FRESHWATER BIOLOGICAL ASSOCIATION
The Ferry House, Ambleside, Cumbria LA22 OLP

MODELLING PHYTOPLANKTON DEVELOPMENT IN THE PROPOSED CARDIFF BAY BARRAGE

A Report to Wallace Evans & Partners
January, 1988

Freshwater Biological Association

Report to Wallace Evans and Partners, Penarth, South Glamorgan

MODELLING PHYTOPLANKTON DEVELOPMENT IN THE PROPOSED CARDIFF BAY BARRAGE

1. INTRODUCTION. This report is intended to supplement, rather than to replace, the final report (Ref. 1) submitted by the Association, entitled "Algal growth in the proposed Cardiff Bay Barrage" (November, 1987). The latter provided an assessment of the limnological conditions likely to obtain in the proposed freshwater lake and the way these would impact upon the dynamics and potential biomass of aquatic algae and higher plants. Its essential conclusions were that the lake was liable to be dominated by phytoplankton, the extent of which would be regulated primarily by the continued fluvial discharge through the lake: at winter flows, most algae would be removed from the lake at a faster rate than could be recouped through growth *in situ* and, as a result, biomass would remain far below the carrying capacity determined by temperature, light and especially the undoubtedly high nutrient loads emanating from the inflowing rivers. In the summer months, however, when potential growth rates of algae are elevated and fluvial discharges typically decline, net increase was shown to be probable and in a very dry summer (such as that experienced in 1976 and again in 1984), biomass might achieve very high proportions. In the light of more detailed data on nutrient loads, provided by Welsh Water, the original projection that nutrients would become limiting had to be revised in favour of a worst-case in which the population would become self-shaded by its own biomass, at a level approaching 500-600 mg chlorophyll m^{-3}.

These deductions prompted considerable concern about the aesthetic appearance of the lake that might be anticipated in a dry summer; in particular, the possibility of surface 'blooms' (or floating scums) of buoyant blue-green algae (or cyanobacteria) such as *Anabaena* and *Microcystis* was regarded as a consequence sufficiently serious to prejudice the viability of the barrage proposals. These challenges were elegantly circumscribed by the Chief Scientist's team at Welsh Water, in the following questions: under what conditions could large algal biomasses have formed in the lake, had it been constructed already? What would have been their duration? What would have been the dominant species? What would have been the likely incidence of surface blooms?

Given that the data available for the last 12 years or so are representative of the range of conditions that might be reasonably anticipated in the foreseeable future, the hypothetical abstractions ought to provide realistic illustrations of what might be encountered in a future barrage lake. Moreover, the respective roles of the key determinants could be investigated theoretically in order to determine the feasibility of various options for artificial control of excessive algal production.

The information necessary to approach these questions was already in place, albeit very much at the state-of-the-art level developed in the preparation of the original report (1). The major difficulty was a logistic one: the model equations involve many individual components which, moreover, alter daily through a complex series of interactive feed-back mechanisms. What was required was the translation of the model to a responsive computer simulation programme that would be capable of making repeated calculations of the environmental conditions obtaining each day, of the daily increment of each species, of the resultant biomass and of the conditions to be set for the following day. This was a formidable task but was nevertheless embarked upon with considerable resolve by the scientific staff of Welsh Water's Bridgend laboratories, employing their experienced programming competence and powerful computing facility. Although the outcome is very much the product of close collaboration between FBA and WW personnel, no commendation of the efforts expended by WW staff, including Phil Nicholas, Kevin Thomas and, especially, Brian Scannell would be too high. It must be admitted that, while there will be no disagreement between WW and FBA about the simulations that have been run, and the specific results that have been generated, the interpretation of likely nuisance is still a matter of experience and judgement and, hence, beyond computational power. Thus, WW has correctly reserved the right to separate assessment, which is why this report appears under sole FBA authorship. This does not override the spirit of collaboration between FBA and WW, neither does it preclude an acknowledgment of the FBA's extreme appreciation to Welsh Water personnel for their industry and persistence in realising the simulations to their present level.

2. THE RATIONALE OF THE SIMULATION MODELS

Before proceeding to the results of the computer simulations, it is necessary to explain the procedures adopted and the reasons for doing so. In order to do so, it is useful to return to the fundamental philosophy of algal growth and its natural controls.

2.1. The algal problem

Algae constitute a heterogenous assortment of plants of evolutionarily primitive organisation. The term 'simple plant' belies their complex physiological functioning and adaptive variation and is deliberately avoided! 'Algae' includes the seaweeds, filamentous and encrusting growths on surfaces of rocks, damp paths and shaded tree trunks. It also includes the microscopic plant life of open waters of lakes and the sea - the phytoplankton. As a generalization, these algae comprise single plant cells or colonies of a relatively small number of such cells, with minimal differentiation of function and organisation into tissues. Each cell may therefore be regarded as a complete, or near-complete, plant. It is equipped with chlorophyll and other pigments that convert radiant solar energy into the chemical energy necessary to build sugars (photosynthesis) from water and carbon dioxide, absorbed across its surface. It is also capable of synthesising proteins from sugars and inorganic solutes, also absorbed over its surface, and which are assembled to increase the living mass of the cell by growth. Eventually, it will have grown sufficiently to divide its accumulated mass between two new daughter cells which then live as separate individuals or add to the colonial mass. Thus, a population of cells has the potential to double its numbers in the time it takes to replicate the biomass of the single cell; in the order of hours to a few days. In this way, it is possible to relate the dynamics (the rate of population change) of phytoplankton to the availability of the raw materials necessary to growth.

The growth requirements of algae are well-known in a general sense: they require access to light; to water (assumed to be freely available!) and carbon dioxide (which is soluble and readily dissolves into water from the air); and to the various dissolved salts which supply the remaining dozen-or-so elements vital to support growth (including nitrogen, phosphorus, sulphur, silicon, iron, sodium, potassium, chlorine, magnesium). Even assuming all these requirements to be satisfied, the rate of uptake, assimilation and growth are regulated by temperature, water-movement and the general ionic environment. Finally, account must be taken of rates of cell mortality, either through death, settlement out of the water, consumption by planktonic animals and attacks of fungal parasites.

It has long been known that the abundance of plankton in lakes is superficially related to the chemical supply, in particular the elements that tend to be least abundant relative to algal requirements: silicon, nitrogen and phosphorus. Indeed, there now exists a family of model equations relating the average crop of phytoplankton (in terms of the concentration of the main photosynthetic pigment, chlorophyll a) to various measures of the supply of phosphorus. The most familiar of these is attributed to Vollenweider (2). While of enormous practical utility, the relevance of the model to the Cardiff Bay problem is dubious: firstly, it does not provide a basis for predicting the periodicity or amplitude of chlorophyll fluctuations about the mean; secondly, it can make no prediction of species composition; and thirdly, its applicability to highly-flushed systems is generally doubted. Moreover, the unmodified supply of phosphorus and nitrogen to the proposed Barrage Lake is known to be high and, at most times, probably sufficient to meet the essential requirements of the algae present.

That an alternative approach is required is obvious. The one adopted herein invokes many of the other physical and biological environmental factors which would be acknowledged to be relevant to algal growth but which, hitherto, have rarely been considered in quantitative assessments of algal production and for which generally applicable models have been unavailable. Its most important element, however, lies in the distinction between the growth sensitivities of algae (their dynamic responses), which have been recently established to be significant, through a combination of observational and experimental analyses (3, 4, 5). Moreover, mathematically significant regressions have been fitted to measured responses plotted against representations of algal morphology (volume, surface area, maximum dimension: 6). The equations for these relationships are thus employed to predict the responses of any named species of known dimensions to any given set of environmental conditions. This is the fundamental philosophy behind the models we have employed below.

2.2. The model components.

(i) Algal growth rates. Eight species have been included in the model simulation. The selection was intended to give a broad representation of the common kinds of algae (small unicells to large colonies and filamentous forms; various taxonomic groups to include diatoms, green algae and blue-green algae) but was influenced by a cursory knowledge of species present in the inflowing rivers. Representative sizes (maximum dimension of algal unit; calculated volume of the nearest-fit geometrical shape; the surface-area of same, ignoring any surface irregularities) were set for each. The Model Equations (6) describing maximum growth capacity of each alga at 20 C, its sensitivity to temperature change (greater among the larger algae) and to the growth-limiting daily light dose (least among the attenuated filamentous forms) were written into the programme. The equations are given in (1); they are not reproduced here as their availability is necessarily restricted at the present time to bona fide sponsors, to be supplied on request.

(ii) Temperature. The key environmental variable, ultimately governing all potential responses, is water temperature. Model surface temperatures were interpolated from WW archived records of the River Taff over the relevant periods. Surface temperatures in a recipient lake would not necessarily be identical, but no compensation for heat exchange has been included in the provisional model. For the model growth as calculations both customary temperature and an Arrhenius equivalent are used to predict the maximum algal-specific growth rate at 20 C and the correction in respect of the actual temperature.

(iii) Vertical mixing. The deduction (1) that the barrage lake would be unlikely to stratify except for very transient periods (a matter of hours), enabled us to treat the water column as a single integrated unit. The assumption of full, continuous mixing determines the assessment of light availability.

