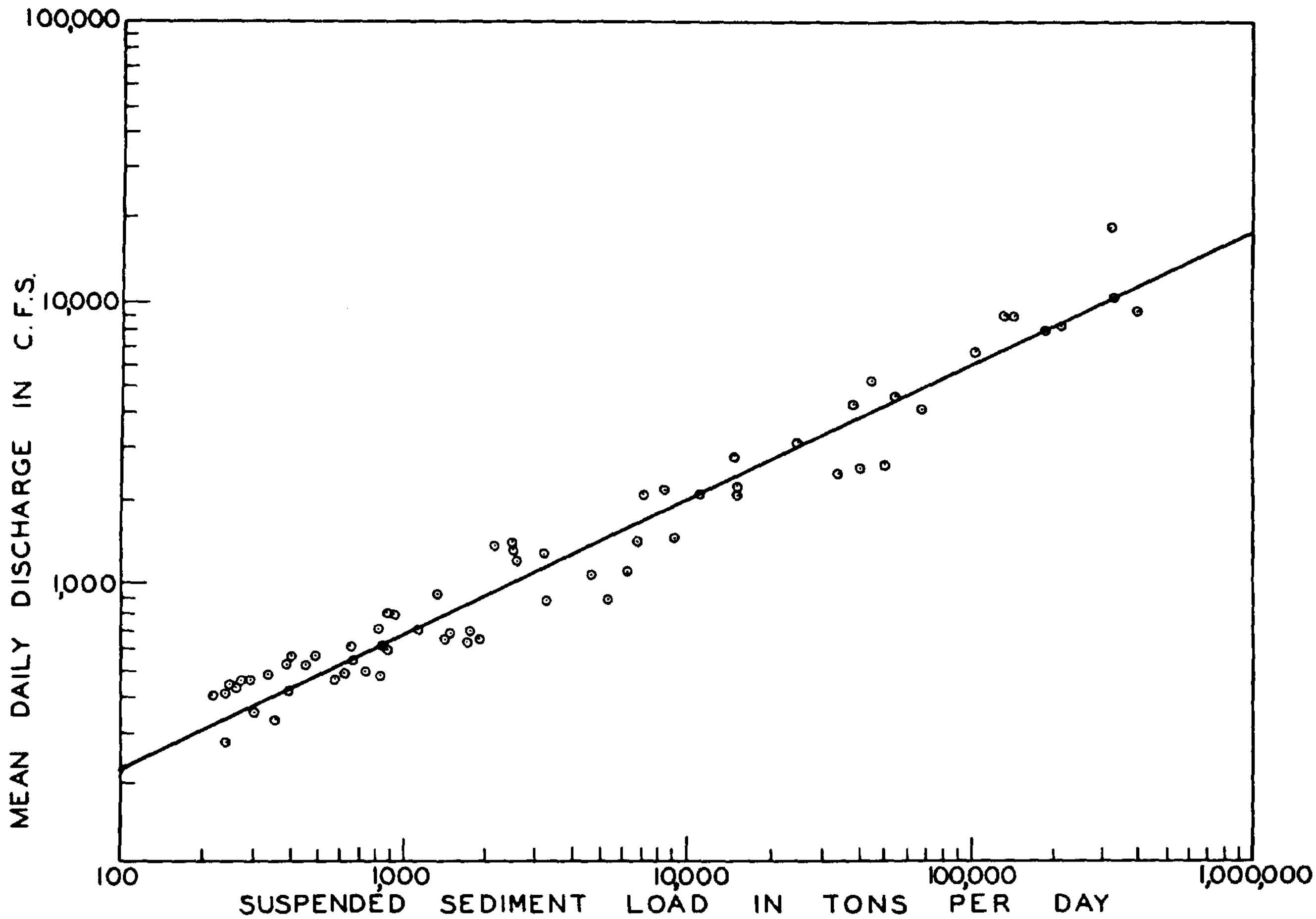


Figure C-1. Sediment discharge rating curve, Elkhorn River, Waterloo, Nebraska

c. Sediment Discharge-Soil Type Relationships. This method relies upon a water runoff-sediment load record to obtain a correlation of sediment yield according to soil classification and cultivated areas. River basins are divided by soil types and annual surface water runoff versus sediment discharge curves are developed for each classification according to the area of cultivated acreage. An example of the relationship developed for 13 drainages of mixed loess and glacial soils is shown in Figure C-2. A comparable correlation was possible for residual limestone, sandstone, and shale soils, but in loessial terrain the results were indeterminate. For further information refer to [29].

