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TRAP EFFICIENCY OF RESERVOIRS

Gunnar M. Brune

Abstract--Forty-four records of reservoir trap efficiency and the factors affecting trap efficiency are analyzed. The capacity-inflow (C/I) ratio is found to offer a much closer correlation with trap efficiency than the capacity-watershed (C/W) ratio heretofore widely used. It appears likely from the cases studied that accurate timing of venting or sluicing operations to intercept gravity underflows can treble or quadruple the amount of sediment discharged from a reservoir. Desilting basins, because of their shape and method of operation, may have trap efficiencies above 90 pct even with very low C/I ratios.

Semi-dry reservoirs with high C/I ratios, like John Martin Reservoir, may have trap efficiencies as low as 60 pct. Truly "dry" reservoirs, such as those in the Miami Conservancy District, probably have trap efficiencies in the 10 to 40 pct range, depending upon C/I ratio.

Introduction

The trap efficiency of a reservoir depends upon a number of factors. Among these are the ratio between storage capacity and inflow, age of the reservoir, shape of the reservoir basin, the type of outlets and method of operation, the grade-size characteristics of the sediment, and the behavior of the finer sediment fractions under various conditions. A number of attempts have been made to correlate trap efficiency with one or more of these factors.

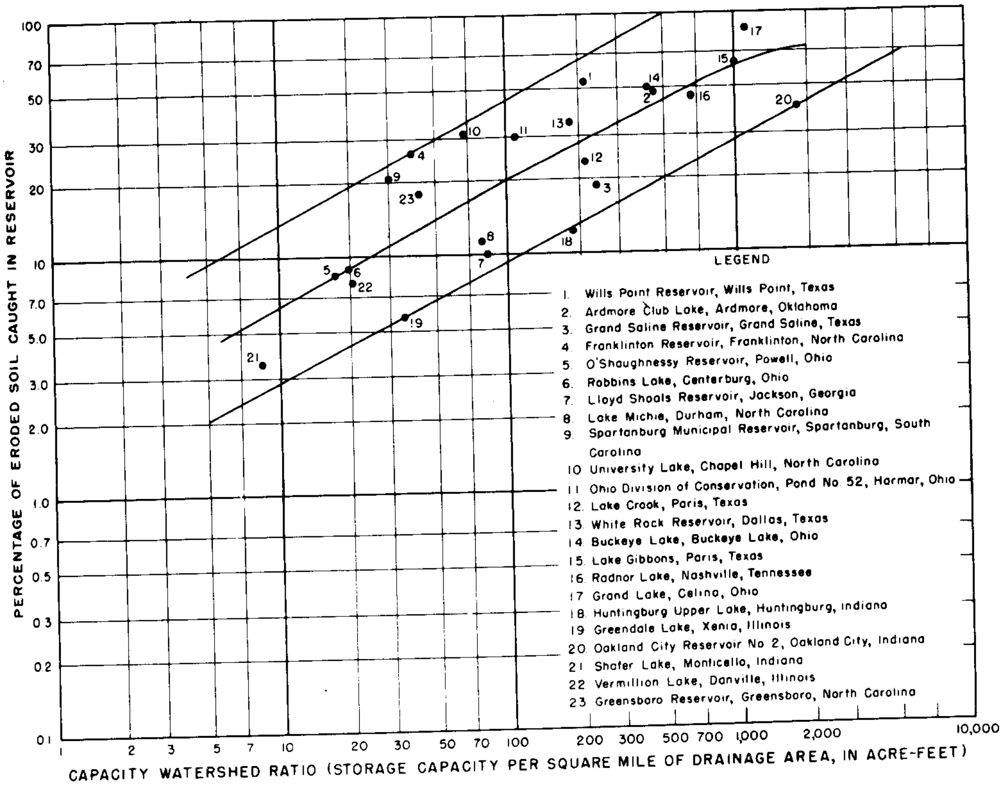


Fig. 1--Percentage of eroded soil caught in reservoir as related to capacity per square mile of drainage area

One of the earlier studies of trap efficiency was made by BRUNE and ALLEN [1941], who developed a curve relating percentage of eroded soil caught in the reservoir with capacity per square mile of drainage area. This curve is shown in Figure 1. The rate of soil erosion in each watershed was estimated by surveys and compared with the rate of reservoir sedimentation. The trap-efficiency values given in this curve, however, are necessarily low, because they are based upon rates of erosion rather than rates of sediment production to the reservoir. As GLYMPH [1951] has pointed out, the rate of sediment production is usually lower than the rate of erosion, and increasingly so the larger the drainage area because of the deposition of some of the eroded material on flood plains and in stream channels.

In the past, the ratio between storage capacity and inflow has been expressed in a general way by the capacity-watershed (C/W) ratio. BROWN [1943] first developed a curve relating C/W ratio and true trap efficiency. This curve, shown in Figure 2, with some additional records, is represented by

$$C_T = 100\,[1 - 1/(1 + 0.1\ C/W)] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where C_T = reservoir trap efficiency, per cent, and C/W = reservoir capacity, acre feet per square mile of drainage area. There is considerable spread in the points.

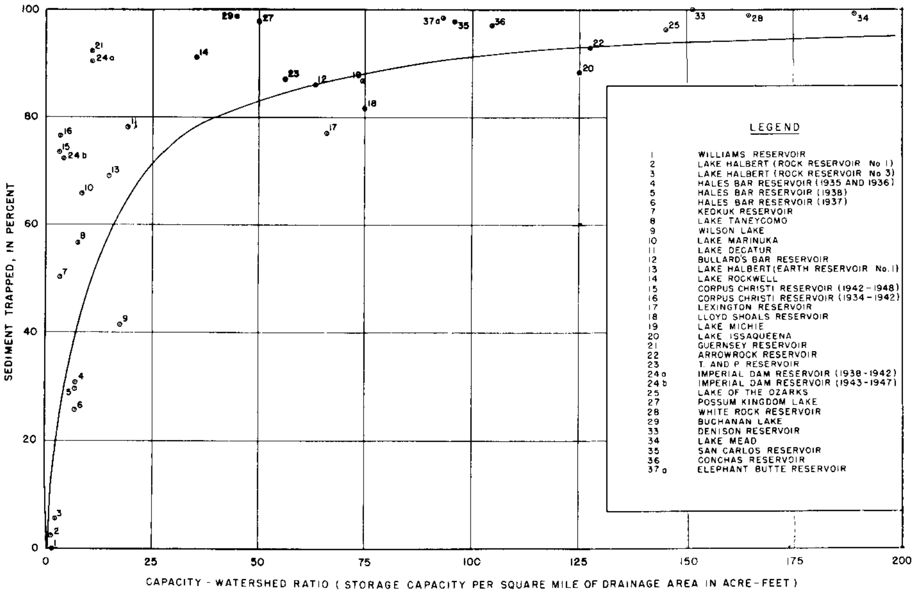
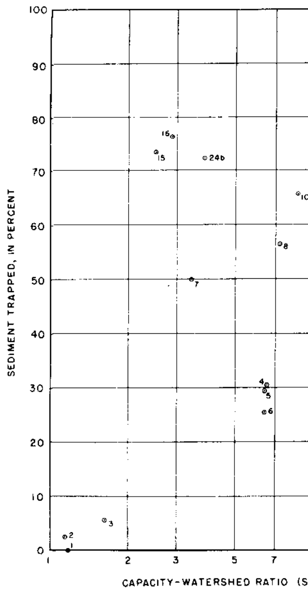