(iv) Underwater light. Light energy perceived by the vertically-mixed algal population is also a key variable. Its evaluation and its effect on specific algal growth is complex. The derivation of these components needed to take account of:

(a) The incident light on the surface. Even under a cloudless sky, this varies with the angle of the sun, so incident light changes in intensity through the solar day and the time course alters each day through the seasons. Moreover, the light reaching the water surface is dependent upon atmospheric conditions, notably cloud cover, and how much penetrates the surface is dependent upon the angle of incidence of the solar rays and the extent of diffusion by cloud above the lake. Having no independent measure of light reaching the surface, we calculated daily integrals for each day from the solar constant, according to published relationships collected in b that compensate for latitude-determined variability, to find the maximum daily radiation income. This figure was corrected by a factor of 0.47 in respect of the visible wavelengths. Initially, a cloud cover of 50% was assumed and this reduces the incident photosynthetically active radiation by an approximate factor of 0.65 (see 7). In later formulations, daily cloud cover values at Rhoose Airport, kindly supplied by The Meteorological Office, were incorporated: at 0/8, the factor was 1; at 8/8 cloud, the factor was 0.3; intermediate cloud cover was scaled in direct arithmetic proportion (see 7). The residual quantity (total incident photosynthetically-active radiation per day) was divided by the day length (sunrise to sunset) to derive a mean instantaneous value for the day. No correction for surface reflectance was incorporated.

b) Sub-surface Penetration Light energy is absorbed exponentially with depth, as expressed in the Beer-Lambert equation:

$$I_z = I_o e^{-\epsilon z}$$

Where I_z is the light obtaining at a given depth, z; I_o is the incident light passing through the lake surface; ϵ is the extinction coefficient; e is the natural logarithmic base. The extinction coefficient has several components - that due to the water itself (ϵ_w), that due non-living suspended matter (ϵ_p) and that due to the phytoplankton ($\underline{n}\ \epsilon_s$, where ϵ_s is the extinction coefficient per unit of phytoplankton chlorophyll and n is the concentration of the chlorophyll in the water. ϵ_s is a property of single algal cells and is correlated with their morphologies (the product of the maximum linear dimensions and the surface-volume ratio of the particle). $n\ \epsilon_s$ for a given population of each alga considered is derived by summation. The extinction due to pure water (ϵ_w) is in the order of 0.2 m^{-1}. Some model simulations have been run with $\epsilon = \epsilon_w + n\epsilon_s$ others with $(\epsilon_p + \epsilon_w) = 0.7\ m^{-1}$, based on a single, ad-hoc measurement made on water from the Taff (Welsh Water, this study). Runs to gauge the effect of altered suspended loads used arbitrarily-altered values for ϵ_p.

c) Light limitation with increasing depth is included in the model. Above a certain threshold level (I_k, algal growth is said to be light-saturated so that, while the condition applies, the temperature-determined specific growth rate may be attained. Below the threshold, growth is linearly attenuated in proportion to the light available. Potential growth in a given light gradient corresponds to the trapezium enclosed on a plot of growth rate, (r), vs irradiance (I) with the dimensions $r_{max} \times (I_o - 0.5\ I_k)$. Translated to the underwater light field, the potential production is given by the product $nr_{max} \times h_p$ where h_p is the height of the water column between the surface and $z_{0.5I_k}$ (the depth at which $I_z = 0.5\ I_k$),

$$\text{i.e.}\quad h_p = (I_o/0.5I_k)/\epsilon$$

It should be noted that under the same given conditions, species which intercept light most efficiently have lower I_k values, so that h_p is far from being identical for all the algae present. This is an important factor selecting between species under conditions of high turbidity. The slope of the r vs I plot, α, is a further correlative of algal morphology. I_k and h_p are worked out for each species, thus:

$$I_k = r_{max}/\alpha \quad ;$$

$$h_p = [I_o/0.5\ (r_{max}/\alpha)]/\epsilon$$

d) Mixing through the light gradient. Finally, allowance must be made for the fact that the algae are not stationary but are constantly moved through it and beyond, arguably into effective darkness. The 'productive' time is t_p and is given by:

$$t_p = T(h_p/h_m)$$

where T is the day length and h_m is the mixed-column height. In shallow or very clear water, where $h_p > h_m$, $t_p = T$. t_p is used to correct temperature-determined growth over 24 h, thus $(r_{max}\ t_p)/24$. Calculations of in situ growth rates of given species under natural conditions observed elsewhere yield tolerably realistic solutions (see 6)

e) Correction for respiration. As originally designed, the model equations supposed that, because the base growth rates were net of respiration, the regression solutions for growth at suboptimal temperature and light levels were scaled directly. This process results in an unrealistic solution in that growth is always positive, the limitation reducing growth rates to ever smaller values. Of course, if photosynthesis is inadequate to meet the respiration requirements, growth is not only 'impossible' but will be negative. As an expedient with some factual basis, later model runs (including all those presented herein) incorporated the following correction: If r_{20} is maximum growth rate at 20C under continuous saturation then R (= respiratory loss) was ascribed a value of 0.15r. Thus, the "new r_{20}" was assumed to be 1.15 x (old r_{20}). Then the correction for temperature effects (r_θ), provided in the model, was applied to generate a new r , equivalent to 1.15 x (old r_θ); $R_\theta = 0.15 r_\theta$. After calculating all further corrections to in situ r values in respect of day length and mixing beyond the specific compensation point, the value $r_{(\theta,I)}$ was subjected to a final correction by subtracting R . Clearly if $R_\theta > r_{(\theta,I)}$ 'new', the final computation would be negative. It would be apparent that this procedure does not violate the original deductions concerning the model provisions for growth under continuous light- and nutrient saturation, since

$$r_\theta + R_\theta - R_\theta = r_\theta.$$

(v) Nutrient limitation. Our simulation model sought to accommodate the effects of limitation of growth caused by an inadequate nutrient supply. A substantial literature exists on the kinetic effects of limiting nutrients on growth rates of certain individual algae (reviewed in 8). Unfortunately, no systematic correlation of these data with any morphological criterion of the algae has been detected. Short of setting limits for the algae concerned (where known) or guessing them for others (where unknown), there seemed no realistic way of incorporating into this provisional model any differentation of selective effects of low nutrient concentrations on the performance of individual species. This must be recognized as a shortcoming of the present computations. On the principle that we should be seeking 'worst case' predictions, we set criteria for all algae based on the possibility that their growth would only be significantly lowered at what could be considered as artificially low levels. Thus, limitation of some species would certainly become apparent before our model runs indicate. On the other hand, nutrient levels prove to be rarely reduced to likely critical levels so the shortcoming is probably correspondingly inconsequential.

The limitations that were introduced were as follows. For phosphorus, we assumed that while a concentration of dissolved reactive phosphorus (SRP) of > 5 mg P m^{-3} obtained, no growth limitation would owe to P. Thus, the computed value of $r_{(\theta,I)}$ was accepted. For values of SRP of 0 to 5 mg P m^{-3}, r_P was scaled arithmetically for each species (e.g. if SRP = 3 mg m^{-3}, r_P is 0.6 r_θ). The model programme then adopts the lower of the two values, r_P or $r_{(\theta,I)}$ 'new' as being the applicable case. It will be noted at once that the model is, in effect, determining whether P, light or temperature is ultimately limiting. Similarly, for combined nitrogen (as the sum of NO_3, NO_2 and NH_4 concentrations in the database), a critical concentration of 80 mg N m^{-3} was set, with an arithmetic scaling of r_N against N concentrations of 0-80 mg N m^{-3}. Whichever was lowest of r_p, r_N or $r_{(\theta,I)}$ 'new' was adopted by the model simulation. Only one caveat was applied in respect of specified nitrogen-fixing species (e.g. of Anabaena) for which it was assumed that any N-deficiency would be compensated.

No other nutrient limitation has been accommodated: these are assumed to be growth-saturating throughout. This is not unreasonable, save that silicon might at times regulate the growth rates of diatoms in the system. A future refinement of the model should include correction options in respect of the other possible limiting resources.

(vi) Biomass losses. Existing biomass is naturally subject to removal by several agencies - death; specific epidemic pathogens; settling to the bottom deposits; consumption by herbivorous animals; outwash from the lake. The former two are stochastic, random events and are not included in the model. Sinking losses could be significant, especially for non-motile species, but these are not yet accommodated in the simulation model. Outwash is built in to the simulations on the basis that the volume of water supplied to the lake in unit time displaces a similar volume into the sea, together with a *pro-rata* proportion of the existing biomass. Grazing was also accommodated and was allowed to affect the phytoplankton on the following basis:

- that significant removal would be inflicted only by *Daphnia*;
- that *Daphnia* would consume only algae below a certain size (set arbitrarily as those having a maximum linear dimension of ≤ 50 µm) and larger algae would be completely unaffected (the basis of which see 9);
- that smaller algae ≤ 50 µm are removed in the proportion F $1\ 1^{-1} d^{-1}$;
- that F is a variable function of temperature and the capacity of the available algal resource (i.e. the crop of algae ≤ 50 µm) present to sustain an increase in grazing biomass and therefore to permit its increase);
- that a base level F = 0.005 be applied as a minimum;
- that F did not increase at all at temperature < 7C;
- that the maximum temperature-determined increase in F , due to growth in the grazing population and recruitment of new individuals in the presence of saturating food concentrations, be an exponential daily function scaled between 0 at 7C and 0.191 at 20C (9):
- that saturation of F applies at ≥ 10 mg m^{-3} chlorophyll (≥ 0.5 g algal C m^{-3}) in the available algal size fraction (3);
- that absolute limitation of increase of F applies ≤ 1.6 mg m^{-3} of available chlorophyll (≤ 0.08 g algal C m^{-3}), when F = 0 (3):

- that when $1.6 <$ available algal chlorophyll < 10, F is a linear function of F at ≤ 10 mg m^{-3}.

