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I. ABSTRACT

A brief account is given about the distribution and cycle of phosphates in the sea in the temperate and tropical waters, the recent investigations in the Indian waters being discussed in some detail. The data on the total phosphorus content of the waters along the Indian coast show that the values for total P are generally more than 3 times and sometimes nearly 40 times the values given by Harvey for the waters of Western English Channel. A hypothesis is presented which would explain the observed cycles of the phosphate–phytoplankton relationships on the Indian coastal waters to some extent, particularly in the Malabar waters. While the monsoon high values are caused by the release of locked-up phosphates in the bottom, it is suggested that a continuous source of replenishment is essentially to be presumed for the long duration of the simultaneous maxima of both phosphates and phytoplankton during the monsoon. Three such sources of replenishment are indicated. The post-monsoon 'erratic' fluctuations in phosphates and phytoplankton can be explained as due to a somewhat cyclical repetition of the usual phenomena of utilization, regeneration and phytoplankton production, until low levels of both phytoplankton and phosphates are established during the subsequent pre-monsoon months.

II. Introduction

An important problem that has for sometime been engaging the attention of marine biologists all over the world is the phosphate cycle. Our present knowledge of this subject is mostly derived from the investigations in the temperate and colder waters. The most intensive work in this direction has been done by the workers in the Marine Biological Laboratory at Plymouth, the standardisation of the methods for the estimation of minute concentrations of phosphates in sea-water by Atkins being actually the beginning of the studies on the phosphate in sea. On the American continent a very large amount of work has been done in recent years at various institutions, such as the Woods Hole Oceanographic Institution, Scripps Institution of Oceanography, California, and the Oceanographical Laboratories of the University of Washington, Seattle. In the Southern hemisphere, some work has been done in Australia (Dakin and Colefax, 1935, Rochford, 1951). A certain amount of work seems to have been done by the Japanese workers, but most of their work has been published in the Japanese language and translations of the same are not easily available.

As a result of all these investigations to date a good deal of knowledge has been gained on the distribution and the cycle of phosphates in the sea and their role in the fertility of the coastal and offshore waters. This knowledge is, however, still very far from complete.

III. Review of Literature

(*a*) *Temperate and cold waters.*—In 1923 Atkins developed the method for phosphate estimation (" the Atkins-Deniges method ") and applied it to the study of the variation of phosphate in a single station in the English Channel. Subsequently the distribution of phosphates have been studied in the three oceans not only by several individual workers in isolated localities but also by expeditions which have worked a number of stations (Sverdrup *et al.*, 1942). The observations have, however, been more or less scattered in nature. But these have given some idea about the horizontal and vertical distribution of phosphate in the open ocean.

Phosphorus exists in the sea in inorganic as well as organic forms and in solution as well as particulate form. This forms an important constituent of all living matter which must collect it from its environment. With the destruction of living matter, it must return to the environment in some form or the other. In sea-water phosphorus is present mainly as phosphate-ions whose distribution is markedly affected by organic agencies. Phosphate-phosphorus has in fact been found to be one of the substances that may limit production of plant life. While much is known about the dissolved inorganic phosphate in sea-water our knowledge is still scanty concerning the amounts of phosphorus present as particulate or dissolved organic phosphorus.

The largest volume of literature is available on investigations in localized areas, the object of these investigations being to get a fairly complete picture of the seasonal cycle of changes in phosphate and also to obtain an idea of the important controlling factors. The seasonal variations of phosphate at a position in the English Channel has been followed at monthly intervals for a number of years by the workers in the Plymouth Laboratory (Harvey, 1955). Dakin and Colefax (1935) have studied the seasonal variations in the phosphate in the waters off New South Wales, Australia. A study of the seasonal variations over a five-year period in the surface waters of the San Juan Channel, Friday Harbour, Pacific Coast, has been made by Phifer and Thompson (1937). Several other workers have studied similar seasonal variations in the phosphate content along with planktological and other marine biological studies. One main thesis that has been brought out as a result of all these investigations is that there is a regular seasonal cycle of phosphate in the temperate and colder waters from year to year. Highest concentrations are found in winter and lowest in spring and early summer. The low concentrations in the summer months are attributed to the outburst of phytoplankton populations which utilise the phosphate for growth and multiplication.