Fig. 2--Trap efficiency as related to capacity-watershed ratio

One difficulty with plotting this type of data on graph paper is that in the low C/W ratio range (under ten acre feet per square mile, the points are crowded, while in the high range (over 250) they cannot be plotted at all without greatly extending the abscissa. The points also follow a curved line, which approaches a trap efficiency of 100 pct asymptotically as the C/W ratio increases. In order to simplify plotting and to obtain a straighter line, the same data have been plotted on semi-log paper in Figure 3. The plotting of points is simplified, and the hyperbolic relationship results in a plot which is closer to a straight line on semi-log paper.

The main reason for the spread of points in this curve is that reservoirs having the same C/W ratio may have very different capacity-inflow ratios, as previously stated by GOTTSCHALK [1948].

A reservoir in an arid or semi-arid region may have a low capacity-watershed ratio yet not receive enough inflow in any one year to cause water to be discharged over the spillway. In contrast, the volume of mean annual flow from a watershed of equal size in a humid area may be equivalent to 25 times that of a reservoir having the same capacity-watershed ratio. In the drier region 100 pct of the incoming sediment load is trapped, whereas in the humid area possibly only 70 pct is trapped.



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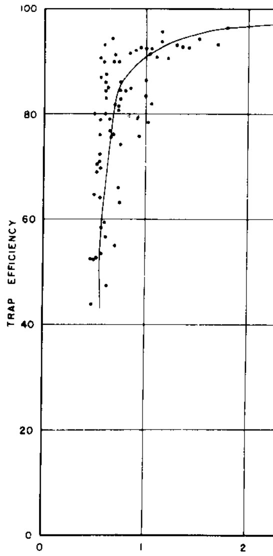

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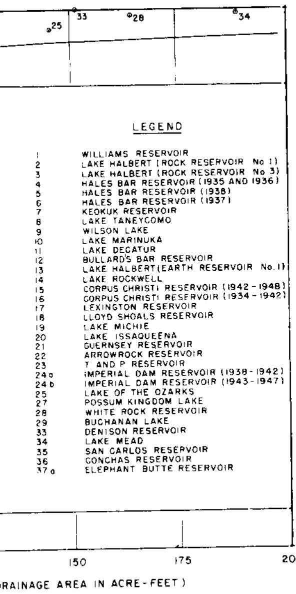

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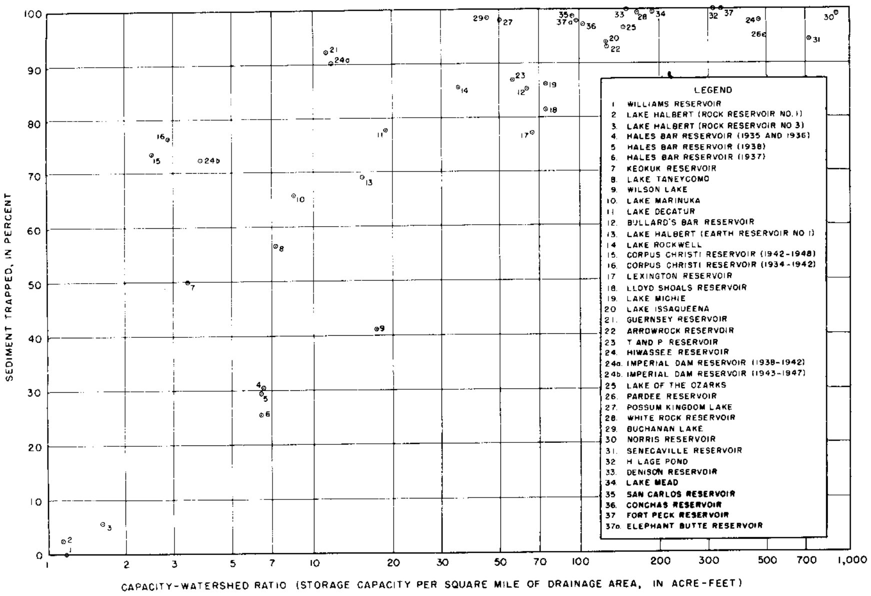

Fig. 3--Trap efficiency as related to capacity-watershed ratio

HAZEN [1914] first introduced the storage, or capacity-inflow, ratio in 1914. He used it for determining reservoir storage requirements, however, and not as an index of sediment trap efficiency.

For individual reservoirs, curves can be drawn correlating trap efficiency with detention time in days. BORLAND [1951] has prepared such a curve for Imperial Dam Reservoir (Fig. 4). Such curves are quite satisfactory for specific reservoirs, since other factors such as sediment characteristics, shape of the reservoir, and method of operation tend to remain constant.

