ROBERT H. MEADE *U.S. Geological Survey, Woods Hole, Massachusetts*

Errors in Using Modern Stream-Load Data To Estimate Natural Rates of Denudation

Abstract: The practice of calculating natural rates of denudation from routinely collected data on the loads of suspended and dissolved matter in modern rivers is subject to several significant errors. The sources of these errors are demonstrated by examples from the Atlantic drainage of the United States, where their total effect has apparently doubled the natural rate of erosion.

The largest error is caused by assuming that modern sediment loads in populated areas represent natural erosion, whereas in fact they mainly reflect the influence of man. Conversion of forests to croplands in the middle Atlantic states causes about a tenfold increase in sediment yield. Coal mining, urbanization, and highway construction have added extra loads of sediment to the streams. Modern sediment loads in the Atlantic-draining rivers are probably 4 to 5 times greater than they would be if the area had remained undisturbed by man.

Errors in calculating the chemical denudation are caused by atmospheric contributions to the dissolved loads of streams and by pollutants that are added directly to stream waters. About one-quarter of the salts in Atlantic-draining streams were contributed from the atmosphere, either as recycled sea salts or as pollutants and soil dust that originally became airborne as a result of the activities of man. Perhaps another one-tenth of the dissolved load consists of industrial and agricultural wastes or acid mine waters that have been added directly to the streams.

CONTENTS

INTRODUCTION

In the last several decades, more and more data have been collected by such agencies as the U.S. Geological Survey and the U.S. Army Corps of Engineers on the loads of suspended and dissolved materials carried by streams of the United States. Although most of these data have been collected for purposes of water management, they have been put to incidental use by geologists who needed a solid basis for estimating the rates of continental erosion and uplift in the geologic past. Judson and Ritter (1964) and Schumm (1963), for example, have

Geological Society of America Bulletin, v. 80, p. 1265–1274, 9 figs., July 1969

extrapolated modern stream-load data to estimate past rates of denudation. Gilluly (1964) has compared the modern rate of denudation, as measured by Dole and Stabler (1909), with the apparent rate of accumulation of Mesozoic and younger sediments in the northern Atlantic coastal region of the United States.

Modern stream-load data of the sort that is routinely collected by the Survey and the Corps, however, must not be taken indiscriminately to represent natural rates of denudation. Routine measurements of dissolved ions and suspended sediments are usually made where the problems of water quality are big enough to justify the expense of collecting the samples and making the analyses. In other words, the data are biased toward the more developed areas of the country and the world. Rates of erosion in these areas are considerably different from those of equivalent virgin areas because man's agricultural, industrial, and urban activities have altered the natural suspended and dissolved loads carried by the streams.

The main problems in using the modern data are illustrated in this paper with studies from the Atlantic drainage of the United States. The problems, discussed in the order of the size of the difference they produce between natural and observed rates of denudation, are: the influence of man on sediment loads, the atmospheric contributions to dissolved loads, and the direct influence of man on dissolved loads. Although these factors have been discussed before at some length, enough information is now available in the Atlantic states to begin to indicate the size and importance of their effects relative to each other and to natural erosion.

ACKNOWLEDGMENTS

I thank the following for enlightening discussions, references to important papers, and especially for their criticisms of the manuscript: J. R. George, James Gilluly, and R. J. Janda of the Geological Survey; S. A. Schumm of Colorado State University, K. O. Emery, D. W. Folger, and D. A. Ross of Woods Hole Oceanographic Institution.

EFFECTS OF MAN ON SEDIMENT LOADS OF STREAMS

The greatest single source of error in using modern stream-load data as a measure of natural denudation comes from the changes in sediment yield that are caused by man-made changes in land use and vegetation. General discussions by Brown (1944, p. 118–128), Leopold (1956), and Copeland (1965), among others, have focused attention on the problem and have pointed out the difficulties of making quantitative measurements of man's effects.

Human activity has affected the amount of sediment in streams draining the Atlantic states ever since the first English settlers landed. The influence of man on sedimentation is perhaps best documented in the Chesapeake Bay region, where clearing of forests and wasteful farming practices (especially those used in raising tobacco) contributed enormous loads of sediment to the rivers (Gottschalk, 1945). Once-clear streams became muddy and formerly deep harbors at the head of tidewater were filled with sediment. Suspended sediment in the Potomac River, whose waters were already somewhat turbid but still suitable for municipal use in 1853, had become so detrimental to water quality by 1905 that the city of Washington had to install a filtration plant (Kemp, 1949). A large part of the head of the Potomac estuary at Washington is now filled with sediment washed from upstream farms, as shown by the comparison of the shorelines of 1792 and 1947 (Fig. 1). The Lincoln and Jefferson Memorials now stand on what was described in 1711 as a suitable harbor for great merchant vessels (Gottschalk, p. 226). The 1792 shoreline is clearly discernible on the ground because it is marked by a distinct change in slope. This change in slope and the large area that has been filled since 1792 indicate that the filling was induced by man rather than nature. Even today, an average of about 2 million cubic meters of sediment is deposited every year near the head of tide in the Potomac (Wolman and others, cited by Wark and Keller, 1963, p. 9). Gottschalk gives other examples of former seaport towns on Chesapeake Bay whose decayed docking facilities are now separated from navigable water by several kilometers of sediment-filled lowland.

