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The dissolved loads of rivers: a global overview

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ABSTRACT Values of mean annual total dissolved load have been assembled from 490 rivers located throughout the world and these data have been used to review the general characteristics of dissolved load transport. Attention is given to the magnitude of dissolved loads and their spatial variation, the temporal variation of dissolved load transport and the relationship between the magnitude of the dissolved and particulate components of total load.

Transport en solution par les rivières: examen sur le plan mondial
RESUME Les valeurs de transport en solution ont été rassemblées pour 490 rivières réparties dans le monde entier. Ces données ont été utilisées pour définir les caractéristiques générales de transport en solution, y compris l'ampleur des transports specifiques en solution et leur variation dans l'espace, la variation temporelle des transport en solution, et l'importance relative du transport en solution et du transport solide en suspension.

INTRODUCTION

Interest in the transport of material in solution by rivers can be traced back for over 100 years. Amongst the earliest studies are those undertaken by Popp and by Letheby on the River Nile in Egypt in 1870 and 1874-1875 respectively (Popp, 1875; Baker, 1880). In most cases this early work focussed on chemical analyses of individual water samples rather than attempting to document the loads transported during specific periods of time, since records of water discharge were generally lacking. Justification for these pioneering studies can be found in an essentially academic interest in geochemistry and also in a more practical concern for the quality of water for both drinking and irrigation.

From these early beginnings, interest in solute transport by rivers has expanded to include geomorphological investigations of rates of chemical denudation and the relative efficacy of mechanical and chemical erosion (e.g. Wolman & Miller, 1960; Webb & Walling, 1982); studies of biogeochemical cycling in small drainage basins (e.g. Likens *et al.*, 1977; Waylen, 1979); assessments of material transport to the oceans (e.g. Clarke, 1924; Alekin & Brazhnikova, 1968; Meybeck, 1976, 1979); concern for the environmental impact of nonpoint pollution and other human activities (e.g. Steele & Gilroy, 1971; Hotes & Pearson, 1977); and the use of hydrochemical properties to elucidate runoff processes (e.g. Skakalskiy, 1966; Newbury *et al.*, 1969). The associated studies have ranged in scale from global assessments of loads entering the oceans to detailed investigations of small basins. Again much of this work has been concerned with the chemical *composition* or river water rather than the *loads* transported by particular rivers, but the expansion of river gauging activity and the need for reliable estimates of element flux in budget studies have encouraged the production of load estimates.

At the global scale, the classic work of Livingstone (1963a) and subsequent studies have now provided meaningful assessments of the average chemical composition of world river water and of rivers draining individual continents. The increasing availability of data on the dissolved loads of the major rivers of the world has also enabled Meybeck (1979) to produce reliable estimates of the total transport of dissolved solids and of individual ions from the land surface of the globe to the oceans. Less attention has, however, been given at the global scale to the general characteristics of records of dissolved load transport including the magnitude of dissolved loads and their spatial variation, the temporal variation of solute transport, and the relationship between the magnitude of the dissolved and particulate components of total load. The authors have attempted to assemble available data on solute loads from a wide variety of rivers in order to review these characteristics of dissolved load behaviour. Attention has been restricted to total dissolved solids loads and individual ion loads are not considered here.

DATA AVAILABILITY AND RELIABILITY

Measurement programmes designed to document total solute loads are in general considerably less frequent than for suspended sediment loads. Whereas many countries operate networks for monitoring suspended sediment loads, few include measurements designed specifically to assess solute loads. Information on solute concentrations is more readily available from water quality surveillance programmes, but these data are commonly inadequate for a meaningful assessment of the loads involved because of either low sampling frequency or the absence of appropriate water discharge data.

In total, values of mean annual total dissolved load were assembled for 490 rivers in which pollution was of limited significance. In some cases this information was obtained from national compilations of hydrological data (e.g. Leifeste, 1974) and in others single values or small groups of data were obtained from the published results of individual research investigations (e.g. Douglas, 1973; Turvey, 1975). Information on mean annual runoff and, where possible, on the suspended sediment load of the river and the major rock types underlying the upstream basin area were also collected for each measuring station. The resultant data set cannot be viewed as entirely representative of global conditions, since certain countries are over-represented and only a few values were available for many regions of Africa and South America. However, it embraces a wide variety of climatic and physiographic conditions and, in the general absence of information on this theme, it provides a worthwhile starting point for this review.

Accurate measurement of dissolved load involves the combination of detailed records of water discharge and solute concentration. It must be clearly recognized that meaningful estimates of total dissolved load cannot be obtained from the product of mean annual water discharge and mean concentration. Significant over-estimation will result in nearly all cases. With many measurement programmes, the sampling frequency is inadequate to define the continuous record of concentration and resort is made to various interpolation and extrapolation procedures (cf. Walling & Webb, 1982). These may introduce a degree of error into the resultant load estimates, but its magnitude is restricted by the limited range of solute concentrations encountered in most rivers. Taking account of this source of inaccuracy and of errors associated with laboratory analysis of solute concentration and with river flow data, it can be suggested that the assembled data set, although of variable quality, probably involves errors in the estimation of annual dissolved loads of ±20% or less. (cf. Walling, 1978). The use of an arbitrary limit of 0.45 μm to distinguish particulates from material in solution inevitably means that most estimates of dissolved load include colloidal particulate material, but the resultant overestimation is likely to be small.

