

THE BEHAVIOUR OF DISSOLVED SILICON DURING ESTUARINE MIXING

II. PRELIMINARY INVESTIGATIONS IN THE VELLAR ESTUARY, SOUTHERN INDIA

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A preliminary investigation was made in February 1968 of the relationship between the concentration of dissolved silicon and chlorosity in the Vellar Estuary. The Vellar River water and the sea water at the mouth of the estuary differed in concentration of dissolved silicon by about two orders of magnitude and the extent of dilution with fresh water was the dominant influence on the distribution of dissolved silicon in the estuary. Biological effects appear to have been unimportant except towards the mouth of the estuary where the concentration of dissolved silicon was lowest. In the upper estuary, where Vellar River water mixed with water of intermediate chlorosity from the lower estuary, there was some removal (on average not more than 10%) of the dissolved silicon entering in river water. The extent to which further mixing was accompanied by removal is uncertain. The distribution in the lower estuary could be interpreted as indicating either that there was further and more substantial removal, or that there was a considerable contribution of fresh water from irrigation canals which had a lower concentration of dissolved silicon than that in the Vellar River water, or that both these processes occurred. Some implications of these alternative interpretations are discussed.

INTRODUCTION

In the first paper of this series (BURTON, LISS and VENUGOPALAN, 1970) it was shown how a study of the behaviour of dissolved silicon in estuarine mixing processes could add to our understanding of the processes that remove dissolved silicon from the ocean. In this paper the results are given of a preliminary investigation of the distribution of dissolved silicon and its relationship with fresh water dilution in the Vellar Estuary, Southern India.

PLAN OF SURVEY

The Vellar River enters the Bay of Bengal near to Porto Novo, about 50 km from Pondicherry. A map of the estuary is given in Figure 1. Close to its mouth the Vellar Estuary connects with an area of backwaters extending southwards

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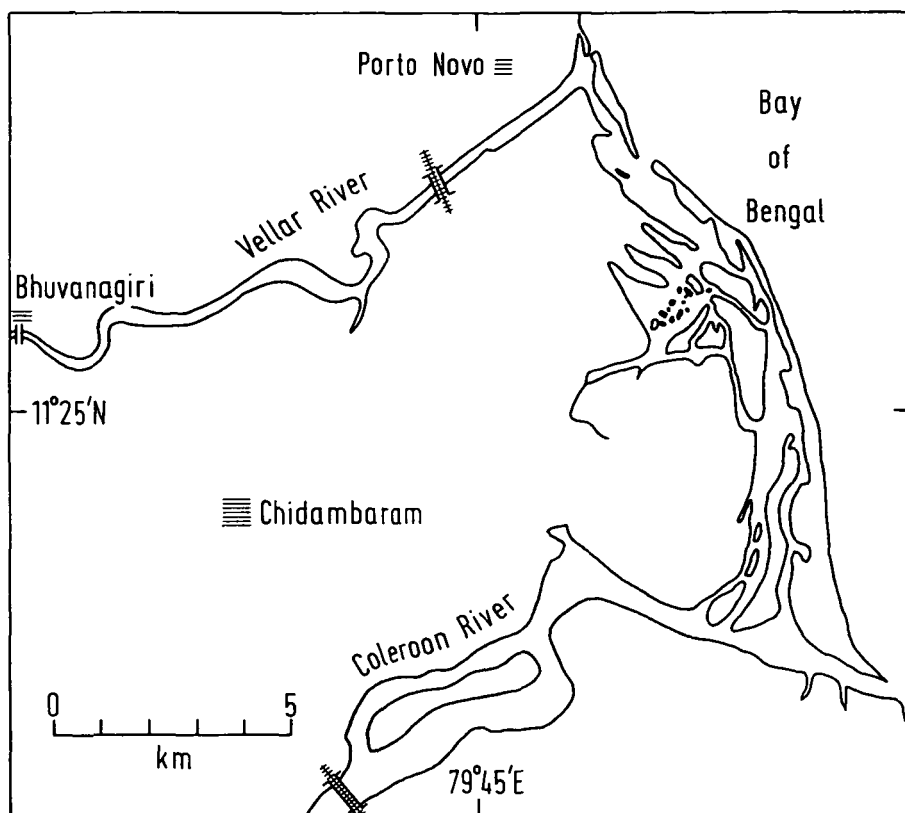


Figure 1. Map of the Vellar and Coleroon Estuaries.

to the estuary of the Coleroon river, some 15 km away. The hinterland of this region is irrigated by a complex system of canals, some of which discharge into the Vellar Estuary.