In the last several decades, farming has declined in some of the Atlantic states, and imprudent agricultural practices have given way to soil-conservation measures that have decreased the sediment loads contributed to streams by farm lands. Data on the concentrations of suspended matter in three large rivers of Georgia (shown in Fig. 2) demonstrate this decrease. During the period from 1934 to 1953

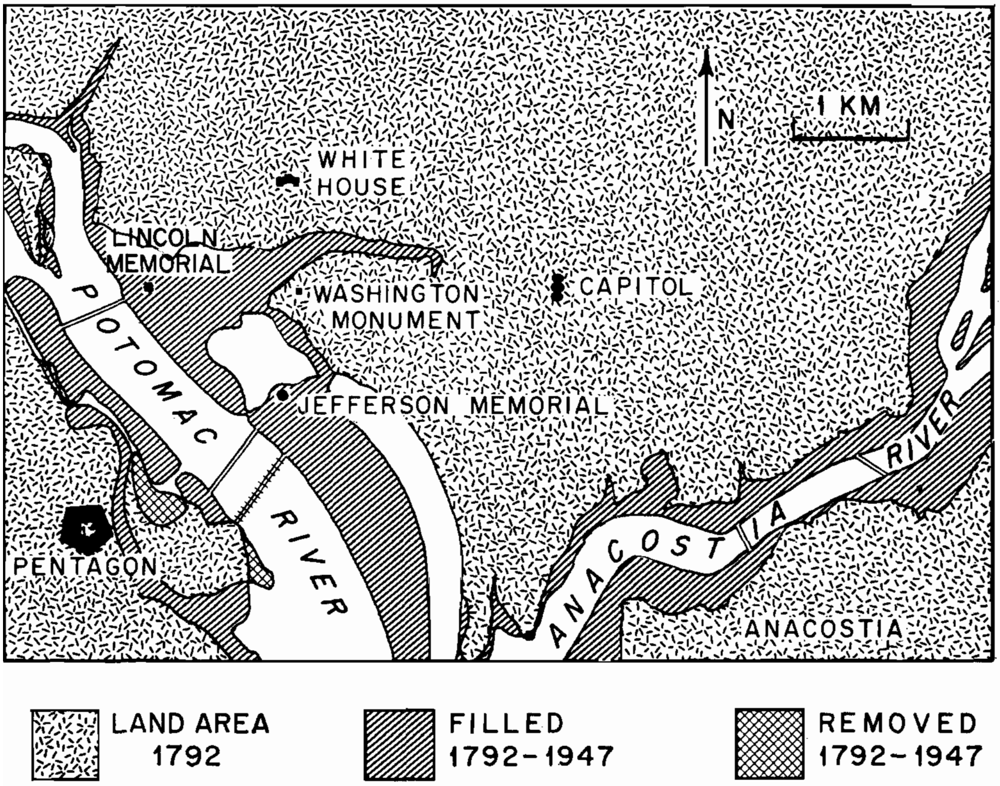

Figure 1. Sediment accumulation in the Potomac River estuary at Washington, 1792–1947 (modified *after* Carr, 1950, Pl. 3). Historical filling of Anacostia River estuary is described by Williams (1942).

there was no concomitant decrease in the mean annual rainfall or runoff in Georgia, so the change in sediment is probably due to the soil-conservation practices that were begun in earnest in the 1930's. Other recent decreases in sediment yield that can be attributed to soil conservation in the Atlantic states have been recorded in the basins of the Gunpowder Falls River of Maryland (O'Bryan and McAvoy, 1966, p. 46–51) and Brandywine Creek of Pennsylvania and Delaware (Guy, 1957; Holtje, 1966).

Even with widespread conservation practices, however, farmland continues to yield large quantities of sediment, as shown by graphs of sediment yield versus cropland in segments of the Potomac and Susquehanna River basins (Fig. 3). Graphs of sediment yield versus forest cover in the same drainage basins (Fig. 4) express the same relations inversely. As a rough estimate, one might say that converting forest land to farms in these areas causes about a tenfold increase in sediment yield.

Coal mining is another activity that has increased the sediment loads of streams. The beds of the Susquehanna, Schuylkill, and Lehigh Rivers of Pennsylvania became so choked with anthracite coal debris by the end of the 19th century that their bottom sediments could be dredged profitably for the coal they contained (Sisler and others, 1928, p. 168–181). Anthracite debris from the Susquehanna River basin is found in the modern bottom sediments of Chesapeake Bay as far as 40 km below the mouth of the river (Ryan, 1923, p. 54, 70–73). Even though the Pennsylvania anthracite industry has declined since 1917, 10 percent of the suspended matter measured in the Susquehanna in the spring flood of 1960 was coal (Williams and George, 1968, p. 36). The Schuylkill River is even more affected by coal mining. More than one-half of the suspended matter measured between 1947 and 1949 in the upper Schuylkill was combustible at 800° C, which with the black color and low specific gravity was an indication