Assuming the development of the filtration capacity to behave according to experimental determination in (3), the grazing provision incorporated in the model is responsive to resource- and temperature-determined components and, in this sense, is realistic.

Grazing is supposed to re-generate nutrients available to future phytoplankton growth. Our model recycles this component completely and instantaneously. This will give an exaggerated view of nutrient regeneration but, at present, no better realistic estimate is available.

2.3 Model assumptions and limitations - a critique

The preceding discussion of the model variables identifies weaknesses in assuming the variabilities of given components, in ignoring certain factors which may be critical for certain algae species at certain times, and in adopting, always, the worst-case condition. Further justification of the model assumptions cannot be advanced, save that they are inadequately compensated in the provisional model and that the compensations would have to be built in to any later, more refined, model simulation of algal dynamics. As it is, the devised model is believed to apply to the present situation in a quasi-realistic manner, but which avoids its fundamental weaknesses to the extent that uncertainties about the model predictions will persist. All that can be said is that, in preparing the model, only those factors which would appear critical to algal growth in the proposed barrage lake have been simulated with approximate realism.

The supposed realism of the simulation depends upon careful experimentation elsewhere (3, 4, 5, 9) but we are not entitled to assume universal applicability. The test of any model lies in its validation, i.e. its ability to predict correctly known responses against known variables. In relation to a proposed lake, no verification is ultimately possible until the lake becomes real. The model, however, is derived from real responses in real systems to real environmental change, and this alone gives some validation. Future work should be directed to compare simulated outcomes to actual outcomes in observed, fully-documented time series elsewhere. Even this has not been possible within the life-time of the provisional model. Therefore, besides straightforward runs of the model to yield hypothetical predictions of what may or may not transpire in a Cardiff Bay barrage lake, we have attempted to separate the contributory factors determining the outcome of simulations. Because we believe that the latter are responsive to factor variation in explicable ways, we offer the simulations with some confidence and interpret them as a valid guide to the mechanisms likely to control algal growth in the proposed lake, as well as reinforcing various management options advanced in the definitive report (1).

The modelled simulations are presented in the following section of this report (§3). Each model run assumes the following provisions UNLESS OTHERWISE STATED:

1. The lake is treated as a single, one-dimensional unit.
2. A universal time step in each computation is 6 h ($^{1}/4$) day).
3. A mean depth of 5.4 m (volume: 10.15×10^6 m^3).
4. R_∂ is 0.15 r_θ.
5. ϵ is 0.73 m^{-1}.
6. Flow and N and P supply data are those actually measured over the period.
7. No artificial alteration of N and P loads is applied.
8. All algae are introduced in the inflow at levels set:
    - 0.1 mg m^{-3} chlorophyll at winter solstice
    - 5.0 mg m^{-3} at the equinoxes
    - 10.0 mg m^{-3} at summer solstice
9. All species present in the inflow constitute equal proportions.
10. Temperature is interpolated from actual observations (2.1. (i) refers).
11. Mean daily cloud cover is that observed at Rhoose.
12. The years 1976-78 (inclusive) are adopted for the simulations.
13. Carbon is never limiting.

3. MODEL RUNS

Model outputs are presented below, the input variables being altered for the purpose stated in each instance. Each graph is sectionalized to show the following:

Top Panel. Species-specific algal biomass through time, on a common scale of chlorophyll concentration.

Second Panel. Species-specific net growth rates and the grazing intensity, F.

Third Panel. The biologically-available nitrogen and phosphorus supplies provided by the inflow.

Bottom Panel. Water temperature, cloud cover, discharge rate.

The input variables are those set in 2.3, unless otherwise stated. Each simulation is preceded by a text page, stating the run conditions and an interpretative statement.

3.1 The Standardized Outcome

Several runs were rehearsed in which all known conditions applied (1-13 in 2.3). Refinement of the input data resulted in relatively minor differences in the outcome. Very similar patterns were produced in every one of the modelled years, the differences being of scale and timing: all showed a spring-early summer growth maximum, of the order 300-400 mg chlorophyll m^{-3}, characteristically dominated by Ankeistrodesmus (a small, fusiform unicellular green alga), followed by a summer maximum, of more variable proportions (100-350 mg chlorophyll m^{-3}), due to the filamentous blue-green alga, Oscillatoria. These maxima are slightly larger than the P-limited projections in the report (1) but are within the maximum light-limited concentrations envisaged.

For simplicity, only the first three years (1976-78 inclusive) are illustrated here: this period includes a very dry, warm summer (1976), a cooler, wetter one (1978): a relatively dry (1975/76) and a rather wet winter (1977/78): hence, the period is a useful one in which to separate particular factors operating.

Features in the plots which should be noted include:

The long period (approx November-March inclusive) in winter when algal chlorophyll is very low (< 10 mg m^{-3} 1976/7 and 1977/8) or develops only erratically (1976: chlorophyll reached 120 mg m^{-3} in mid-March). This is not due to a failure of algae to grow (second panel) and nor to a lack of nutrients (third panel): indeed, the concentrations of both nitrogen and phosphorus are relatively high at these times (1 to 3 g DIN m^{-3}; 0.2 to 0.5 g SRP m^{-3}). Neither is it constrained by peaks in grazing activity, which are shown as transient, mainly summer phenomena (second panel). On the other hand, the collapse of biomass in the autumn and its subsequent low levels clearly fit with the periods of elevated fluvial discharges into the lake (bottom panel). Moreover, careful comparison of the relevant plots in the upper and lower panels reveals the relationships between the early decline in flow in 1976 and the development of the Ankistrodesmus population and between other brief incidents of increased flow through summer and minor distortions in the plots of standing specific biomass.

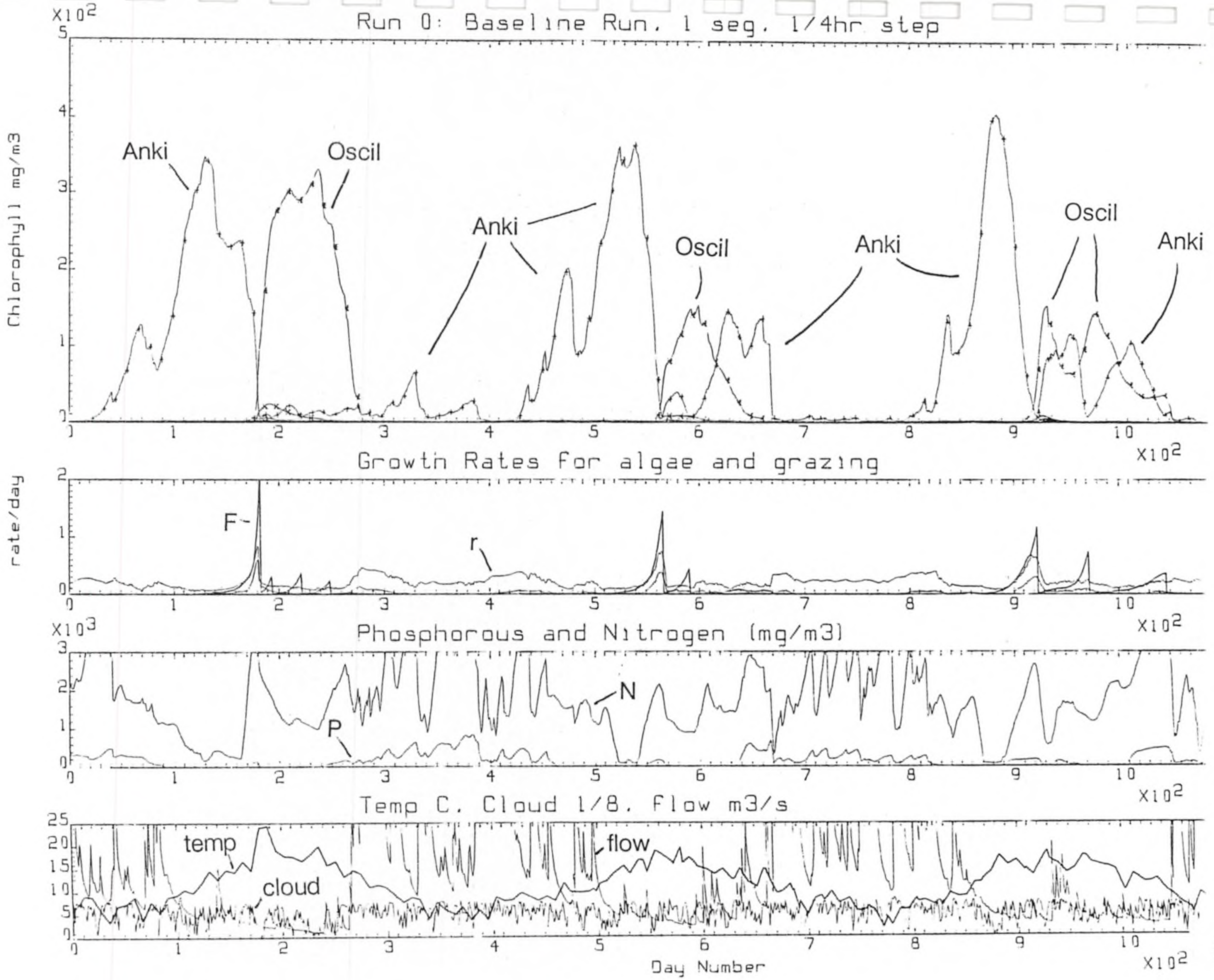
The abrupt decline in Ankistrodesmus in summer corresponds to peak levels of grazing activity: these develop only at warmer temperatures and in the presence of abundant, suitable foods. Other, ungrazed algae (chiefly Anabaena and, especially, Oscillatoria) then assume dominance.