Conditions in the estuary show a wide seasonal variability. At the time of the monsoon in late autumn the estuary may be flushed with fresh water but with the cessation of flooding the salinity at the mouth rises again to values above 30‰. DYER and RAMAMOORTHY (1969) made detailed hydrographic studies in the period from January to February, 1967 and found that, associated with a reduction in river flow over that period, the characteristics of the estuary changed from those of a salt wedge type to those of a well stratified type.

The present work was undertaken during February and early March, 1968. The river flow was low throughout this period, January having been virtually rainless, and conditions were thus uniformly similar to those during the later period of the survey by DYER and RAMAMOORTHY (1969). The main survey was made from 7. to 15. February. Different sections of the estuary were sampled on successive days; before and during the survey regular samples were taken of sea water at the mouth of the estuary and fresh water from the Vellar

River at Bhuvanagiri (close to the road bridge shown in Figure 1). Shortly after the main survey, samples were collected from the backwater and some of the main irrigation canals. The survey was intended to examine the main features of the distribution of dissolved silicon as part of the work of the marine station on the productivity of the estuary and its relationship with hydrographic and chemical features. It was more specifically intended, however, to give information on the extent of any removal of dissolved silicon during estuarine mixing and it was accordingly important to obtain samples well distributed over the entire salinity range. At the time of the survey, water of salinity below 10‰ was found only in the upper part of the estuary (beyond the railway bridge shown in Figure 1). In this section surface samples distributed through the salinity range were obtained from points chosen on the basis of *in situ* measurements of salinity. In the lower estuary, surface and subsurface samples were taken at the fixed stations established for regular hydrographic measurements (DYER and RAMAMOORTHY, 1969).

METHODS

Samples were collected and stored in polypropylene or polyethylene bottles. Within five hours, at most, of collection, a known volume of the water sample was filtered through a weighed membrane filter ("Oxoid", retentivity 0.5 to 1.0 μ). The filter was dried at 110°C and reweighed. Aliquots of the filtrate were analysed without delay for dissolved silicon by the method of MULLIN and RILEY (1955); in the context of this paper dissolved silicon refers to the forms which are reactive in this procedure. Analyses of replicate samples showed satisfactory precision (coefficient of variation 0.92%) but it was found difficult to eliminate a slight tendency for silicon to dissolve from the glass sinter supporting the filter. Regular checks of this effect were made by analysing filtered water before and after refiltration. The contamination was usually less than 5 $\mu\text{g Si/l}$ with a maximum of 20 $\mu\text{g Si/l}$. This degree of contamination was negligible for most of the samples but lower values were probably systematically overestimated to a significant though slight extent. Salt error corrections were determined initially by analysing aliquots of the samples with the addition of a known amount of silicon. Average correction factors derived from these measurements were applied to later samples. Unfiltered aliquots were used for the determination of chlorosity (STRICKLAND and PARSONS, 1965).

RESULTS AND DISCUSSION

The results for dissolved silicon concentration and chlorosity, obtained in the survey, are shown in Figure 2. The Vellar River water at Bhuvanagiri had a chlorosity of less than 0.1 $\text{g/l}_{(20)}$ and a dissolved silicon concentration of $18.4 \pm 0.3 \text{ mg Si/l}$. The results in Figure 2 show the inverse relationship of dissolved silicon concentration and chlorosity that would be expected for mixing of river water rich in dissolved silicon with sea water of much lower dissolved silicon content. It is apparent, however, that the values do not fit a linear relation corresponding to simple mixing of Vellar River water and the most saline water present at the mouth of the estuary. There are two effects that could explain