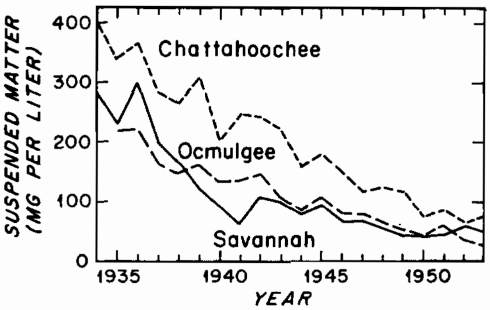

Figure 2. Decrease in average concentration of suspended matter at municipal water intakes (Atlanta, Macon, and Augusta) on three Georgia rivers, 1934–1953 (modified *after* Stall, 1962; additional data from U.S. Army Engineer District, Savannah, 1961, Fig. 2-d).

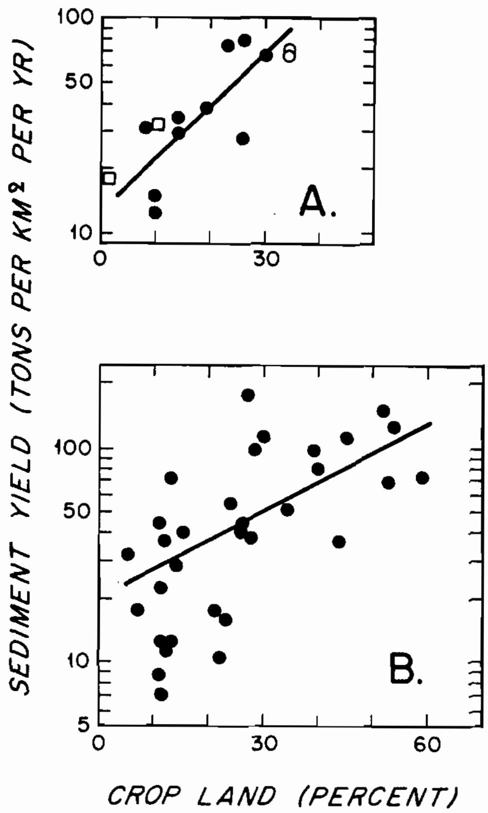

Figure 3. Relations between sediment yield and crop land. (A) In unglaciated tributary basins of Susquehanna River, 1951–1965 (Williams and George, 1968, p. 30). Squares represent basins in unglaciated Appalachian Plateau; dark circles, Valley and Ridge Province; open circles, Piedmont Lowlands. (B) In tributary basins of Potomac River, 1959–1962 (Wark and Keller, 1963, p. 25). Different physiographic provinces not indicated.

of the large amount of coal in suspension (White and Lindholm, 1950, p. 18). Even though desilting basins and other measures begun in the late 1940's had diminished sediment loads sharply (Biesecker and others, in press, report a 90-percent reduction in sediment yield between 1950 and 1960), the Schuylkill during the years 1947 to 1957 still carried the largest sediment load per unit area of any river east of the Rocky Mountains that was included in the compilation by Judson and Ritter (1964, p. 3397).

Urbanization is the most recent activity in the Atlantic states to contribute large amounts of sediment to streams. Sediment loads from land that is being cleared or filled for the building of houses, roads, and other facilities in the area between Washington and Baltimore have been described in a comprehensive paper by Wolman and Schick (1967). An example of sediment concentrations in storm runoff from a small area near Washington that was converted from rural use to suburban housing is shown in Figure 5. During the construction period, the concentration of the sediment in the runoff increased some 20 to 30 times, and then decreased again when the construction was completed. During this 5-year period, the annual sediment yield from this site averaged about 9000 tons/km^2. Other construction sites in the metropolitan area around Washington and Baltimore have yielded annual sediment loads that ranged from 2000 to 50,000 tons/km^2 (Wolman and Schick, 1967, p. 454). The total land cleared in any recent year in the four counties of Maryland in the metropolitan area ranged from 3 to more than 10 km^2 (p. 460). Guy (1965, p. 37) estimates that the Potomac River alone will receive 1 million tons of sediment per year from streams draining the metropolitan Washington area. Considering the construction of highways and suburbs that is going on in other areas of the Atlantic seaboard, the amount of extra sediment contributed every year must amount to several million tons.

Wolman's (1967) schematic summary of changes in sediment yield with changing land use in a typical area between Washington and Baltimore is shown in Figure 6. Until the end