In the course of the studies on the seasonal cycles of phosphates in the different regions it was found necessary to know about the sources of availability of the phosphates and how the concentration in the sea is regulated so as to produce well-defined seasonal cycles. As the study of the seasonal cycles have, in most cases, been restricted to the coastal waters—both from the point of view of convenience of observations as well as from the necessity to exploit these waters for the fishery wealth—the first and most important hypothesis put forward was that relating to the importance of rivers and other forms of land drainage in contributing to the phosphate content of the neritic waters (Harvey, 1927, p. 174; Sverdrup *et al.*, 1942, p. 213). But Riley's (1937) work on the influence of the Missisipi river drainage on the phosphate content of the Northern waters of the Gulf of Mexico has shown that river waters do not contribute appreciably to the phosphate content of the Gulf waters. Recently, Graham, Amison and Marvin (1954) in their studies on the phosphorus content of waters along the West Coast of Florida have also shown that the rivers on this coast opening out into the Gulf do not contribute in any measurable degree to the phosphate content of the waters of the Gulf. One of the main reasons as stated by Harvey (1955) is that in general, river waters do not have a high phosphate content—hardly exceeding 0·16–0·32 μg. at. P/L, unless heavily polluted.

The importance of bottom deposits as a source of phosphates has been stressed by a number of workers. In certain shallow areas phosphatic concretions with high phosphorus concentrations have been found. The mode of origin of these concretions is not known (Sverdrup *et al.*, 1942). Only in recent years attempts have been made to study the mechanism of exchange of phosphates between the bottom deposits and the overlying column of water. Among these may be mentioned the works of Hutchinson (1941) in Linseley Pond, Connecticut, Mortimer (1941 and 1942) in English Lakes, Miller (1952) on Biscayne Key, Florida and the work of Rittenberg, Emery and Orr (1955) in the basins off the Californian coast. Rochford (1951) as a result of his work on the Australian estuarine waters has provided a considerable volume of data on the phosphates and has given an indication of the nature of changes taking place in the bottom muds leading to the release of phosphates to the overlying water. Attempts have been made by Stephenson (1949) and Carritt and Goodgal (1954) to study, under controlled laboratory conditions, the mechanisms involved in the release of phosphates from the muds. The interchange of phosphate between the offshore sea floor and the water above has also been indicated by Cooper (1951) during his studies on the chemical properties of sea-water in the neighbourhood of the Labadie Bank. Evidence of regeneration from the bottom was seen in this case where the bottom was muddy and none where it was otherwise.

The biological aspect in the cycle of phosphates may be briefly summarised as the utilisation of phosphates by the phytoplankton and subsequent regeneration, probably through bacterial activity from the dead and decaying matter. A good summary of the biological factors involved in the phosphate cycle in the sea has been given by Harvey (1955). Harvey has stated that

(i) Some species of phytoplankton can absorb phosphate as quickly as they need it for rapid growth when its concentration exceeds a threshold value whose magnitude lies in the region of 0·52 μg.-at. P/L;

(ii) They can continue absorption of phosphate and its conversion into organic phosphorus compounds throughout day and night; and

(iii) They can build up a reserve of storage product which cannot be used directly for further synthesis without prior dephosphorylation and that light sets free or activates the phosphorylase concerned.

