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THE FBA-WELSH WATER SIMULATION

MODEL OF PHYTOPLANKTON DYNAMICS IN FLUSHED SYSTEMS

Authentication in a Coastal Lagoon

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THE FBA-WELSH WATER SIMULATION MODEL OF PHYTOPLANKTON  
DYNAMICS IN FLUSHED SYSTEM - AUTHENTICATION  
IN A COSTAL LAGOON

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SUMMARY

This article presents the outcome of attempts to simulate the recorded changes in phytoplankton mass of Slapton Ley during a 12-month period (1970-1971) using the FBA-Welsh Water model evolved to anticipate water-quality problems in the proposed Cardiff Bay Barrage. The direct fit proved to underestimate the main summer crop of Anabaena and Peridinium and was unrealistic in failing to exhaust the dissolved inorganic nitrogen and in depleting phosphorus to the limits of detection. However, adding an internal-load component of suitable magnitude not only simulated the scale and timing of the observed summer maximum but nitrogen fell to limiting levels, while the residual phosphate in the lake water was also of the observed order. Subject only to this modification, the Cardiff Bay model proved to be capable of simulating with considerable accuracy, the actual plankton events in Slapton Ley, nearly two decades beforehand.

## INTRODUCTION

As part of its feasibility study and assessment of environmental impact of the proposal to close Cardiff Bay by a barrage, in effect creating a freshwater lake, the Cardiff Bay Development Corporation, through its consulting engineers, Wallace Evans & Partners, commissioned a report from the Association on the prospects for algal growth. This report (1) recognised that the chemical condition of the two major inflows, the Taff and Ely rivers would impart to the lake a high capacity to support algal growth but that the biomass and, indeed the species composition, would be controlled for substantial periods by flushing of the barrage by high fluvial inputs. The implication for water quality is that algal growth would be most apparent at times of greatest public interest in the lake - when the weather is warm and dry.

Following extensive consultations among the Corporation, the Consulting Engineers, the Water Authority and the Association, it was agreed that it would be desirable to translate these possibilities to a computer-based simulation. This was despite the fact that such models are very much state-of-the-art, inevitably oversimplified and, hitherto, had proved scarcely practical. New approaches to in situ growth capacities, in terms of temperature, light and nutrient availability, plus a responsive 'grazing loop' had been used in a recent theoretical discussions of algal dynamics (since published as 2), were available to the Association; coupling this with access to competent programming skills and the powerful mainframe at Welsh Water's Bridgend base made a joint project an attractive proposition. Further funding was made available and within two months, a fully plausible, responsive model was in place which simulated not only the effects of recorded weather, flow patterns and nutrient loads of the Taff and Ely rivers, assembled over the previous twelve years, upon the phytoplankton of a notional lake but it was also used to test the management options (flow regulation, nutrient stripping) by simulation.

These findings were reported early in 1988 (3) and have been used extensively in the planning and design of operational management strategies for the barrage scheme. The unfamiliarity of simulation models of this scale has led, quite properly, to questions about their reliability and, also quite properly, there have been expressions of desire to see some model validation. However, no such further work has been commissioned, nor has the potential for development been practically explored although a scheme to achieve this has been discussed by the partners to the model development. The following authentication has been undertaken on the Association's initiative to illustrate its applicability to the Cardiff Bay problem and to demonstrate its potential for further development.

#### LIMITATIONS OF THE CARDIFF BAY MODEL

It is essential to emphasise certain features of the simulation model which limit its direct application (and, hence, its utility in validation) to other lakes in general. As explained in (1) and (3), the implicit purpose of the predictions was to determine "The worst case" - the phytoplankton would not be more abundant than  $\underline{x}$  under conditions  $\underline{y}$ . In this approach, one assumes phytoplankton grows to its temperature-, light- and nutrient- restricted capacity, for as long as circumstances allow, and that the losses sustained are minimal. Because no thermal segregation is accommodated, because sedimentational removal is excluded and because grazers are supposed to eat only algae and to be resource-regulated entirely by the algal foods available, several major loss mechanisms are excluded. No alga is parasitized or attacked by micrograzers; no alga fails to grow as fast as possible whenever conditions allow; all nutrients are regenerated instantaneously when an alga is consumed. The only controlling mortality that is anticipated is flushing. Whilst this is assumed to be the major source of loss, this model will never describe well events in a long-retention time, deep, stratified reservoir. That will require a rebuild of the fundamental provisions of the model itself: something which has yet to be attempted. Because the model assumes a shallow, frequently

flushed lake, then it is against the plankton performances in such a lake that its authenticity should be judged.

#### THE PROTOTYPE: SLAPTON LEY, DEVON

Fortuitously or otherwise, the Association happened to hold data from Slapton Ley in Devon. They were obtained in happier days of science when its motivation was basic curiosity. As it happened, the pilot attempts lasting about one year to investigate the roles of the hydrobiological inputs, nutrient loads and effects on the unusual temporal distribution of phytoplankton in the Lower Ley led to more detailed work on the lake nutrient budget (4) and, eventually, a university doctorate on the dynamics of the phytoplankton in relation to hydraulics (5). It is the original data that remained the property of the Association and readily to hand for the present purposes. Nevertheless, it is appropriate to record the collaborative nature of the exercise and the role of colleagues at the Slapton Ley Field Centre in collecting the original samples.