Little information is available on the variability of long term records of annual dissolved load and therefore the confidence limits associated with estimates of *mean annual* dissolved load derived from a short period of record. However, available data suggest that the variability of annual solute loads is less than that of annual runoff totals. If the coefficient of variation (c_v) of annual runoff totals of 0.45 suggested by Nordin & Meade (1981) as being characteristic of rivers in the USA is taken as a starting point, the equivalent c_v of annual dissolved loads might be tentatively estimated at about 0.35. Combination of this value with simple standard error statistics would indicate that an estimate of mean annual dissolved load based on 10 years of record is likely to be within ±25% of the true mean with a 95% level of confidence. Sixty years of record would be necessary to produce an estimate of mean annual dissolved load within ±10% of the true mean with a similar degree of confidence. The c_v of annual runoff totals has been shown to decrease with increasing mean annual runoff and with increasing basin area (Kalinin, 1971), and the margins of error could therefore be smaller for many rivers. Nevertheless, it must be accepted that an estimate of mean annual dissolved load included in the current data set could, in an extreme case, differ from the true mean by ±40%.

THE MAGNITUDE OF DISSOLVED LOADS

Figure 1 provides a frequency distribution of the 490 values of mean annual dissolved load considered in this analysis. The maximum value of 311 t $km^{-2}year^{-1}$ is associated with the River Iller (953 km^2) in the Federal Republic of Germany, which drains a mountainous limestone region on the northern margin of the Alps. Minimum values below 1.0 t $km^{-2}year^{-1}$ are associated with Dutch Creek (0.34 t km^{-2} $year^{-1}$), James River (0.66 t $km^{-2}year^{-1}$) and Sage Creek (0.84 t km^{-2}

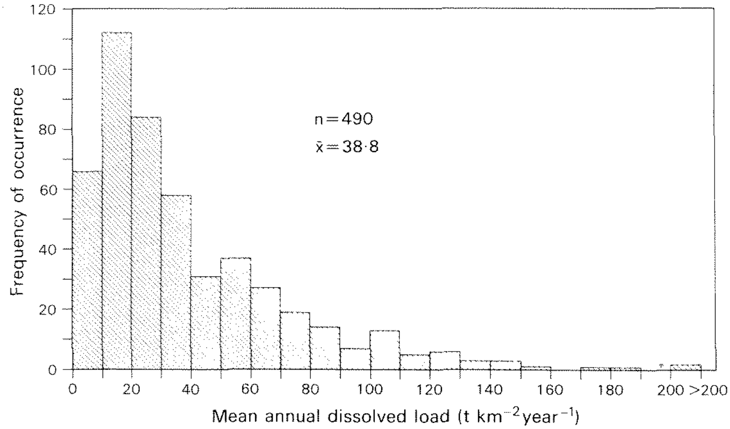

FIG.1 Frequency distribution of the values of mean annual dissolved load included in the global data base.

year^{-1}), three intermediate-sized drainage basins of 21.6, 123.6 and 67.6 km^2 respectively, in southern Alberta, Canada (cf. McPherson, 1975). It can be suggested from Fig.1 that values of total dissolved load in excess of 150 t km^{-2} year^{-1} are relatively rare, but it is likely that loads may exceed the maximum of 311 t km^{-2} year^{-1} cited here in some areas of the globe. Meybeck (1972) refers to a single year estimate of the total dissolved load of the River Dranse, a tributary of lake Geneva which drains an area of calcareous rocks, of 500 t km^{-2} year^{-1} and this probably represents a realistic assessment of the global maximum. Any evaluation of minimum loads must be complicated by the inclusion of ephemeral and intermittent streams, since in these cases loads may only be transported on a few days of the year. However, this explanation is unlikely to be significant for Dutch Creek and the James River cited above because their annual runoff totals are 457 and 242 mm respectively.

The mean load associated with the 490 rivers included in Fig.1 is 38.8 t km^{-2} year^{-1}. This value is encouragingly close to Meybeck's (1979) estimate of the mean dissolved load transport from the land surface of the globe to the oceans of 33.3 t km^{-2} year^{-1}. On the basis of the sample represented in Fig.1 it may be suggested that the dissolved loads of world rivers typically lie in the range 5-100 t km^{-2} year^{-1}.

SPATIAL VARIATION

In attempting to account for spatial variation in dissolved loads at the global scale, a number of workers have pointed to the general influence of climate embodied in a positive relationship between annual dissolved load (D) and mean annual runoff (Q). A similar trend is evidenced by the global data set assembled in this study (Fig.2(a)). Least squares regression provides a relationship of the form:

$$D = 3.3\ Q^{0.385} \qquad (r = 0.49) \qquad (1)$$

The degree of explanation provided by annual runoff as an independent variable is, however, relatively low and can in part be accounted for by the inclusion of a common variable (Q) in both sides of the relationship (D = Q x concentration). The trend of this regression relationship is similar to that established by Livingstone (1963b) and Meybeck (1976, 1977) from studies of world rivers and by Langbein & Dawdy (1964) from a generalized analysis of US rivers (Fig.2(b)), although Langbein & Dawdy (1964) suggest that the relationship evidenced a gradual flattening at annual runoff in excess of 75 mm. There is little evidence of such flattening in the data plot presented in Fig.2(a).