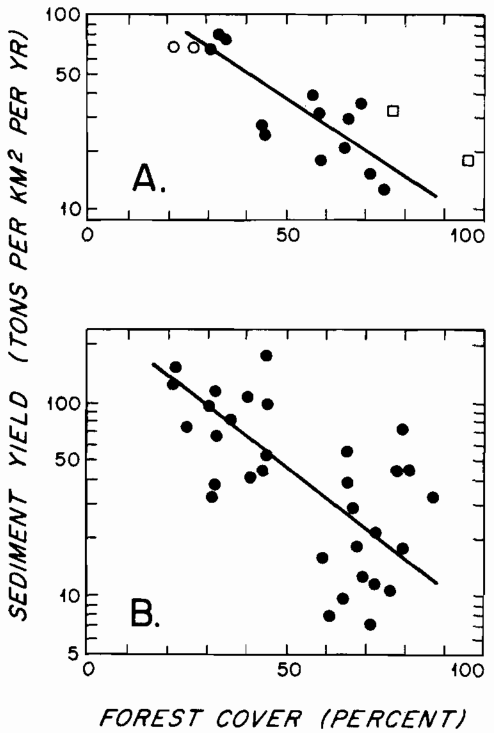

Figure 4. Relations between sediment yield and forest cover. (A) In unglaciated tributary basins of Susquehanna River, 1951–1965 (Williams and George, 1968, p. 29). Physiographic provinces indicated as in Figure 3. (B) In tributary basins of Potomac River, 1959–1962 (Wark and Keller, 1963, p. 24).

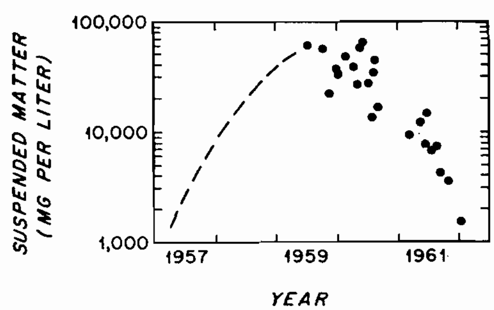

Figure 5. Sediment concentration observed in storm runoff from area (about 0.2 km²) of residential construction at Kensington, Maryland, 1957–1962 (Guy, 1965, p. 34). Construction began in 1957 and was completed in 1961. Dashed line represents estimates based on visual observations of construction area and drainage channels.

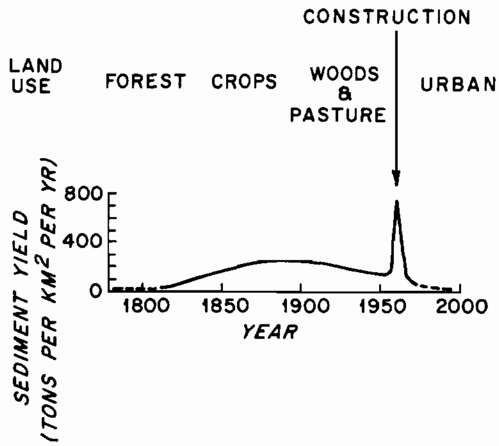

Figure 6. Schematic representation of changes in sediment yield accompanying changes in land use in a fixed area of the Maryland piedmont (modified after Wolman, 1967, p. 386).

of the 18th century, the area remained in its original forested condition, and sediment yields were low. The area was converted to crop farms in the 19th century, and the sediment yields increased accordingly. During the first half of the 20th century, soil-conservation measures were introduced and some lands reverted to woods and pasture while awaiting their conversion to suburbs and cities; both these effects caused the sediment yields to decrease somewhat. During the period when the lands are converted to urban use, the sediment yields are extraordinarily large, but this period is relatively short. After the area becomes a city with paved streets and planted lawns, the sediment yields become small again. But the important point to remember is that, in terms of present land use, most areas of the Atlantic states are still along the high parts (crops to construction) of Wolman's sediment-yield curve.

Although these considerations of man's influence on sediment yields should not be applied indiscriminately outside the Atlantic states, other areas have analogous problems. In the Coastal Plain of northern Mississippi, sediment yields from cultivated lands are 10 to 100 times the yields from equivalent areas of forested lands (Ursic and Dendy, 1965, p. 51). In Oregon and California, logging activities have added sediment to the streams (Anderson and Wallis, 1965, p. 23; Fredricksen, 1965). In the Willamette Valley of Oregon, farmland is estimated to yield 3 times as much sediment per unit area as forested land (H. W. Anderson, 1954, p. 280). In eastern Australia, farming and other changes in vegetation have increased the sediment yields (Douglas, 1967). In Italy, measurements made around archeological sites near Rome show that the intensive use of the land by man that began a century or two before Christ caused about a tenfold increase in the rate of erosion (Judson, 1968).

ATMOSPHERIC CONTRIBUTIONS TO THE DISSOLVED LOADS OF STREAMS

Although much has been written about airborne salts and how they contribute to the dissolved loads of streams (work reviewed by Clarke, 1924; p. 53–57; more recent papers by Conway, 1942, p. 142–147; Eriksson, 1955; Junge and Werby, 1958; Gorham, 1961; Douglas, 1964), two of the most widely quoted estimates of the regional chemical denudation of the United States do not take this factor into account (Dole and Stabler, 1909; Livingstone, 1963, p. G38).