The role of bacteria in the phosphate cycle in the sea has been worked out by Renn (1937) and Waksman and Renn (1936). The same has been explained by the following hypothesis by Stephenson (1949) with reference to his experimental work on aerated estuarine mud samples and sea-water:

"(i) When mud and sea-water are mixed by stirring, or when muddy sea-water is filtered, or when the filtrates are agitated, bacteria are destroyed;

(ii) Their protoplasm, rich in phosphorus, is broken down by living bacteria, with release of phosphate;

(iii) The bacteria grow, using the remaining organic matter, now poor in phosphorus; and

(iv) During growth, they reabsorb the phosphate previously released."

In a study of the cycle of phosphorus in the Western basin of the North Atlantic, Seiwell (1935), Seiwell and Seiwell (1938) have shown that the sinking of the decomposing plankton in sea-water results in oxygen consump-

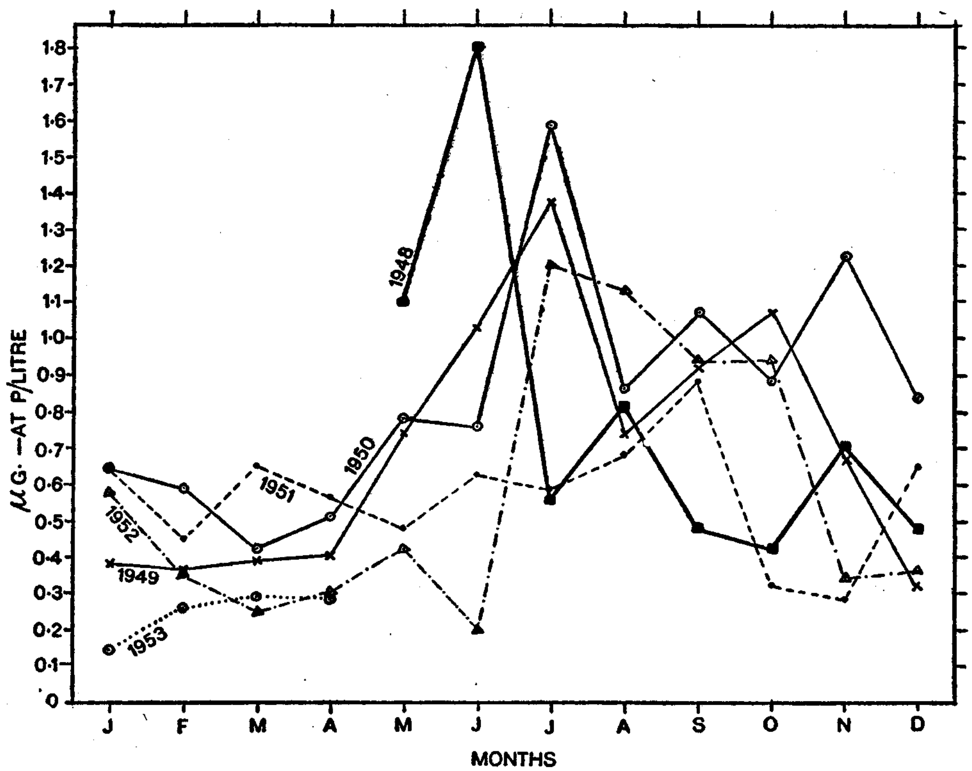

FIG. 1. Showing the mean monthly values for phosphates in the surface waters off the Malabar Coast during the years, 1948 to 1953.

tion and phosphate liberation. Cooper (1935) and Waksman, Hotchkiss, Carey and Hardman (1938) have also shown that bacteria liberate phosphate from dead zooplankton added to sea-water.