With the exception of that developed by Meybeck (1977), the relationships presented in Fig.2(b) all exhibit gradients or exponents of <1.0. This in turn indicates that an inverse relationship exists between total solute concentration and annual runoff, as proposed for the USA by Langbein & Dawdy (1964), Durum *et al.* (1960) and Holland (1978). It is difficult to equate the exponent of *c.* 1.0 suggested by Meybeck (1977) with such clear evidence of an inverse relationship between concentration and annual runoff, since this would imply that concentrations remained essentially constant as runoff increased. Furthermore, the suggestion by Holland (1978) that total dissolved load may be virtually independent of runoff for annual runoff values in excess of 100 mm does not find support in the data plotted on Fig.2(a).

Although the relationship between total dissolved load and annual runoff presented in Fig.2(a) exhibits considerable scatter, the positive trend (slope <1.0) may be related to general climatic control. In the case of dissolved solids originating from rock weathering, an increase in moisture availability will increase the rate of chemical weathering and solute removal. The lack of evidence of a tendency towards constant solute loads at high levels of runoff in Fig.2(a) suggests that rates of solute release are not limiting in areas of high runoff, although any such trend could be obscured by the heterogeneity of the data base. In the case of the contribution of atmospheric fallout to the fluvial transport of dissolved material, the resultant loads could again be expected to increase with increasing precipitation input and therefore runoff.

The considerable degree of scatter in the relationship between annual dissolved load and runoff (Fig.2(a)) can be attributed to other climatic and physiographic controls including temperature, seasonality, the rainfall/runoff ratio, rock type and vegetation. Meybeck (1979) has suggested that it is possible to develop a typology of characteristic dissolved load transport based on major physiographic zones, and the associated mean values of annual runoff and annual dissolved load have been superimposed on the Meybeck (1977) dissolved load/annual runoff relationship (cf. Fig.2(b)) in Fig.2(c). It is, however, difficult to make positive suggestions regarding the climatic controls subsumed in this typology since, as Meybeck (1979) notes, contrasts between individual physiographic regions may also be the result of varying rock types within the zones. Thus the positive residual associated with the temperate zones could be ascribed to the greater abundance of sedimentary rocks as well as to climatic influences. Increased data availability, particularly from small and intermediate sized drainage basins, is

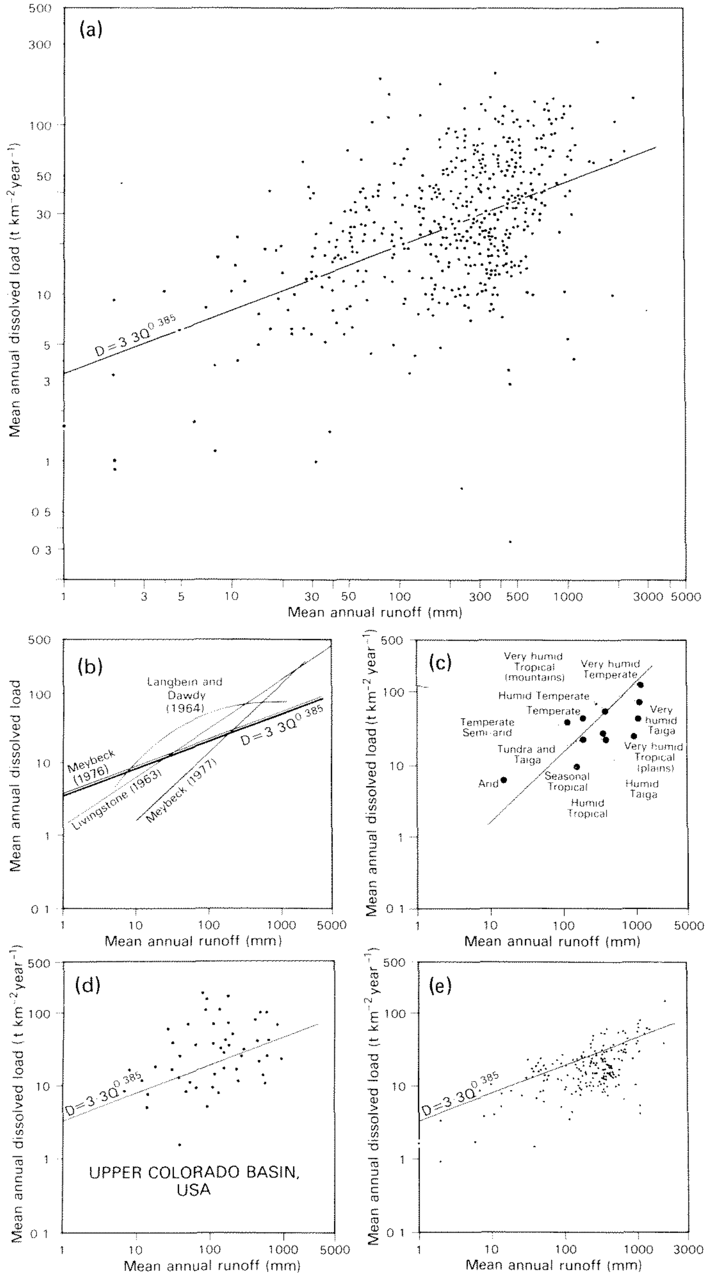

FIG.2 The relationship between mean annual dissolved load and mean annual runoff. The relationship for the global data set is plotted in (a) and the associated regression line is compared with the relationships produced by other workers in (b). The typology of dissolved load transport based on physiographic zones developed by Meybeck (1979) has been superimposed on the Meybeck (1977) relationship in (c). (d) demonstrates the degree of scatter in the dissolved load/runoff relationship encountered in the Upper Colorado basin, USA, and data points representing those rivers in the global set draining areas of igneous rock have been superimposed on the regression line established for the total data set in (e).

required to elucidate the relative importance of these various controls.