In the streams of the Atlantic states, substantial proportions of the dissolved loads of streams are contributed by the atmosphere. Feltz and Wark (1962) estimated, on the basis of a few measurements, that rainfall in the Potomac River basin contributed about 8 tons of dissolved matter per square kilometer per year, or about 20 percent of the total dissolved load of the Potomac. More comprehensive studies made in North Carolina and New Hampshire (Fig. 7) show that, exclusive of bicarbonate, 30 to 50 percent of the load of dissolved solids in stream waters have been contributed from the atmosphere. Bicarbonate is also present in the precipitation and stream waters of both areas, but, because its source in stream waters is problematical (particularly in the problem of how much of it is derived from interactions between plants and the atmosphere—R. J. Janda, unpublished manuscript) and because the analytical data were incomplete, bicarbonate was not included in Figure 7. Even assuming that the bicarbonate in the stream waters is derived entirely from the dissolution of bedrock, however, the atmospheric contribution to the dissolved loads of the streams amounts to 20 percent (North Carolina) and 50 percent (New Hampshire).

Most of these airborne salts should be subtracted from the stream load before making estimates of natural rates of denudation. Some of them represent recycled sea salts, which certainly should be subtracted. Other salts come from air pollution or soil dust, and these should also be subtracted because they represent additions that are due mainly to the activities of man—whether they are pollutants from industrial sources or soil dust stirred up during construction or farming activities. (Incidentally, recent studies suggest that man's contribution to the material in the atmosphere is also increasing: *see* McCormick and Ludwig, 1967; Peterson and Bryson, 1968).

Local studies in other, more inland, areas indicate the importance of the atmospheric contribution to stream loads. Hembree and Rainwater (1961) combined their own measurements of solutes in streams draining the Wind River Mountains of Wyoming with Junge and Werby's (1958) measurements of solutes in

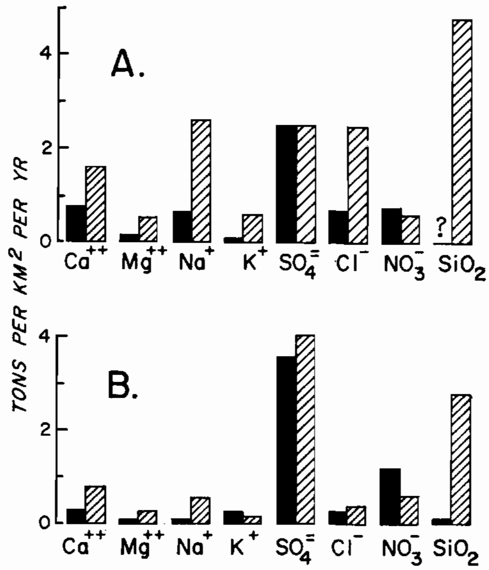

Figure 7. Comparison of input of ions contributed by precipitation (dark shading) with output of ions removed by streams (cross hatching). (A) In 19,000 km² area of North Carolina piedmont, 1962–1964 (Gambell and Fisher, 1966, p. K35; Fisher, 1968, p. M18). Silica in streams estimated as roughly equivalent to total of Ca, Mg, and Na (Billingsley and others, 1957, p. 49). (B) In small (<1 km²) experimental watershed in White Mountains, New Hampshire. Cation data measured 1963–1965 (Likens and others, 1967, p. 784); chloride data, 1965–1966 (Juang and Johnson, 1967, p. 5643–5644); sulfate, nitrate, and silica, 1964–1966 (Fisher and others, 1968, p. 1124).

precipitation in the same region. Their data show that airborne salts account for about 35 percent of the dissolved loads of streams draining granitic terranes and about 20 percent of those draining a mixed terrane of granitic and sedimentary rocks. A similar study in the Sangre de Cristo Mountains of New Mexico by Miller (1961) showed that solutes from precipitation account for about one-half the dissolved loads of streams draining quartzites, one-third of those draining granites, and one-tenth of those draining sandstones and claystones.

EFFECTS OF MAN ON DISSOLVED LOADS OF STREAMS

All rivers in developed areas of the modern world contain pollutants in solution that reflect human activities in their watersheds. Wastes from industries and concentrated drainage from mines, farms, and cities add to the dissolved material carried by streams. Pollution is so prevalent in the Atlantic states that prudent people no longer swim in most of the large rivers. Drinking untreated river water is unthinkable. Certainly one should not assume that their dissolved loads represent only natural denudation.

The increase in dissolved load that follows the increasing use of river water by cities and industries is described by Anderson and Faust (1965) in the Passaic River of northern New Jersey. During 1963, nearly half of the river flow was diverted for domestic and industrial supplies, an increase of more than 30 percent since 1950. Much of the withdrawn water was diverted to other drainage basins; about 10 percent of it was returned to the Passaic as industrial or municipal waste. In the period from 1948 to 1963, as shown in Figure 8, the concentration of dissolved solids at the average flow of 33 m^3/sec increased by more than 30 percent, and the dissolved load per unit water discharge increased considerably. The Passaic River is an extreme case of a moderate-sized river in an area where industries are concentrated and rapidly growing, but the study shows a process that probably has been going on at a slower rate in the larger streams of the eastern United States since the beginning of intense industrialization a century or so ago.