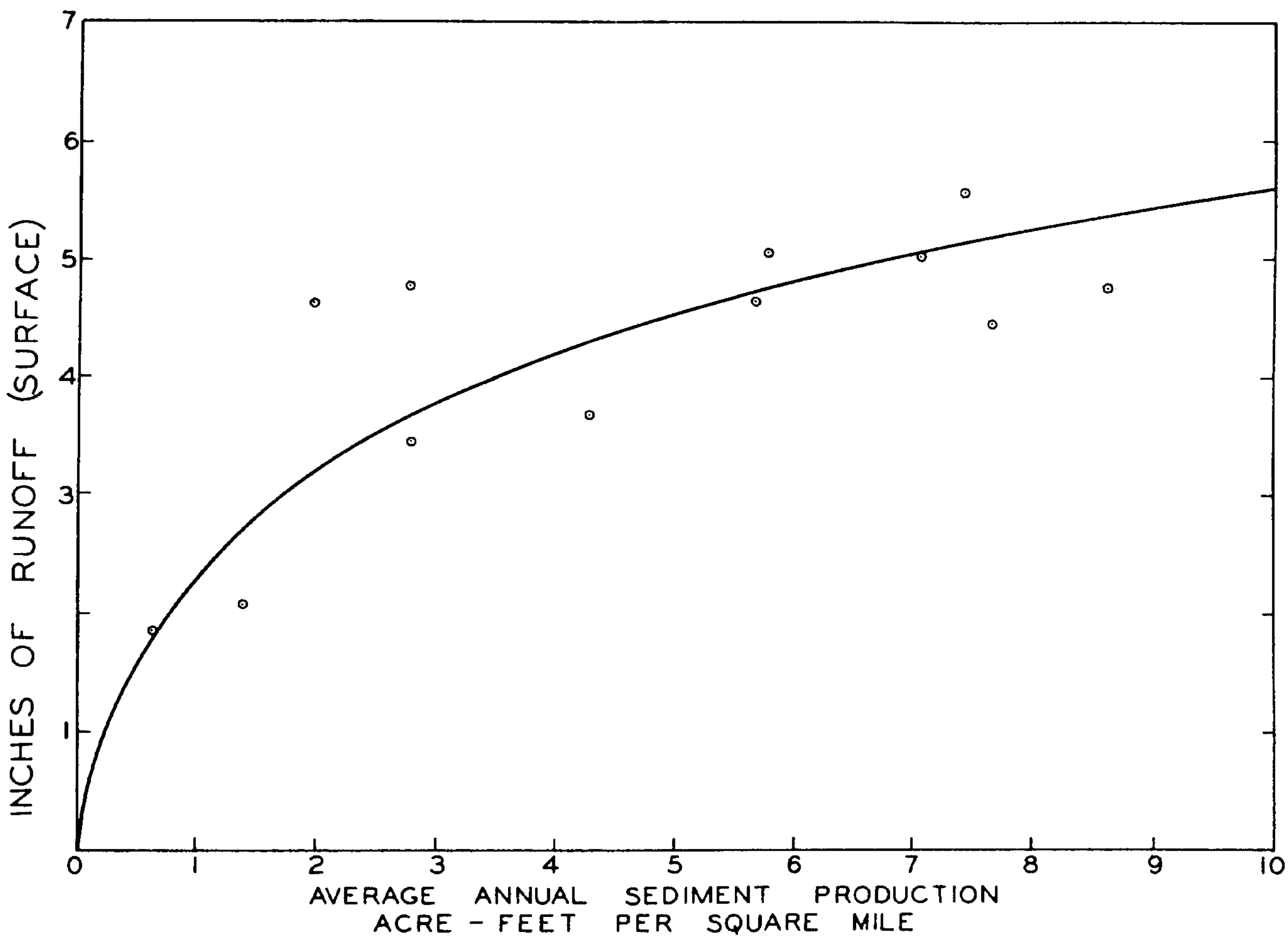
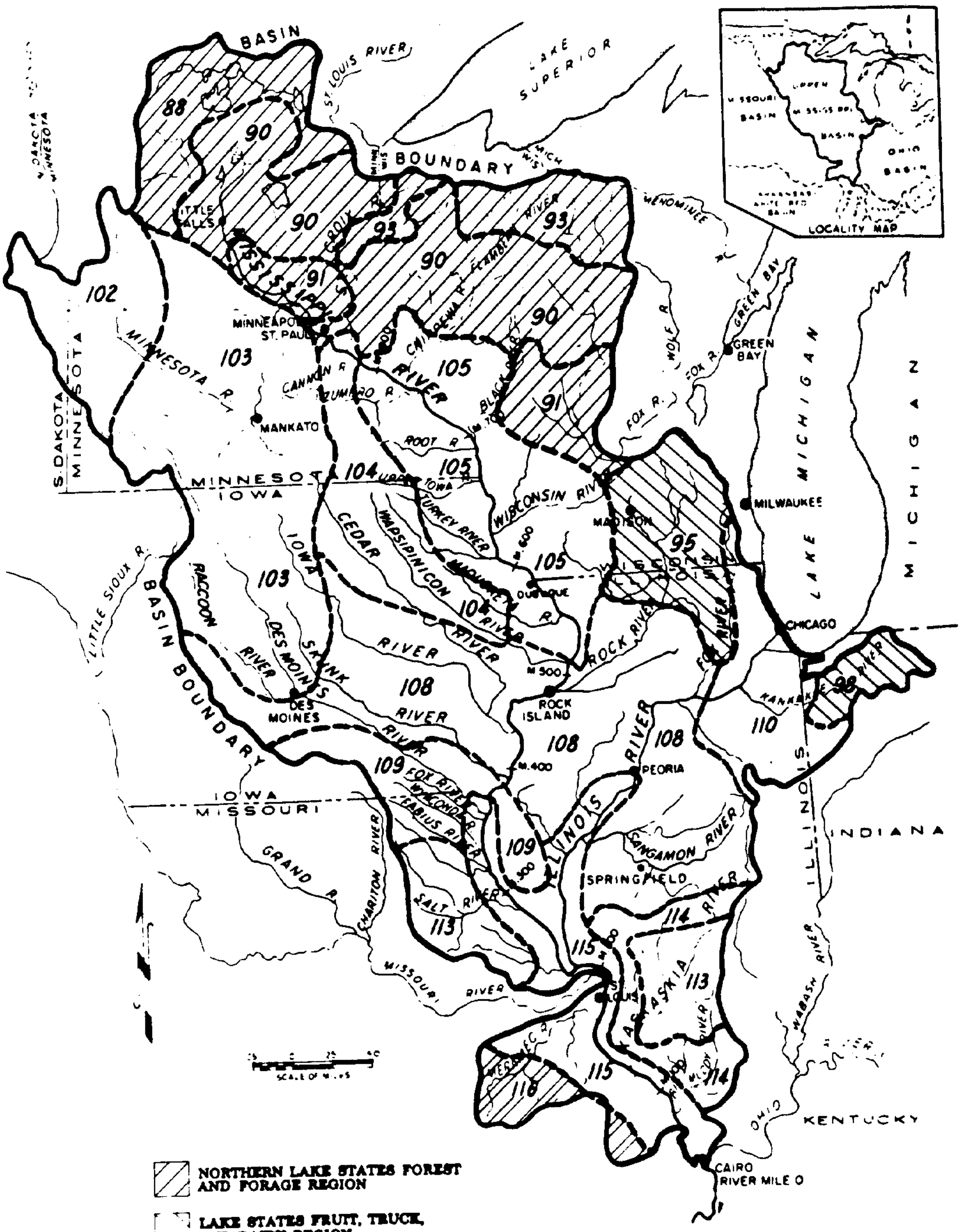


Figure C-2. Average annual runoff for mixed loess and glacial soils

d. Dominant Basin Characteristics. The similarity of the dominant physical characteristics of a drainage basin versus the measured sediment production is the basis for this method. The dominant characteristics included land use, relief and topography, climate, water, and soil types. Land resource areas are used to group the defined individual sediment yield rates into comparable area categories. Both suspended sediment load and reservoir sedimentation survey records are used to establish yield rates by drainage area or time increments for a given base period. The flow duration principle is applied to short term records to the base period. Such adjustments require establishment of sediment discharge-to-stream flow relationships for the period of measurements and then correlating this data to the long term flow regiment of the stream. The method has produced indications of sediment yield trends with time in several instances. Figures C-3, C-4, and C-5 depict the general features of this method. For details see [40].