An indication of the degree of scatter associated with the dissolved load/annual runoff relationship *within* a given climatic zone is provided by Fig.2(d) which plots this relationship for data representing 50 measuring stations within the 283 600 km^2 basin of the Upper Colorado River in the southwest USA. The degree of scatter of these values around the regression line developed for the global data set is almost as great as that associated with the latter data. Much of this scatter may be related to the influence of variations in basin lithology which would appear to exert a major, if not dominant, influence on the magnitude of dissolved load. It is now well accepted that the dissolved loads of rivers draining basins underlain by igneous rocks are generally considerably lower than those found in areas of sedimentary rocks. Figure 2(e) clearly demonstrates this by superimposing those data points from the global data set representing basins underlain by igneous rocks, on the regression line produced for the entire data set. The majority of the points fall well below the regression line, again emphasising the importance of lithological controls on the global variation of dissolved loads.

Lithology assumes increasing importance in controlling spatial variations in dissolved loads as the scale of study decreases and other climatic and physiographic factors assume greater uniformity. For example, Fig.3 illustrates an attempt by the authors to produce a generalised map of the dissolved loads of small, essentially unpolluted, streams in Britain (cf. Walling & Webb, 1981). Loads range between 10 and in excess of 200 t $km^{-2} year^{-1}$. The resultant pattern partly reflects the influence of the positive relationship between load and annual runoff, because this accounts for the relatively low loads in the southeast of the country. However, lithology exerts an overriding influence, since the large areas of minimum dissolved load in the west of the country are predominantly areas of maximum runoff, but are underlain by resistant solute-deficient rocks. Furthermore, several of the mapped boundaries between load classes are closely related to the pattern of geological outcrops.

TEMPORAL VARIATION

Studies of short-term variations in dissolved load transport must take into account the inverse relationship between total dissolved solids concentrations (C) and discharge (Q) as the dominant control. Correlation coefficients associated with relationships of the form:

$$C = a\ Q^{-b} \qquad (2)$$

are frequently in excess of -0.8, emphasizing the high degree of explanation associated with this simple function. Figures 4(a) and (b) illustrate typical relationships of this form for two rivers in contrasting environments. In both cases the degree of explanation is high, although the exponents differ considerably. In the case of the Dolores River, concentrations range over more than an order of

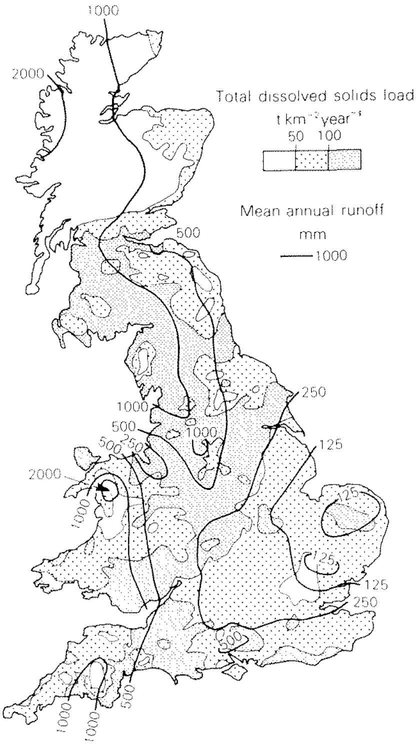

FIG.3 A comparison of the spatial variation of dissolved solids loads of small unpolluted streams in Britain with the pattern of annual runoff. The isopleths of mean annual runoff are based on Ward (1981).

magnitude, whereas the River Barle exhibits only a threefold range of variation. Studies of equivalent relationships for other rivers suggest that the magnitude of the exponent b is inversely proportional to the maximum levels of concentration encountered. This has a logical physical explanation in that concentrations associated with peak flows will tend towards those found in the storm rainfall due to the short residence time of much of the storm runoff. Since these concentrations will always be relatively low, the exponent will inevitably depend on the magnitude of the concentrations associated with low flows, although the range of flows involved will also be important.

A literature survey undertaken by the authors has provided values of the exponent b for 370 rivers. Many of these correspond with those included in the compilation of load data introduced above and, although they are not fully representative of all areas of the globe, they provide a useful basis for reviewing the values typical of world rivers. Figure 4(d) presents a frequency distribution of the 370 exponents. Nearly all (97.6%) are negative and these range between 0 and -1.0, with the majority falling between 0 and -0.4. The overall mean is -0.17. This is in accord with what might be expected from consideration of the estimate of the mean total solute concentration of world river water proposed by Meybeck (1979)

(89.2 mg l^{-1}) and the variation of the exponent b with mean concentration suggested by Figs 4(a) and (b).