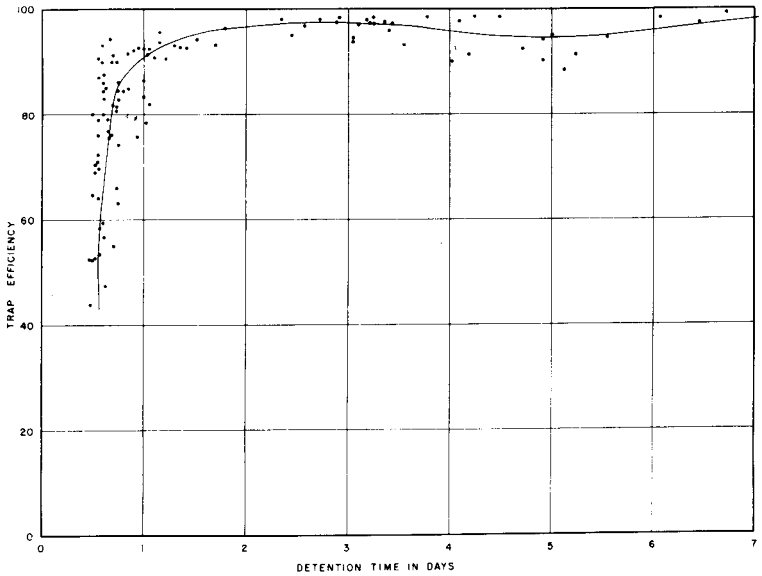

Fig. 4--Trap efficiency as related to detention time, Imperial Dam Reservoir, Yuma, Arizona

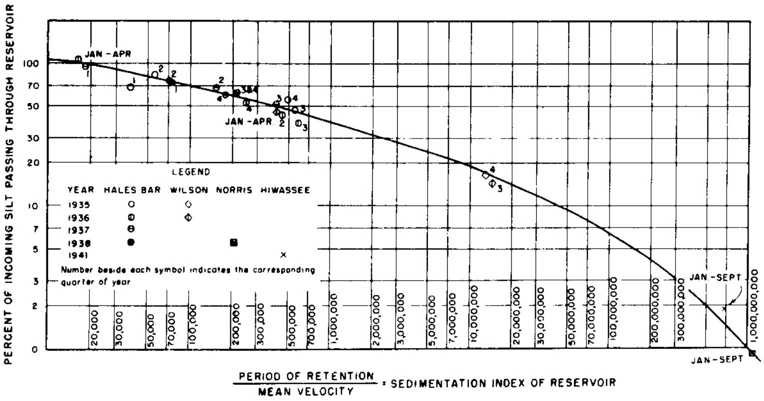

Fig. 5--Per cent of incoming silt passing through reservoir as related to sedimentation index, TVA reservoirs

CHURCHILL [1948] has taken into account both detention time and velocity of flow through the reservoir. He has developed a "sedimentation index" which represents the period of retention divided by mean velocity. His curve, relating trap efficiency to the sedimentation index for several TVA reservoirs, is shown in Figure 5. While this curve is very satisfactory where the data are available, such information as period of retention and mean velocity are not readily available for most reservoirs.

Methods used in the present study

For the present study a thorough search was made for all reliable records of reservoir trap efficiency, canvassing all of the agencies of the Federal Inter-Agency River Basin Committee known to be interested in this subject. Information was also gathered on capacity, annual inflow, shape of reservoir basin, type of outlets and method of operation, observed gravity underflows or "density" currents, and any other pertinent data.

Some 44 records were gathered, and are summarized in Table 1. Of these, 40 are for normal ponded reservoirs, with information on the effect of sluicing and venting operations on three. Two records are for desilting basins, and two for semi-dry reservoirs.

It is possible to study trap efficiency of reservoirs by a number of different methods, and it was necessary to use practically all of them in this study. The methods used are described briefly in the following paragraphs.

(1) Reservoir surveys with suspended-load measurements downstream--In this type of study the annual sediment accumulation in the reservoir is measured, and sediment passing over the dam or through outlets is sampled. The sum of the two yields the total sediment load of the stream. This method was used on most of the records, including Senecaville, Keokuk, Lake of the Ozarks, Taneycomo, Denison, Buchanan, Lexington, Lloyd Shoals, Williams, Issaqueena, Conchas, San Carlos, Mead, Imperial Dam, Possum Kingdom, Guernsey, Pardee, Bullard's Bar, and John Martin Reservoirs.

(2) Reservoir surveys with suspended-load measurements upstream--Suspended-sediment measurements upstream, corrected to include bed load, provide an index of the total rate of sediment production. The reservoir survey shows what proportion of this is trapped. This type of study was used for Corpus Christi Reservoir during the 1934-1942 period and for Hadley Creek Desilting Basin.

(3) Reservoir surveys with suspended-load measurements up and downstream--In these cases the method used is similar to that described under (1). The suspended-load measurements upstream from the reservoir provide an additional check on the total sediment load of the stream, and (when corrected to include bed load) should equal the sum of the sediment deposited in the reservoir and that measured as passing the dam. This method was used for Marinuka, Wilson, Norris, Hiwassee, T and P, Corpus Christi (1942-1948), Arrowrock, and Hales Bar Reservoirs.

(4) Suspended-load measurements up and downstream with no reservoir survey--Suspended-load measurements upstream from the reservoir provide a measure of the total sediment load. Suspended-load measurements downstream show what proportion of the sediment passes the dam, and the difference is what is trapped. This method was used for Fort Peck Reservoir.

(5) Reservoir surveys with turbidity measurements downstream--This method is similar to that described under (1), except that turbidity records are substituted for suspended load records.

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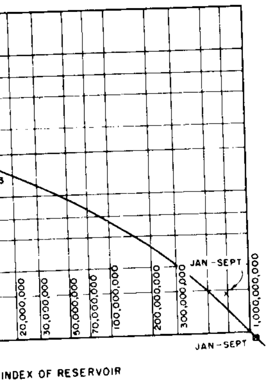

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For the fine sediment which is carried over a dam or through outlets in suspension, turbidity measurements are often of sufficient accuracy for use in determining sediment load. A number of simultaneous suspended-load and turbidity measurements are usually taken, in order to establish a correction factor for use with turbidity records. This type of study was made on Decatur, Rockwell, Michie, and White Rock Reservoirs.

(6) Reservoir survey and observation of outlet--In this type of measurement it is known by observation that no water or sediment has ever been discharged over the spillway or through outlets in the dam. The only water losses have been through evaporation and seepage. In such cases the sediment measured in the reservoir represents the total load of the stream, and the trap efficiency is 100 pct. This method of study was used on the H. Lage Pond, Iowa.