(*b*) *Tropical waters*.—The amount of published work on the subject of the phosphate cycle in tropical waters is very small in comparison with the publications on the temperate waters. Relatively speaking, systematic hydrological investigations in the tropical waters are more or less of recent origin which explains the smaller number of publications from this region. Most of the work done so far relates to inshore waters. Among the earliest publications may be mentioned that of Orr (1928–29) on the waters in the neighbourhood of the Great Barrier Reef, off the North-East Australian coast. Delsman's paper on the plankton in the Java Sea (1939) includes a short discussion on the phosphate cycle in those waters. Tham Ah Kow (1953) has worked on the physical, chemical and biological conditions of the waters of the Singapore straits in which he has included studies on the phosphate content also. Some work has been done in the coastal waters around Zanzibar by Newell (Private communication) but the same does not appear to have been published so far. Investigations on the chemistry of the Caribbean and Cayman seas by Rakestraw and Smith (1937) and on the Venezuela Bay by Redfield (1955) have given us some idea of the distribution of phosphates in the tropical waters in the Western hemisphere. During recent years the work of the Pacific Oceanic Fishery investigations group in the equatorial and tropical areas of Pacific Ocean (1954) have furnished some data on the trends in the distribution of phosphates in these grounds. The reports published by them were intended more to present a tabulated data of the various oceanographic factors including phosphates and dissolved oxygen. The phosphate content in the surface layers in most of the stations worked by them ranged between 0·25 and 0·82 μg.-at. P/L. Values as low as 0·06 μg.-at. P/L have been encountered in a few instances. A relatively higher concentration of phosphates about the equator, in the surface layer, has been shown to be an evidence for equatorial upwelling.

Investigations in the Indian waters have been restricted to localized areas along the coast and the earliest paper giving values for phosphate content is that of Chidambaram and Menon (1945) for the Malabar Coast. The paper by Bal *et al.* (1946) gives a systematic account of the physico-chemical conditions of the waters of the Arabian Sea near the Bombay Harbour during the year 1944–45. The seasonal distribution of phosphates has been given along with other factors for this area. The scope of these data is restricted as the station in which the samplings were done was very much influenced by the waters from inside the harbour and a certain amount of pollution is indicated.

The investigations by Jayaraman (1951) on the waters of the Bay of Bengal represents the earliest attempt to understand the distribution and seasonal cycle of nutrients—particularly phosphates—on the east coast of India. The studies were initiated as a preliminary to understanding the fundamental problem of the productivity of the tropical inshore waters. Observations were carried out over a period of 17 months and this author has been able to observe seasonal variations somewhat similar to those observed in the temperate waters. Very high phosphate values have been observed in the months, May–September, the range of values being 0·5–3·0 μg.-at. P/L the highest value being in the month of August. October–March seems to be the period of phosphate minima in this area, the lowest value being in November. This work has also shown an inverse correlation between phosphates and dissolved oxygen in these waters.

The observations in this region were continued by Ramamurthi (1953) who found that in 1951–52, the seasonal differences were not as marked as before. The range of phosphate values in this case was 0·3–1·2 μg.-at. P/L the maximum being in May and minimum in February. Ramamurthi has also recorded the vertical distribution of the dissolved phosphate at 12 fathoms.

In the southern section of the east coast, studies were made by Jayaraman on the waters of the Gulf of Mannar and Palk Bay near Mandapam (1954) and by Chacko, Valsan and Pillai (1954) on the waters of the Kundugal Channel of the Gulf of Mannar. The mean monthly values for phosphates obtained by Jayaraman in the vicinity of Mandapam varied between 0·15 and 0·30 μg.-at. P/L in the Gulf of Mannar and between 0·12 and 0·25 μg.- at. P/L in Palk Bay. The phosphate content of these waters is, in general, low and also there does not appear to be any marked seasonal cycle. There is no instance, however, when these waters have been completely exhausted of phosphates. Chacko, Valsan and Pillai (1954) and Chidambaram, Rajendran and Valsan (1951) have obtained somewhat similar values for the waters of the Gulf of Mannar in the stations different from those worked by Jayaraman. In the Kundugal Channel, Chacko *et al.* have indicated the possibility of the waters deriving the nutrients from the land source.