NORTHERN LAKE STATES FOREST AND FORAGE REGION

LAKE STATES FRUIT, TRUCK, AND DAIRY REGION

CENTRAL FEED GRAINS AND LIVESTOCK REGION

EAST AND CENTRAL GENERAL FARMING AND FOREST REGION

Figure C-3. Land resource regions and major land resource areas.

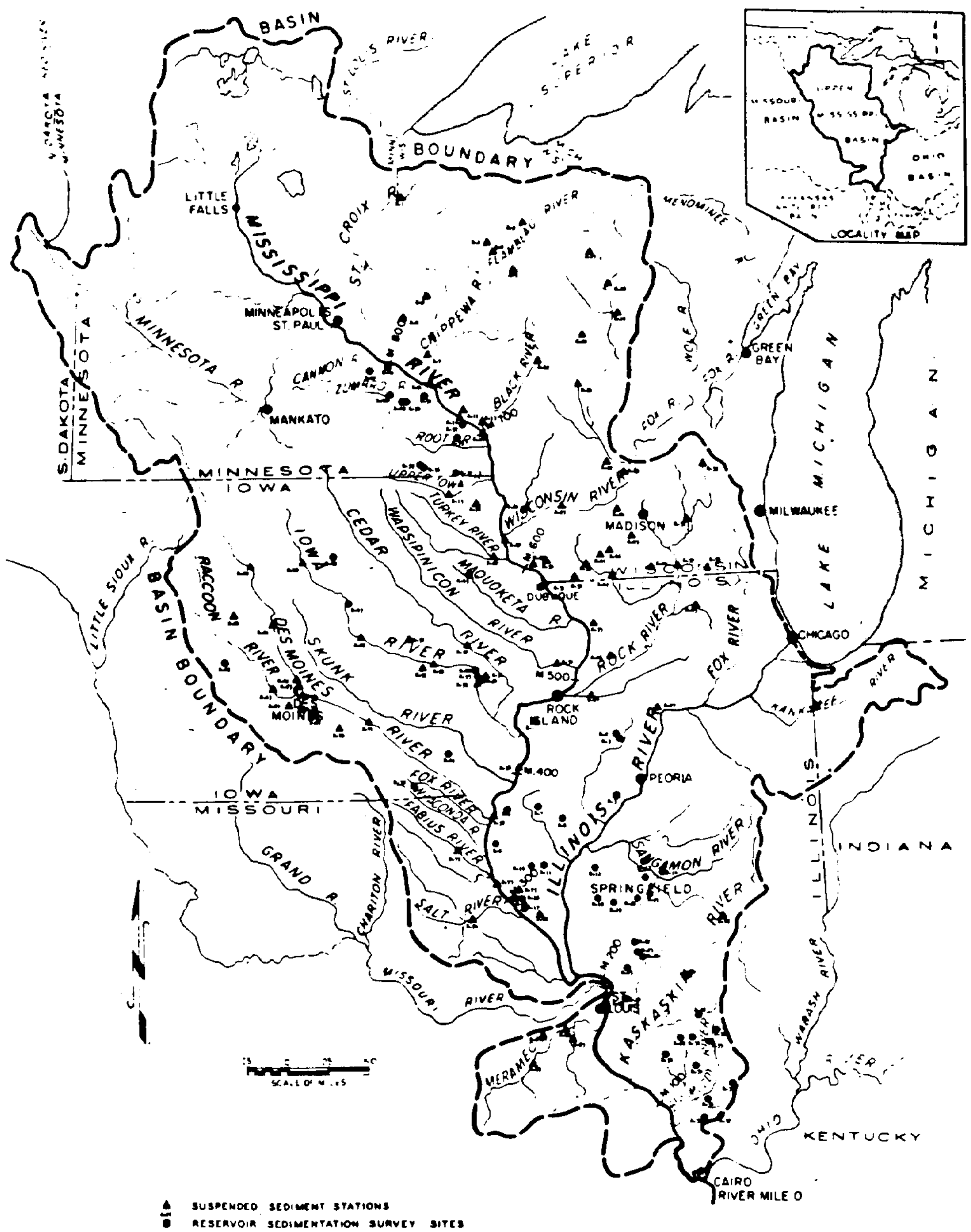


Figure C-4. Location of basic data.