Of present relevance are the size of Slapton Lower Ley (see Fig 1) - 0.77 km<sup>2</sup>, its universal shallowness (mean depth, ca. 1.6 m) and its fluctuant storage volume (0.5 - 2.1 x 10<sup>6</sup> m<sup>3</sup>; mean ca. 1.2 x 10<sup>6</sup> m<sup>3</sup>) is small in comparison to its catchment area (46 km<sup>2</sup>). Some 30 to 40 x 10<sup>6</sup> m<sup>3</sup> of water is discharged to the lake annually, over half of it through the Gara River and about two thirds of it between October and March (5). The mean retention time in water is about 16 days on occasions falling to 2-3 days but in summer it can be much longer, approaching infinity. The ley is adjacent to the sea, though this is coincidental to the authentication!

Slapton Ley has several major inflows which load large amounts of N(125-148 g N m<sup>-2</sup>ann<sup>-1</sup>) and P(1.6-2.1 g P m<sup>-2</sup>ann<sup>-1</sup>) (ref 4) though most of this was assumed to be washed, untapped, to the sea Fig 1. It may well be so for the nitrates which remain in solution but there is probably good reason for anticipating that some of the dissolved P brought into the lake might be detained as settled particles of live biomass, detritus and chemical

precipitation.

The phytoplankton of the lake is typically sparse until March or April when there is usually a spring bloom of Asterionella or Stephanodiscus. Brief, small flowerings of other algae follow in May-June before a more sustained build-up of larger, ungrazed algae leads to very large standing crops (see Fig 2) maintaining dominance during the dry weather flow (6). In both 1970 and 1971, the main summer species were Peridinium (sp. not verified) and the filamentous cyanobacterium Anabaena solitaria, which together achieved a maximum recorded biomass equivalent to 538 mg chlorophyll  $\text{m}^{-3}$  in 1970 and 1073 mg  $\text{m}^{-3}$  in 1971. One of the intriguing features of the Ley at that time was, despite the apparent abundance of nitrogen (load ratio; 60-90N: 1P by weight; 130 to 200N: 1P molecular) the relation to typical algal cell requirements (7N: 1P by weight; 16N: 1P molecular), it was usually nitrogen that fell most rapidly towards its detection limits ( $< 2 \text{ mg m}^{-3}$ ) during the summer period. Indeed, dissolved phosphorus concentrations, generally in the range 20-65 mg  $\text{Pm}^{-3}$  during the winter and early spring months of minimal algal growth, increased through summer to concentrations in the large 180-210 mg  $\text{m}^{-3}$ . These observations are supported by the population dynamics of Anabaena solitaria, a well-known nitrogen-fixing organism, which became most abundant during July and August in both years and which carried a high density of nitrogen-fixing bodies, the heterocysts.

That these particular events occurred during the particular period of study is emphasised. The published information in respect of earlier years (eg 6) and unpublished reports of the character of the phytoplankton of Slayton Ley in subsequent years may show significant departures from the present data set and to which the present attempt at simulation applies. In no sense should the situation be judged other than against the recorded changes during 1970/71.

## BUILDING THE SIMULATION MODEL

## RUN 1

Clearly, the requirement to authenticate the simulations of the basic model for Cardiff Bay demanded that adjustments to the model processes should be minimal. In fact, certain deficiencies in the data set and its summer to summer timespan prevented a simple substitution of flow rates and input concentrations of N and P. The conditions introduced are set out in this section.

- (a) The selection of the eight algae included in the simulation runs was changed to suit the typical species composition in Slapton Ley:

Chlorella\*, Stephanodiscus\*, Asterionella\*, Rhodomonas,  
Scenedesmus\*, Anabaena, Microcystis\*, Peridinium.

The species marked \* were in the original model. Appropriate M, S and V values for Rhodomonas and Peridinium were inserted from data in (7). The dimensions of the Anabaena were altered, from the same source, in respect of A. solitaria rather than of A. circinalis.

- (b) Temperatures refer to automatic records at the lake surface: a midday value was selected; though liable to day-time warming and night-time cooling, the choice of day-time temperatures may be the more realistic for calculating growth rate. Complete mixing and the applicability of the surface temperature to the entire water column was assumed throughout.
- (c) No records of cloud cover were available, so  $I_0$  required approximation. A 4/8 cloud cover was assumed to apply at all times, so that  $I_0 = I_{\max} (0.7 \times 4/8) + 0.3 = 0.65 I_{\max}$  for each day calculation.
- (d) All data on flows, chemical concentrations and, indeed, the phytoplankton composition cover the period September 1970 to August 1971. Because the model works on the premise of a small inoculum and a daily rate of change, simulations ideally begin at low biomass periods. A model 730-day period was thus created comprising:

days 1-250: Actual records for second calendar year, days 366-615.

days 251-585: Actual records for period Sept. 1970-August 8 1971.

days 586-730: Actual record of days of first calendar year, days 221-365.

