

A quantitative assessment of the nutrient phosphate transported by particles in a tropical river

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SUMMARY

An assessment is presented of the importance of the silt-bound phosphorous as a plant nutrient in a major river of Papua New Guinea. The availability of this nutrient was tested using an algal bioassay. It was essential for this to differentiate the particle sizes since clay sizes ($< 4 \mu\text{m}$ diameter) possessed $\times 10$ the amount of available P than did larger particles.

Combining these data with previously published models for the amount of transported suspended load produced a quantification of the P nutrient transport. For the delta region where most of the river's productivity is located, the suspended load portion was substantially more important than the dissolved portion, but these portions were similar to each other half way along the catchment for where it is proposed to build a large dam. The data enabled useful statements to be made concerning the environmental impact of the dam.

KEY WORDS : Suspended silt — Phosphate — Algal bioassay — Papua New Guinea.

RÉSUMÉ

ESTIMATION QUANTITATIVE DU PHOSPHATE ASSIMILABLE TRANSPORTÉ PAR LES PARTICULES DANS UNE RIVIÈRE TROPICALE

On présente une évaluation de l'importance du phosphore lié à la vase, comme élément nutritif dans un grand fleuve de Papouasi, Nouvelle-Guinée. La disponibilité de cet élément a été testée en utilisant la technique de bioessai. Pour cela, il a fallu faire une distinction entre les différentes tailles des particules, parce que les particules d'argiles ($< 4 \mu\text{m}$ diamètre) possèdent 10 fois plus de phosphore disponible que les plus grandes particules.

Ces données ont été appliquées à un modèle qui prédit la quantité de matériel transporté en suspension, afin de calculer les quantités de phosphore transporté par ces particules. La quantité du matériel en suspension était beaucoup plus importante que la partie dissoute dans le delta, où la productivité du fleuve est la plus importante. A mi-chemin du fleuve, où la construction d'un grand barrage est envisagée, les quantités de phosphore dissoutes et en suspension étaient semblables. Sur la base de ces données, il est possible de faire des considérations concernant les effets du barrage sur l'environnement.

MOTS-CLÉS : L'argile en suspension — Phosphate — Biotests sur les algues — Nouvelle Guinée.

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INTRODUCTION

It has become increasingly appreciated over the last decade that the amount of nutrients transported by suspended particles in rivers can be of great biological importance in the nutrient economy of the receiving standing waters (GOLTERMAN, 1975a, 1975b: 407-413).

Usually this is understood to mean the inorganically associated nutrients rather than those organically combined. But since similar physico-chemical bondings can occur with the organic particles as with the inorganic ones, functionally it is not possible to distinguish these pools clearly. However, it has usually been accepted that the inorganic pool, is more important than the organic pool, the latter often tending to consist of relatively refractory material yielding primary nutrients only after a lengthy period of bacterial decomposition, if it does so at all (WETZEL, 1975: 543-549).

In spite of the manifest importance of silt loadings in rivers there are very few quantitative assessments of the nutrient transported in this way. The reason must be partially due to the technical difficulties involved in deciding what is really metabolically available nutrient. This concerns the manner and strength of the bondings.

The bonding of NH_4^+ and NO_3^- to inorganic particles is fairly uncomplicated, and both radicals are readily liberated by ion exchange reactions. The amounts of NH_4^+ and NO_3^- which can be extracted from silt into 1 mol l^{-1} KCl by the standard soil methods may reasonably be considered as available to organisms, assuming the ambient concentration of these radicals is low enough to allow for net exchange to solution. However, the relative amount of silt-transported nitrogen is far less than for the phosphorous, and so is ecologically less significant in this respect.

The difference is due to the bonding of orthophosphate being much more complex than for the N. There are a variety of chemically definable P pools (cf. GOLTERMAN, 1973) but the main one is due to the ready co-precipitation of orthophosphate with, and adsorption onto, hydrated metal compounds. In natural waters these are largely Fe compounds, though Al can sometimes be significant. There will not be any stoichiometric relationship between the orthophosphate and Fe.

Since such precipitates must be deposited over surfaces the availability of the PO_4^{3-} as a nutrient from this source might also be expected to be a function of surface area. It follows that small diameter particles with large surface area: volume ratios will consequently carry more P per unit weight than will large diameter particles with lower

surface area: volume ratios. This feature is amplified by clay particles being electro-chemically active and able to bind ions far more than can larger particles. Such properties, together with the fact that the smaller the particle the more readily it will remain in suspension and be transported, mean that it is essential to differentiate the contribution from the various particle sizes when calculating the nutrient effects of suspended load.