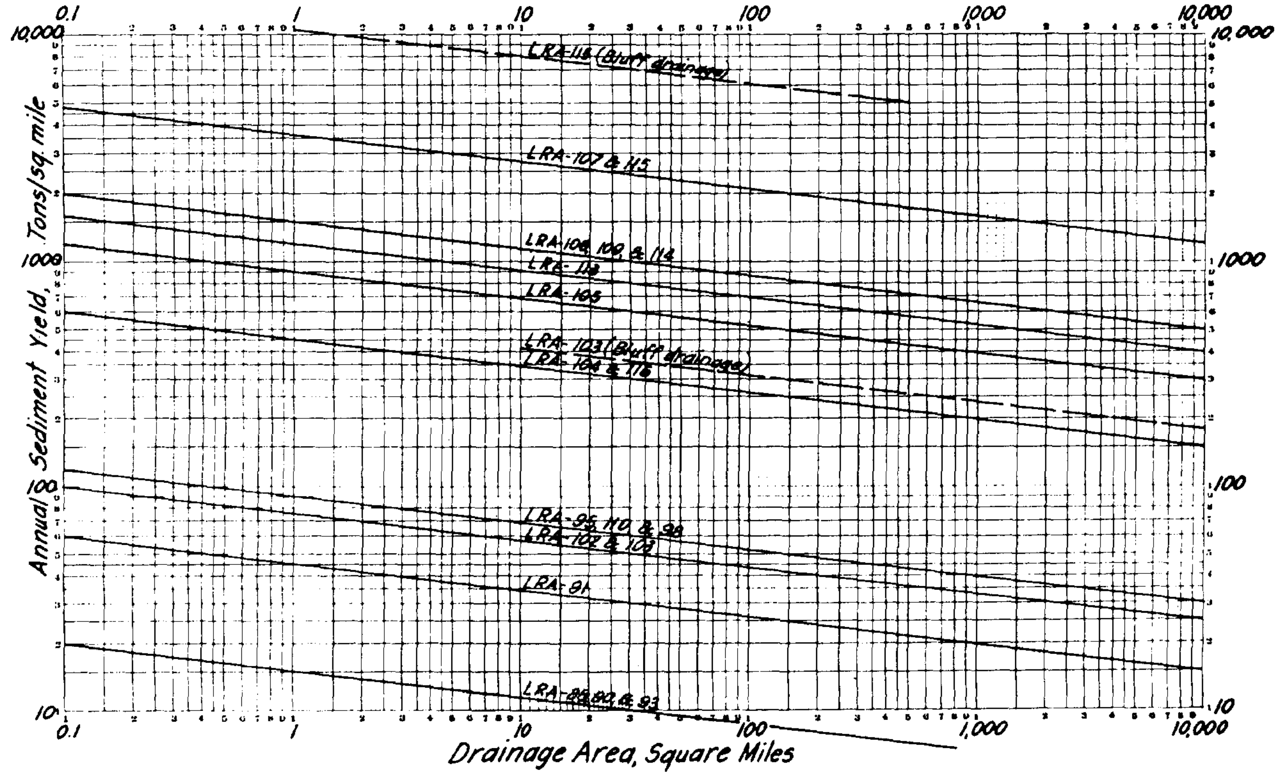


Figure C-5. Observed sediment yields, all land resource areas.

e. Sediment Yield by Isogram Intervals. Except for the degree of individual basin analysis, a similarity exists between this and the preceding method. This method recognizes the dominant physical characteristics and measured sediment production records of the basin, but in addition, relies upon personal knowledge and engineering judgment to evaluate the sediment yield characteristics of a basin. The method was developed for use as a task force expedient by a group of interagency sedimentation specialists to document sediment yield rates for large river basins. Yield rates for standard periods of time are derived by extrapolation of shorter period records by one of three procedures: comparing sediment load-water discharge relations between periods of record and the standard period, derivation of sediment-water regression curves for increments of drainage area, or evaluating relations between intermittent sediment measurements made over short time periods. The final delineation of isogram lines is based upon group experience and judgment. A typical end product of this method is shown on Figure C-6. Examples of this method can be found in any one of the seven subbasin sedimentation reports prepared by the Task Force on Sedimentation for the Missouri River Basin Comprehensive Framework Study, submitted for limited distribution to participating agencies of the Missouri Basin Inter-Agency Committee in 1968 and 1969.