Collapse of the grazer biomass provides for renewed increase of *Ankistrodesmus*. In 1978, three such grazer peaks are clearly identifiable, each directly related to the depletion of suitable food algae.

All of this is in accord with the theoretical report. It is emphasised again that the precise scaling and phasing of peaks depends upon the response to the model provisions and that the species dominance simulated depends upon the relative abilities of the algal species introduced in the model. *Ankistrodesmus* might be equally substituted by another alga or by one on the list if the performance characteristics departed even only slightly from that predicted by the morphological properties. Some intuition is required to suggest that *Ankistrodesmus* might be substituted by *Chlorella* (another small green alga) or by *Asterionella* (a colonial diatom with a high affinity for low light) but not by (say) *Microcystis* or *Anabaena*.

Each of these statements are tested in subsequent model runs, which attempt to separate the impact of each input component.

Fig.3.1

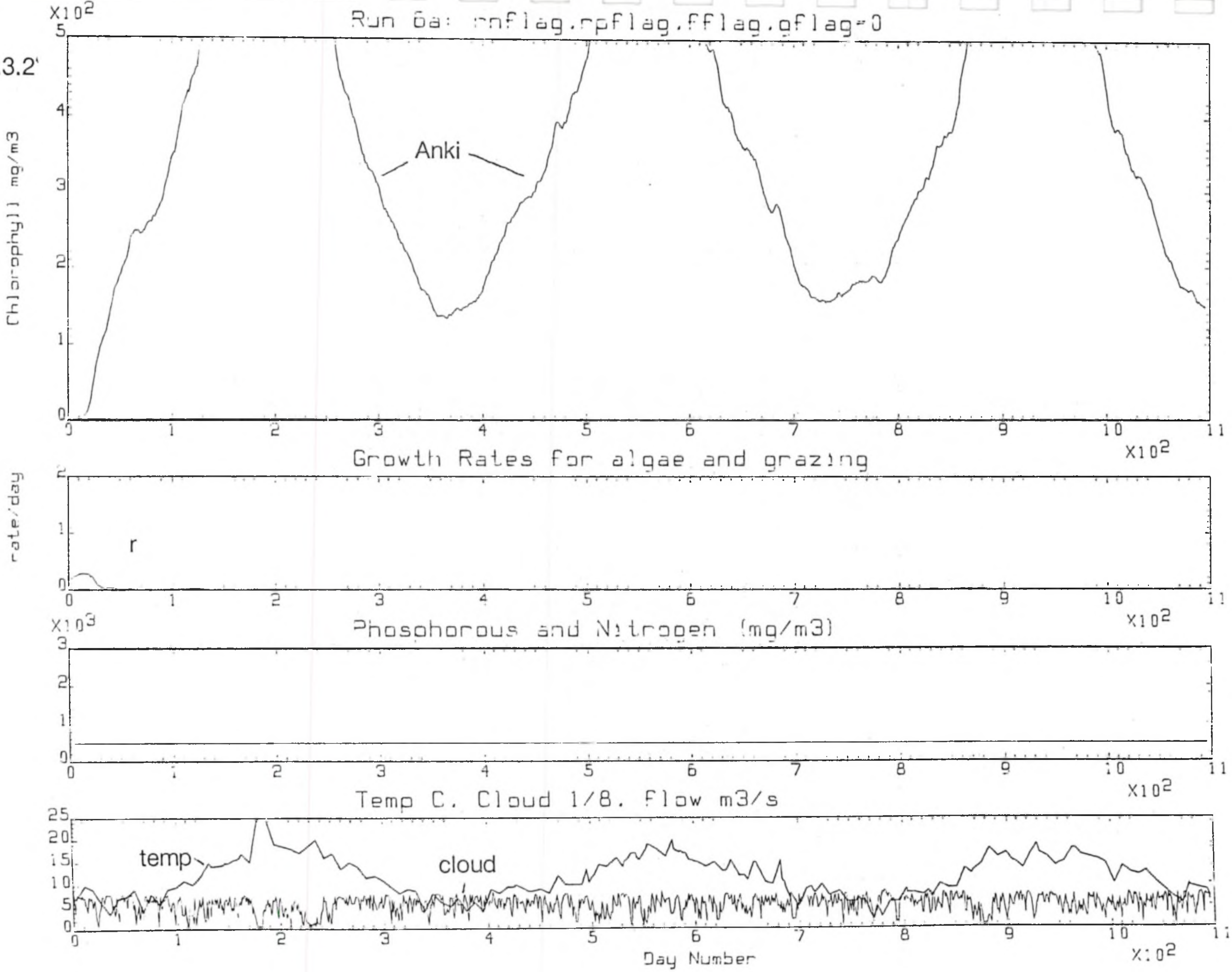

X10^2
Run 0: Baseline Run, 1 seg, 1/4hr step
Chlorophyll mg/m3
0
1
2
3
4
5
Anki
Oscil
Anki
Oscil
Anki
Oscil
Anki
0
1
2
3
4
5
6
7
8
9
10
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
F
r
0
1
2
3
4
5
6
7
8
9
10
X10^2
X10^3
Phosphorous and Nitrogen (mg/m3)
0
1
2
3
N
P
0
1
2
3
4
5
6
7
8
9
10
X10^2
Temp C, Cloud 1/8, Flow m3/s
0
5
10
15
20
25
temp
flow
cloud
0
1
2
3
4
5
6
7
8
9
10
Day Number
X10^2

3.2 Removal of throughflow (flushing), resource limitation, grazing

The next step is to remove the supposed controls on biomass development. The effect of outwash was removed by substituting a zero flow (but without altering the simulated actual, "real" N and P loads; the effects of nutrient limitation were altered by setting N and P to continuously saturating levels. Grazing was excluded through by-passing that part of the "loss" loop.

Run 3.2 shows the effect of simultaneously removing all three constraints. The plot is continuously dominated by large maxima, approaching 600 mg m^{-3}, of *Ankistrodesmus*, regulated entirely by the variation in day length and its own self-shading. Note that except at the initial phase of growth in the model, the biomass is almost always at its ultimate light-limited level and the *in situ* growth rate is barely registered on the plots.

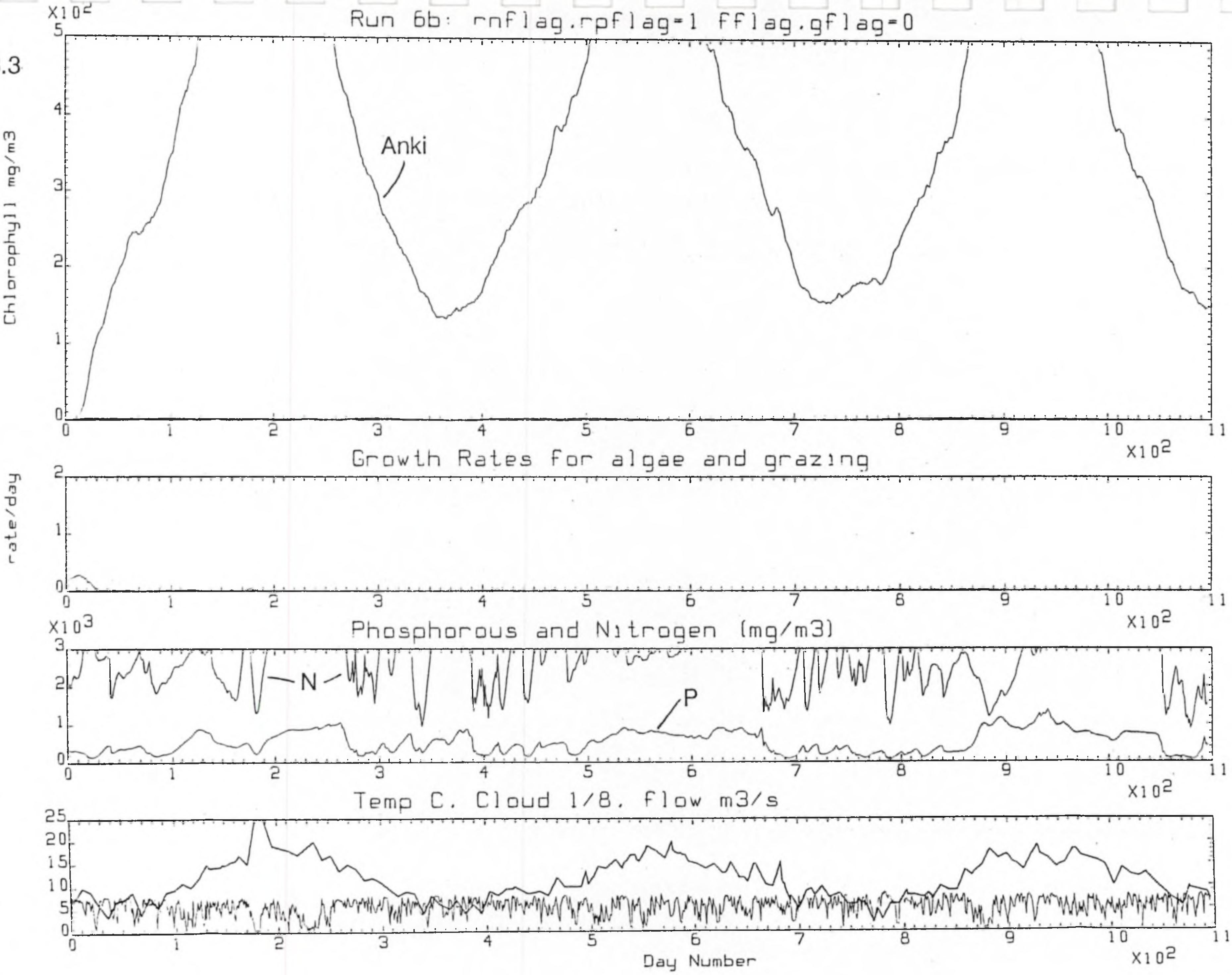
Fig.3.2


Run 6a: rnflag.rpflag.fflag.oflag=0
X10^2
Chlorophyll mg/m3
0
1
2
3
4
5
Anki
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
r
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
X10^3
Phosphorous and Nitrogen (mg/m3)
0
1
2
3
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
Temp C. Cloud 1/8. Flow m3/s
0
5
10
15
20
25
temp
cloud
0
1
2
3
4
5
6
7
8
9
10
11
Day Number
X10^2