Positive values of the exponent were only encountered in a very few cases, and would seem to reflect two causative factors. In the first case, positive values of b are occasionally associated with rivers exhibiting extremely low levels of solute concentration and can be tentatively explained by the dominance of atmospheric sources. In such situations, maximum dissolved solids concentrations may be encountered during storm events when surface runoff mobilises soluble material that has accumulated at the surface as a result of

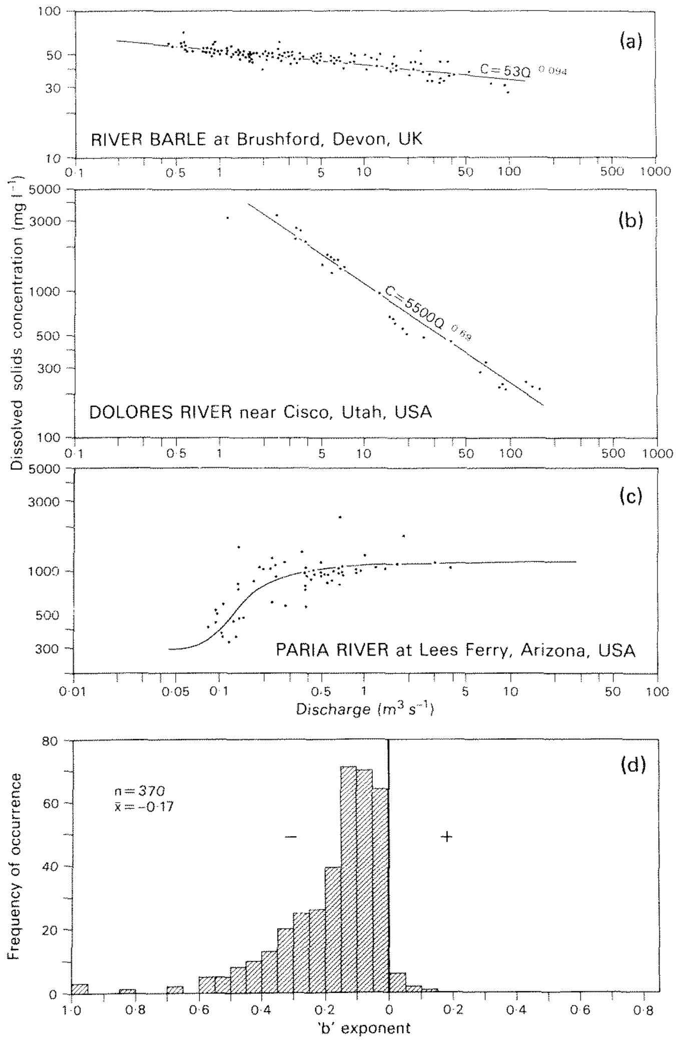

FIG.4 The relationship between total dissolved solids concentration and discharge for three contrasting rivers (a, b, c) and the frequency distribution of the exponent values exhibited by a global sample of 370 rivers (d). Data for the Dolores and Paria Rivers were obtained from Iorns et al. (1965).

atmospheric fallout or evaporation of prior rainfall. In the second case, no characteristic level of solute concentration is evident and a geological explanation may be invoked. Thus it is possible to envisage a situation where baseflow originates largely from one rock unit and exhibits relatively low solute concentrations in comparison to surface runoff generated predominantly from another rock unit. This is the explanation proposed by Iorns *et al.* (1965) to account for the relationship between dissolved solids concentration and discharge recorded in the Paria River, Arizona (Fig.4(c)). More complex relationships involving combinations of both positive and negative trends which may be ascribed to similar controls have been documented by Gunnerson (1967) and Walling & Webb (1981).

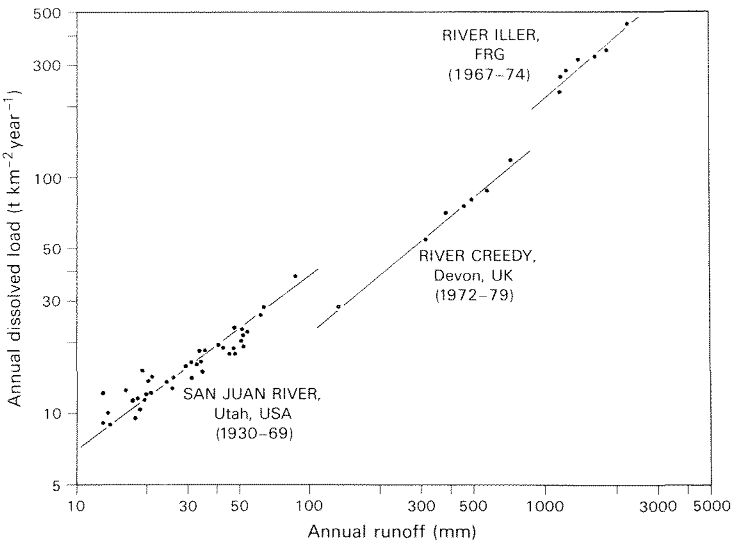

FIG.5 The relationship between annual dissolved load and annual runoff exhibited by three rivers in contrasting morphoclimatic zones.