Thus, it will be evident that the simulation run inputs two years of environmental data, the second being identical to the first in every detail. The comparison can only be valid for the period of factual data, ie from day 250 to 600.

Result of run 1 The output of the first simulation run is reproduced in Fig 3. The result was initially disappointing but did show several encouraging aspects, including the clear responsiveness to high winter flows and the seasonal fluctuations in abundance of Asterionella (spring) and Anabaena (summer), whereas the dominance of all peaks by Chlorella and Rhodomonas would indicate that the output was not controlled by the grazing subroutine of the model. The grossly underestimated magnitude of the simulated summer chlorophyll (  $50 \text{ mg m}^{-3}$  cf  $1070 \text{ mg m}^{-3}$  in life and cf. the spring prediction of  $\leq 70 \text{ mg m}^{-3}$ ), was evidently severely constrained by phosphorus availability: (dissolved phosphorus is found to be at zero from April to October) whereas in reality, it was nitrogen that was exhausted in the Ley. Nitrogen fell only sporadically below  $1 \text{ g m}^{-3}$ .

#### MODEL RUN 2

Several experimental runs were conducted in which the model components were varied but the basic provision of the model remained unaltered. Apart from flow displacement, which, by definition, has the anticipated major impact on biomass regulation in a flow-dominated system, only the use of the 'PFlag' in the model invoked a significant response. That is, of the other variables that may be switched on or off in the simulation, phosphorus was the one most frequently controlling biomass when flow was low. Interestingly, the size of the spring crop was little altered but the summer crop could proceed to limitation of light; however, the nitrogen was exhausted and Anabaena become the dominant.



These trials indicated that, at the very least, the original simulations (Model Run 1) had underestimated the P available. The measured concentrations in the inflows and in the lower Ley itself were of dissolved phosphorus; other fractions would have been excluded in the data set without necessarily being unavailable to phytoplankton growth. Moreover, the model inputs take no account of internal loading. Certainly, at the time the original data were collected, no attention was paid to this possibility. Since the early 1970's, of course, extensive work has been carried out on the mechanisms and fractions of internal loading. It is not appropriate to review the findings in any detail beyond that phosphorus can move from the interstitial water of the superficial sediments in shallow, oxic water (8). Two caveats must presumably apply, namely that the phosphorus concentration must be greater in the surface sediment than in the water (9), ie the gradient must be in favour of sediment-->water movement, and, as a corollary, over a full annual cycle, the net load to the sediment can scarcely be less than the import therefrom. Thus, assuming an areal loading rate of not less than  $1.6 \text{ g P m}^{-2}$  and that this was entirely consigned eventually to the sediment, then an internal load would be scarcely likely to exceed the same amount (though it could be argued that release and resedimentation could take place on an unlimited number of occasions). A flux of  $1.6 \text{ g m}^{-2}$  during the 180-day deficiency period shown in Fig 3 is equivalent to a daily flux of  $8.9 \text{ mg P m}^{-2} \text{ d}^{-1}$ , or, on a volume basis, around  $5.5 \text{ mg P m}^{-3} \text{ d}^{-1}$  between day 90 and day 270 of each year. Accordingly, Run 2 was a direct repeat of Run 1 but for the addition of  $5 \text{ mg P m}^{-3}$  each day from day 90 to day 270 (incl.) and from day 455 to day 635 (incl.).

Result of Run 2 Extracts of the output from Run 2 are shown in Fig 4. The spring peak of chlorophyll was extended, still dominated by Rhodomonas and Chlorella, to a maximum of  $105 \text{ mg m}^{-3}$ , while in the summer maximum ( $120\text{-}130 \text{ mg m}^{-3}$ ), though clearly still constrained by P, was now dominated by Anabaena.

## MODEL RUN 3

Following the logic of Run 2, the internal P load was arbitrary doubled to  $+10 \text{ mg P m}^{-3} \text{ d}^{-1}$  for the mid-year periods. This figure cannot be justified on known facts but the assumption of a substantial undissolved P-load or of a more frequent internal recycle would not be unreasonable. Testing of such speculations is one of the advantages that the model set up provides. It would have been possible to test many other internal-load quantities and periods but model run 3 was considered sufficient in the event.

Result of Run 3 Extracts of the Run 3 output are shown in Fig 5. The features are the realistic exhaustion of nitrogen, the summer enhancement of phosphorus to around  $200 \text{ mg P m}^{-3}$  and the production of an Anabaena dominated-biomass maximum of nearly  $900 \text{ mg m}^{-3}$ , supplemented almost exclusively by Peridinium. Only the spring-bloom capacity of  $150 \text{ mg m}^{-3}$  appears to have overestimated (by a factor of 2) the actual recorded events in 1971.

When the relevant section of the predicted chlorophyll output is superimposed upon the trace of measured chlorophylls as in Fig 6, the 'goodness of fit' is readily appreciated. Indeed, it is a coincidence many modelers would be extremely pleased to obtain.