Drainage from coal mines is a particularly large source of dissolved matter in streams of the Appalachian region. Coal deposits, some of which have been mined intensively for more than 100 years, lie beneath about 150,000 km^2 of the Appalachian states (Biesecker and George, 1966, p. 2). Water that drains the coal mines is strongly acid and contains large amounts of iron, aluminum, manganese, sulfate, and sulfuric acid in solution (Durfor and Anderson, 1963, p. W8-W9). In the North Branch Potomac River, which drains a strip-mining area of West Virginia, the net dissolved load per unit area is 3 times the average for the rest of the Potomac Basin (Feltz and Wark, 1962). In the Schuylkill River basin of Pennsylvania, the total dissolved solids and the dissolved sulfate discharged from the part of the basin that contains coal mines account for nearly 40 and 60 percent, respectively, of the dissolved solids and sulfate discharged by the whole river, even though the same part of the basin contributes only 25 percent of the total water (White and Lindholm, 1950, p. 92, 113). In the West Branch Susquehanna River in Pennsylvania, 20 major fish kills between 1948 and 1962 were caused by mine effluents that were washed downstream by localized rains in the mining region (Biesecker and George, 1966, p. 5). In fact, no major river in Pennsylvania is free of mine effluents (P. W. Anderson, 1963; Durfor and Anderson, 1963; McCarren, 1964; McCarthy and Keighton, 1964).

The mineral fertilizers and pesticides that are used in farming also augment the dissolved loads of natural waters. An example is described by Pfischner (1968) from the citrus-growing area of central Florida. The amount of dissolved matter in small lakes in the area is directly related to the proportions of their

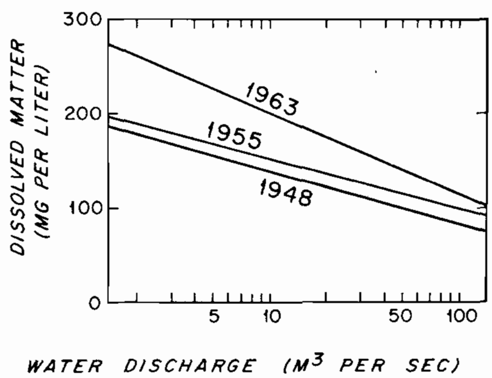

Figure 8. Relations between water discharge and concentration of dissolved matter in the Passaic River at Little Falls, New Jersey (Anderson and Faust, 1965, p. D215). Regression lines computed by method of least squares.

drainage basins that are devoted to citrus groves (Fig. 9). Furthermore, the lakes that have the greater concentrations of dissolved matter seem to be the ones surrounded by the older groves. Sulfate is the major dissolved constituent in most of the lakes, and its main source is probably the sulfur that is applied frequently on the surrounding groves to control spider mites and fungus.

DISCUSSION AND CONCLUSIONS

By stressing the unnatural factors that contribute to erosion, I have not intended to belittle the importance of the natural influences such as the sizes and reliefs of drainage basins and the types of underlying rocks. But before making use of data, one should stop to ask what has really been measured. The influences of man and airborne salts on stream loads are difficult to evaluate, but they are not trivial and they cannot be ignored.

Even though the present information is still sketchy, one can make a tentative estimate of the difference between the natural and measured rates of denudation of the Atlantic states. As the present dissolved load of the Atlantic streams is nearly equivalent to the detrital load (Judson and Ritter, 1964, p. 3400), the errors in estimating each type of load are roughly equivalent. Considering the distribution and effects of different land uses in the Atlantic states, I estimate that the present sediment loads are four to five times what they were before the European settlers arrived. On the basis of the studies made in North Carolina and New Hampshire, I estimate that about one-fourth of the dissolved loads of the streams represents material contributed by the atmosphere. Another one-tenth of the dissolved load may represent material added directly to the streams by human activity. Previous estimates of the natural rate of denudation of the Atlantic states therefore have probably been too large by at least a factor of 2.

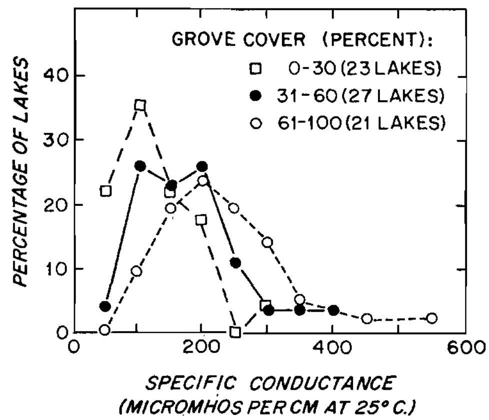

Figure 9. Relations between dissolved content of waters and coverage of citrus groves in small lake basins of Orange County, Florida, as shown by percentage-frequency distributions of specific conductance of lake waters in basins having different proportions of land in citrus groves, 1966 (Pfischner, 1968, p. B193). Specific conductance is directly proportional to the dissolved content.

REFERENCES CITED

Anderson, H. W., 1954, Suspended sediment discharge as related to streamflow, topography, soil, and land use: Am. Geophys. Union Trans., v. 35, p. 268–281.

Anderson, H. W., and Wallis, J. R., 1965, Some interpretations of sediment sources and causes, Pacific coast basins in Oregon and California, p. 22–30 *in* Proceedings of the Federal Inter-Agency Sedimentation Conference 1963: U.S. Dept. Agriculture Misc. Pub. 970.