On the Malabar Coast detailed investigations on the hydrology and plankton of the inshore waters have been carried out by George (1953). He has given a discussion of the phosphate cycle in those waters and has correlated the same with the occurrence and seasonal cycle of plankton. He has observed very high phosphates in the waters after the onset of the monsoons and attributes it to the churning of the mud bottom during this stormy period. He also suggests that the mountain streams opening out in the neighbourhood might be exerting some influence. The occurrence of high values during the monsoon period has been observed by him in all the years of his study. In the post-monsoon months, George has observed variations in phosphate content differing from year to year. George has also observed that the bottom samples of water invariably showed a high value throughout the year and found that the differences were more striking during the monsoon months and during the period of mud bank formation. The normal range of phosphate values, according to George, was 0·35–0·56 μg.-at. P/L which increases substantially during the monsoon. The occurrence of high phosphate values has been shown to be a regular feature and it is interesting to note that there was a swarming of diatoms in all these months. The usual phenomenon of depletion of phosphates during the period of diatom outburst observed in temperate waters has not been noticed by this author in the monsoon period. In the post-monsoon months, however, he has observed variations in phosphate content corresponding to the periodic outbursts of diatoms. Thus the variations in phosphate, according to George, has shown different trends in monsoon and non-monsoon months. Panikkar and Jayaraman (1953) have suggested that besides the local turbulence, the northerly transport of the waters (during S.-W. Monsoon) which have upwelled near the Maldive-Laccadive ridge might be one of the factors contributing to the high phosphate content of the waters of the Malabar Coast.

A detailed account of the role of bottom muds in the phosphate cycle of Malabar Coast has been given by Seshappa (1953) and Seshappa and Jayaraman (1956). The factors involved in the retention and release of phosphates from the mud have been examined in these papers. It has been found that there are differences in the nature and composition of the muds between monsoon and non-monsoon months. High moisture and silt content and high concentration of phosphates in the interstices of the muds were the most important features during the pre-monsoon months. From the pre-monsoon to the monsoon months, there is a sudden reduction in the values for all these factors with a high increase of phosphates in the overlying column of water.

IV. Observations on Total Phosphorus Content

The importance of the total phosphorus estimations (combined organic and inorganic) in a study of phosphate cycles in different waters has been indicated by Redfield *et al.* (1937), Armstrong and Harvey (1950) and

Ketchum *et al.* (1955). Harvey (1950) has stated that total phosphorus values in the waters help to distinguish one water mass from another and the phosphorus content is a measure of its potential fertility having a relation to annual production of vegetation and zooplankton. Soule *et al.* (cited by Ketchum and others 1955) have also used total phosphate values to identify different water masses in the North Atlantic. In reviewing the work on the phosphate cycle in Indian waters, it seemed useful to include a short account of our preliminary studies in the distribution of total phosphorus in the waters along the Indian Coast. The data included in this section have not been published before and are based on analyses of samples collected from 42 stations, in each of the periods July–August and in January–February—the former, representing the period of South-West Monsoon and the latter, North-East Monsoon. Table I shows the values for total P in the coastal waters in the different latitudes. The determination of the total P was done according to the procedure described by Rochford (1951). The method used for deriving the average values for each latitude has been described by Jayaraman and Gogate (1956, under publication). An examination of the total P values of the waters of the west and east coasts reveals the following features:—

In the Period, July–August

1. The total P values along the different latitudes vary between 2·1–12·8 μg.-at. P/L on the West Coast and 1·7–3·0 μg.-at. P/L on the East Coast.

2. On the West Coast, the values are higher north of 13° N. Latitude than south of it.

3. On the East Coast, the highest value for total P is seen in 19° N. In general, the distribution of total P is more uniform on the East Coast than on the West Coast.

In the Period, January–February

1. The range of values from latitude to latitude is from 1·1–5·5 μg.- at. P/L on the West Coast and from 1·1–4·7 μg.- at. P/L on the East Coast.