3.3 Removal of throughflow (flushing) and grazing

The next figure shows the effect of nutrient limitation on simulation 3.2 as being minimal. This is not necessarily indicating that nutrients are never a limiting factor: the effect is partly due to dissolved nutrients not being removed from the system (but see §§3.4, 3.7, 3.8).

Fig.3.3

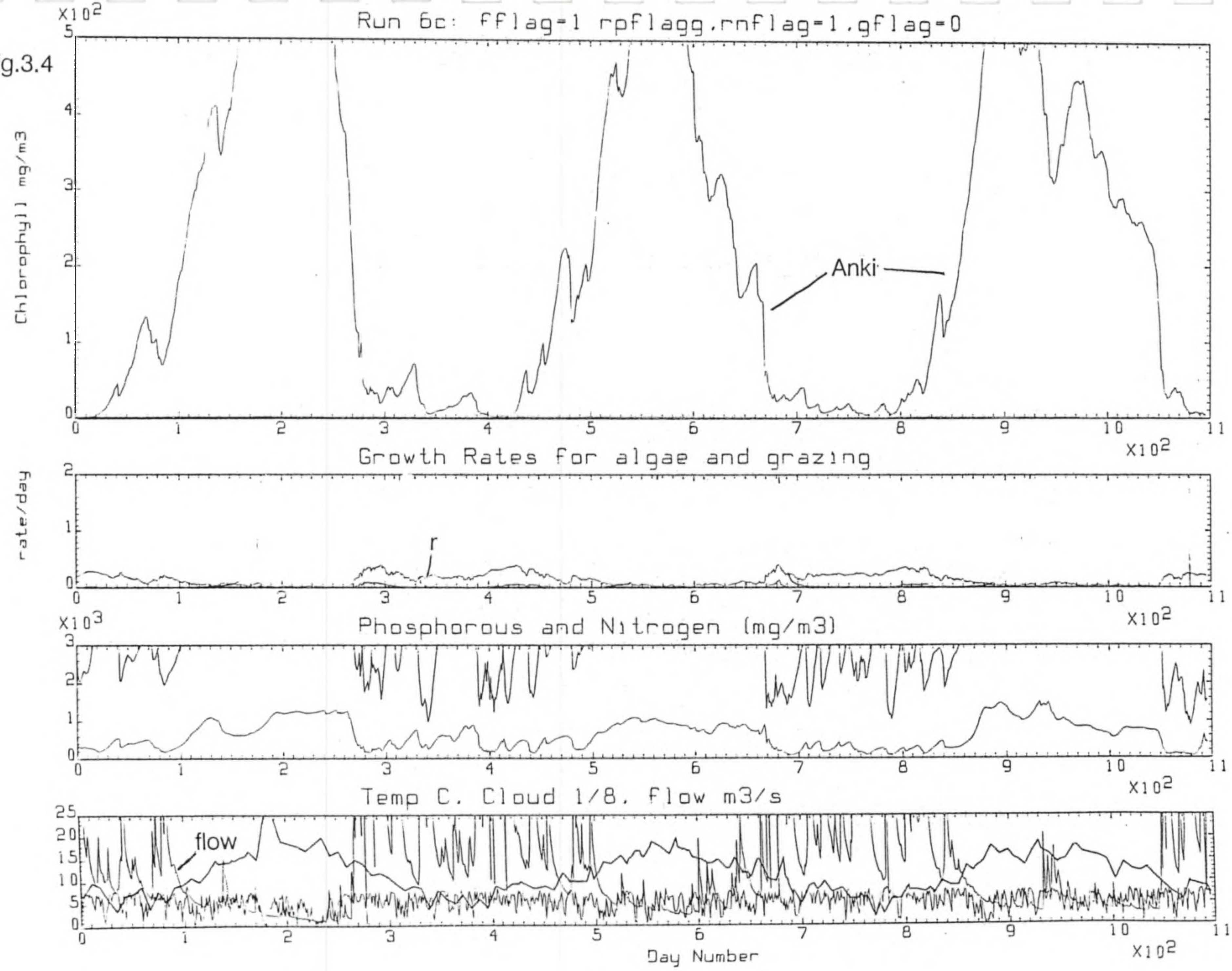

Run 6b: rnflag.rpflag=1 fflag.gflag=0
X10^2
Chlorophyll mg/m3
Anki
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
Growth Rates for algae and grazing
rate/day
X10^3
Phosphorous and Nitrogen (mg/m3)
N
P
Temp C. Cloud 1/8. flow m3/s
25
20
15
10
5
Day Number

3.4 Removal of resource limitation and grazing

Here, the effect of reimposing "real" flows through the lake but without any resource limitation are shown in 3.4. Compared to the previous figure, the biomass peaks are now more clearly delimited and substantially truncated (peaks barely exceed 500 mg chlorophyll m^{-3}). Fairly rapid growth is maintained in winter with biomass responding in interludes of reduced flow.

Note that algal biomass is again continuously dominated by Ankistrodesmus. It would appear that grazing is a key factor in the replacement of dominance illustrated in § 3.1, above.

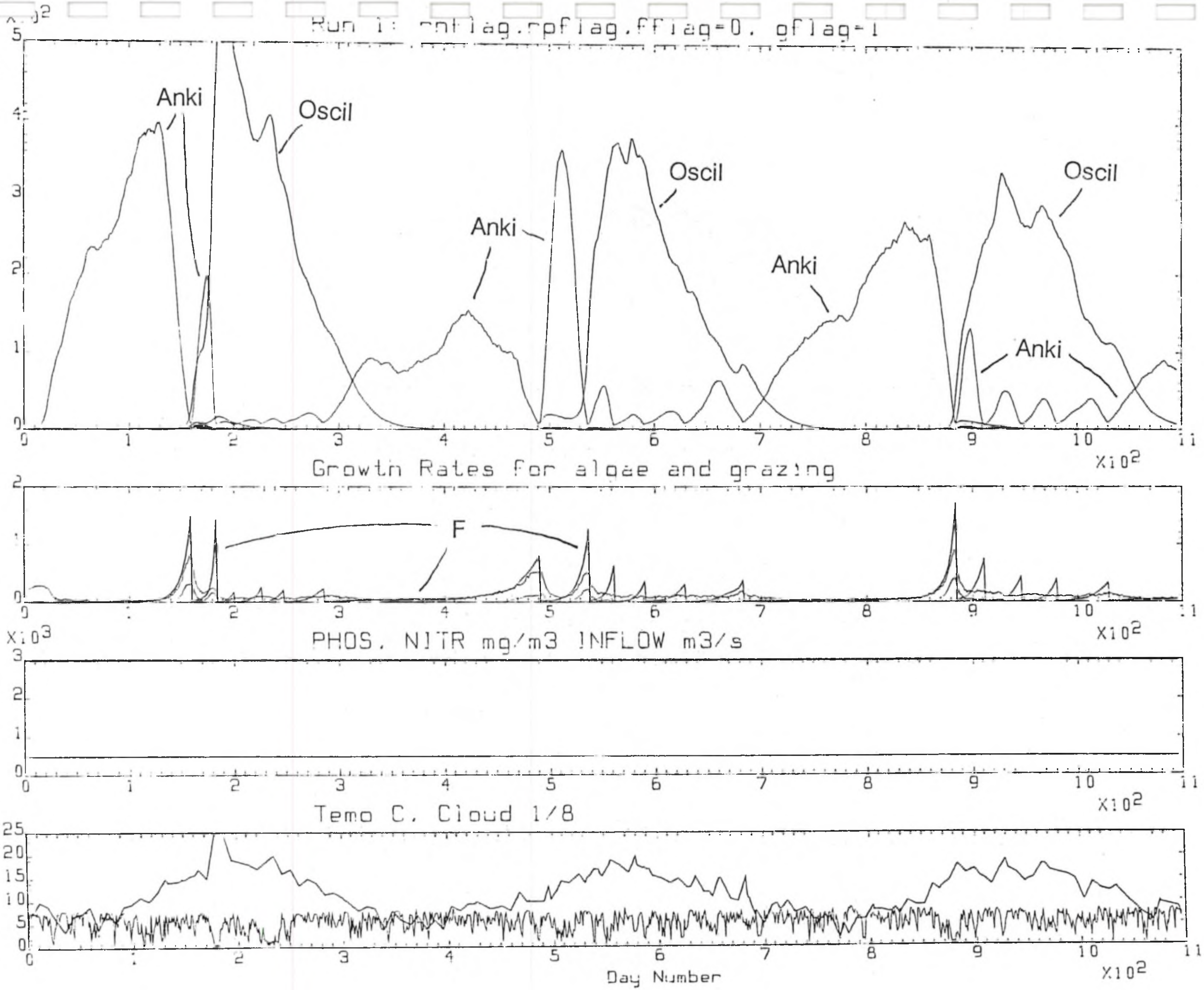
Fig.3.4


Run 6c: fflag=1 rpflagg,rnflag=1,gflag=0
X10^2
Chlorophyll mg/m3
0
1
2
3
4
5
Anki
Growth Rates for algae and grazing
rate/day
r
X10^3
Phosphorous and Nitrogen (mg/m3)
Temp C. Cloud 1/8. flow m3/s
flow
0
5
10
15
20
25
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
Day Number