Anderson, P. W., 1963, Variations in the chemical character of the Susquehanna River at Harrisburg, Pennsylvania: U.S. Geol. Survey Water-Supply Paper 1779-B, p. B1–B17.

Anderson, P. W., and Faust, S. D., 1965, Changes in quality of water in the Passaic River at Little Falls, New Jersey, as shown by long-term data: U.S. Geol. Survey Prof. Paper 525-D, p. D214-D218.

Biesecker, J. E., and George, J. R., 1966, Stream quality in Appalachia as related to coal-mine drainage, 1965: U.S. Geol. Survey Circ. 526, 27 p.

Biesecker, J. E., Wood, C. R., and Lescinsky, J. B., in press, Water resources of the Schuylkill River basin: Pennsylvania Dept. Forests and Waters.

Billingsley, G. A., Fish, R. E., and Schipf, R. G., 1957, Water resources of the Neuse River basin, North Carolina: U.S. Geol. Survey Water-Supply Paper 1414, 89 p.

Brown, C. B., 1944, The control of reservoir silting: U.S. Dept. Agriculture Misc. Pub. 521, 166 p.

Carr, M. S., 1950, The District of Columbia, its rocks and their geologic history: U.S. Geol. Survey Bull. 967, 59 p.

Clarke, F. W., 1924, The data of geochemistry (5th ed.): U.S. Geol. Survey Bull. 770, 841 p.

Conway, E. J., 1942, Mean geochemical data in relation to oceanic evolution: Royal Irish Acad. Sci. Proc., v. 48, sec. B, p. 119–159.

Copeland, O. L., Jr., 1965, Land use and ecological factors in relation to sediment yields, p. 72–84 *in* Proceedings of the Federal Inter-Agency Sedimentation Conference 1963: U.S. Dept. Agriculture Misc. Pub. 970.

Dole, R. B., and Stabler, Herman, 1909, Denudation, p. 78–93 *in* Papers on the conservation of water resources: U.S. Geol. Survey Water-Supply Paper 234.

Douglas, Ian, 1964, Intensity and periodicity in denudation processes with special reference to the removal of material in solution by rivers: Zeitschr. Geomorphologie, v. 8, p. 453–473.

—— 1967, Man, vegetation, and the sediment yields of rivers: Nature, v. 215, p. 925–928.

Durfor, C. M., and Anderson, P. W., 1963, Chemical quality of surface waters in Pennsylvania: U.S. Geol. Survey Water-Supply Paper 1619-W, p. W1-W50.

Eriksson, Erik, 1955, Air borne salts and the chemical composition of river waters: Tellus, v. 7, p. 243–250.

Feltz, H. R., and Wark, J. W., 1962, Solute degradation in the Potomac River basin: U.S. Geol. Survey Prof. Paper 450-D, p. D186-D187.

Fisher, D. W., 1968, Annual variations in chemical composition of atmospheric precipitation, eastern North Carolina and southeastern Virginia: U.S. Geol. Survey Water-Supply Paper 1535-M, p. M1-M21.

Fisher, D. W., Gambell, A. W., Likens, G. E., and Bormann, F. H., 1968, Atmospheric contributions to water quality of streams in the Hubbard Brook Experimental Forest, New Hampshire: Water Resources Research, v. 4, p. 1115–1126.

Fredricksen, R. L., 1965, Sedimentation after logging road construction in a small western Oregon watershed, p. 56–59 *in* Proceedings of the Federal Inter-Agency Sedimentation Conference 1963: U.S. Dept. Agriculture Misc. Pub. 970.

Gambell, A. W., and Fisher, D. W., 1966, Chemical composition of rainfall, eastern North Carolina and southeastern Virginia: U.S. Geol. Survey Water-Supply Paper 1535-K, p. K1-K41.

Gilluly, James, 1964, Atlantic sediments, erosion rates, and the evolution of the continental shelf: some speculations: Geol. Soc. America Bull., v. 75, p. 483–492.

Gorham, Eville, 1961, Factors influencing supply of major ions to inland waters, with special reference to the atmosphere: Geol. Soc. America Bull., v. 72, p. 795–840.

Gottschalk, L. C., 1945, Effects of soil erosion on navigation in upper Chesapeake Bay: Geog. Rev., v. 35, p. 219–238.

Guy, H. P., 1957, The trend of suspended-sediment discharge of the Brandywine Creek at Wilmington, Del., 1947–1955: U.S. Geol. Survey Open-File Rept., 55 p.

—— 1965, Residential construction and sedimentation at Kensington, Md., p. 30–37 *in* Proceedings of the Federal Inter-Agency Sedimentation Conference 1963: U.S. Dept. Agriculture Misc. Pub. 970.

Hembree, C. H., and Rainwater, F. H., 1961, Chemical degradation on opposite flanks of the Wind River Range, Wyoming: U.S. Geol. Survey Water-Supply Paper 1535-E, p. E1-E9.

Holtje, R. K., Jr., 1966, Hydrologic trends of the Brandywine Creek, Pennsylvania: Colorado State Univ., M.S. thesis, 65 p.