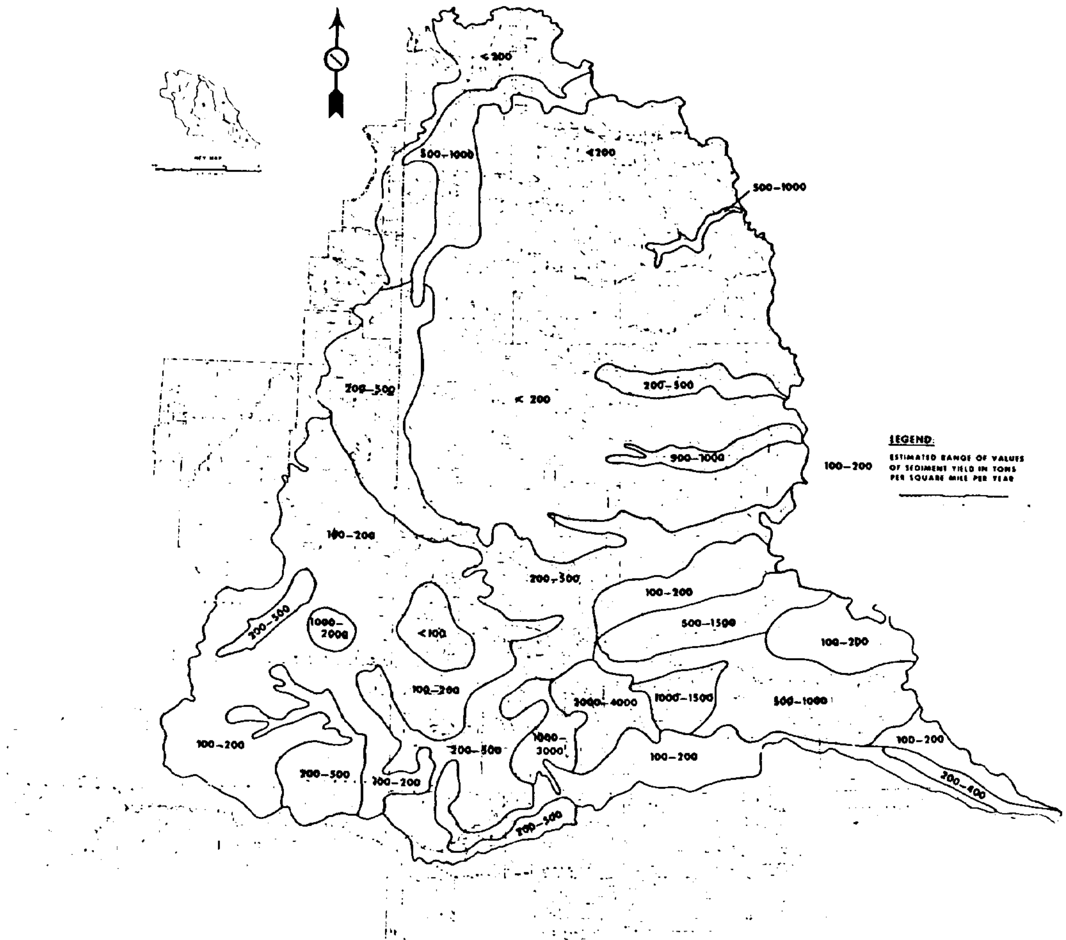


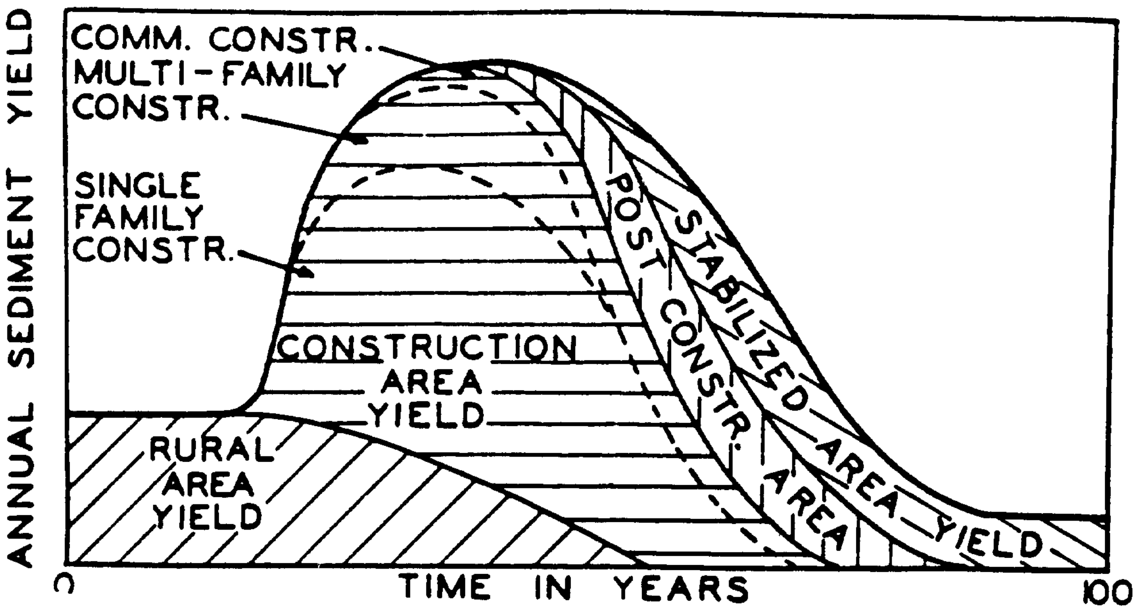
Figure C-6. Western Dakota Tributaries Subbasin No. 3 sediment yield from areas in excess of 100 square miles.

f. Sediment Yield During Urban Expansion. The techniques of this method are still in the developmental stage. The basic premise in the transition of rural lands to urban usage over given time periods is that sediment yield rates accelerate from agricultural values to a high peak during landscaping or construction, then decline to a lower plateau as the land "heals," and finally level off at some low stable rate representative of business or residential lands. A projection of urban expansion limits, provided by the local metropolitan planning authority, serves as a base for converting contributing drainages from rural use to single family, multi-family, or commercial usage. Integration of yield rates for increments of area in various stages of development permits a continuous assessment over the design life of the project. Judgmental extrapolation of limited urban runoff and sediment yield measurements is currently necessary, but data collection programs that concentrate on storm runoff measurements can quickly improve this limitation. A generalized schematic outline of this method, as being developed by the Omaha District, is shown in Figures C-7 and C-8.

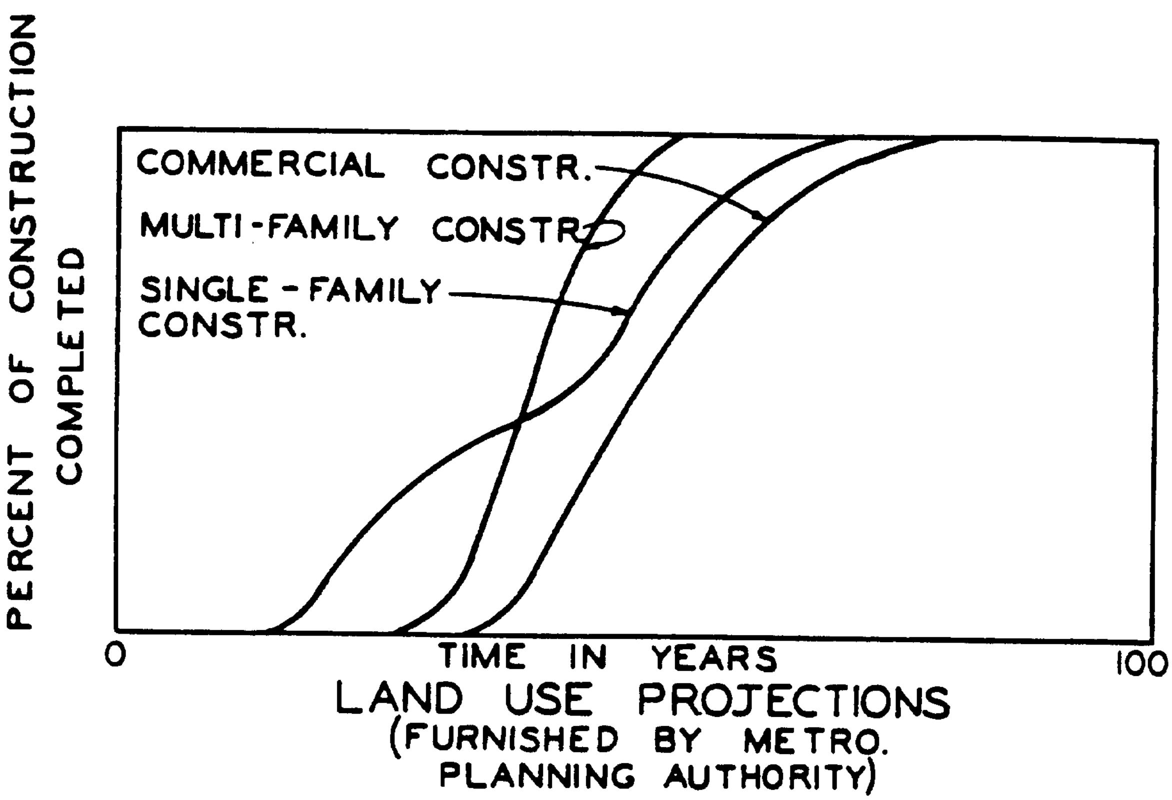
C-4. <u>Reservoir Sedimentation Surveys.</u>

a. Sediment Yield Per Unit of Drainage. The application of this method is widespread because of its simplicity in relating measured rates of sediment yield to the contributing drainage area increment. Numerous correlations are possible within certain ranges of drainage area by soil types, runoff volumes, watershed-capacity ratios, dominant discharge, land use, physiographic areas, and many other parameters. Most Corps applications of these yield rates pertain to contributing drainage greater than 100 square miles, so correlation with the conventional soil loss parameters is not common. The principal source of reference data is [61]. A typical example of this method can be noted in Figure C-9.

b. Yield Production for Debris Basins. This is a special application used to determine the sediment yield into flood control debris basins in mountainous terrain. The method was developed from observed debris volumes that reflect ground conditions influenced by prior rain runoff and areas subjected to partial or complete "burns." Influencing factors include size and shape of drainage area; steepness of canyons and side slopes; geological characteristics; type and density of plant cover; recency of burns; and frequency, duration, and intensity of storms. Measured debris volumes are adjusted to a common base and curves developed for separate corrections of the major factors affecting debris production. Table C-1 summarizes the details of this method. Further information is available in [50].



a. Sediment yield by land use.



b. Projected rate of land use change from rural to urban.