3.5 Removal of throughflow (flushing) and resource limitation

With respect to 3.2, the next run reimposes grazing on an otherwise resource-replete, unflushed population. The most noteable effect is the reintroduction of a species replacement: *Oscillatoria* rapidly occupies the 'space' created by collapse of the *Ankistrodesmus* and which it can continue to dominate in summer, presumably by virtue of its conservative (ungrazed) biomass and its better utilization of low, biomass-restricted light availability. It is worth noting, too, that *Ankistrodesmus* increases slowly in the autumn and early spring when the *Oscillatoria* is temperature-limited. As a result, grazing is reimposed earlier in the following year so that the peak biomasses are also controlled sooner.

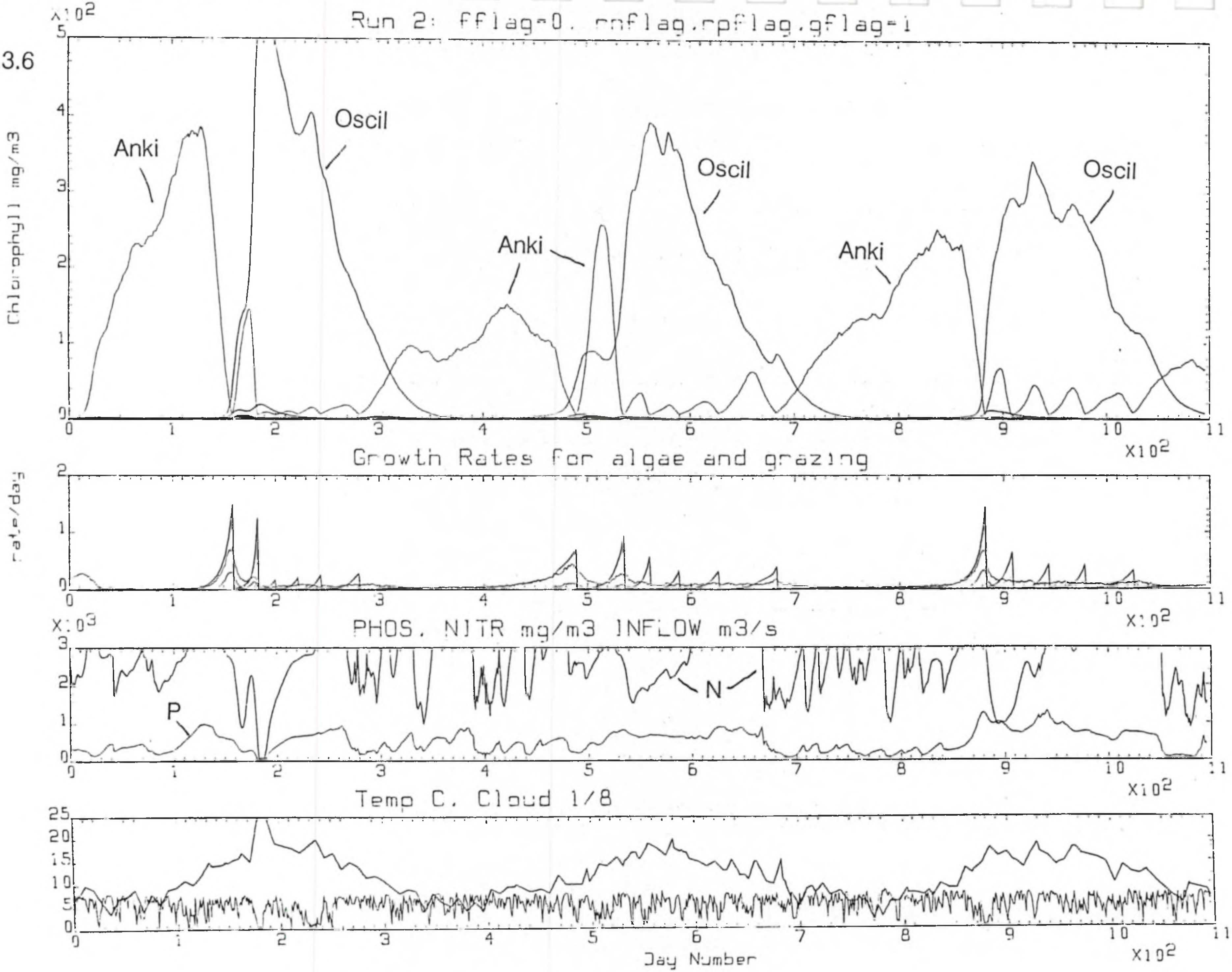
Fig.3.5


Run 1: rnflag.rpflag.fflag=0. gflag=1
X10^2
Chlorophyll mg/m3
0
1
2
3
4
5
Anki
Oscil
Anki
Oscil
Anki
Oscil
Anki
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
F
X10^2
PHOS. NITR mg/m3 INFLOW m3/s
X10^3
0
1
2
3
X10^2
Temp C. Cloud 1/8
0
5
10
15
20
25
Day Number
X10^2

3.6 Removal of throughflow (flushing)

Now we can subject the grazed population to natural nutrient loads. Very little difference is detected between Figs 3.5 and 3.6. No clear limitation by N or P is evident.

Fig.3.6


Run 2: fflag=0, rnflag,rpflag,gflag=1
X10^2
Chlorophyll mg/m3
Anki
Oscil
Anki
Oscil
Anki
Oscil
0 1 2 3 4 5
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Growth Rates for algae and grazing
rate/day
0 1 2
X10^3
PHOS, NITR mg/m3 INFLOW m3/s
P
N
0 1 2 3
Temp C, Cloud 1/8
0 5 10 15 20 25
Day Number

3.7 Removal of nutrient limitation

If 'real' throughflow and grazing are reintroduced, but no nutrient limitation is allowed, we find that something close to the baseline run (3.1) is restored, with a spring 'burst' of *Ankistrodesmus* being replaced by *Oscillatoria* and then, by a low winter biomass. The magnitude of these crops is also very similar, as can be compared directly overleaf where Fig. 3.1 is reproduced.