2. Highest value is found in 22° N. on West Coast and in 15° N. on the East Coast.

3. Between 19° and 22° N. the values are much higher on the West Coast.

4. South of 18° N. the values are nearly of the same order of magnitude barring a few deviations.

Suryanarayana Rao (Private communication) has also obtained similar high values from an inshore station near Calicut. In both the periods, there

TABLE I

Distribution of salinity and total phosphorus in the coastal waters around India

Period	N. Lat.	West Coast (Arabian Sea) Salinity S‰	West Coast Total phosphorus μg. P/L	West Coast Total phosphorus μg.-at. P/L	East Coast (Bay of Bengal) Salinity S‰	East Coast Total phosphorus μg. P/L	East Coast Total phosphorus μg.-at. P/L
July-August 1952 (S.-W. Monsoon)	22	..	..	..	..	..	..
	21	..	..	..	31·46	56	1·8
	20	..	..	..	26·53	53	1·7
	19	..	..	..	25·82	93	3·0
	18	36·53	99	3·2	30·66	74	2·4
	17	36·18	105	3·4	32·68	71	2·3
	16	36·35	99	3·2	33·21	71	2·3
	15	35·55	87	2·8	33·82	65	2·1
	14	36·00	198	6·4	34·43	62	2·0
	13	34·61	397	12·8	33·91	68	2·2
	12	..	..	..	..	..	..
	11	32·50	81	2·6	34·09	71	2·3
	10	33·57	81	2·6	33·57	81	2·6
	9	34·09	65	2·1	33·73	62	2·0
	8	34·96	81	2·6	33·73	71	2·3

Period	N. Lat.	West Coast (Arabian Sea) Salinity S‰	West Coast Total phosphorus μg. P/L	West Coast Total phosphorus μg.-at. P/L	East Coast (Bay of Bengal) Salinity S‰	East Coast Total phosphorus μg. P/L	East Coast Total phosphorus μg.-at. P/L
January-February 1953 (Close of N.-E. Monsoon)	22	36·33	171	5·5	..	..	..
	21	..	71	2·3	30·62	56	1·8
	20	..	71	2·3	29·92	56	1·8
	19	35·24	90	2·9	33·61	50	1·6
	18	35·71	62	2·0	33·60	68	2·2
	17	35·88	37	1·2	34·67	34	1·1
	16	34·32	71	2·3	33·90	81	2·6
	15	33·96	50	1·6	34·67	146	4·7
	14	33·44	50	1·6	34·58	68	2·2
	13	33·26	78	2·5	34·31	56	1·8
	12	33·78	34	1·1	34·14	40	1·3
	11	..	..	..	34·14	43	1·4
	10	33·61	53	1·7	33·44	59	1·9
	9	33·44	43	1·4	35·19	43	1·4
	8	33·35	62	2·0	35·53	37	1·2

is no correlation between the values for total P and salinity. In other words, as stated by Armstrong and Harvey (1950), the geographical distribution of total P does not coincide with the geographical distribution of salinity in the present instance also.

Armstrong and Harvey (1950) have stated that the total P in Western English Channel is as little as 0·32 μg.-at. P/L while in other areas it is double or more than double. The present set of values are more than 3 times and sometimes nearly 40 times this value. Kalle (cited by Armstrong and Harvey, 1950) has shown that in the turbid waters of the southern North Sea a large quantity of phosphorus is present as detritus—giving values as high as 1·3–1·6 μg.-at. P/L at some positions.

V. GENERAL REMARKS

The following important points have been brought out in regard to the distribution of phosphates in the tropical waters as a result of the recent investigations in the Indian waters. It should, however, be mentioned that these should not be taken as representing truly the conditions in the more open waters of the tropical regions.