Figure C-7. Sediment yield by land use type during urban expansion.

ANNUAL SEDIMENT YIELD FROM SOURCE AREAS					
YEAR	RURAL	CONSTRUCTION	POST CONSTR.	STABILIZED	TOTAL
1	X				X
2	X				X
3	X				X
4	X	Y			X+Y
5	X	Y			X+Y
6	X	Y	Z		X+Y+Z
7	X	Y	Z		X+Y+Z
8	X	Y	Z	W	X+Y+Z+W
•	•	•	•	•	•
•	•	•	•	•	•
•	•	•	•	•	•
•	•	•	•	•	•
n-8	X	Y	Z	W	X+Y+Z+W
n-7		Y	Z	W	Y+Z+W
n-6		Y	Z	W	Y+Z+W
n-5			Z	W	Z+W
n-4			Z	W	Z+W
n-3			Z	W	Z+W
n-2				W	W
n-1				W	W
n				W	W
TOTAL	ΣX	ΣY	ΣZ	ΣW	Σ(X+Y+Z+W)

Figure C-8. Total sediment yield for all land uses.

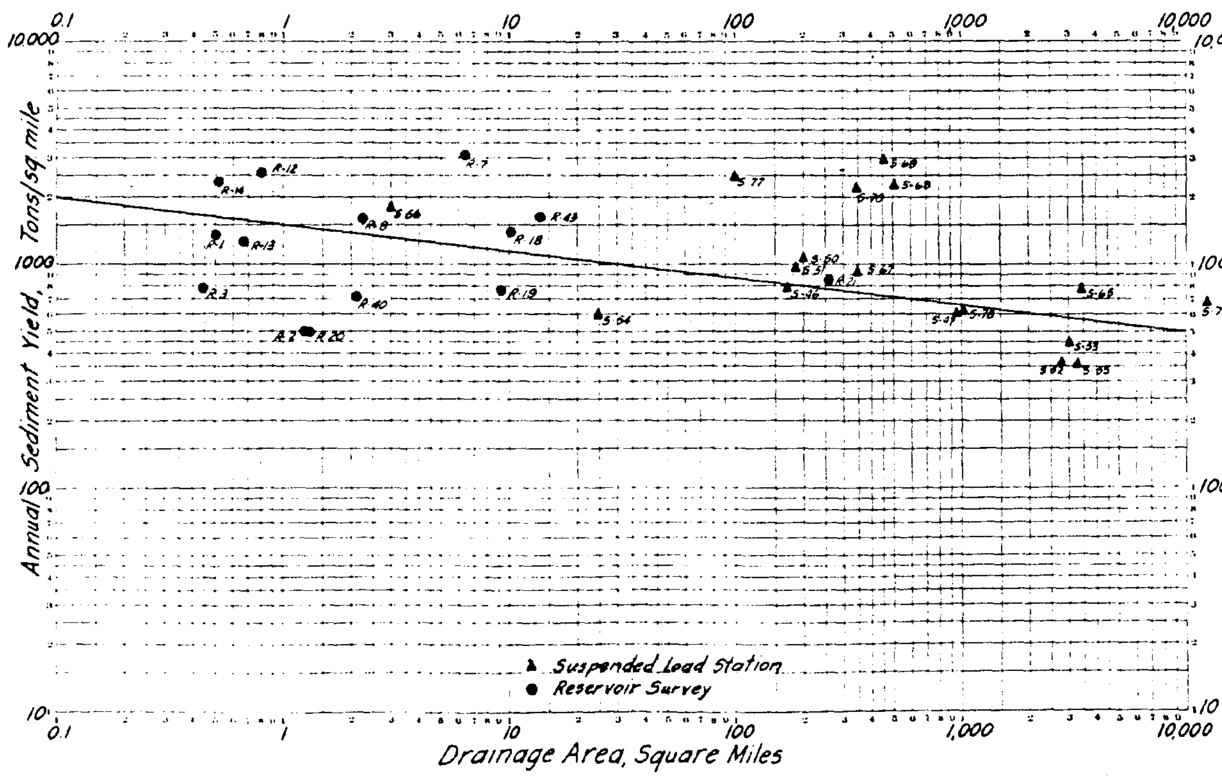


Figure C-9. Observed sediment yields, land-resource area 108.

TABLE C-1.

Observed data and computed debris production for selected debris basins in the Los Angeles area.