Fig.3.7

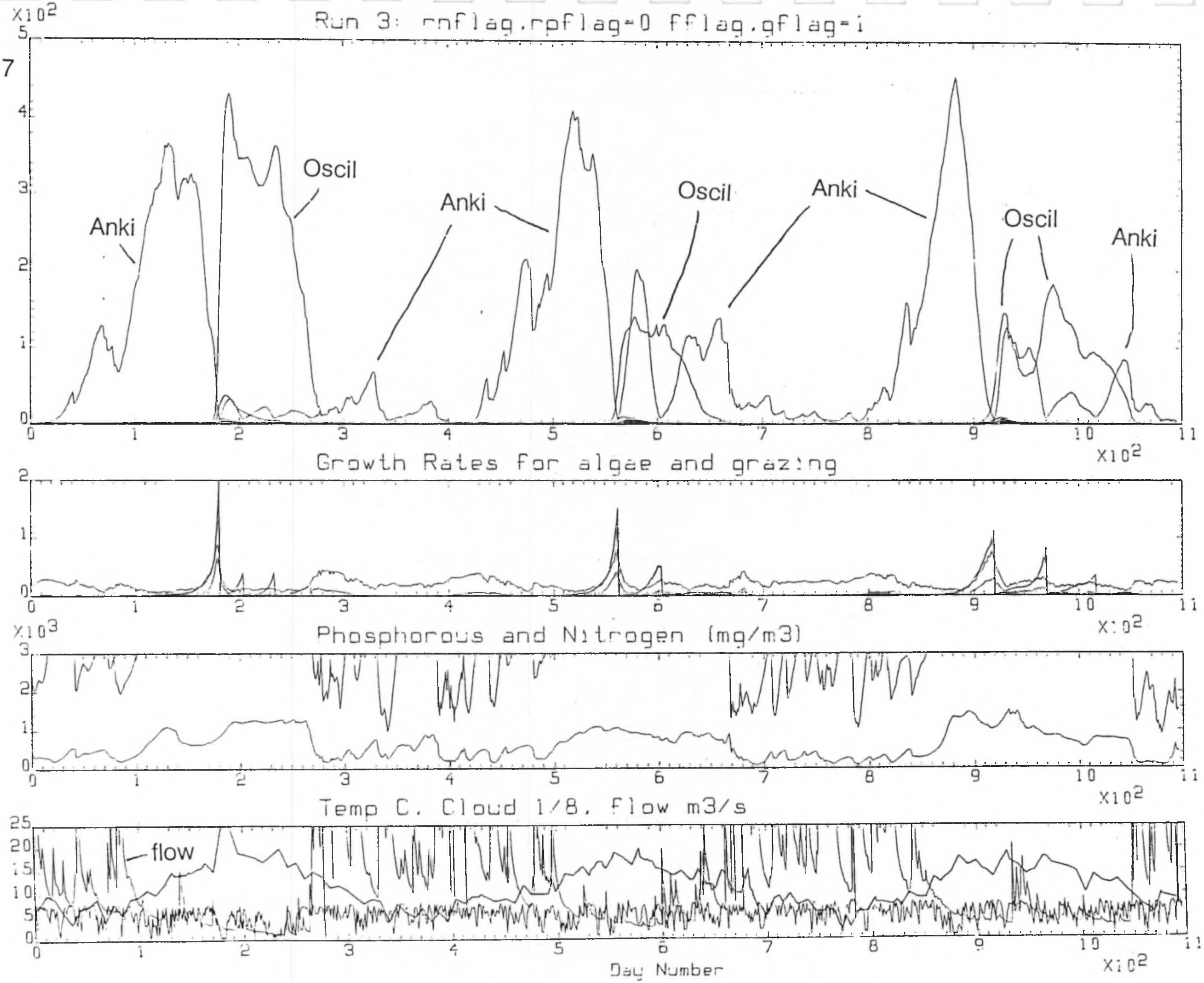
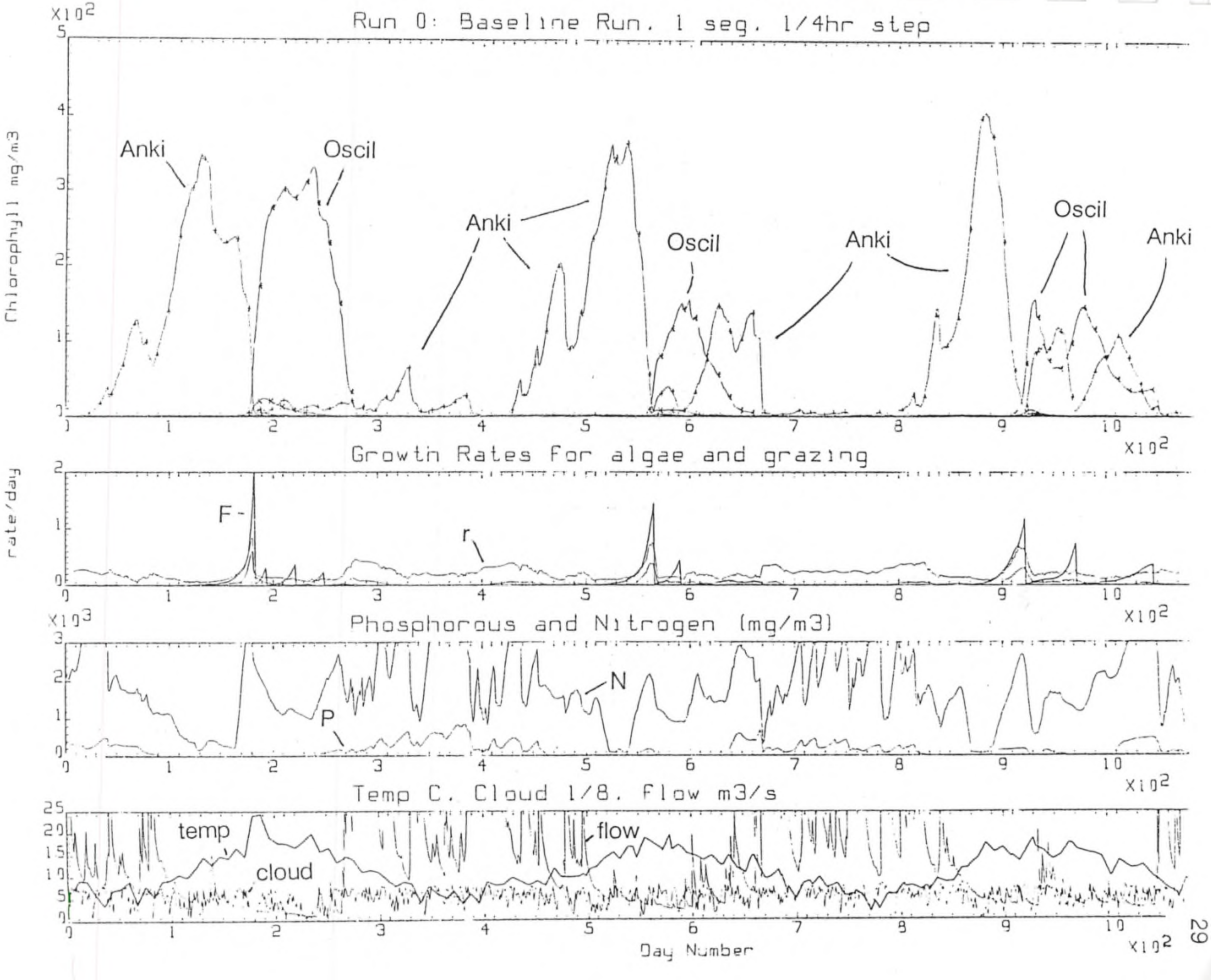

Run 3: rnflag.rpflag=0 fflag.gflag=1
X10^2
5
4
3
2
1
0
Anki
Oscil
Anki
Oscil
Anki
Oscil
Anki
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Growth Rates for algae and grazing
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
X10^3
Phosphorous and Nitrogen (mg/m3)
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Temp C. Cloud 1/8. flow m3/s
25
20
15
10
5
0
flow
0 1 2 3 4 5 6 7 8 9 10 11
Day Number
X10^2

Fig.3.1


Run 0: Baseline Run. 1 seg. 1/4hr step
X10^2
Chlorophyll mg/m3
Anki
Oscil
Anki
Oscil
Anki
Oscil
Anki
Growth Rates for algae and grazing
rate/day
F
r
Phosphorous and Nitrogen (mg/m3)
X10^3
N
P
Temp C. Cloud 1/8. Flow m3/s
temp
cloud
flow
Day Number
X10^2

3.8 Effects of nutrient (P) reduction

We have shown that throughflow and grazers are the primary intermediaries of net phytoplankton biomass accumulation, with which the simulated "real" nutrient loads apparently do not interfere. This finding has some relevance to the practical opportunities for stripping phosphorus from the Taff (and Elai) inflows. Since most phosphorus enters the lake in winter also leaves it untapped and, thus, plays little part in regulating crops, we have imposed the effects of severe P-limitation as a result of stripping only between Julian days 90 and 270 of each year (approx April-September inclusive). In Fig. 3.8.1, the envisaged 'removal' success is set at 60%; in 3.8.2, a more efficient plant is supposed to remove 85% of the inflowing P. In the former case, the late summer growth of Ankistrodesmus in 1977 (see 3.1) is slightly reduced but, otherwise, the effect is negligible. At 85% removal, however, the maximum biomass attained by Ankistrodesmus and Oscillatoria is severely curtailed (< 200 mg chlorophyll m^{-3}) at all times.