## DISCUSSION AND CONCLUSION

By adjusting the input components to the Cardiff Bay model, in respect of recorded loads of nutrients to Slapton Ley, South Devon, in 1970/71 and of justified assumptions concerning their fate in the lake, the model has been shown to produce a most credible simulation of the biomass and periodicity actually observed at that time. It marginally exaggerated the size of the spring bloom but not its timing, while the 1971 summer maximum was extremely well simulated. Of the eight species introduced into the simulation, the two participating in the summer peak (Anabaena and Peridinium) were correctly discerned through, in reality, Peridinium was the more abundant of the two.

Although the model did not correctly identify the spring dominance of Stephanodiscus, Asterionella, Chlorella and Rhodomonas were the principal subdominants.

This is a satisfying outcome and lends great strength to the claim of the model to simulate natural events. That the first run did not achieve an exact fit and that adjustments were necessary before an acceptable fit was generated does not reduce the utility of the model. It is repeated, the model was not altered, only the variables that were put into it. Models can only ever be as good as the data entered. In this instance, the experimentation with variables until an acceptable fit was generated, has enabled us to learn a little more about the dynamics of the natural system being modelled. This is surely one of the objects of modelling systems at all!

#### ACKNOWLEDGEMENT

Dr Tony Irish and Mrs Margaret Hurley assisted in building the computer file on Slapton, in the execution of the runs and in devising the graphics. Bob and Lorna Troake collected the sample and made the discharge measurements at Slapton Ley, where their work was to lead to the setting up of one of the more significant hydrological/hydrochemical catchment studies of the decade. None of us anticipated the present use of those data.

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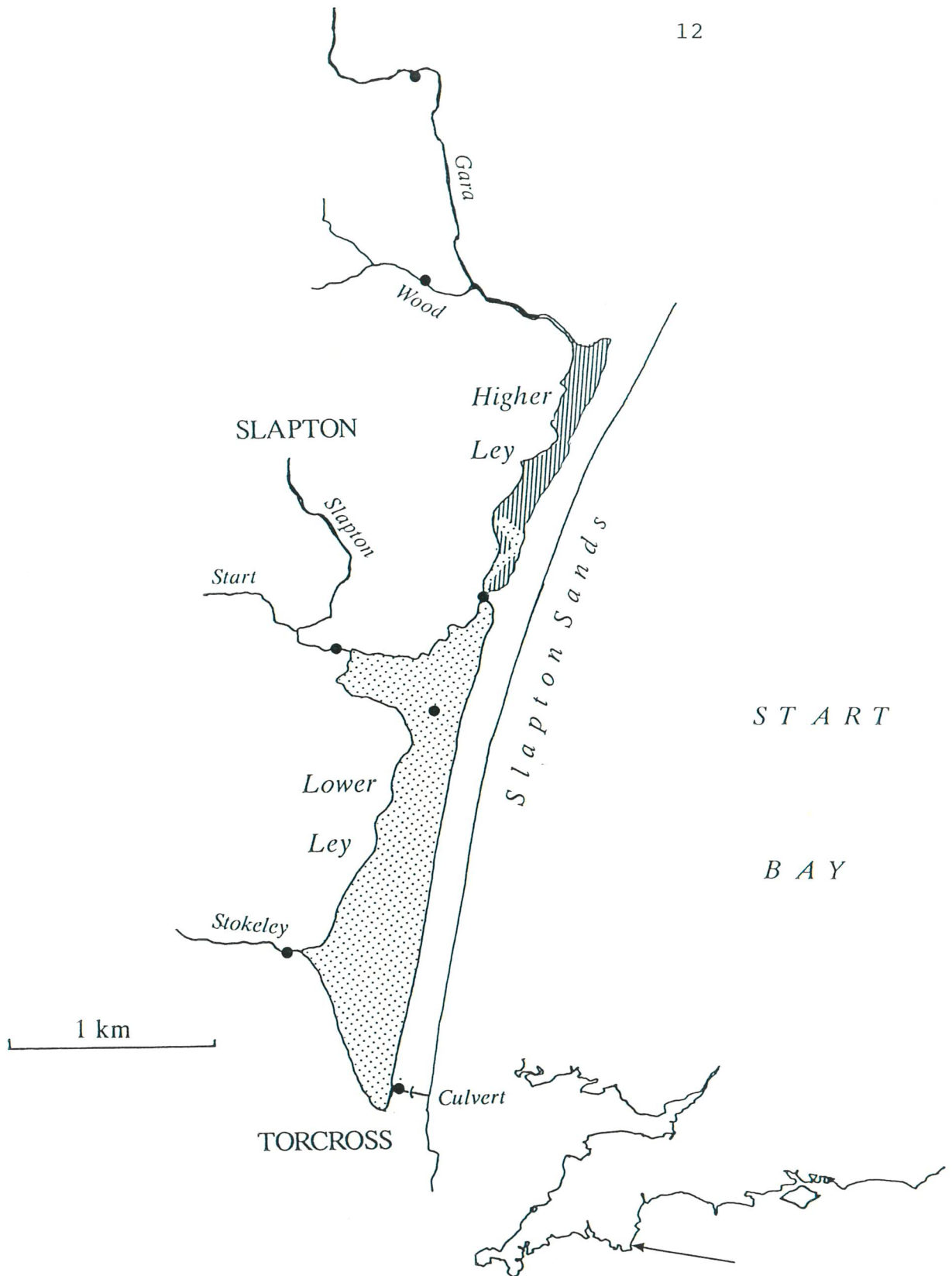


Fig 1 Sketch map of Slapton Ley, S. Devon. The Higher Ley is almost wholly dominated by reedswamp: modelling only applies to the Open Lower Ley.