In view of the complexity of the P pools many workers, as for this account, have resorted to algal bioassay to assess this nutrient's availability. Some caveats associated with this technique are discussed below.

THE LOCATION

Taking the above factors into consideration a study has been made of the P transported in the Purari River (Papua New Guinea) (Fig. 1). This river is in the humid tropics, it drains a densely forested catchment and has a very high silt load (mean approx. 250 mg l^{-1}). It is large, with a mean annual discharge of 2500 $\text{cm}^3 \text{ s}^{-1}$ and a catchment area of 33000 km^2 .

The interest in this river was initiated because it was required to assess the ecological importance of a proposed large dam which was thought would restrict the amount of silt transported to ecosystems below the dam, and, by trapping the silt behind the dam, permit excessive primary production within the planned impoundment.

METHODS

The surface of the river bed is highly unstable, and particles move into suspension from it depending on the prevailing discharge which can vary through an order of magnitude during the day. Samples were taken from the surface of the river bed for experimentation on the assumption that this material was functionally inseparable from that which could be filtered from the water but which was too difficult to accumulate in large quantities for the desired analyses. The particle size distribution will of course be different in the two situations but this does not influence the experiments reported here.

Fifteen samples from along the river (Fig. 1) were mixed together and a single large sub-sample of this treated as follows: A separation of particles was made by simple resuspension in distilled water and allowing separation by gravity along measuring cylinders. Subsamples were then taken at different levels, working from the top downwards. The actual size distribution of particles separated in this way was measured in a Coulter Counter using an electro-