Debris basin			Burn in drainage area		Debris-producing flood		Observed debris production during flood		Observed debris rate adjusted to 100 percent burn 1st year	Debris production factors for—				Correction factors					Computed debris production	
No.	Name	Drainage area	Year	Area	Year	Years after burn	Total	Rate		Slope	Drainage density	Hypsometric index	3-hour rainfall	Slope	Drainage density	Hypsometric index	3-hour rainfall	Total	For maximum 1 square mile with 100 percent burn 1st year[3]	For year of observed flood and actual area burned
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)
	La Cresenta Area:	*Square miles*		*Square miles*			*Cubic yards*	*Cubic yards per square mile*	*Cubic yards per square mile*	*Feet per mile*	*Miles per square mile*		*Inches*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Cubic yards*	*Cubic yards*
1	Dunsmuir	0.84	1933	0.78	1938	5	58,800	70,000	695,000	1,390	1.7	0.54	2.94	99	97	98	67	64	1,220,000	106,000
2	Eagle-Goss	.61	1933	.46	1938	5	40,900	67,050	767,000	1,480	3.3	.25	2.89	100	84	33	64	18	342,000	19,400
3	Haines	1.53	1933	1.01	1938	5	52,000	33,990	423,000	1,040	2.4	.46	2.85	92	95	98	62	52	1,010,000	117,000
4	Hall-Beckley	.83	1933	.63	1938	5	86,300	103,980	1,185,000	930	2.2	.50	2.82	88	96	100	61	59	990,000	73,000
5	Hay	.20	1933	.06	1938	5	12,600	63,000	1,190,000	1,290	.6	.65	2.72	97	99	76	56	40	760,000	9,700
6	Pickens	1.84	1933	1.75	1938	5	122,200	66,410	650,000	940	3.4	.47	2.93	88	82	99	67	48	910,000	160,000
7	Shields	.27	1933	.24	1938	5	33,500	124,000	1,320,000	1,570	2.5	.51	2.90	100	94	100	65	61	1,160,000	34,400
8	Snover	.23	1933	.11	1938	5	16,800	73,040	1,110,000	1,280	3.5	.54	2.82	97	81	98	61	46	874,000	15,500
	Pasadena Area:																			
9	Fair Oaks	.21	1935	.21	1938	3	12,000	57,140	257,000	1,180	0	.21	2.34	95	100	25	36	9	171,000	9,600
10	Fern	.30	1935	.30	1938	3	20,700	69,000	310,000	1,180	4.8	.41	2.42	95	51	92	39	17	323,000	24,600
11	Las Flores	.45	1935	.31	1938	3	36,000	80,000	495,000	1,610	3.2	.58	2.62	100	85	94	49	39	741,000	60,000
12	Lincoln	.50	1935	.50	1938	3	8,000	16,000	72,000	780	4.6	.31	2.39	81	57	60	38	11	209,000	25,600
13	West Ravine	.25	1935	.24	1938	3	29,800	119,200	555,000	1,290	0	.40	2.40	97	100	90	38	33	627,000	39,500
14	Bailey	.58	1953	.46	1954	1	65,000	112,070	140,000	1,520	2.6	.50	1.70	100	93	100	12	11	209,000	104,000
	Burbank Area:																			
15	Brand	1.03	1927	.77	1943	[4]10	3,100	3,010	99,000	910	3.0	.50	1.70	87	88	100	12	9	171,000	5,300
16	Sunset	.44	1927	.42	1938	[4]10	6,600	15,000	495,000	1,610	2.0	.48	1.93	100	97	99	18	17	323,000	4,800
17	Stough	1.65	([4])	([4])	1943	([4])	33,500	20,300	670,000	1,020	4.4	.62	2.64	91	63	85	52	25	475,000	20,000
	Beverley Hills Area:																			
18	Nichols	.94	([4])	([4])	1938	([4])	17,900	19,040	626,000	480	.9	.56	2.48	57	99	96	42	23	437,000	12,600

[3] 1,900,000 times total percent from column 19.
[4] 10 years or more assumed to have no effect on debris production.

C-5. Reconnaissance Inspections. The following methods are directed toward establishing preliminary estimates of sediment yield for large drainage areas. On occasion, the investigation details have been expended to cover studies of design scope for small to moderate drainages. Their basic premise consists of a quick but detailed reconnaissance inspection of the contributing drainage area by two or more sedimentation specialists, who, by experience, are capable of making estimates of sediment yield rates. During the field reconnaissance they collectively establish representative point rates for increments of major drainages within the overall study basin. This technique is particularly applicable for a degree assessment of contributing versus noncontributing drainage as influenced by soil management practices, smaller reservoirs or ponds, or irrigation diversion projects. If the basin is relatively small, perhaps less than 1000 square miles, the estimates for even third-order or a fourth-order stream can become quite detailed. For large basins, selected streams might be covered in more detail and the remainder left to a random choice of inspection. The end product is usually similar to that shown in Figure C-6.

a. Interpolation of Rates Within a Basin. This method requires several points of measured sediment yield, by either sediment sampling or reservoir surveys, within the basin drainage. One of these points should be located near the mouth of the basin to reflect the total measured yield from the drainage. During the field reconnaissance these measured rates are used as a comparative guide for estimating yield rates for small increments of the unmeasured drainages. When enough point estimates are established, a yield contour map is developed. Using digitizing or planimetering processes, drainage area increments of equal yield rates are totaled for the major drainages within the basin. A summation of these totals and division by the contributing drainage area value gives an average sediment yield rate for the subject increment. These increment rates are checked against the measured increment rates for verification. If they are not reasonably comparable, adjustments to selected point estimates are justified to bring the integrated total into balance with measured data.

b. Extrapolation to Unmeasured Watersheds. The basic procedure is similar to that above except that a comparison between the total estimated and measured rates for a basin is not possible. Prior to the field inspection of the unmeasured drainage, the reconnaissance team usually makes a preliminary inspection of the measured drainages being used as the extrapolation base. This visual inspection requires additional time and effort but serves as an effective means for comparative extrapolation. The validity of this method is dependent upon the degree of extrapolation, but apparent satisfactory results have been produced within a restricted time period.

C-6. Methods Involving Predictive Equations. The second category involves predictive equation methods. Most of the individual methods discussed below apply to the solution of specific problems. They differ from the preceding methods in that the predicted sediment yield relates primarily to channel contributions rather than from a watershed drainage. The Corps' use of predictive equations for determining watershed yields is very limited.

a. Sediment Transport Relationships. There is a variety of methods in this classification but the most common is the Einstein approach, with one of its many modifications, or the more recent Toffaleti procedure. Their use for sediment yield predictions usually relates to channel stabilization projects involving aggradation or degradation problems. But their application is also common in establishing the magnitude or rate of unmeasured suspended or bed sediment load values. Estimates of such values are extremely important in certain instances when establishing yield rates from measured suspended sediment load records, as is required in the flow duration-sediment rating curve method. An excellent discussion of the Einstein and Toffaleti methods, plus others, and a listing of complete references can be found in [2].

b. Detention-Time Method. This method was developed to predict the volume of sediment trapped by a run-of-the-river reservoir project. It is based upon empirical relationships between the time required for a water discharge to pass through the reservoir and the percentage of sediment deposited. Detention time is defined as the ratio of reservoir storage to the inflow discharge rate at any given time. Curves of detention time versus percent of wash load and percent of bed material load deposited are shown in Figure C-10. As the reservoir volume is depleted by deposition, the detention time is reduced and the yield rate per unit of flow increases. Reference details for this method can be found in Dardanelle Reservoir Design Memorandum No. 6, Part IV, "Sedimentation," prepared in October 1957 by the Little Rock District.

c. Soil Erosion-Delivery Ratio Method. This category covers both the sediment delivery and sheet erosion prediction methods developed by the Department of Agriculture. The application of these methods to Corps projects is generally limited to small watersheds of less than 25 to 50 square miles. The Musgrave equation [43] is probably still preferred over the universal soil loss equation for smaller drainages. However, more useful are the various empirical equations developed by such authors as Anderson, Barnes, Brune, Glymph, Gottschalk, Heinemann, Kohler, Maner, Piest, and others [2].

d. Tail Water Degradation. Several methods are included in this grouping. Their principal function is to predict degradation trends; but, as part of the computational procedure, sediment yield values for the degrading reach are developed. Factors considered in their application include composition of the bed material and its coarsening with time, the magnitude of future flows and changes in flow characteristics such as channel shape, depths, velocity, and slope.