• denotes regular sampling and/or gauging points, whence all basic data were derived.

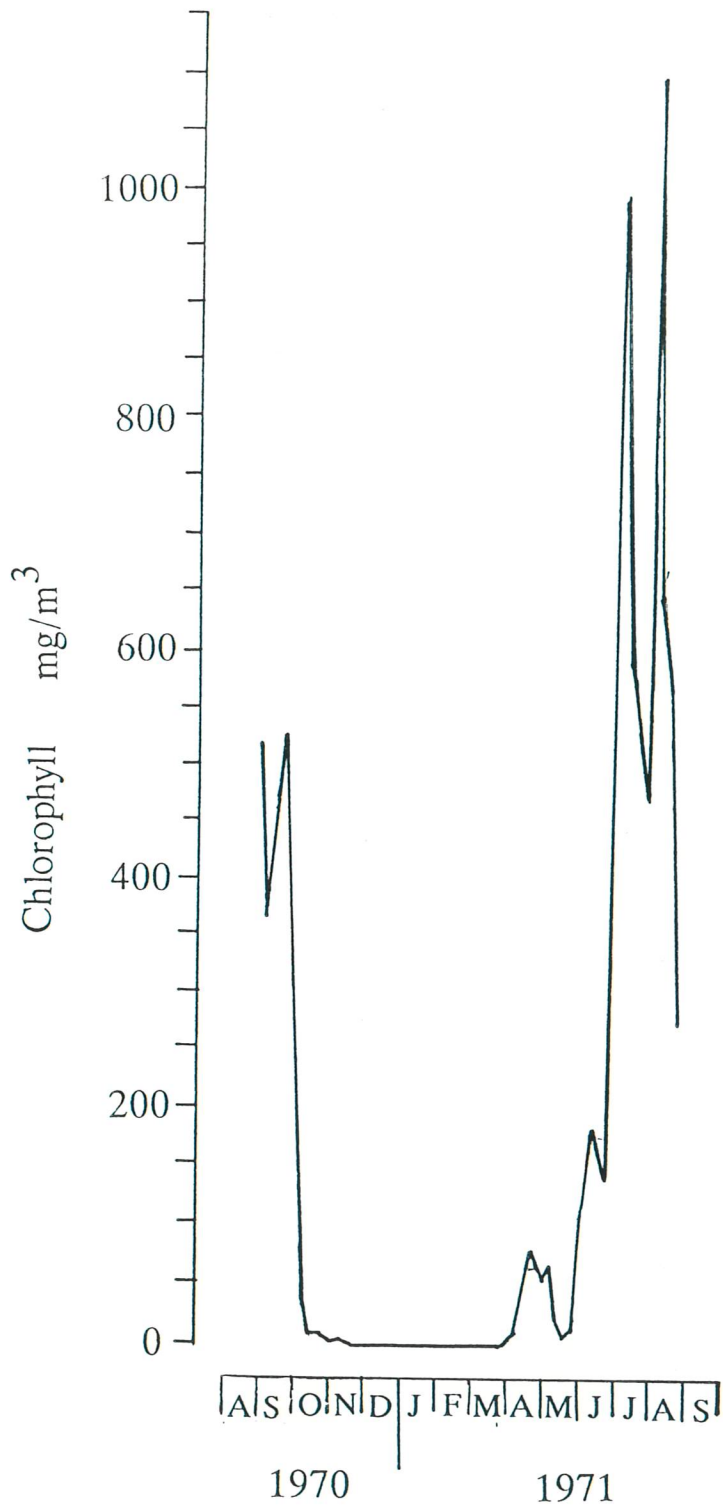


Fig 2 Weekly variations in the concentrations of chlorophyll *a* in Slapton Lower Ley, 1970-1971.