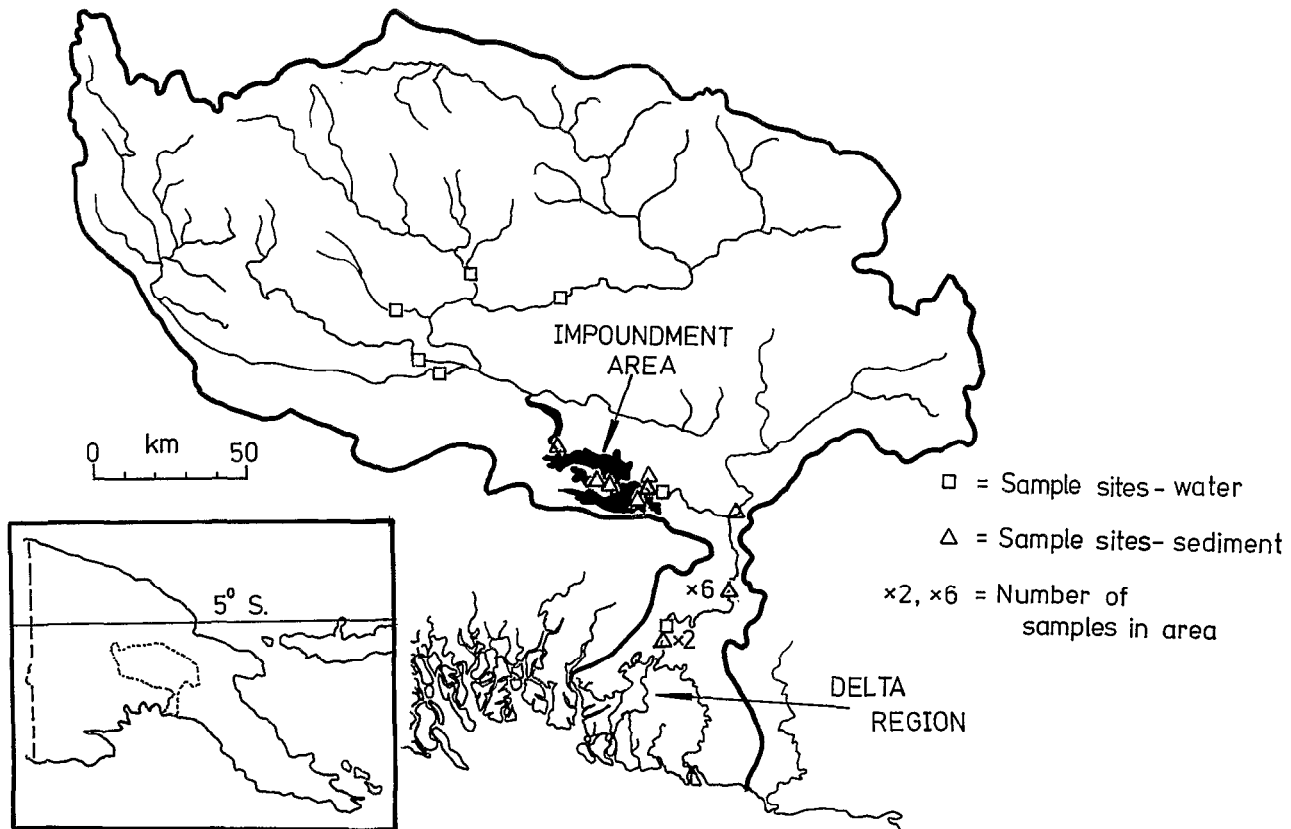


FIG. 1. — Map showing sampling stations and location of proposed dam on the Purari River. Inset: The position of the catchment in Papua New Guinea

lyte of 2 % NaCl. No dispersant was used (contrary to conventional soil grain size analysis) because the particle size distribution approximating to the natural conditions was required, irrespective of whether the particles were really aggregations of smaller ones or not. Further methodological details are given by VINER (1982).

A standard acid extraction with 1 mol l⁻¹ H₂SO₄ was made on these fractions after accumulating them onto membrane filters. This removes orthophosphate associated with the Fe hydroxides. This phosphate may be considered loosely bound and therefore of possible biological significance (GOLTERMAN, 1973).

After filtration, the filtrate was analysed for PO₄-P by the molybdate blue method and for Fe by absorption spectroscopy.

The extracted samples, now on the filter, were allowed to take up phosphate from standard solutions containing 1 mg l⁻¹ PO₄-P so as to see to what

extent the elimination of Fe had on the phosphate uptake capacity.

A parallel algal bioassay was done in 250 ml Erlenmeyer flasks using *Stichococcus chodati* (Ulotrichales; unicellular). This is a fast growing species of undemanding nutrient preferences. The basic nutrient medium used was Gorham's ASM-1 (GOTHAM *et al.* 1964). Controls were (a) algae + P deficient medium (for minimal growth), and (b) algae + complete medium (for maximum growth). Other flasks contained algae + sediment of known air dried weight + P deficient medium. All flasks had other nutrients present in excess. The flasks were illuminated at 85 μ Einsteins cm² sec⁻¹ on a rotary shaker moving at 75 r.p.m. Growth was monitored by methanol extracted chlorophyll-a until maximum yield was attained (about 3 weeks) in the flasks containing sediment.

To assess the quantitative importance of silt-born phosphate monitoring of the dissolved ortho-

TABLE I

Summary of dissolved orthophosphate data (from VINER, 1979) for the Purari River sampled at various locations separated into upper (tributaries), middle and lower locations within the catchment. See text and figure 1. All values in $\mu\text{g PO}_4\text{-P l}^{-1}$

	Number of Samples	Range	Mean	Standard Deviation
Highland tributaries.	10	1.9-6.5	4.16	1.61
Wabo Dam Site.....	25	0.5-2.7	1.57	0.47
Mapaio Village.....	14	0.3-1.6	1.00	0.34

phosphate concentration in the Purari River was also carried out. The results of this are reported fully in VINER (1979) and are summarized here (Table I). They are based upon samples taken at stations in the Highland tributaries, at the proposed Wabo dam site about half way along the catchment, and in the Delta region (Fig. 1).

The nutrient work was combined with a sediment transport study (PICKUP, 1977, 1980) so as to allow calculations for the P budget. PICKUP based his computer programme for the model for the transport of silt on that devised by the U. S. Army Corps of Engineers (1974, 1977) which has also been used successfully by THOMAS and PRAHSUN (1977) and COMBS, THOMAS and RUSSO (1977) in flumes and natural rivers.

RESULTS AND DISCUSSION

These are summarised in Figure 2 and Table 1, and are as follows:

The extracted amounts of Fe increased very steeply with decreasing particle size, but calcium extracted at the same time showed no such relationship. In Figure 2 this is expressed as a surface area: volume ratio to accentuate the surface area function. Were the relationship to be only a function of surface area a straight line graph would result, which apparently is not the case. However the data are insufficient to differentiate whether such a relationship may hold for grain sizes which are smaller than half way through the silt range ($< 15 \mu\text{m}$ diameter).