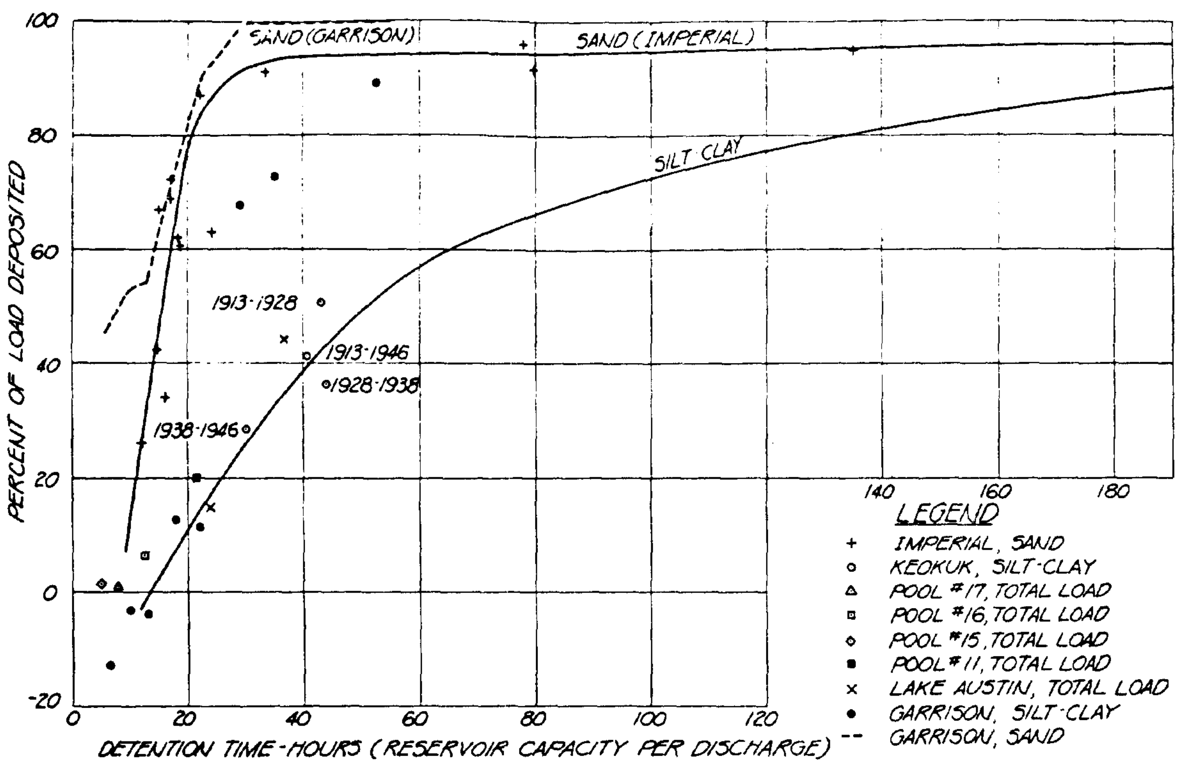


Figure C-10. Dardanelle Lock and Dam, Detention time versus percent of load deposited.

Section III. Future Needs

C-7. Planning and Design. During the past decade a shift in emphasis has taken place within the Corps regarding the need for sediment yield predictions. Until the mid 1950's, sediment was viewed primarily as a malignant growth that reduced the effectiveness of reservoirs, flood ways, navigation channels and harbors. This was also the period of "big dam" planning and construction, in which sediment depletion rates played a relatively minor role in design because of the voluminous storage allotted for multiple purpose use. The need for sediment yield predictions for large drainage areas has essentially vanished. As an indication, about 15 years ago the Corps was operating 135 sediment load stations of which 43 percent had drainage areas greater than 5000 square miles, 27 percent were in the 500 to 5000 range, and 30 percent were less than 500 square miles. At present the number of stations has doubled, with a shift to a percentage ratio of 25:37:38. Almost half of the active stations are operated for planning or design purposes. For example, during 1969, the Corps had under construction 23 reservoir projects for hydroelectric power and flood control, 64 for flood control and multipurpose use, and 84 local flood control protection projects. Now, emphasis seems to be focused on projects with sediment contributing drainages that generally vary within the 500- to 2500 square mile range. But if our prediction approach is to continue on an empirical basis, long term data records for drainage areas within this bracket are inadequate, particularly for reservoir survey data. It is estimated that there are some 28,000 reservoirs in the United States, yet we have sediment yield records on only 4 percent. But more significant is the fact that of the 1200 individual reservoirs listed in the 1965 summary of reservoir survey data, 80 percent of the documented record ranges below 50 square miles and 90 percent below 500 square miles. A scarcity of data exists for drainage areas between the small drainage basin projects typical of the Soil Conservation Service(SCS) and the traditional, large basin projects typical of the Corps of Engineers, US Bureau of Reclaimation(USBR), and Tennessee Valley Authority(TVA). Consequently, the basis for yield predictions by empirical methods will be weak for watershed sizes within this bracket until data records are obtained by measurements or by transposition using enhanced correlation techniques.

C-8. Dual Roles. Today, the dirty word "sediment" has dual connotations; it must now be recognized from both a beneficial and detrimental point of view. On one hand, sediments rank as a major cause of water pollution, but on the other hand, they play a dominating role in water quality control due to their assimilation capabilities. Apparently they also serve similar dual roles as catalytic or transporting agents in physical, chemical, or biological processes. With the current focus of Corps activities in areas of environmental control, urban development or expansion, and wastewater management, the recognition of such aspects is receiving prime attention in planning and design. But unanswered questions continue to outnumber even qualified answers. There is an unquestionable need increase knowledge of the role sedimentation plays in environmental processes before proceeding with detailed planning and design of projects.

C-9. Traditional methods need improvement. The immediate needs of the Corps of Engineers in expansion of sediment yield prediction methods will probably be focused along two major channels: definition of empirical relationships for drainage areas of moderate size, and establishment of the role sediments play in the complex environmental process. Computer methods for mathematical simulations and modeling will undoubtedly play a key role in the solution of some of these problems. Past experience however, has demonstrated that one or two standard methods or universal equations, regardless of their complexity, will not meet the diverse needs for engineering, planning, and design. Therefore, efforts to develop simple methods for resolving practical problems will continue.