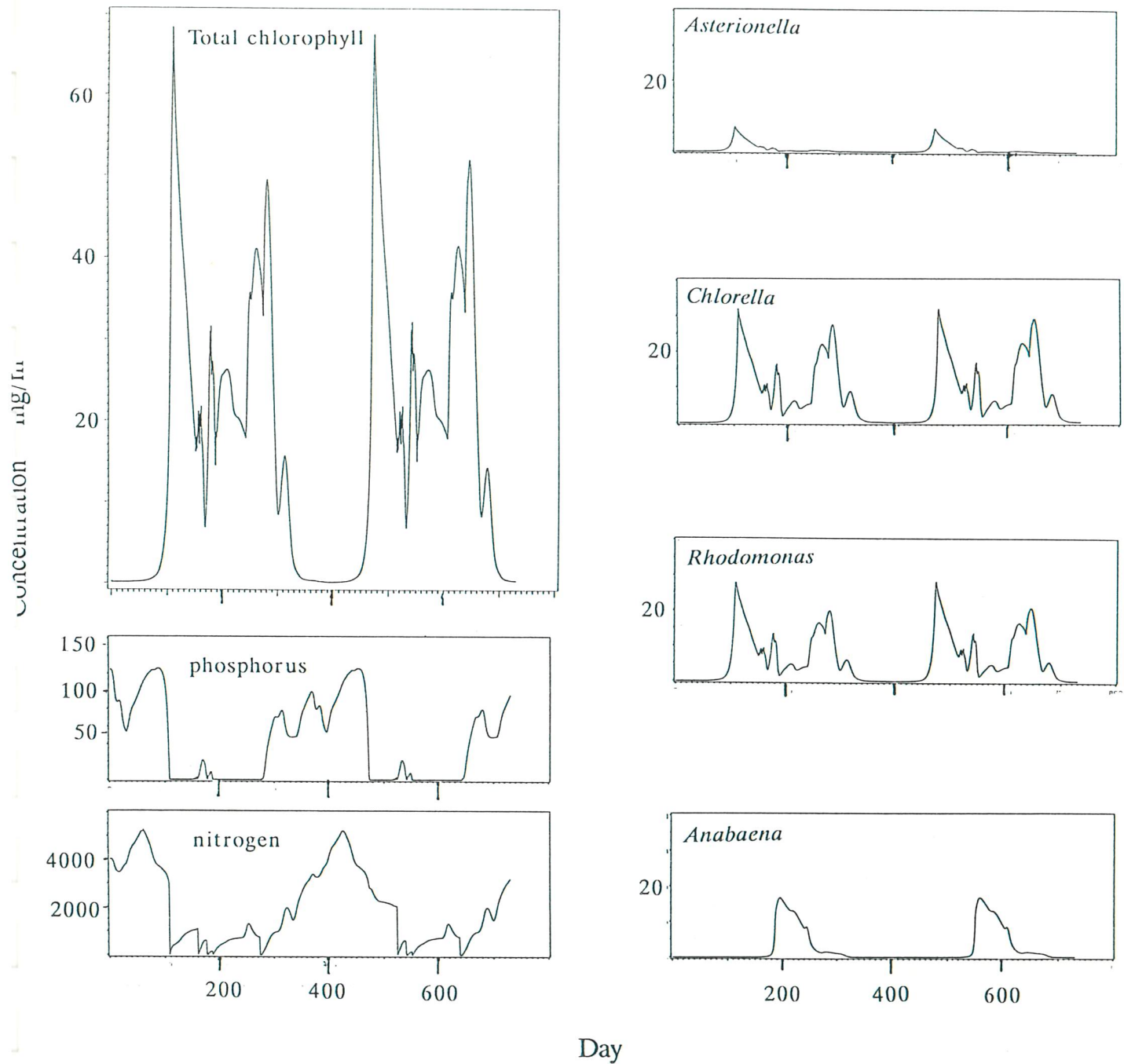


Fig 3 Model Run 1, showing output of unmodified Cardiff Bay Model from calculated nutrient inputs into Slapton Ley and measured temperatures at the Lower Ley buoy. Panels show simulations of variability in population size of four algal species, of total chlorophyll and the concentrations of dissolved phosphorus and nitrogen.