The orthophosphate extracted together with the Fe also increased with surface area but there was not a constant ratio between them, suggesting that although there is some correlation between phosphate and iron the relationship is not a simple one.

The algal bioassay showed markedly greater phosphate nutrient potential for the smaller particle sizes, the curve being similar in form to the Fe extraction and PO_4^{3-} re-absorption ones. There are some obvious limitations to the bioassay method,

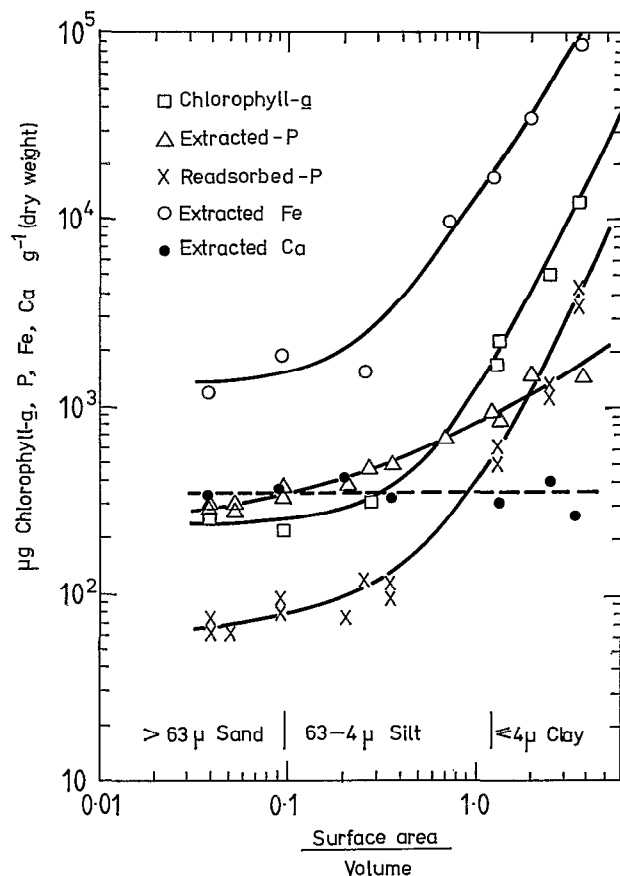


FIG. 2. — Graphical presentation with respect to sediment particle size of the orthophosphate, iron and calcium extracted with $1.0 \text{ mol l}^{-1} \text{ H}_2\text{SO}_4$, and the amount of orthophosphate resorbed after this extraction.

The amount of chlorophyll-a yield using an algal bioassay on unextracted sediment is also shown

the most important being the uncertainty as to whether the results obtained are merely appropriate for the test organism used, and so may not be used to generalise to the field situation. One has therefore to choose a test organism which is not known to have unusual nutrient or growth characteristics. In practice the potential error arising from using a single organism is likely to be small. The bioassay monitors the maximum biomass yield, and there may well be differences for this between the test organism and a natural community, but such disparity will be due to the organisms' differing efficiencies for nutrient uptake. This will only be expressed at low nutrient concentrations when approaching exhaustion of the nutrient pool and the cessation of growth. Thus the final yield difference would only be a small portion of the total biomass.

It must be emphasized that the bioassay gives an estimate of the maximum potential nutrient availability. The real amount may be less than this, but such a difference is probably less for the smaller grains than for the larger ones because of the ease with which the smaller particles will remain in the zone of phytoplankton growth and hence in a situation to yield phosphorus to metabolism.

The phosphorus within the bioassay algae could not be determined separately from that of the sediment particles. However, in the control culture where there was no sediment, but where growth was unrestricted by nutrients (which were supplied in excess), the P to chlorophyll-a ratio was 0.81 ± 0.03 ($n=5$). For the exponential growth phase in the cultures supplied with sediment it is probably fair to assume that a similar algal P:chlorophyll-a ratio existed. In which case the equivalent of about 80 % of the recorded weight of chlorophyll was phosphate taken up from the sediment. Thus the chlorophyll curve shows that the algae could use substantially more phosphate from the smaller sediment particles than would have been deduced from the acid extraction.