(7) Comparative reservoir surveys--This method is typified by the Lake Halbert reservoir system, Texas. Lake Halbert lies at the lower end of a drainage area in which are located 11 small reservoirs. Lake Halbert has a very high capacity-watershed ratio and capacity-inflow ratio, and undoubtedly has a trap efficiency close to 100 pct. In addition, some sediment is trapped in the upstream reservoirs. The system of reservoirs as a whole may therefore be assumed to trap virtually all of the sediment that reaches it. By comparing the annual rate of sediment accumulation per square mile for a particular reservoir with that for the whole system of reservoirs, and assuming that the rates of sediment production are uniform throughout the system, its trap efficiency may be determined.

It is necessary, in taking suspended-load measurements downstream from a dam, to take them as near the dam as possible, because streams tend to pick up a new sediment load quickly downstream from reservoirs by scouring and degrading their channels. For example, as BROWN [1950b] has pointed out, the average sediment concentration in the Colorado River below Hoover Dam as of 1947 increases from 0.006 pct 12.8 miles below the dam to 0.091 pct 98.6 miles below the dam, or 15 times. Such a change can cause grave errors in computations of trap efficiency if suspended-load measurements far downstream from the dam are used.

It is also necessary to take dredging into account in computing trap efficiency. Since areas dredged in a reservoir usually fill with sediment again in a short time, dredging tends to increase the amount of sediment trapped in a reservoir. In studying Lake Marinuka, Wisconsin, for example, amounts of sediment dredged from the lake were excluded from the computations of sediment trapped.

Note in Table 1 that reservoirs and ponds of all sizes have been used, ranging from a farm pond with 0.038 sq mi drainage to Imperial Dam Reservoir, draining 184,600 sq mi. The chief criteria in selecting reliable records were accuracy with which trap efficiency could be determined and the availability of information on the various factors which affect trap efficiency. As GOTTSCHALK [1948] has stated, the laws of sediment deposition are the same for all types of reservoirs, including stock ponds. Likewise, the trap efficiency of reservoirs is affected by the same factors, regardless of the size of the reservoir.

It has long been recognized [BROWN, 1950b] that capacity-inflow (C/I) ratio would be a more accurate index of trap efficiency than the capacity-watershed (C/W) ratio which has heretofore been so widely used. The C/W ratio must be used within definite hydrologic regions, and not as an index of comparison over the country as a whole, for, as is obvious, with the same C/W ratio the trap efficiency will increase as the runoff per unit area decreases.

The main objection in the past to the use of the capacity-inflow ratio has been that records of inflow are lacking for some existing reservoirs. In an effort to get around this difficulty, the annual runoff map shown in Circular 52 of the U. S. Geological Survey was used to estimate the runoff from the few reservoir watersheds where detailed inflow records are lacking. The capacity-inflow (C/I) ratio was then computed in terms of acre feet of storage capacity per acre foot of annual water inflow. C/I ratios are shown in Table 1 along with other pertinent data for the reservoirs used in this study.

Discussion of results

Normal Ponded Reservoirs--The records from Table 1 have been plotted in Figure 6. Note that the correlation for normal ponded reservoirs (conventional reservoirs as distinguished from desilting basins and dry reservoirs), operated without any special efforts at sluicing sediment, is much better using the C/I ratio than using the C/W ratio, as was done in Figure 3.

Records 32-37a represent reservoirs such as Fort Peck Reservoir and Lake Mead which have C/I ratios greater than 1.0. In other words, these reservoirs have a capacity larger than the annual

Table 1--Representative records of reservoir trap efficiency

Record	Reservoir	Stream	Location	Drainage area	Period of record	Average annual sediment prod. per sq mi of drainage area	C/W[a]
				sq mi	yr	ton	ac ft/ sq mi
	Normal ponded reservoirs						
1	Williams	E. Fork White R.	Williams, Ind.	4,700	9.3	434	1.19
2	Lake Halbert (Rock Res. 1)	Elm Creek	Corsicana, Tex.	5.37	69	8480	1.16
3	Lake Halbert (Rock Res. 3)	Elm Creek	Corsicana, Tex.	1.52	69	8480	1.63
4	Hales Bar (1935-1936)	Tennessee R.	Chattanooga, Tenn.	21,790	2.00	306	6.46
5	Hales Bar (1938)	Tennessee R.	Chattanooga, Tenn.	21,790	1.00	306	6.39
6	Hales Bar (1937)	Tennessee R.	Chattanooga, Tenn.	21,790	1.00	306	6.41
7	Keokuk	Mississippi R.	Keokuk, Iowa	119,000	23	219	3.43
8	Lake Taneycomo	White R.	Forsyth, Mo.	4,610	22.4	494	7.34
9	Wilson Lake	Tennessee R.	Florence, Ala.	30,750	2.25	242	17.3
10	Lake Marinuka	Beaver Creek	Galesville, Wis.	138.6	72	272	8.5
11	Lake Decatur	Sangamon R.	Decatur, Ill.	906	24.2	341	18.9
12	Bullard's Bar	No. Fk. Yuba R.	No. San Juan, Calif.	480	19.2	504	62.9
13	Lake Halbert (Earth Res. 1)	Elm Creek	Corsicana, Tex.	1.13	69	8480	15.1
14	Lake Rockwell	Cuyahoga R.	Kent, Ohio	205.5	36	117	34.5
15	Corpus Christi (1942-1948)	Nueces R.	Corpus Christi, Tex.	16,800	6.0	65.0	2.48
16	Corpus Christi (1934-1942)	Nueces R.	Corpus Christi, Tex.	16,800	7.6	65.0	2.92
17	Lexington	Leonard's Creek	Lexington, N. C.	6.83	4.7	851	66.1
18	Lloyd Shoals	Ocmulgee R.	Jackson, Ga.	1,414	24.3	653	74.6
19	Lake Michie	Flat River	Durham, N. C.	167.5	8.75	408	74.5
20	Lake Issaqueena	Six-Mile Creek	Clemson, S. C.	14.02	11.4	1569	125
21	Guernsey	North Platte R.	Guernsey, Wyo.	16,200	20	292	11.2
22	Arrowrock	Boise River	Boise, Idaho	2,170	32.64	475	127
23	T and P	Town Creek	Weatherford, Tex.	6.24	8.5	1217	55.9
24	Hiwassee	Hiwassee R.	Murphy, N. C.	968	0.75	503	453
24a	Imperial Dam (1938-1942)	Colorado R.	Yuma, Ariz.	184,600	5.0	2170	11.7
24b	Imperial Dam (1943-1947)	Colorado R.	Yuma, Ariz.	184,600	5.0	2170	3.81
25	Lake of the Ozarks	Osage R.	Bagnell, Mo.	14,000	17	580	145
26	Pardee	Mokelumne R.	Buena Vista, Calif.	430	14	217	488
27	Possum Kingdom	Brazos R.	Palo Pinto, Tex.	14,098	7.75	650	49.9
28	White Rock	White Rock Creek	Dallas, Tex.	99.1	25	2104	74.6
29	Buchanan Lake	Colorado R.	Burnet, Tex.	21,000	7.1	216	44.7
30	Norris	Clinch R.	Norris, Tenn.	2,912	0.75	422	918
31	Senecaville	Wills Creek	Senecaville, Ohio	121	5.1	1026	727
32	H. Lage Pond	Small Branch	Aspinwall, Iowa	0.038	11.0	6270	318
33	Denison	Red River	Denison, Tex.	38,291	6.2	723	151
34	Lake Mead	Colorado R.	Boulder City, Nev.	167,800	13.25	1044	189
35	San Carlos	Gila River	Globe, Ariz.	12,900	18.19	601	96.0
36	Conchas	So. Canadian R.	Tucumcari, N. M.	7,350	10.3	512	104
37	Fort Peck	Missouri River	Fort Peck, Mont.	57,725	12	120	337
37a	Elephant Butte	Rio Grande	Hot Springs, N. M.	25,923	32.33	854	93.2
	Desilting basins						
38	All-American Canal	Colorado R.	Yuma, Ariz.	184,600	10.0	406	0.061
39	Hadley Creek, New	Hadley Creek	Kinderhook, Ill.	77	5.01	2490	36.7
	Semi-dry reservoirs						
40	John Martin	Arkansas R.	La Junta, Colo.	18,933	5.4	450	36.3
41	Senecaville (1936-1939)	Wills Creek	Senecaville, Ohio	121	3.2	1026	731