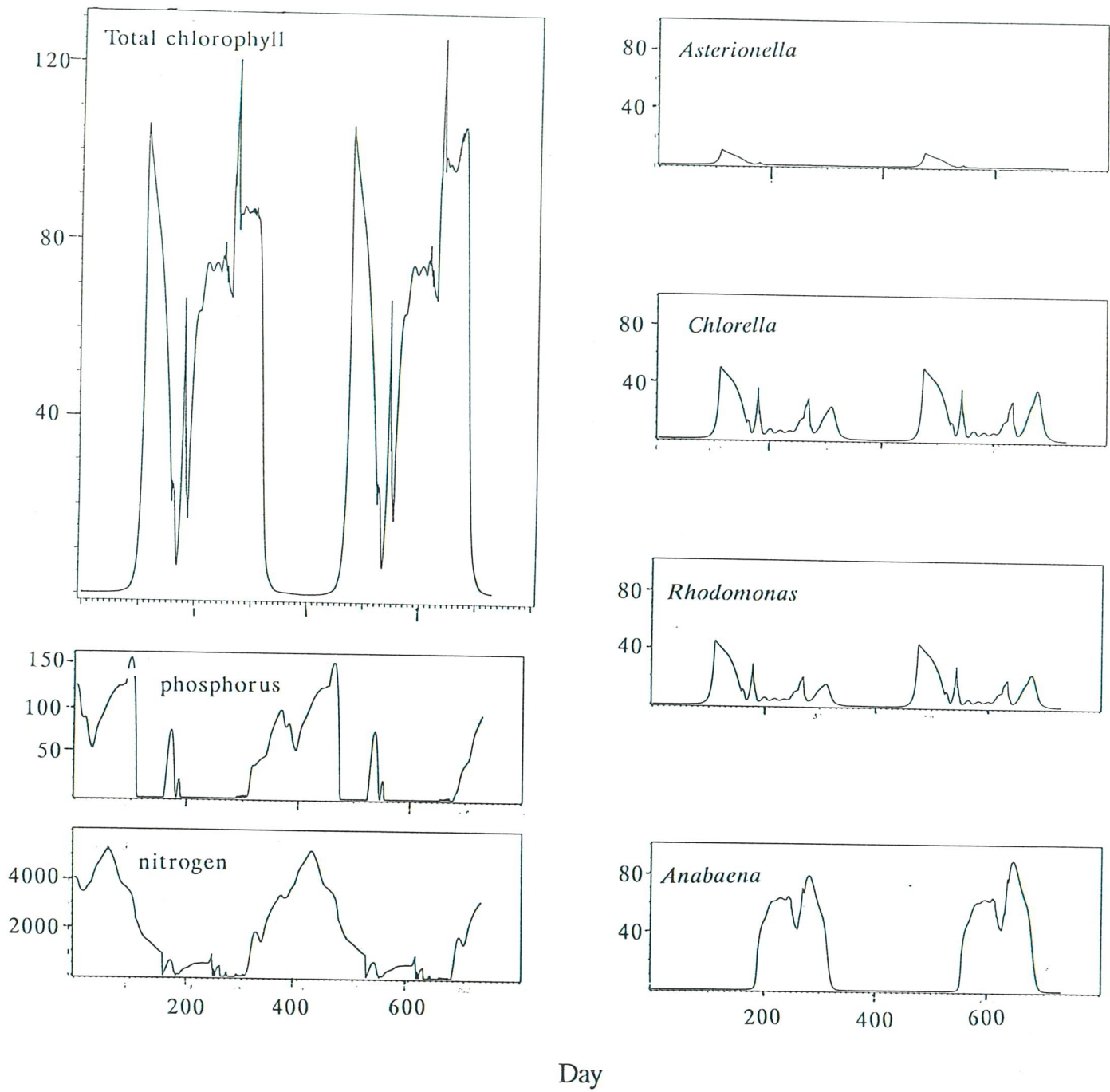


Fig 4 Model Run 2, with all original variables as in Run 1 save for the simulated addition of  $5 \text{ mg P m}^{-3} \text{ d}^{-1}$  from day 90 to day 270 (incl.) and from day 455 to day 635 (incl.).



