Rates of Regional Denudation in the United States

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Abstract. Data, in large part collected since World War II, allow a recalculation of the rates of regional erosion in the United States. These data indicate a rate of denudation for the United States as a whole of 2.4 in./1000 years, or about twice that of older estimates. The most rapid rate, 6.5 in./1000 years, is recorded from the Colorado drainage. The slowest rate, 1.5 in./1000 years, is found in the Columbia basin. Other drainage areas and their rates are the Pacific slopes, California, 3.6 in./1000 years; the western Gulf of Mexico, 2.1 in./1000 years; the Mississippi River watershed, 2.0 in./1000 years; the South Atlantic and the eastern Gulf of Mexico, 1.6 in./1000 years, and the North Atlantic, 1.9 in./1000 years.

INTRODUCTION

The leveling of the continents by weathering ıd erosion has long been recognized as an in-gral part of a complex cycle of crustal change. ecause we can observe and measure this proc-s, we can hope to establish the rate at which ıe continents are destroyed. By extrapolation ıis rate can be applied to past or future time. e base such an extrapolation on the assump-ons that (1) the present rate of erosion is cor-ectly determined and (2) the present rate re-ects with fair accuracy past and future rates erosion.

Dole and Stabler [1909] estimated regional osion rates in the United States. Others have nce studied the rate of erosion in the United tates, particularly *Fisk et al.* [1954], *Gilluly* 1955], *Menard* [1961], *Corbel* [1959], and *chumm* [1963]. In the most recent paper, *chumm* [1963] adopts data from *Langbein ıd Schumm* [1958] to document the rates of osion in the United States within drainage ısins averaging 1500 mi² in area. The compila-on by Dole and Stabler, however, remains the ost comprehensive statement of present-day gional erosion rates in the United States.

Few data were available to Dole and Stabler, ıd estimates for many drainage basins were ısed on records that were continuous for only year. Records now available show that the ınual sediment load does in fact vary by as much as a factor of 5 in successive years.[2] Dole and Stabler recognized the danger of the extrapolation of the data and pointed out (p. 82) that 'denudation estimates based on average suspended matter for one year may be in error by as much as 50 per cent.'

In the present paper we evaluate the rates of regional denudation in the United States using more adequate data than those available to Dole and Stabler, and none of their data was used for our estimates.

THE DATA

Dole and Stabler stated clearly the complexity of estimating erosion in volumetric terms on the basis of weight measurements of particles carried in streams. However, assuming that the specific gravity of transported material is similar to that of the outer crust, they concluded that 165 pounds of eroded material is equal to the removal of 1 ft^3 of surface rock. The corresponding specific gravity is 2.64.

We have calculated rates of denudation on the same basis. Accordingly, denudation in inches per thousand years (D) is equal to a constant times the weight of the annual sediment pro-

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[2] For example, the 8-year record of the Delaware River at Trenton, N. J., shows that the maximum annual suspended load of 2,320,000 tons was recorded for the 12-month period of October 1954 through September 1955. The minimum annual suspended load at the Trenton station was 431,000 tons, recorded during the preceding 12-month period.

duction per unit area of the drainage basin. This can be stated by the equation

$$D = 5.2 \times 10^{-3} \text{ (tons/mi}^2 \text{ year)}$$

a minor rearrangement of the equation presented by Dole and Stabler. An alternative basis for the calculation is contained in the table prepared by Dole and Stabler (p. 81). This table allows rapid determination of erosion rates for materials of different densities.

Denudational rates are presented regionally according to subdivisions similar to those of *Dole and Stabler* [1909], *Durum et al.* [1960], and *Livingstone* [1963]. They are shown in Figure 1. The rate of denudation for each contains a factor for suspended load, for dissolved load, and for bed load, as discussed below.

Suspended load. The suspended load is the largest fraction of the load moved by the river. Inaccuracies in computation of the suspended load therefore lead to proportionally greater errors in the rate of denudation than inaccuracies in the traction or dissolved loads do. All rates reported here, except that for the Columbia River, are based on suspended sediment records that span at least three consecutive years, and usually more. Continuous records for only a little more than a year are available for the Columbia River (Table 1).