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[a] C/W is capacity-watershed ratio in acre feet per square mile. [b] Capacity-inflow ratio in acre feet of capacity per acre foot of annual

[c] Figures in brackets refer to trap efficiency with sluicing or venting operations in effect.

Table 1--Representative records of reservoir trap efficiency

Location	Drainage area	Period of record	Average annual sediment prod. per sq mi of drainage area	C/W^{a}	Average annual inflow	C/I^{b}	Trap efficiency^{c}	Reference
	sq mi	yr	ton	ac ft/ sq mi	ac ft/ sq mi		pct	
Williams, Ind.	4,700	9.3	434	1.19	747	0.0016	0	
Corsicana, Tex.	5.37	69	8480	1.16	399	0.0029	2.3	(20)(4)
Corsicana, Tex.	1.52	69	8480	1.63	399	0.0041	5.8	(20)(4)
Chattanooga, Tenn.	21,790	2.00	306	6.46	1260	0.0051	30.5	(18)(14)
Chattanooga, Tenn.	21,790	1.00	306	6.39	1260	0.0051	29.7	(18)(14)
Chattanooga, Tenn.	21,790	1.00	306	6.41	1260	0.0051	25.7	(18)(14)
Keokuk, Iowa	119,000	23	219	3.43	370	0.0093	50.0	(10)(12)(5)
Forsyth, Mo.	4,610	22.4	494	7.34	783	0.0094	56.3	(22)
Florence, Ala.	30,750	2.25	242	17.3	1190	0.0145	44.9	(18)(4)(14)
Galesville, Wis.	138.6	72	272	8.5	549	0.0155	65.4	(10)(11)
Decatur, Ill.	906	24.2	341	18.9	560	0.0338	78.0	(8)(10)(6)(5)(11)
No. San Juan, Calif.	480	19.2	504	62.9	1660	0.0378	83.4	(9)
Corsicana, Tex.	1.13	69	8480	15.1	399	0.0378	69.3	(20)(4)
Kent, Ohio	205.5	36	117	34.5	698	0.0494	85.8	(11)
Corpus Christi, Tex.	16,800	6.0	65.0	2.48	45.8	0.0541	73.7	(7)
Corpus Christi, Tex.	16,800	7.6	65.0	2.92	45.8	0.0638	76.7	(7)
Lexington, N. C.	6.83	4.7	851	66.1	907	0.0730	77.2	(4)
Jackson, Ga.	1,414	24.3	653	74.6	923	0.0807	81.4	(26)(2)(13)
Durham, N. C.	167.5	8.75	408	74.5	747	0.0998	86.3	(25)(2)(13)
Clemson, S. C.	14.02	11.4	1569	125	987	0.127	94.2 [84.1]^{c}	(40)(27)(4)
Guernsey, Wyo.	16,200	20	292	11.2	74.2	0.151	92.2	(29)(23)
Boise, Idaho	2,170	32.64	475	127	742	0.171	93.0 [90.3]^{c}	(28)
Weatherford, Tex.	6.24	8.5	1217	55.9	293	0.191	87.0	
Murphy, N. C.	968	0.75	503	453	1660	0.273	98.1	(18)(14)
Yuma, Ariz.	184,600	5.0	2170	11.7	55.5	0.211	90.2	(4)(23)(1)
Yuma, Ariz.	184,600	5.0	2170	3.81	55.5	0.0686	72.3	(4)(23)(1)
Bagnell, Mo.	14,000	17	580	145	498	0.292	96.7	(33)
Buena Vista, Calif.	430	14	217	488	1560	0.313	95.0	(9)
Palo Pinto, Tex.	14,098	7.75	650	49.9	63.4	0.787	98.0	(21)
Dallas, Tex.	99.1	25	2104	74.6	202	0.812	99.3	(24)(2)(13)
Burnet, Tex.	21,000	7.1	216	44.7	53.3	0.837	98.6	(4)
Norris, Tenn.	2,912	0.75	422	918	970	0.946	99.1	(18)(4)(14)
Senecaville, Ohio	121	5.1	1026	727	768	0.947	94.3	(37)(10)(6)(5)(11)
Aspinwall, Iowa	0.038	11.0	6270	318	261	1.22	100.0	(17)
Denison, Tex.	38,291	6.2	723	151	108	1.40	100.0	(34)(5)
Boulder City, Nev.	167,800	13.25	1044	189	77.3	2.44	99.4	(39)(2)(4)(6)(5)(23)
Globe, Ariz.	12,900	18.19	601	96.0	26.7	3.59	98.0	(31)(2)(4)(23)(6)
Tucumcari, N. M.	7,350	10.3	512	104	27.2	3.82	97.3 [95.8]^{c}	(32)(36)(23)
Fort Peck, Mont.	57,725	12	120	337	72.5	4.65	100.0	(38)(35)(12)
Hot Springs, N. M.	25,923	32.33	854	93.2	45.4	2.05	98.6	(30)(23)(2)(4)
Yuma, Ariz.	184,600	10.0	406	0.061	55.5	0.0011	91.7	(4)(6)
Kinderhook, Ill.	77	5.01	2490	36.7	432	0.0850	98.8	(11)
La Junta, Colo.	18,933	5.4	450	36.3	21.3	1.71	62.2	(4)
Senecaville, Ohio	121	3.2	1026	731	768	0.953	48.4	(37)(10)(6)(5)(11)