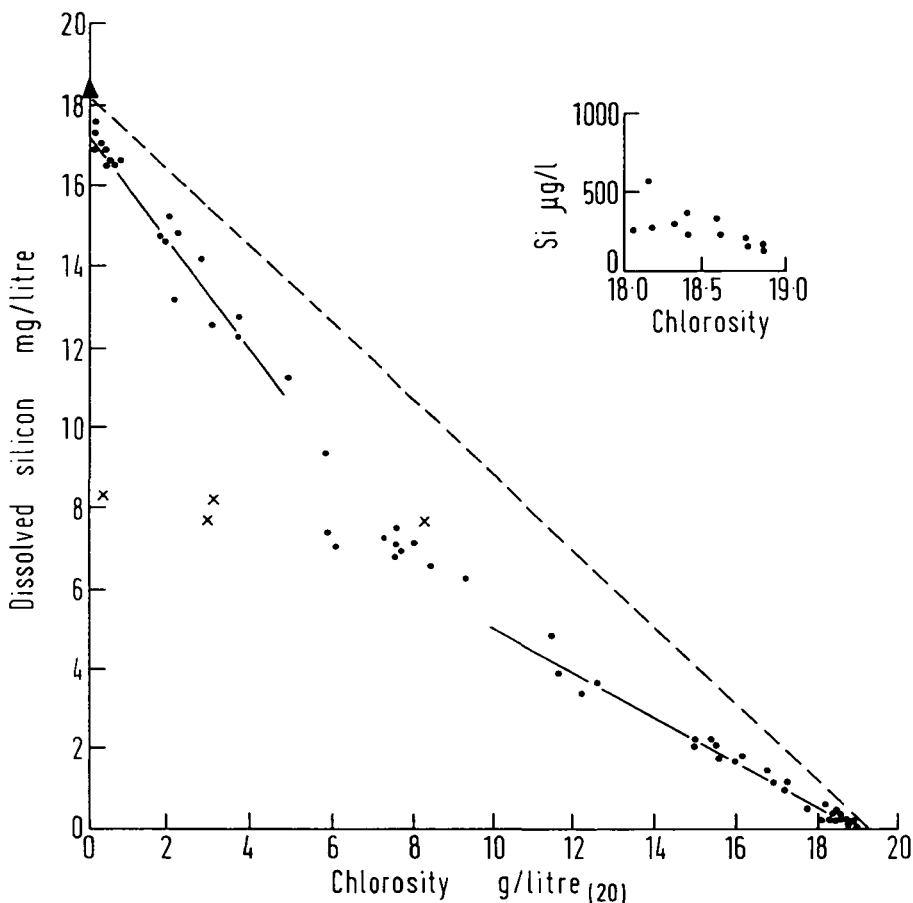


Figure 2. The relationship between chlorosity and concentration of dissolved silicon in the Vellar Estuary. The full lines show the regressions of dissolved silicon concentration on chlorosity for the ranges indicated and the broken line shows the theoretical relationship for simple mixing of Vellar River water with surface inshore water of the Bay of Bengal. The insert shows the results for samples of chlorosity greater than 18 g/l₍₂₀₎, on an expanded scale.

- Water from the estuary
- × Water from the irrigation canals
- ▲ Water from the Vellar river

this deviation from a linear relationship. It could arise if mixing of the two components were accompanied by removal of dissolved silicon or it could be due to the presence in the lower estuary (where all samples of chlorosity greater than 5 g/l₍₂₀₎ were collected) of fresh water from another source with a dissolved silicon concentration lower than that in the Vellar River.

Interpretation of the results on the basis solely of the first explanation would indicate removal within the estuary of about 40% of the dissolved silicon entering in river water. The average amounts removed, as calculated for various ranges of chlorosity are as follows:

Chlorosity range (g/l ₍₂₀₎)	0-5	5-10	10-15	15-19
Average removal Si (%)	10	36	43	41

On this basis a large increase in the extent of removal would thus have occurred early in the mixing processes in the lower estuary. Several considerations suggest, however, that fresh water from another source may have had an effect and, therefore, that these calculations on the basis of two mixing components could lead to overestimation of removal.