Some 300 stations record suspended sediment loads in the United States. We have used those listed in Table 1. These represent approximately 60% of the area of continental United States, exclusive of Alaska. In each region the rate of denudation represented by the suspended load is extrapolated to the entire region from the rate found for the portion sampled.

We have used the records for the farthest downstream station in the computations. Thus in the Mississippi drainage the single station at Baton Rouge forms the basis for the estimate of the rate of denudation for the entire drainage basin. We have, however, examined the records of many upstream stations and compared them with the downstream station which includes them. We find that the summing of the parts of the drainage basin represented by the upstream stations gives a rate of sediment production that is in good agreement with that of the farthest downstream station.

Dissolved load. The suspended sediment load constitutes the major part of the total load and is therefore the dominant factor in the present study. Nevertheless, the dissolved load is significant, and under certain conditions of climate and rock type, solution may become the most important process of erosion, as is illustrated in the South Atlantic–eastern Gulf of Mexico region and perhaps in the Columbia basin. Consequently, we offer estimates for the dissolved load in each of the major drainage basins.

Three studies [*Dole and Stabler*, 1909; *Durum et al.*, 1960; *Livingstone*, 1963] give estimates of chemical denudation in all the drainage

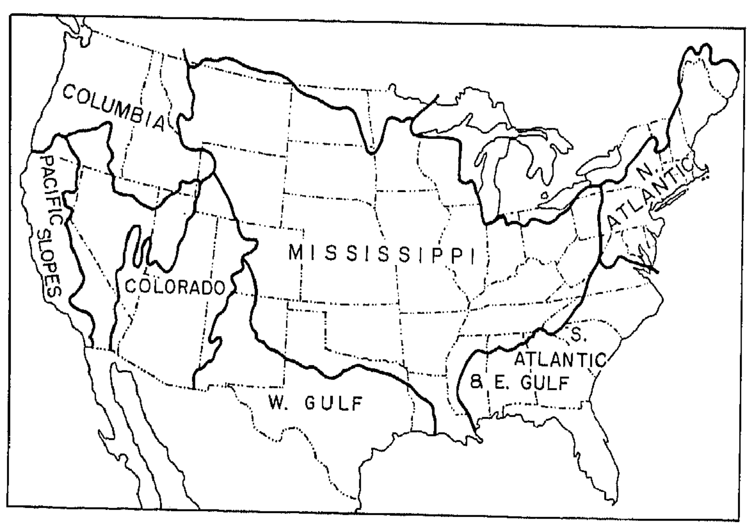

Fig. 1. Index to regions referred to in text.