are mile. ^{b}Capacity-inflow ratio in acre feet of capacity per acre foot of annual inflow.
ing or venting operations in effect.

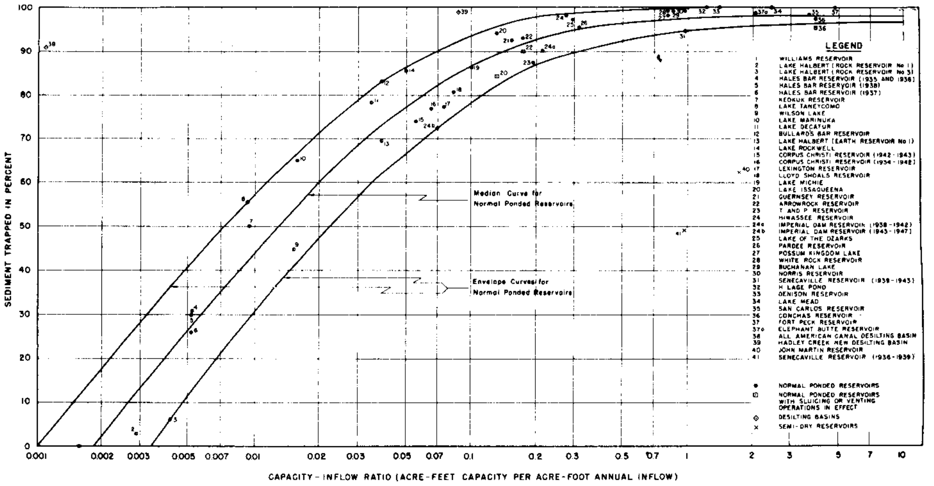

Fig. 6--Trap efficiency as related to capacity-inflow ratio, type of reservoir, and method of operation

runoff from their watersheds. When the effects of evaporation and seepage are also considered, it is obvious that water will rarely be spilled over the dams of such reservoirs, and that their trap efficiency must therefore be close to 100 pct.

The C/I ratio thus provides a means of differentiating between the "holdover storage reservoirs" and "seasonal storage reservoirs" described by **MADDOCK** [1948]. Reservoirs with a C/I ratio of 1.0 or less may be classed as seasonal storage reservoirs, and those with a ratio greater than 1.0 as hold-over storage reservoirs.

The C/I ratio is a combination of the C/W ratio and annual inflow. The C/I ratio, in acre feet of capacity per acre foot of annual inflow, may be obtained by dividing the C/W ratio, in acre feet per square mile of drainage area, by the annual inflow, also in acre feet per square mile of drainage area.

Reservoirs may have very different C/W ratios and annual inflows, yet have the same C/I ratio, and the same trap efficiency, other factors being equal. For instance, a reservoir in the more humid part of the country may have a C/W ratio of 100, an annual inflow of 1000 acre feet per square mile, and a C/I ratio of 0.1. Another reservoir in a more arid region may have a C/W ratio of 10, an annual inflow of 100 acre feet per square mile, and the same C/I ratio, 0.1. Both reservoirs, assuming they are of the normal ponded type, will have roughly the same trap efficiency (around 87 pct, from Figure 6).

Theoretically, no reservoir can have a trap efficiency of zero per cent until its capacity is reduced to zero or the runoff approaches an infinite quantity. Similarly, a trap efficiency of 100 pct is theoretically impossible until the capacity reaches an infinite quantity or the runoff reaches zero. Actually, an inspection of Table 1 and Figure 6 shows that there are several instances on record of trap efficiencies of zero and 100 pct.

For example, Williams Reservoir, a power reservoir near Williams, Indiana, was built in 1911. In 1930 cross sections were established by the Corps of Engineers, and in 1939 these cross sections were re-run by the Soil Conservation Service. This reservoir, which has a very low C/W ratio (1.19) and C/I ratio (0.0016), probably trapped some sediment between 1911 and 1930. During the period of measurement, however, from 1930 to 1939, there was a net scour of 275 acre feet, or an increase in capacity of 5.0 pct. Thus the trap efficiency was less than zero for this period. It appears probable that reservoirs of very low C/I ratio may alternately fill and scour, depending upon stream-flow conditions, and may thus have a trap efficiency of zero or less during periods of scour.

The three instances of measured trap efficiency of 100 pct are at the H. Lage Pond, Fort Peck Reservoir, and Denison Reservoir. The Lage Pond, as previously mentioned, has never spilled over, and the only water losses which have occurred have been through evaporation and seepage.

In regard to Fort Peck Reservoir,
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> Water sediment samples are c
> discharge channel and analyses of
> discharged from the reservoir is c
> efficiency of the Fort Peck Reserv

Similarly, a letter dated May 9, 19
Tulsa, Oklahoma, states:

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Since this date, however, at least
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Hence, it is obvious that if inflow
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<u>Sluicing and venting</u>--In Table 1 a
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The fact that sluicing was carried on o
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At Conchas Reservoir, New Mexic
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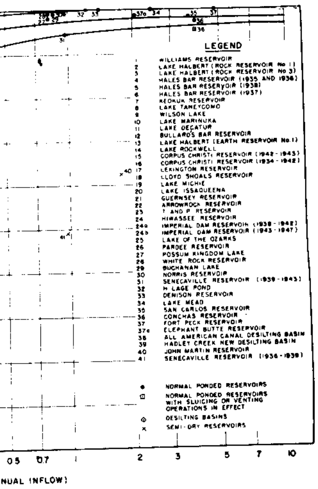

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In regard to Fort Peck Reservoir, a letter dated May 3, 1951, from the Fort Peck District Office, Corps of Engineers, Fort Peck, Montana, states as follows:

> Water sediment samples are obtained periodically at the tunnel outlets and the spillway discharge channel and analyses of these samples have disclosed that the amount of sediment discharged from the reservoir is quantitatively negligible. On this basis, therefore, the trap efficiency of the Fort Peck Reservoir may be considered to be approximately 100 pct.