Analysis of longer term variations in annual solute loads is severely limited by the paucity of readily available long-term records. However, some preliminary conclusions may be advanced. Figure 5 presents the relationship between annual dissolved load and annual runoff for three rivers in contrasting climatic zones. Only seven years of data are available for the Rivers Creedy and Iller, but the record for the San Juan River extends over 40 years. In each case a clearly defined relationship exists and the exponent is <1.0, with the two European rivers exhibiting values of *c.* 0.85 and the San Juan River a value of *c.* 0.75. These values suggest that the variability of annual solute loads will in general be less than that of annual runoff. This may in turn be accounted for by the inverse relationship between total solute concentration and flow depicted in Fig.4. The coefficient of variation of the annual solute loads of the San Juan River is approximately 38%. Values of *c.* 38% and *c.* 20% are associated with the Rivers Creedy and Iller, respectively, but a greater length of record is required to substantiate these levels. In the absence of more definitive guidelines, it is suggested that the c_v of annual solute loads for a river could be provisionally estimated as approximately 80% of the c_v of the annual runoff totals.

THE RELATIVE MAGNITUDE OF DISSOLVED AND PARTICULATE LOADS

Estimates of the total transport of dissolved and particulate material from the land surface of the globe to the oceans have clearly demonstrated the dominance of particulate transport. Thus if the estimate of the total suspended sediment load of 13.5×10^9 t year^{-1} produced by Milliman & Meade (1983) is compared with the equivalent estimate for dissolved load of 3.718×10^9 t year^{-1} produced by Meybeck (1979), a ratio of 3.6 is evident. Using available estimates of suspended sediment and dissolved loads transported to the oceans from the individual continents, Gregory & Walling (1973) suggested that the ratio varied between 18.8 (Asia) and 0.8 (Europe), but dissolved loads exceeded particulate load only in the case of Europe.

Turning to the relative magnitude of dissolved and particulate loads for individual rivers, some controversy exists concerning the trend of the general relationship between the magnitude of these two load components. Using data representing the major drainage regions of the USA, Judson & Ritter (1964) suggested that an inverse relationship existed between mean annual dissolved load and particulate load (Fig.6(b)). Other workers such as Alekin & Brazhnikova (1962), Strakhov (1967), Gregory & Walling (1973) and Meybeck (1976, 1977) have, however, pointed to a positive relationship. The positive trends suggested by data from various physiographic zones presented by Strakhov (1967) are illustrated in Fig.6(b) and the relationship established by Meybeck (1977) for major world rivers is depicted in Fig.6(c). Arguments to support these conflicting views have focussed on the contrasting relationships between the magnitude of particulate and dissolved loads and annual runoff in the case of Judson & Ritter (1964) and the contention that increased mechanical erosion will in general be coupled with increased chemical erosion advanced by other workers.

Figure 6(a) illustrates the relationship between mean annual dissolved load and suspended sediment load for 302 rivers in the global data set for which data on both load components were available. No clear trend is apparent, although some evidence of a positive relationship exists. The absence of a clear relationship between the magnitude of dissolved and suspended sediment loads for this sample of world rivers can be accounted for by the different sets of factors controlling the magnitude of the two load components and by contrasting response to individual controls. Thus, whereas a clear positive relationship between annual dissolved load and annual runoff has been noted in Fig.2(a) no such simple relationship exists for suspended sediment loads (cf. Walling & Kleo, 1979). For example, Douglas (1967) suggests that the relationship between annual suspended sediment load and annual runoff is positive for runoff values <50 mm and >400 mm, whereas an inverse relationship operates at intermediate levels of runoff. Lithology may also exert