TABLE 1. Suspended Sediment Loads by Individual Stream Basins

Region and River	Location	Drainage Area, mi²	Average Annual Suspended Load, tons × 10³	Period of Time for Records	T/mi² yr	Erosion Rate, in./1000 yr	Source
N. Atlantic							
Delaware	Trenton, N. J.	6780	998	10/49–9/57	147	0.8	*
Schuylkill	Philadelphia, Pa.	1893	993	11/47–9/57	524	2.7	*
Juniata	Newport, Pa.	3354	345	1/51–9/57	103	0.5	*
Scantic	Broad Brook, Conn.	98	7.26	11/52–9/57	74	0.4	*
S. Fork Shenandoah	Front Royal, Va.	1638	171	4/52–9/56	104	0.5	*
Rappahannock	Remington, Va.	616	76.8	4/50–9/57	125	0.7	*
Rapidan	Culpepper, Va.	465	74.2	4/50–9/56	160	0.8	*
S. Atlantic and eastern Gulf							
Roanoke	Altavista, Va.	1802	437	10/52–9/56	242	1.3	*
Yadkin	Yadkin College, N. C.	2280	808	1/51–9/57	354	1.8	*
Tombigbee	Jackson, Ala.	≈19,000	2,290	10/52–9/60	120	0.6	†
Alabama	Claiborne, Ala.	≈22,000	2,130	10/52–9/60	97	0.5	†
Chattahoochee	Columbia, Ala.	≈8000	1,120	10/52–9/60	139	0.7	†
Western Gulf							
Colorado	San Saba, Tex.	30,600	3,610	10/50–9/57	118	0.6	*
Rio Grande	San Acacia, N. M.	26,770	9,420	10/47–9/56	352	1.8	*
Pecos	Puerto de Luna, N. M.	3970	2,720	10/48–9/57	685	3.6	*
Rio Hondo	Roswell, N. M.	947	545	10/51–9/57	575	3.0	*
Mississippi							
Mississippi	Baton Rouge, La.	1,243,500	305,000	10/49–9/61	244	1.3	‡
Colorado							
Colorado	Grand Canyon, Ariz.	137,800	149,000	10/25–9/57	1082	5.6	*§
Pacific slopes in California							
Alameda	Niles, Cal.	633	221	10/56–9/60	349	1.8	‖*
San Joaquin	Vernalis, Cal.	14,010	347	10/56–9/60	25	0.1	‖*
Sacramento	Sacramento, Cal.	≈27,500	2,580	10/56–9/60	94	0.5	‖*
Napa	St. Helena, Cal.	81	63.3	10/57–9/60	781	4.1	‖
Eel	Scotia, Cal.	3,113	18,200	10/57–9/60	5846	30.4	‖
Mad	Arcata, Cal.	485	1,800	10/47–9/60	3711	19.3	‖
Trinity	Hoopa, Cal.	2,846	3,250	10/56–9/60	1141	5.9	‖*
Columbia							
Snake	Central Ferry, Wash.	103,500	13,100	4/50–7/52**	127	0.7	¶
Columbia	Pasco, Wash.	102,600	10,300	6/50–7/52**	100	0.5	¶
Green	Palmer, Wash.	230	70.8	10/53–9/57	308	1.6	*

* U. S. G. S. Water Supply Papers, Quality of Water.
† Unpublished reports. U. S. Army Corps of Engineers; Mobile, Ala.
‡ Unpublished reports. U. S. Army Corps of Engineers; New Orleans, La.
§ U. S. G. S. Professional Paper.
‖ Unpublished reports. U. S. G. S.; Branch of Quality of Water; Sacramento, Cal.
¶ Unpublished reports. U. S. Army Corps of Engineers; Walla Walla, Wash.
** Incomplete records.

TABLE 2. Estimates of Annual Chemical Denudation As Given by Various Authors

Drainage Region	Denudation, tons/mi² yr		
	Dole and Stabler [1909]	*Durum et al.* [1959]	*Livingstone* [1963]
Colorado	51	17	65
Pacific slopes, Calif.	177	81	103
Western Gulf	36	31	118
Mississippi	108	99	110
S. Atlantic and eastern Gulf	106	80	175
N. Atlantic	130	126	163
Columbia	100	112	163

basins considered in the present paper. Table 2 shows the range in chemical erosion as estimated in the three studies.

Although the estimated range of chemical erosion is large, the effect of the total rate of denudation based on the extremes reported is not great. For example, the range of chemical erosion in the Western Gulf region is such that the highest estimate is three times greater than the lowest. However, using the highest and lowest chemical rates, we estimate that the rate of total denudation varies by 0.5 in./1000 years. This situation is obviously controlled by the presence of large amounts of suspended loads in the waterways of the area; that is, the dissolved load is a minor part of the total load.

For the purposes of this paper we use the rates developed by *Livingstone* [1963]. Table 2 shows that these rates of chemical erosion are the highest reported in the three studies except in the case of the Pacific slopes in California, in which area Livingstone's figure is intermediate between the other two.

Bed load. Reliable data for bed load exist for very few localities. *Serr* [1950] reported bed loads of 50% of total clastic load at certain times in the Niobrara River near Cody, Nebraska. *Vice and Serr* [1950] estimated that the traction load may at times account for 55% of the total solids moved by the Middle Loup River near Dunning, Nebraska.

These rates are high, and it seems doubtful that such large traction loads are normal for rivers as they deliver sediment to the continental margin. *Fisk et al.* [1954] estimated that the amount of bed load entering the Gulf of Mexico from the Mississippi River is between 7% and 10% of the total detrital load. The amount of sediment deposited in Lake Mead between 1935 and 1948 was almost identical to the amount of suspended load during the same interval [*Gould*, 1960; *Howard*, 1960].