Similarly, a letter dated May 9, 1951, from the Tulsa District Office, Corps of Engineers, Tulsa, Oklahoma, states:

> There has been no significant sediment outflow from Denison Reservoir since the normal pool was filled in 1945, so its trap efficiency to date is virtually 100 pct. No density currents have been observed to pass entirely through the reservoir up to the present time.

Since this date, however, at least one density current has been observed to pass completely through the reservoir and reach the outlets of Denison Dam.

Hence, it is obvious that if inflow is not sufficient to counteract water losses by evaporation and seepage, there will be no water or sediment losses over the spillway or through outlets, and the trap efficiency will be actually 100 pct. Similarly, if water inflow is so low that water releases can be made only rarely, the velocity of the water through the reservoir will be very low. Practically all of the sediment load will settle out, and what little water is released will be essentially clear. In such cases the trap efficiency may be considered virtually 100 pct.

Sluicing and venting--In Table 1 and Figure 6 are also shown the effects of various attempts to sluice or vent additional amounts of sediment from reservoirs. At Arrowrock Reservoir, Idaho, sluicing out sediment deposits through the bottom outlets or sluice gates during periods of relatively low discharge is estimated to have reduced the trap efficiency from 93.0 to 90.3 pct, and to have increased the sediment loss from the reservoir by 39 pct [SEAVY, 1948a]. The average discharge below Arrowrock Dam for 33 years has been 2230 cu ft/sec, as compared with an average discharge of only 605 cu ft/sec on the 270 days during which sluicing operations were conducted. The fact that sluicing was carried on only during periods of low stream discharge and low sediment concentrations is probably the major reason for its low effectiveness in removing sediment from the reservoir. Future sluicing operations are not contemplated because of possible downstream damage to fish and to the proposed Lucky Peak Dam.

At Conchas Reservoir, New Mexico, sluicing has been carried on whenever sufficient water has been available, from 1942 to 1948. Ordinarily, sluicing has been done during periods of low discharge. No large floods occurred during this period, but it was noted that on several occasions when the conduits were open during smaller floods, "the sediment content of the discharge continued to remain at a much higher value than usual for as much as several days, indicating that some of the sediment was possibly furnished from a density flow through the reservoir" [U. S. CORPS OF ENGINEERS, 1950a].

Sluicing operations have decreased the trap efficiency of Conchas Reservoir from an estimated 97.3 to 95.8 pct, and have increased the sediment loss from the reservoir by 56 pct. The relatively low effectiveness is probably due largely to the fact that no effort has been made to time sluicing operations to intercept gravity underflows and thus pass heavily sediment-laden water out of the reservoir. That sluicing has been more effective than at Arrowrock Reservoir is a reflection of the fact some gravity underflows were accidentally encountered. The Conchas Reservoir study indicates that flushing to remove sediment that has already settled is ineffective except immediately upstream from the sluice intakes. Sluicing operations are expected to be discontinued when water can no longer be spared from irrigation projects.

At Lake Issaqueena, Clemson, S. C., venting of sediment-laden water through a gate near the base of the dam was carried on from August, 1940, to April, 1942 [ZWERNER, and Others, 1942]. Just after the flood of August, 1940, the suspended matter concentration in flow coming from the outlet pipe was 552 ppm, while that passing over the spillway was 183 ppm. Gravity underflows were intercepted and passed through the dam during nine periods of storm runoff.

The trap efficiency of the lake was lowered from 94.2 to 84.1 pct by these venting operations. The sediment loss from the lake was increased by 174 pct. As stated by BROWN [1944], it seems clear from the observations that if the gates had been opened according to a pre-arranged plan governed by forecasting flood flows in the drainage area, at least ten per cent of the incoming sediment, and possibly as much as 25 pct, could have been vented through the two outlets, without adversely affecting water storage in the lake.

It appears, therefore, that sluicing or venting operations have much better chances of accomplishing their purpose when they are timed to intercept gravity underflows as they reach the dam. If gravity underflows are not present, such operations should at least be timed to meet the higher sediment concentrations brought in by flood flows. It is likely that accurate timing to intercept gravity underflows can treble or quadruple the amount of sediment lost from the reservoir.

Desilting basins--The trap efficiency of desilting basins is governed largely by their shape. Hadley Creek New Desilting Basin, Illinois, for example (Table 1 and Fig. 6) covers 280 acres but has an average effective depth of less than four feet. A normal ponded reservoir with the same C/I ratio would have a trap efficiency of about 85 pct. This basin, however, traps 98.8 pct of the sediment reaching it, largely because of its shallowness and the small interval of time required for the sediment to reach the bottom. There are other factors, such as the coarse nature of the incoming sediment and the location of the desilting basin at a point where the stream gradient decreases abruptly.

An even more efficient type of desilting basin is exemplified by the All-American Canal Desilting Basins, Arizona (Table 1 and Fig. 6). In this case, method of operation, in addition to the other factors mentioned, greatly influences the trap efficiency. These basins are equipped with rotary scrapers which deposit the sediment in collecting trenches [BROWN, 1944]. Thence it is forced into a system of sludge-disposal piping and carried back to the river below. A normal ponded reservoir with a C/I ratio as low as these basins could be expected to have practically no trap efficiency at all, and yet the basins trap 91.7 pct of the sediment reaching them.

Thus, desilting basins may be expected to have trap efficiencies above 90 pct in a much lower range of C/I ratios than for normal ponded reservoirs (Fig. 6). Without mechanical removal of sediment, such high trap efficiencies may extend downward to a C/I ratio of around 0.02. With mechanical removal, they may extend much lower, even to 0.001.

Dry reservoirs--Although no information is available on the trap efficiency of truly dry reservoirs such as those in the Miami Conservancy District, Ohio, two reservoirs which have been operated in a semi-dry condition provide some suggestive figures (Table 1 and Fig. 6).