Two factors may have been influential in this. Firstly, sorption phenomena of phosphate with clays and sediment can take some time to reach equilibrium, the duration depending upon the nature of the material. Only 2 to 3 hours were given for extracting the Purari material which may not have been long enough for complete extraction. By contrast the bioassay took about 3 weeks.

Secondly, the acid extraction does not incorporate organically associated phosphorus. When in P depleted conditions, as in the bioassays, algae commonly produce phosphatase enzymes capable of breaking down 'organic' phosphates. Such enzymes are not inactivated by the presence of sediment (GOLTERMAN 1973). Further, the bioassays were not axenic. Abundant bacteria were present, although only one algal species, which could have contributed to organic breakdown. No analysis of organic material was made upon the different particle sizes, but analysis of Kjeldahl nitrogen for non size fractionated samples yielded $859 \mu\text{g N g}^{-1}$ (dry weight), indicating a substantial quantity of organic material present. The disparity between the chlorophyll yield results and the extractable P results could therefore be due to 'organic' phosphate.

It is probably unwise to seek a simple relationship between the phosphate which was reabsorbed and the other data. It likely only shows that the adsorption sites, of whatever sort, are not eliminated by the Fe previously extracted, and that there still remains a strong surface area influence. After acid extraction the nature of these remaining adsorption

sites need not necessarily be similar to those of the unextracted material.

When the bioassay information was combined with a sediment transport model (Table I) the nutrient P transported by silt to the mangrove delta system of the Purari river was found to be between 192-1400 t.y⁻¹. This accounts for most of the total input since the dissolved orthophosphate load was found to be 50-88 t.y⁻¹. A major but smaller proportion of silt P contributed to the impoundment, should it be built, was estimated at 42.6-305 t.y⁻¹. The dissolved P contribution to here of 79-157 t.y⁻¹ is thus in the same range as for the silt.

The higher dissolved component at the dam site station should be noted. There is some evidence that there could be progressive adsorption of phosphate onto the silt during transport downstream. Table 2 shows dissolved orthophosphate concentrations for places distributed along the Purari catchment; the highland tributaries, the dam site, and a village located just out of the tidal conditions of the delta (see map, Fig. 1).

The sampling was done at different times whenever opportunity arose, which was at random with respect to flow of water and to weather conditions. A Student *t*-test was applied to find if there is any statistically significant difference between the mean concentrations at the three locations (with the highland tributaries being grouped together as one location). This showed a 99.9 % probability of a real difference between each location. Unfortunately an insufficient number of samples of silt were taken to see whether this result was reflected in the silt. The full analytical data are already reported in VINER (1979).

CONCLUSIONS

For the prediction of the nutrient environmental impact of silt it is essential to discriminate between the particle sizes. The clay sizes may be a small portion of total weight of the suspended load but they can bear orders of magnitude greater amounts of P nutrient per gram than larger sizes. Also the clay sizes are likely to remain in suspension more effectively.

There is a very close association of phosphorus with the iron, which would be expected if there was a precipitation of hydrated iron oxide, which adsorbs phosphate, over the grain surfaces. However, there was no apparent surface area relationship with calcium, suggesting therefore that co-precipitation of phosphate as the Ca-P mineral hydroxyapatite was of no importance. The calcium in this instance is more likely to have been from limestone which is abundant in the catchment.

Because of the complicated nature of phosphate association on particles a bioassay method can be very effective in estimating nutrient effectiveness of particles. As used here it showed that the chemical extraction clearly underestimated the nutrient capacity.

Current hydrological and sedimentological computer programmes, based upon simple field measurements of discharge rates and suspended load weight, can predict how much of sand, silt and clay is transported through any portion of a river or through a lake upon it. This allows for the above nutrient information to be used to calculate nutrient budgets which incorporate the suspended load of rivers. This has been done for the Purari River,

one of the major waterways of Papua New Guinea, and has provided useful background information relating to the environmental effects of establishing a large dam on the river. The total inorganic P loading upon the lake would be 102-462 tonnes, or 0.42-1.6 g m⁻²y⁻¹. Between about one and two thirds of this P would be particle borne.

Assuming that fluctuations in discharge from the lake will be reduced to a minimum by efficient management the dissolved and clay bound phosphate would be sufficient to maintain the present delta ecosystem and its associated high productivity of fisheries.

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