For the purposes of this study we assume that the bed load represents approximately 10% of the detrital load.

Discussion

The dissolved and solid loads per square mile removed annually by rivers from the United States as a whole and from its several major regions are listed in Table 3. These amounts are then expressed as inches of erosion per thousand years. We do not intend to imply in the table that each basin in a given region is eroding at the same rate as every other basin in that region. There is wide range of sediment production from one basin to the next within a given region. No single small basin can be expected to mirror the regional rate of erosion. Conversely, the regional rate cannot be applied to any local area.

Furthermore, we cannot assume that the material eroded from a small, headwater basin in, say, western South Dakota will be immediately reflected in the load delivered at the Mississippi delta. Material moving from its position as a part of fresh bedrock follows a slow, halting, devious course, as natural processes transport it from the land to the ocean. But, recognizing this, we must accept as fact that all material moved by a stream has come from the land and that this material represents denudation of the stream's drainage basin. Thus there is a balance between material transported by the streams and that produced on the slopes. It is not our purpose to present or discuss the many interesting data available on erosion of small areal units. We are concerned instead with generalizations on a subcontinental scale.

Livingstone [1963] points out that a significant part of the dissolved load is derived by water during its underground percolation, particularly in humid regions. Therefore, a consid-

TABLE 3. Rates of Regional Denudation in the United States

Drainage* Region	Drainage Area, $mi^2 \times 10^3$	Runoff, $ft^3/sec \times 10^3$	Load T/mi^2 yr Dissolved	Solid	Total	Denudation, in./1000 yr	Area Sampled, %	Avg. Years of Record
Colorado	246	23	65	1190	1255	6.5	56	32
Pacific slopes, Calif.	117	80	103	597	700	3.6	44	4
Western Gulf	320	55	118	288	406	2.1	9	9
Mississippi	1,250	620	110	268	378	2.0	99	12
S. Atlantic and eastern Gulf	284	325	175	139	314	1.6	19	7
N. Atlantic	148	210	163	198	361	1.9	10	5
Columbia	262	345	163	125	288	1.5	39	<2
Totals	2,627	1,658	121	340	461	2.4		

* Great Basin, St. Lawrence, Hudson Bay drainage not considered.

erable part of the dissolved load is provided by rocks at some depth and not by the surface material which is the source implied in calculating a rate of denudation. Over a period of years this anomaly is erased as the rocks providing the dissolved load are exposed at the surface by erosion and then removed. Even so, this does not alter the fact that the part of the present rate of denudation derived from chemical loads does not represent a lowering of the present surface.

We find the over-all denudation rate for the United States to be twice that arrived at by Dole and Stabler. We also find, region by region, higher rates of erosion than Dole and Stabler found. The exception is in the Mississippi drainage, where there is no difference between our figure and that of Dole and Stabler (see Table 4). For this region Dole and Stabler had access to relatively long-range records. Dole and Stabler's estimates for the Mississippi River drainage were based on a 15-year record provided by the Corps of Engineers, U. S. Army. This paper is based on a 12-year record covering a different period, also supplied by the Corps of Engineers. Other estimates of the erosion rates in the Mississippi River basin have been made by *Fisk et al.* [1954], *Gilluly* [1955], and *Jacobs et al.* [1959], as shown in Table 5.

The calculated rate of denudation for the Colorado River basin may be the most reliable

TABLE 4. Comparison between Regional Denudation Rates Reported Here with Those Reported by *Dole and Stabler* [1909]

Drainage Region	Denudation Rate, in./1000 yr: *Dole and Stabler* [1909]	This Report
Colorado	2.3	6.5
Pacific slopes, Calif.	1.3	3.6
Western Gulf	0.6	2.1
Mississippi	2.0	2.0
S. Atlantic and eastern Gulf	1.4	1.6
N. Atlantic	0.9	1.9
Columbia		1.5

estimate of the present study, because it is based on a 32-year continuous record. Although at variance with the estimates of Dole and Stabler, the rapid erosion indicated for this basin is not surprising. Some earlier figures are equally high and, in some cases, greater than our figure [see *Gould*, 1960; *Wolman and Miller*, 1960; *Hunt*, 1956]. In general, all these reports demonstrate that denudation in the Colorado River basin is progressing at a rate of