Juang, F. H. T., and Johnson, N. M., 1967, Cycling of chlorine through a forested watershed in New England: Jour. Geophys. Research, v. 72, p. 5641–5647.

Judson, Sheldon, 1968, Erosion rates near Rome, Italy: Science, v. 160, p. 1444–1446.

Judson, Sheldon, and Ritter, D. F., 1964, Rates of regional denudation in the United States: Jour. Geophys. Research, v. 69, p. 3395–3401.

Junge, C. E., and Werby, R. T., 1958, The concentration of chloride, sodium, potassium, calcium, and sulfate in rain water over the United States: Jour. Meteorology, v. 15, p. 417–425.

Kemp, H. A., 1949, Soil pollution in the Potomac River basin: Am. Water Works Assoc. Jour., v. 41, p. 792–796.

Leopold, L. B., 1956, Land use and sediment yield, p. 639–647 *in* Thomas, W. L., Jr., *Editor*, Man's role in changing the face of the earth: Chicago, Univ. Chicago Press.

Likens, G. E., Bormann, F. H., Johnson, N. M., and Pierce, R. S., 1967, The calcium, magnesium, potassium, and sodium budgets for a small forested ecosystem: Ecology, v. 48, p. 772–785.

Livingstone, D. A., 1963, Chemical composition of rivers and lakes, Chap. G, p. G1-G64 *in* Data of geochemistry, 6th edition: U.S. Geol. Survey Prof. Paper 440-G.

McCarren, E. F., 1964, Chemical quality of surface water in the West Branch Susquehanna River basin, Pennsylvania: U.S. Geol. Survey Water-Supply Paper 1779-C, p. C1-C40.

McCarthy, L. T., Jr., and Keighton, W. B., 1964, Quality of Delaware River water at Trenton, New Jersey: U.S. Geol. Survey Water-Supply Paper 1779-X, p. X1-X51.

McCormick, R. A., and Ludwig, J. H., 1967, Climate modification by atmospheric aerosols: Science, v. 156, p. 1358–1359.

Miller, J. P., 1961, Solutes in small streams draining single rock types, Sangre de Cristo Range, New Mexico: U.S. Geol. Survey Water-Supply Paper 1535-F, p. F1-F23.

O'Bryan, Deric, and McAvoy, R. L., 1966, Gunpowder Falls, Maryland—uses of a water resource today and tomorrow: U.S. Geol. Survey Water-Supply Paper 1815, 90 p.

Peterson, J. T., and Bryson, R. A., 1968, Atmospheric aerosols: increased concentrations during the last decade: Science, v. 162, p. 120–121.

Pfischner, F. L., Jr., 1968, Relation between land use and chemical characteristics of lakes in southwestern Orange County, Florida: U.S. Geol. Survey Prof. Paper 600-B, p. B190-B194.

Ryan, J. D., 1953, The sediments of Chesapeake Bay: Maryland Dept. Geology, Mines and Water Resources Bull. 12, 120 p.

Schumm, S. A., 1963, The disparity between present rates of denudation and orogeny: U.S. Geol. Survey Prof. Paper 454-H, p. H1-H13.

Sisler, J. D., Fraser, Thomas, and Ashmead, D. C., 1928, Anthracite culm and silt: Pennsylvania Geol. Survey, ser. 4, Bull. M-12, 268 p.

Stall, J. B., 1962, Soil conservation can reduce reservoir sedimentation: Public Works, v. 93, no. 9.

U.S. Army Engineer District, Savannah, 1961, Results of prototype investigations, vol. 2 of Savannah Harbor, Georgia, investigation and model study: U.S. Army Engineer District, Savannah, 33 p.

Ursic, S. J., and Dendy, F. E., 1965, Sediment yields from small watersheds under various land uses and forest covers, p. 47–52 *in* Proceedings of the Federal Inter-Agency Sedimentation Conference 1963: U.S. Dept. Agriculture Misc. Pub. 970.

Wark, J. W., and Keller, F. J., 1963, Preliminary study of sediment sources and transport in the Potomac River Basin: Interstate Comm. Potomac River Basin Tech. Bull. 1963–11, 28 p.

White, W. F., and Lindholm, C. F., 1950, Water resources investigations relating to the Schuylkill River Restoration Project, October 1947–December 1949: Pennsylvania Dept. Forests and Waters, 125 p.

Williams, K. F., and George, J. R., 1968, Preliminary appraisal of stream sedimentation in the Susquehanna River basin: U.S. Geol. Survey Open-File Rept., 49 p.

Williams, M. T., 1942, A history of erosion in the Anacostia drainage basin: Washington, D.C., Catholic Univ. America Press, 59 p.

Wolman, M. G., 1967, A cycle of sedimentation and erosion in urban river channels: Geografiska Annaler, v. 49A, p. 385–395.

Wolman, M. G., and Schick, A. P., 1967, Effects of construction on fluvial sediment, urban and suburban areas of Maryland: Water Resources Research, v. 3, p. 451–464.

Manuscript Received by The Society December 6, 1968
Publication Authorized by the Director, U.S. Geological Survey
Woods Hole Oceanographic Institution Contribution no. 2007