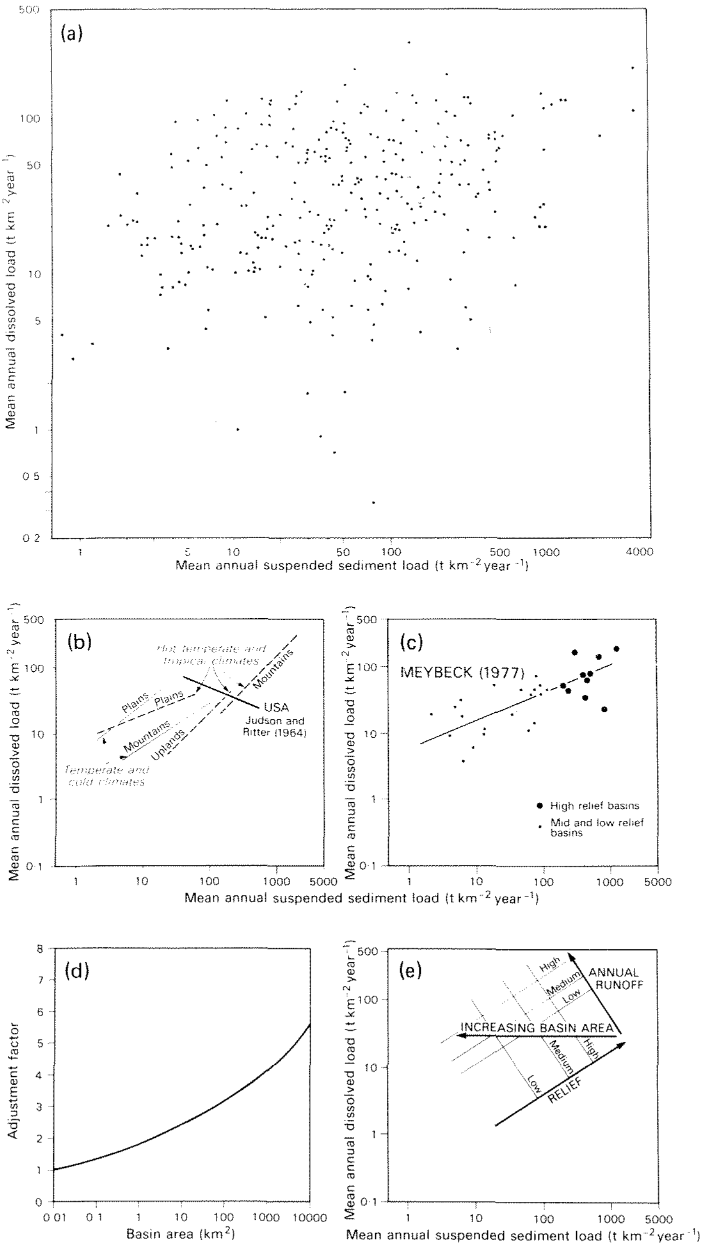

FIG.6 The relationship between the magnitude of dissolved and suspended sediment loads. Data from the global data set have been plotted in (a) and relationships suggested by data presented in Strakhov (1967), by Judson & Ritter (1964) and by Meybeck (1977) are illustrated in (b) and (c). (d) provides a possible indication of the adjustment necessary to standardise specific suspended sediment yields from basins of different size to an area of 0.01 km^2 and (e) isolates various trends contributing to the scatter apparent in (a).

contrasting controls in that calcareous rocks will frequently produce high dissolved loads, whereas the lack of surface runoff may result in relatively low suspended sediment loads.

Basin area may also exert a strong influence on the relative magnitude of the two load components. An inverse relationship between specific sediment yield and basin area has been widely documented and ascribed to a decrease in sediment delivery efficiency as drainage area increases (e.g. ASCE, 1975), but no such trend exists for dissolved load. Thus, specific dissolved load might reasonably be expected to remain essentially constant as drainage area increases, whilst the sediment yield declines, producing an increase in the relative importance of the dissolved load component. Taking the proposal of ASCE (1975) that the logarithmic relationships between specific sediment yield and basin area and between the sediment delivery ratio and basin area typically exhibit a negative exponent of -0.125, Fig.6(d) provides a tentative indication of the adjustment factor necessary to standardise values of suspended sediment yield to a basin area of 0.01 km^2.

Following the discussion of Meybeck (1977) and developing the comments introduced above, it is possible to suggest that the scatter in the relationship between the magnitude of dissolved and suspended sediment loads presented in Fig.6(a) evidences several trends. Basin relief exerts a major influence on both dissolved and suspended sediment loads and available evidence suggests that both components increase as relief increases (Fig.6(e)). If this effect is removed, it is possible to consider the influence of annual runoff and in this case it may be proposed that, whereas dissolved loads increase with increasing annual runoff (cf. Fig.2(a)), suspended sediment loads frequently decline (Fig.6(e)). This latter trend accounts for the inverse relationship between the magnitude of dissolved and suspended loads advanced by Judson & Ritter (1964) (Fig.6(b)). By considering the yields from large drainage regions, rather than individual drainage basins, Judson & Ritter (1964) were effectively holding relief constant and emphasising the influence of variations in annual runoff between the regions. Semiarid regions exhibited maximum suspended sediment loads and minimum dissolved loads whereas dissolved loads increased and suspended sediment loads, declined in regions with increased runoff. Finally, it can be suggested that increasing basin area will frequently cause a decline in suspended sediment load with no associated change in the dissolved load (Fig.6(e)).

Figure 7 presents the relationship between the magnitude of the suspended sediment/dissolved load ratio and mean annual runoff for the global data base. Values of the ratio range from in excess of 100 to <0.05 and the particulate component exceeds the dissolved component in more than 60% of the cases. Considerable scatter is evident, but there is some evidence of an inverse relationship between the magnitude of the ratio and mean annual runoff at the global scale. This conforms to the findings of Langbein & Dawdy (1964) for the USA and may be explained by the clear positive relationship between annual dissolved load and annual runoff coupled with the lack of any well-defined simple relationship between suspended sediment load and runoff or perhaps a tendency for sediment loads to decrease with increasing runoff (cf. Fig.6(e)).

It is important to recognize that the data presented in Fig.7 do not themselves provide a meaningful basis for evaluating the relative efficacy of mechanical and chemical denudation. In the first place, only a proportion of the total dissolved solids load of a river will represent the products of chemical weathering of soil and rock. Other sources include atmospheric inputs (wet and dry fallout) the contribution of atmospheric CO_2 in the production of HCO_3^-, and pollution. Meybeck (1979) has estimated that the two former sources account for approximately 15% and 30% respectively of the total dissolved load transported from the land surface of the globe to the oceans and that pollution increases this total load