TABLE 5. Estimates of Rates of Denudation in the Mississippi and Colorado Drainages

	Rate of Denudation, in./1000 yr
Mississippi Drainage	
Dole and Stabler [1909]	2.0
Fisk et al. [1954]	1.7*
Gilluly [1955]	1.0†
Jacobs et al. [1959]	0.46
This report	2.0
Colorado Drainage	
Dole and Stabler [1909]	2.3
Gould [1960]	5.58–9.52‡
Wolman and Miller [1960]	7.1
Hunt [1956]	5.58
This report	6.5

* Detrital load only.

† As calculated by *Menard* [1961].

‡ Least value = removal of solid rock. Greatest value = removal of soil.

approximately 6 in./1000 years, as shown in Table 5.

It is surprising, as pointed out by *Howard* [1960], that the records indicate a definite change in the amount of sediment carried by the Colorado since 1942. If only the data from 1943–1957 were available, the calculated rate of erosion in the Colorado River basin would be 4.2 in./1000 years, which is significantly lower than the rate of 6.5 in./1000 years indicated by the 32-year record. *Thomas et al.* [1960] state that this difference is not a function of changes in sampling techniques. We must conclude that a change in some fundamental control of erosion has occurred during this period.

Table 3 shows that the areas now being eroded most rapidly are in the arid and semiarid southwestern quadrant of the United States. Conditions favoring maximum erosion seem to develop with low precipitation in areas underlain chiefly by sedimentary rocks. In a very general way, the amount of detrital load produced in each region increases with decreasing discharge per unit area. The detrital load is the dominant component of a river's load. This points again to an increasing rate of denudation with decreasing precipitation. This trend must reverse below a certain critical point of decreased precipitation. From extremely dry areas little or no water may reach the sea, and hence no net loss in material is experienced. In this respect *Langbein and Schumm* [1958] discovered that, in drainage basins averaging 1500 mi², sediment loads in streams are at a maximum in areas of effective rainfall of a little more than 10 in./year. The sediment load decreases as the annual effective precipitation varies above or below this critical value. *Schumm* [1963] expressed these data in rates of erosion per 1000 years.

In examining the rates of regional erosion, we note that although erosion rates increase with decrease in discharge per unit area, they do not increase quite as rapidly as the majo component, the detrital load, increases. This i so because the absolute dissolved load decrease with decreasing discharge per unit area. Thi inverse relation between clastic and dissolve load is shown in Figure 2. The decrease in chem-ical erosion in more arid areas partially equal-izes the regional rates from climate to climate

The rates of regional erosion reported her are rapid in terms of geologic time. *Gillul* [1949, 1955] has presented data suggesting tha erosional rates, at least in what is now mid continental United States, have been essentiall the same through the whole of the Cenozoic a they are today.

Taking the average height of the Unite States above sea level as 2300 feet and assum ing that the rates of erosion reported here ar representative, we find that it would take 11 t 12 million years to move to the oceans a volum equivalent to that of the United States lyin above sea level. At this rate there has bee enough time since the Cretaceous to destro such a landmass six times. Accepting this figu creates the problem of maintaining a cont

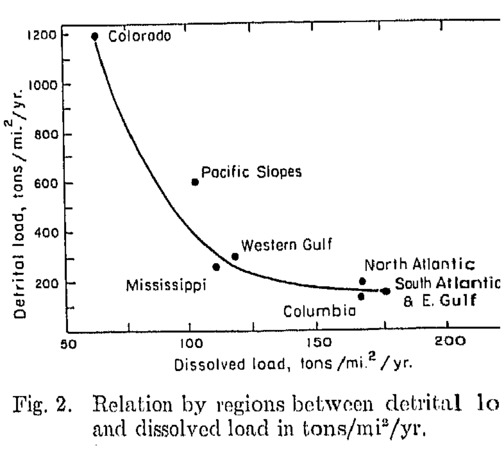

Fig. 2. Relation by regions between detrital lo and dissolved load in tons/mi²/yr.

ıental mass at high elevations, a problem be- ɣond the intent of this report.

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