In most of the typical temperate waters (*e.g.*, English Channel) the maximum values for phosphates in the surface waters has been below 0·7 μg.-at. P/L. Much higher values have, however, been reported in some exceptional instances such as the waters of the San Juan Channel (Phifer and Thompson, 1937). In the waters along the Indian Coast—both in the West Coast and in some areas on the East Coast—the upper limit of values have been found to be much higher than in the temperate waters. The maximum values for the phosphate content of the waters of Malabar Coast have been shown to be 2·94 μg.-at. P/L (George, 1953) and 3·00 μg.-at. P/L for the waters off the Madras City—East Coast (Jayaraman, 1951). The mean monthly values fluctuate between 0·10 and 1·80 μg.-at. P/L in the Malabar waters and between 0·30 and 1·20 μg.-at. P/L in the Madras waters. In the waters near Mandapam, however, the range is 0·15–0·26 μg.-at. P/L. It could thus be seen that the phosphate concentrations of the surface waters along the Indian Coast are much higher or nearly of the same order of magnitude as those of the typically temperate waters.

It is also to be mentioned that as in the temperate waters, the phosphate values show distinct seasonal trends, more particularly in the waters along the Malabar Coast. The seasons in our waters are, however, closely related to the prevalence of the monsoons, especially the South-West Monsoon along the West Coast of India. Along the East Coast, the Madras waters have shown a marked seasonal cycle of phosphates during one year but the same has not been repeated in a subsequent year. The phosphate content of the waters near Mandapam has, however, not shown any marked seasonal trend. It is, therefore, observed that although the actual concentrations of phosphates have been high in a number of areas, marked seasonal cycles have been consistently obtained only in the waters along the Malabar Coast. From the point of view of marine biology, the knowledge of marked seasonal cycles of phosphates, as well as other nutrients is of great interest as it would help in the prediction of seasons of high and low organic production.

The most important correlation that has been so far established between the biology of the sea and its phosphate content is in relation to the production of phytoplankton which, in its turn, limits the quality and quantity of the animal life in any marine area. An inverse relationship between phytoplankton and phosphate content has been observed to be the rule in temperate waters. In the Malabar waters, George (1953) observed that phytoplankton peak was during the monsoon months, but the phosphates also showed peak values during all these months; following the monsoon months, there were minor peaks of phosphates and also phytoplankton. Prasad (1954) states that relationships other than mere utilization and production must be involved in the phosphate cycle in the waters near Mandapam. He also states (1956), "It is often believed that the normal relationship between plankton and nutrients is inverse, although the converse has also been observed (Riley, 1941). This assumption of inverse relationship is based primarily on the observations made in temperate areas, and very little information is available on the nature of relationship that exists between plankton and the various nutrient salts in the tropical areas." Some light is thrown on this problem by the intensive investigations at Calicut (George, 1953; Seshappa, 1953 and Seshappa and Jayaraman, 1956).

The facts at present known about the phosphate levels and the biological cycle in the inshore waters at Calicut (Malabar Coast) are as follows:—

1. During the South-West Monsoon (June–August) both phosphates and phytoplankton are very high; at the commencement of the monsoon there is a heavy mortality of the bottom animals and the sea is rough throughout the period.

2. During the post-monsoon months, the sea is calm. Resettlement of bottom animals takes place, and there are minor peaks of both phytoplankton and phosphate values, the fluctuations being "erratic".

3. During the following pre-monsoon months, the sea is calm and both the phytoplankton and phosphate values are low. The bottom deposits

contain high quantities of adsorbed and interstitial phosphates, the latter being low during the monsoon and show " erratic " fluctuations during the post-monsoon months.

Seshappa and Jayaraman (1956) have suggested that the monsoon increase of phosphates is due to the agitation of the bottom deposits releasing the interstitial phosphates; the sources of phosphate in the deposits are mentioned to be the decaying material resulting from the large-scale mortality of bottom animals and also the laterite silt brought in by land drainage.