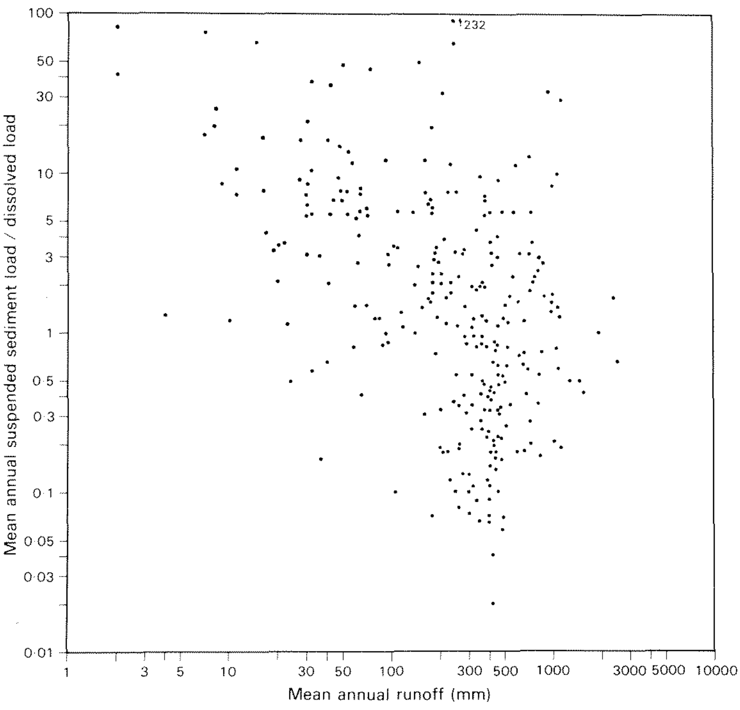

FIG.7 The relationship between the mean annual suspended sediment/dissolved load ratio and mean annual runoff exhibited by the global data set.

by *c.* 12%. In many rivers, therefore, only about 50% of the total dissolved load may be attributable to chemical weathering, and this proportion will be even smaller for rivers draining crystalline rocks. In the case of the suspended sediment load, there are many problems in attempting to link local erosion rates and downstream sediment yields (cf. Trimble, 1981; Walling, 1983). Evidence suggests that in many locations as little as 10% of the total particulate material eroded within a drainage basin may find its way to the outlet, and Fig.6(d) attempts to indicate the adjustment factor that may be necessary to estimate local upstream erosion rates from measurements of downstream sediment yield undertaken on large rivers. Taking these findings, it may be suggested that mechanical erosion is of considerably more importance in landscape development than indicated by a simple comparison of particulate and dissolved loads. The global ratio of particulate to dissolved load transport of 3.6 introduced earlier may need to be increased by an order of magnitude in order to produce a meaningful estimate of the relative importance of mechanical and chemical erosion.

Significant contrasts also exist in the variability of annual suspended sediment and dissolved loads and in the relationship between load and annual runoff. Figure 8 compares the relationships between annual suspended sediment and dissolved load and annual runoff for three rivers in contrasting climatic zones. In the Rivers Creedy

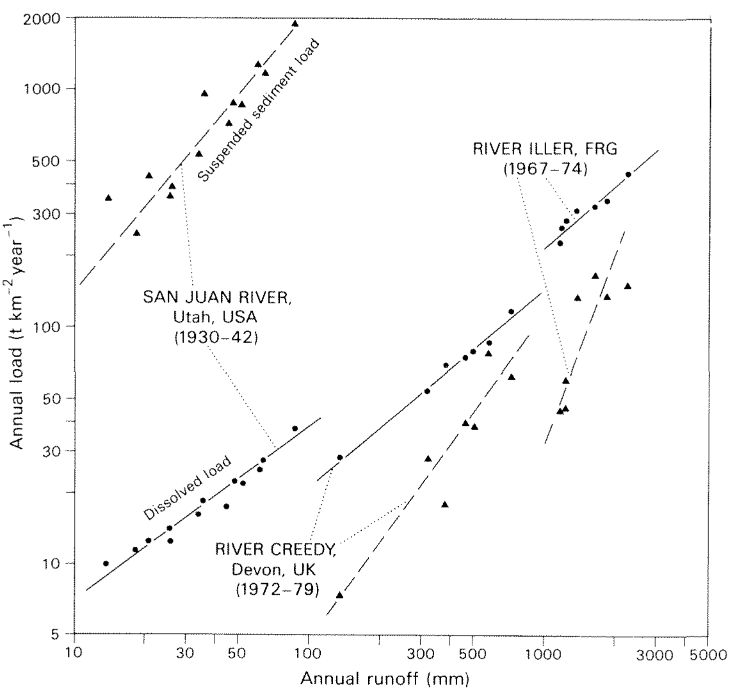

FIG.8 A comparison of the relationships between annual dissolved and suspended sediment loads and annual runoff for three rivers in contrasting morphoclimatic zones.

and Iller, dissolved loads exceed particulate loads, whilst the particulate component is dominant in the San Juan River. In all three rivers, the exponent of the relationship between sediment load and annual runoff is >1.0, whereas values of <1.0 have been shown to be characteristic of the dissolved load relationship (Fig.5). Sediment loads therefore exhibit greater variability than dissolved loads on an annual basis and are more responsive to variations in annual runoff and to extreme events due to the positive relationship between suspended sediment concentration and discharge.

CONCLUSION

Although this global analysis of dissolved loads is necessarily restricted by the limited availability of data in both space and time and by its generalized approach, some meaningful patterns are apparent. The production of an acceptable map of global variations in dissolved loads must, however, await the extension of measurement activity to areas of the world for which little or no data are available, and further multivariate analysis of the influence of climate, geology and other physiographic factors would be facilitated by the collection of data from relatively small basins exhibiting essentially homogenous conditions. Moreover, extension of such a study to consider individual ions as well as the total solute content would provide further information on the relative importance of these controls in influencing various solute sources. It is to be hoped that data collection and processing activities will expand over the next decade and that more detailed analysis will extend and improve our current knowledge of the dissolved loads of rivers.

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