Senecaville Reservoir, Ohio, for example, a flood-control reservoir, was completed in October 1936 [U. S. ENGINEER OFFICE, 1945] but not put into operation until early in 1940. A small lake was established by the structure with the gates wide open. A sedimentation survey was made in December 1939 and another in March 1945. The first survey showed a much lower rate of sediment accumulation than the second, although the annual runoff was higher during the first period, and the rate of sediment production from the watershed is assumed to have been approximately the same for both periods (Table 1). These surveys, supplemented by suspended-load measurements at the dam from January, 1939, to January, 1942, indicate that the trap efficiency was much lower during the first period (48.4 pct) than during the second period (94.3 pct). An examination of the history of the reservoir suggests the cause. Although the reservoir has a total capacity of 88,500 acre feet, it was held near 3700 acre feet prior to December, 1939, because much of the land in the basin had not yet been purchased. As a result, most flows were passed unrestricted through the reservoir, and much sediment was also carried through. After 1939, the conservation pool was raised to 43,500 acre feet, with much greater volumes of water being held during flood periods. Hence the trap efficiency increased markedly.

John Martin Reservoir, Colorado, is another example of a reservoir which has been operated in a semi-dry condition. This flood control and irrigation reservoir was completed in 1943, with a total capacity of 701,200 acre feet. Since that time it has frequently been dry, and has never during the period of this study (1943-1948) stored more than 244,700 acre feet of water. Much water and sediment has consequently been passed through the dam with little restriction, and the trap efficiency is unusually low, 62.2 pct, for a reservoir with such a high C/I ratio (1.71).

Thus it is apparent that even hold-over storage reservoirs like John Martin, if operated so as to allow large flows of water to pass through the dam, may have trap efficiencies in the 60 pct range rather than above 90 pct as would be expected with normal operation. Reservoirs with lower C/I ratios, operated in a similar manner, may be expected to have still lower trap efficiencies. Truly dry reservoirs, such as the Miami Conservancy District reservoirs, undoubtedly have much lower trap efficiencies, probably in the ten to 40 pct range, depending chiefly upon C/I ratio.

Although the relationship shown in Figure 6 between trap efficiency and C/I ratio appears to be reasonably good for normal ponded reservoirs without sluicing operations in effect, it is apparent that a great deal of additional work is required in the field of reservoir trap efficiency.

Particularly, field studies are needed o
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Particularly, field studies are needed on dry reservoirs and on the various types of desilting basins. Further field and laboratory studies are also needed of the feasibility of venting gravity underflows and high sediment concentrations from various types of reservoirs.

Conclusions

The more important conclusions reached in this study are as follows:

(1) The capacity-inflow (C/I) ratio offers a much closer correlation with reservoir trap efficiency than the capacity-watershed (C/W) ratio heretofore widely used, because it affords a measure of not only the relative capacity, but also the runoff from the watershed.

(2) The C/I ratio also provides an index to the type of reservoir; that is, reservoirs with C/I ratios of 1.0 or less may be classed as seasonal storage reservoirs, and those with a ratio greater than 1.0 as hold-over storage reservoirs.

(3) Although theoretically no reservoir can have a trap efficiency of zero or 100 pct, under actual field conditions true trap efficiencies of zero or 100 pct are sometimes found.

(4) Efforts at sluicing or venting sediment from reservoirs vary in effectiveness. At Arrowrock Reservoir, where the sluicing was done entirely during low discharge periods, the sediment loss from the reservoir was increased by 39 pct. At Lake Issaqueena, where venting was partially timed with gravity underflows through the lake, the sediment loss was increased by 174 pct. It appears likely that accurate timing of venting operations to intercept gravity underflows can treble or quadruple the amount of sediment lost from a reservoir.

(5) Desilting basins, largely because of their shape, have much higher trap efficiencies than normal ponded reservoirs. For desilting basins not equipped for mechanical removal of sediment, trap efficiencies above 90 pct appear to prevail with C/I ratios as low as 0.02. With mechanical removal of sediment, such high trap efficiencies may be found in even lower C/I ratio ranges, as low as 0.001.

(6) Semi-dry reservoirs may be expected to have much lower trap efficiencies than normal ponded reservoirs. Even hold-over storage reservoirs like John Martin, if operated so as to allow large flows of water to pass unrestricted through the dam, may have trap efficiencies in the 60 pct range rather than above 90 pct, as would be expected with normal operation. Truly dry reservoirs, such as those in the Miami Conservancy District, probably have trap efficiencies in the ten to 40 pct range, depending upon C/I ratio.

(7) Further field and laboratory studies are needed, particularly on the trap efficiency of desilting basins and dry reservoirs and on the feasibility of venting gravity underflows from various types of reservoirs.

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INDICATORS OF EROSI

Abstract--A need is recogniz
occurrence of erosion on watersh
celerated erosion, some factors t
ing erosion. The paper then desc
observation in disturbed and undi
or not erosion has been accelerat

In the course of forest influences
to determine the effect of watershed d
velopment of a set of erosion indicato
low the consistent and definite apprais
phases: (1) recognition of active eros
damage done by it. This paper is con
of its cause and the appraisal of its da
described in this paper were develope
equally well in areas disturbed by othe

When active erosion is recognize
tion, or is it the result of some waters
sion, the chances are that it can be re
accelerated erosion, it can probably b
is taken soon enough. The two proces
man's ability and need to control them
SHARPE [1938], and recently discusse

Geologic erosion is generally rec
the action of water, wind, and gravity,
MILLER [1928] as: ". . .the breaking u
Earth's surface by weathering and sol
moving ice, or winds which use rock f

Geologic erosion proceeds so slo
that residual soil exists on sloping lan
erosion is even slower than the extre
tions, normal geologic erosion rates n
sidence of the land. Except for the lo
heavals, however, such changes take p
teration may occur over hundreds or t

Accelerated erosion, on the other
before our very eyes. It is defined by
'man-induced' erosion . . ." The acti
celeration in the rate of erosion that n
conditions. Accelerated erosion is of
fertility, causes rapid sedimentation o
done by floods. By poor practices in c
otherwise disturbing the land surface,

Destruction of the vegetal canopy
the agents of erosion. In bare areas,
diminished velocity, and gravity can c
damaged to a great extent by such dist
to help stabilize the soil mass. But er
also needed to prevent soil loss. The
considering the effect of raindrops fal