The fertilization experiments in the Scottish lochs (Marshall and Orr, 1948) have shown that when large quantities of phosphates are added to sea-water and other conditions are suitable, phytoplankton blooms follow within a few days of fertilization, the phosphate values falling steeply within a couple of weeks and the plankton values also coming down a little later. This loss of phosphates is due partly to utilization by phytoplankton and partly to adsorption and interstitial retention in the bottom deposits. Hayes and Coffin (1951) added radioactive phosphorus to lakes with the objective of studying the cycle of added phosphate. They found that the photosynthetic activity of the phytoplankton removed only a part of it. Precipitation as ferric phosphate according to them might have removed another part, sorption on to suspended solids, a third portion and lastly lateral diffusion and eddy mixing might have effected further reduction of phosphate. These authors have stated that all these factors are of importance and the relative contribution of each of these factors is dependent, to a large extent, on local conditions.

The plankton bloom in Malabar Coastal waters continues practically throughout the monsoon season and if the phosphate increases in the water column during this period were only limited to what has accumulated up to the commencement of the monsoon as a result of the local turnover, it would appear likely that the quantities thus released would be insufficient to cause the continuous high phosphate values in the waters during the monsoon months and also to sustain such a high level of plankton production. Additional and extraneous sources must, therefore, be presumed. Evidence has already been mentioned about two such sources, namely land drainage and mortality of bottom animals. A third source of replenishment is possible in the onshore transport of the upwelled water near the Maldive-Laccadive Ridge (Panikkar and Jayaraman, 1953). It seems obvious, in any case, that unless a continued replenishment of the phosphates is available, the local accumulation by itself would be insufficient to sustain high phytoplankton and phosphates for such a long period.

The various "erratic" relationships noticed by George (1953) can be explained by the following assumptions which appear to be reasonable on the basis of the literature reviewed in this paper.

1. In general, a high phosphate production is followed by a high phytoplankton production, the ascending curves for the P and phytoplankton being parallel to each other until optimum levels are reached.

2. If there is no continued replenishment of the phosphate the phytoplankton maximum is of a short duration; otherwise it is of a longer duration.

3. When the phytoplankton maximum is reached and there is no further replenishment of the phosphate, utilization will exceed availability and phosphate will show a downward trend resulting in the well-known normal reciprocal relationship of low phosphate and high phytoplankton.

4. This stage is eventually followed by decrease in phytoplankton as a result of grazing by zooplankton and also death.

5. Regeneration *in situ* of phosphate following (4) due to liberation of the phosphatases during the decay of the plant cells.

6. Repetition of phytoplankton bloom, phosphate utilization, etc., as above, subject to other conditions being suitable.

7. Return of stable conditions at the sea bottom and establishment of a low level of phytoplankton production along with low levels of phosphates; locking up of phosphates in the bottom deposits.

8. Release of the nutrients from the sea bottom and initiation of the annual cycle.

In Fig. 1 are shown the monthly mean values of the phosphates in the surface waters of the Malabar Coast from 1948–53. The trends shown in the different years appear to fit in well with the above hypothesis.

VI. Summary

1. A brief account is given about the distribution and cycle of phosphates in the sea in the temperate and tropical waters, the recent investigations in the Indian waters being discussed in some detail.

2. Some original observations on the total phosphorus content of the waters along the Indian Coast from 84 stations covering two seasons of the year are also presented. The values for total phosphorus are seen to be more than 3 times and sometimes nearly 40 times those given by Armstrong and Harvey (1950) for the Western English Channel.

3. A hypothesis is presented which would explain the observed cycles of the phosphate–phytoplankton relationships on the Indian Coast to some extent, particularly in the Malabar waters. While the monsoon high values

of phosphates are caused by the release of locked-up phosphates in the bottom, it is suggested that a continuous source of replenishment is essentially to be presumed for the long duration of the simultaneous maxima of both the phytoplankton and phosphates during the monsoon. Three such sources of replenishment are indicated. The post-monsoon 'erratic' fluctuations in phosphates and phytoplankton can be explained as due to a somewhat cyclical repetition of the usual phenomena of utilization, regeneration and phytoplankton production, until low levels of phosphates and phytoplankton are established during the subsequent pre-monsoon months.

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