Following the survey of the estuary, samples of water were collected from four of the irrigation canals entering the lower estuary. The results are also shown in Figure 2. One sample had a chlorosity and dissolved silicon concentration typical of the estuarine water. The other three samples had lower chlorosities and each had a dissolved silicon concentration which was substantially below that for Vellar water of similar chlorosity. A significant contribution of fresh water with these characteristics would have markedly affected the situation in the estuary. Some information on the implications of an interpretation on the basis that such a process was dominant in affecting the distribution of dissolved silicon in the lower estuary was obtained from a statistical analysis of the results.

The regression of dissolved silicon concentration on chlorosity for samples of chlorosity greater than 10 g/l₍₂₀₎ was:

$$\text{Si}(\mu\text{g/l}) = 10690 - 562 \text{ Cl/l}_{(20)} \quad (1)$$

This regression ($r = -0.99$, d.f. = 27) is shown in Figure 2. The inclusion of samples with chlorosities between 5 and 10 g/l₍₂₀₎ alters the regression only slightly. The relationship in the lower estuary between chlorosity and dissolved silicon concentration was thus similar to that which would arise from the dilution of sea water with fresh water having a dissolved silicon concentration intermediate between that of the Vellar River water and the water of the irrigation canals *i.e.* a mixture of water from these sources. From the limited information on the concentration of dissolved silicon in the canal waters it may be calculated that their contribution to the volume of fresh water entering the lower estuary would have had to be about twice that of the Vellar River in order to account for the observed distribution on the basis of mixing without further removal of dissolved silicon. Unfortunately, it is not possible to compare this estimate with figures for actual discharges. Discharges from the river and the canals are controlled by sluices. During the dry season the water flow is very low and probably comprised mainly of leakage water. The discharge records do not provide a basis to judge the relative importance of the sources under these conditions.

In view of this uncertainty it is not possible to conclude which factor, removal of dissolved silicon or dilution with canal water, had the greater influence on the observed distribution. The good fit to a linear relationship of the results for the lower estuary would be consistent with the view that the presence of canal water was an important factor but it does not establish that this effect occurred. If removal were the sole factor responsible, then the fraction removed must have increased markedly at a chlorosity of about 6 g/l₍₂₀₎ which coincides with that for the least saline water present in the lower estuary. Clarification of the relative importance of the two factors is particularly needed because estuarine removal of a substantial fraction of the dissolved silicon

entering in river water, if established, would be an unusual phenomenon (see BURTON *et al.*, 1970).

The values for chlorosity and dissolved silicon concentration for the samples from the upper estuary (with chlorosities below 5 g/l₍₂₀₎) also showed a satisfactory fit to an inverse linear relationship, the regression being:

$$\text{Si}(\mu\text{g/l}) = 17350 - 1328 \text{ Cl/l}_{(20)} \quad (2)$$

The relationship ($r = -0.97$, d.f. = 17) is similar to that which would be predicted for the simple mixing of Vellar River water with water of the lower chlorosity range found in the lower estuary. It indicates, however, that there was removal in the upper estuary of a small fraction of the dissolved silicon entering in the river water. The extent of removal estimated from this relationship is lower than that calculated earlier on the basis of simple mixing of two components but whatever assumptions are made concerning the origin of water in the lower estuary, the extent of removal in the upper estuary was on average not more than 10%.

Under the conditions prevailing at the time of the survey, water entering the Vellar Estuary through the backwaters was too saline to have significantly affected the distribution of dissolved silicon in the estuary as a whole. Samples collected in the backwater, with chlorosities ranging from 17.58 to 18.66 g/l₍₂₀₎, had dissolved silicon concentrations which accorded with those for samples of similar chlorosity from the estuary. The estuarine water samples of highest chlorosities, from the mouth, showed considerable variation in dissolved silicon concentration over the period of the survey (see Figure 2). These variations may have been associated with biological factors such as the intense outbursts of phytoplankton production which occur in these waters (SAVAGE, 1969). Because the dissolved silicon concentration of the water at the mouth was about two orders of magnitude lower than the concentration in the Vellar River water, variations in its concentration had a negligible effect on the distribution within the estuary as a whole. Regression equation (1), fitted to the values over a wider range of chlorosities, clearly gives an inadequate description of the situation in the mouth waters. The true high chlorosity end-member of the mixing series in the estuary is the surface in-shore water of the Bay of Bengal entering both directly and through the backwater. Results for a profile in the Bay, 3 km beyond the estuary bar, are given in Table 1.