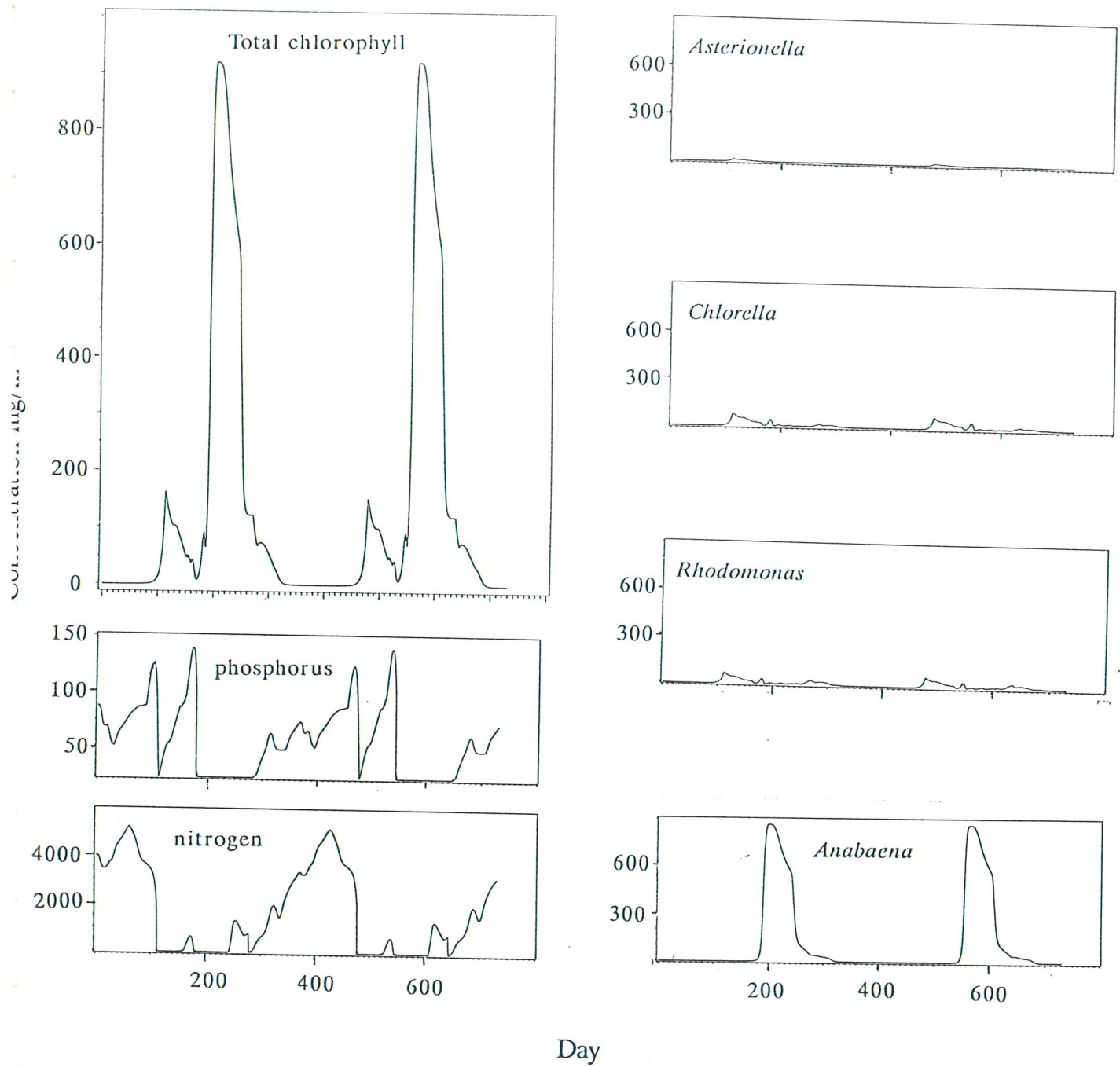


Fig 5 Model Run 3, with all original variables as in Run 1 save for the simulated addition of  $10 \text{ mg P m}^{-3} \text{ d}^{-1}$  from day 90 to day 270 (incl.) and from day 455 to day 635 (incl.).

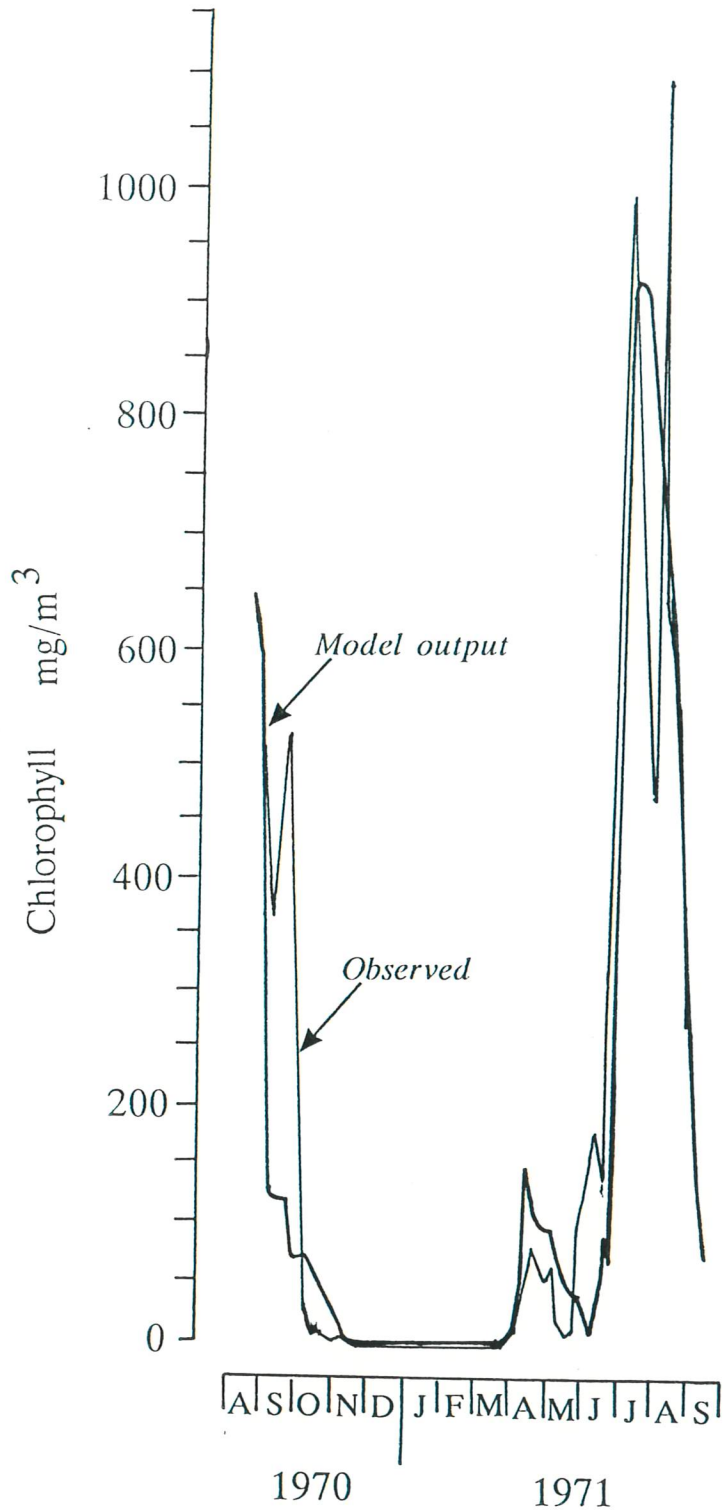


Fig 6 The relevant section of the chlorophyll simulation from Fig 5 superimposed upon the observed fluctuation as recorded in Fig 1.