Except at the mouth of the estuary, biological effects on the distribution of dissolved silicon were minor. This is indicated by the dominant influence of fresh water dilution on the distribution and is particularly emphasized by the fact that samples of closely similar chlorosity in the intermediate range,

TABLE 1. Chlorosity and dissolved silicon concentration for samples from inshore water of the Bay of Bengal

Depth m	Chlorosity g/l ₍₂₀₎	Dissolved Silicon μg/l
0	19.36	163
3	19.32	210
6	19.32	202
9	19.34	217
11	19.36	217

obtained at different depths in different parts of the estuary, showed similar concentrations of dissolved silicon.

The measurements of suspended matter in the estuary showed that the amounts of total particulate material ranged from approximately 12 to 45 mg/l with an average value of 20 mg/l.

Four samples of water collected from the Coleroon River shortly after the survey were also analysed. The results were:

Chlorosity (g/l ₍₂₀₎)	0.10	0.10	0.85	0.87
Dissolved Si (mg/l)	10.6	10.5	9.7	10.0

The concentration of dissolved silicon in the Coleroon River was thus considerably lower than that in the Vellar River and somewhat similar to that in the fresh water of the irrigation canals draining into the Vellar Estuary. Much of the water in the canals is derived from the Coleroon but this similarity would not necessarily have been expected in view of the distance involved and the complex processes that intervene; more work is needed before it is possible to comment on its significance.

This preliminary study shows that the extent of fresh water dilution had the major influence on the distribution of dissolved silicon in the Vellar Estuary. There appears to have been removal in the upper estuary of a small fraction (on average not more than 10%) of the dissolved silicon entering in the Vellar River. More substantial removal may have occurred during further mixing but the results for the lower estuary could be explained by the presence of fresh water from the irrigation canals. No conclusive interpretation can be made without direct information on the water discharges to the estuary. If removal were small then a fuller understanding of what appears to be a complex situation in the estuary might be achieved by the use of the natural labelling of the sources of fresh water with different concentrations of dissolved silicon to trace the relative importance of these sources as influences on the composition of the water in the estuary under various circumstances. This information could be of basic importance for an understanding of the chemical hydrography and productivity of the estuary and further investigations are being made.

SUMMARY

1. Measurements of dissolved silicon and chlorosity were made on samples collected in the Vellar Estuary in February 1968. Analyses were made also of fresh water entering the estuary and other related samples.
2. There was a difference in dissolved silicon concentration of about two orders of magnitude between the seawater at the estuary mouth and the Vellar River water, the latter containing about 18 mg Si/l. Dissolved silicon concentrations for samples of intermediate chlorosity diverge considerably from a simple inverse linear relationship corresponding to simple mixing of these two components.
3. The observed divergence from a single inverse relationship between dissolved silicon concentration and chlorosity could be due to *either* (a) the removal in the estuary of about 40% of the dissolved silicon entering in river water.
or (b) a major contribution, relative to the total inflow, of fresh water from

irrigation canals, which had a dissolved silicon concentration considerably below that in the Vellar River water.
 or (c) a combined effect of removal and dilution with fresh water from the canals.

It is not possible from the present evidence to conclude which process was dominant in affecting the distribution.

4. In the upper estuary, where Vellar River water mixes with water of intermediate chlorosity from the lower estuary, there appears to have been removal of a small fraction (on average not more than 10%) of the dissolved silicon entering in the river water.

5. Biological effects on the distribution of dissolved silicon appear to have been unimportant except in the mouth waters with low concentrations of dissolved silicon.

6. If further work shows that there is a significant contribution of fresh water to the lower estuary from irrigation canals as well as from the river then the natural labelling of the sources of fresh water with different concentrations of dissolved silicon could provide a means of estimating the relative amounts of fresh water derived from these sources.

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