Fig.3.8.1

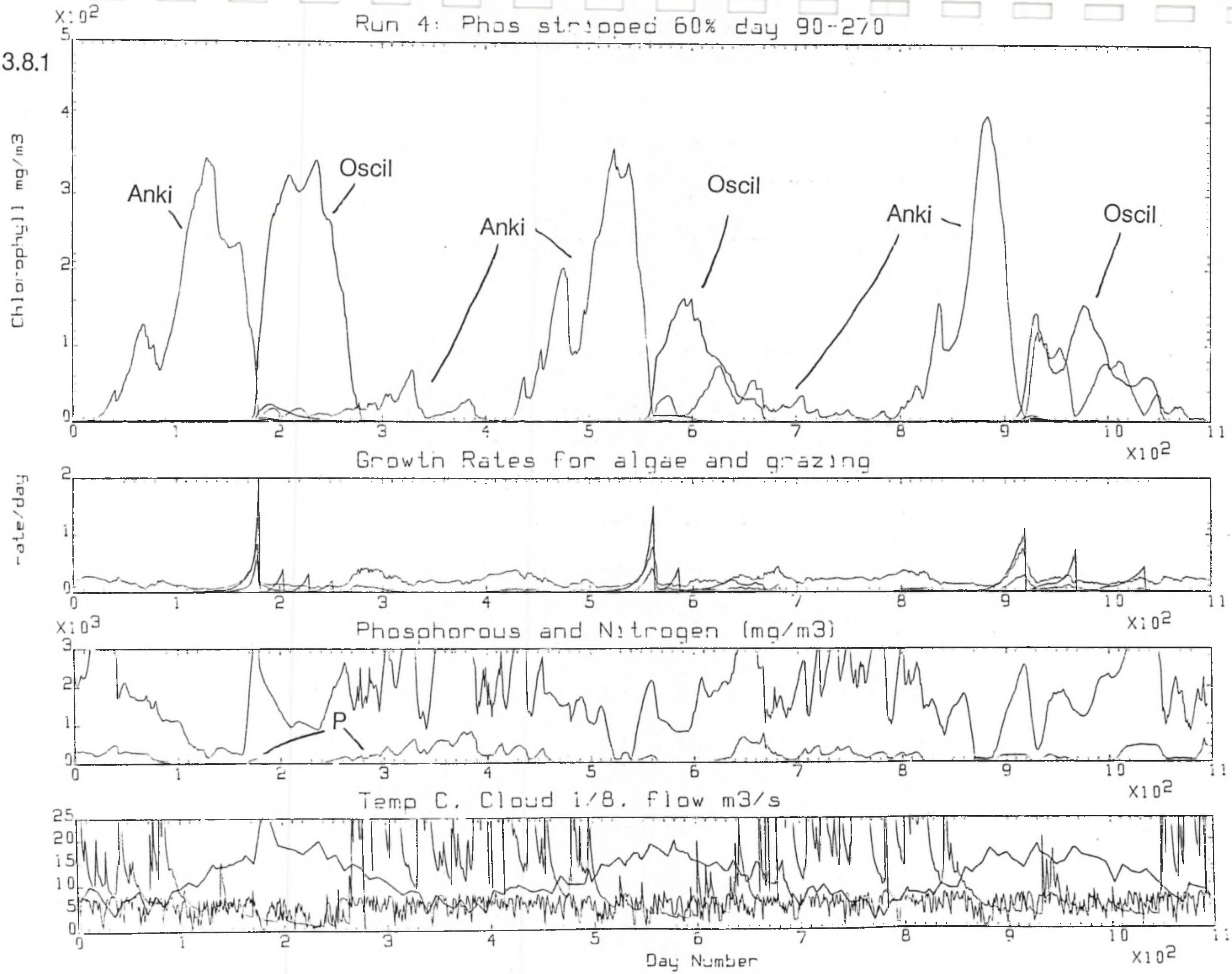
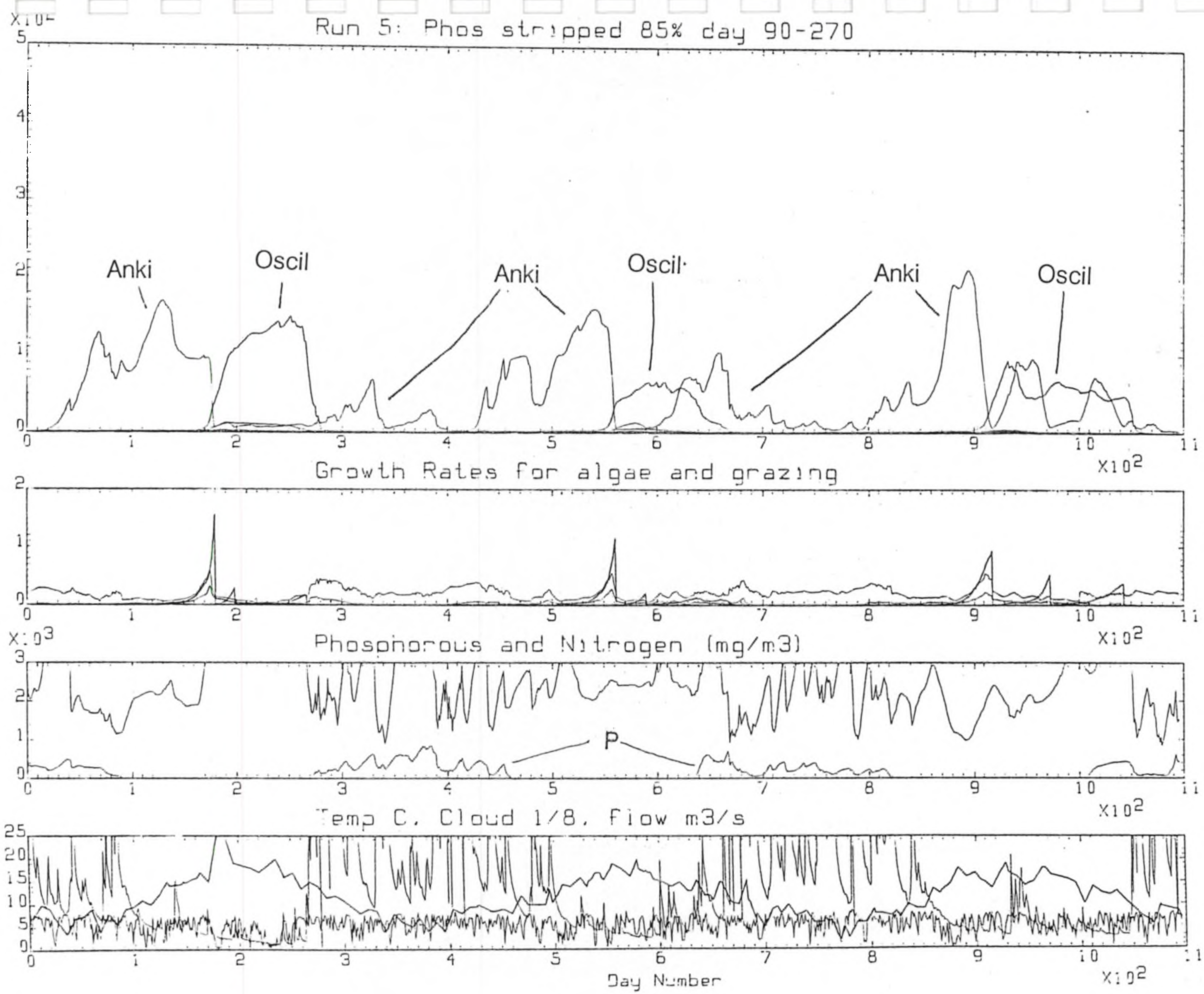

Run 4: Phos stripped 60% day 90-270
X10^2
Chlorophyll mg/m3
0
1
2
3
4
5
Anki
Oscil
Anki
Oscil
Anki
Oscil
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
X10^3
Phosphorous and Nitrogen (mg/m3)
0
1
2
3
P
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
Temp C. Cloud 1/8. Flow m3/s
0
5
10
15
20
25
0
1
2
3
4
5
6
7
8
9
10
11
Day Number
X10^2

Fig.3.8.2


Run 5: Phos stripped 85% day 90-270
X10²
Chlorophyll mg/m3
0
1
2
3
4
5
Anki
Oscil
Anki
Oscil
Anki
Oscil
0
1
2
3
4
5
6
7
8
9
10
11
X10²
Growth Rates for algae and grazing
rate/day
0
1
2
X10²
Phosphorous and Nitrogen (mg/m3)
X10³
0
1
2
3
P
X10²
Temp C, Cloud 1/8, Flow m3/s
0
5
10
15
20
25
Day Number
X10²

3.9 Varying the respondent algal suite

In the next stage, we attempted to trace the performance of the other algae 'available' in the model to test whether their failure to generate significant populations in the preceding runs owed to some feature of their ability to respond to the environmental conditions set or whether it was purely a competitive 'exclusion' effect. Of the eight species placed in the model, the most prolific (*Ankistrodesmus*) was omitted first, then each of the others in order of their ability to 'exploit' the reduced competition, until only one species was left. The results of this exercise are illustrated in Figs 3.9.1 - 3.9.7.

3.9.1. *Exclusion of Ankistrodesmus*. When Ankistrodesmus is excluded from the model, the next fastest-growing algae, *Chlorella* and *Asterionella* dominate the vernal growth, but the populations are nevertheless smaller (< 150 mg chlorophyll m^{-3}). The additional unconsumed resource in 1976 permitted a larger *Oscillatoria* maximum, but other species are scarcely affected.

3.9.2. *Exclusion of Ankistrodesmus and Chlorella*. Predictably, alleviation of 'competition' with *Chlorella*, *Asterionella* quickly dominated the vernal period. *Stephanodiscus* (another diatom) and *Scendesmus* produced notable subdominant populations.

3.9.3. *Exclusion of Ankistrodesmus, Chlorella and Stephanodiscus* left *Asterionella* a clear vernal dominant but *Anabaena* now figured significantly in the sequence.

3.9.4. *Exclusion of Ankistrodesmus, Chlorella, Stephanodiscus and Asterionella* allowed *Scenedesmus* to dominate in spring (100-200 mg chlorophyll m^{-3}) and also permitted an earlier increase in *Oscillatoria*. Note the lower grazing intensity illustrated in 3.9.4 (second panel).

3.9.5. *Exclusion of Ankistrodesmus, Chlorella, Stephanodiscus, Asterionella and Scenedesmus*. When the 'available' algal flora is reduced to only the blue-green algae *Oscillatoria*, *Anabaena* and *Microcystis*, the 'spring' maximum disappears altogether. The *Oscillatoria* maximum commences a little earlier but its maximum biomass is scarcely altered.

3.9.6. *Exclusion of all algae save Anabaena and Microcystis*. In this eventuality, significant increase of *Anabaena* is permitted for the first time. The implication is that only when it is freed from competition by faster-growing species using available light more efficiently, *Anabaena* is able to make a significant contribution to the biomass. *Microcystis* makes very little impression.

3.9.7. *Exclusion of all algae save Microcystis*. When all other species are removed, *Microcystis* is allowed to develop significant populations. Even then its growth rate is normally too slow to counter rapid outwash, except when low flow and relatively high temperatures obtain simultaneously. As with *Anabaena* (3.9.6), *Microcystis* has the potential to develop surface scums and these could prove unacceptable when generated from even quite low populations. On the basis of the model simulations, these algae would be unlikely to form nuisance populations except in dry summers and after all other species had failed to achieve prior dominance.

Other runs were conducted to determine the constraints on *Microcystis* growth including the removal of throughflow (3.9.8) and providing unlimited nutrient resources (3.9.9) and both (3.9.10). Of these, only 3.9.8 closely resembles 3.9.7, suggesting that throughflow largely regulates its dynamics, after competition is removed.

Fig.3.9.1

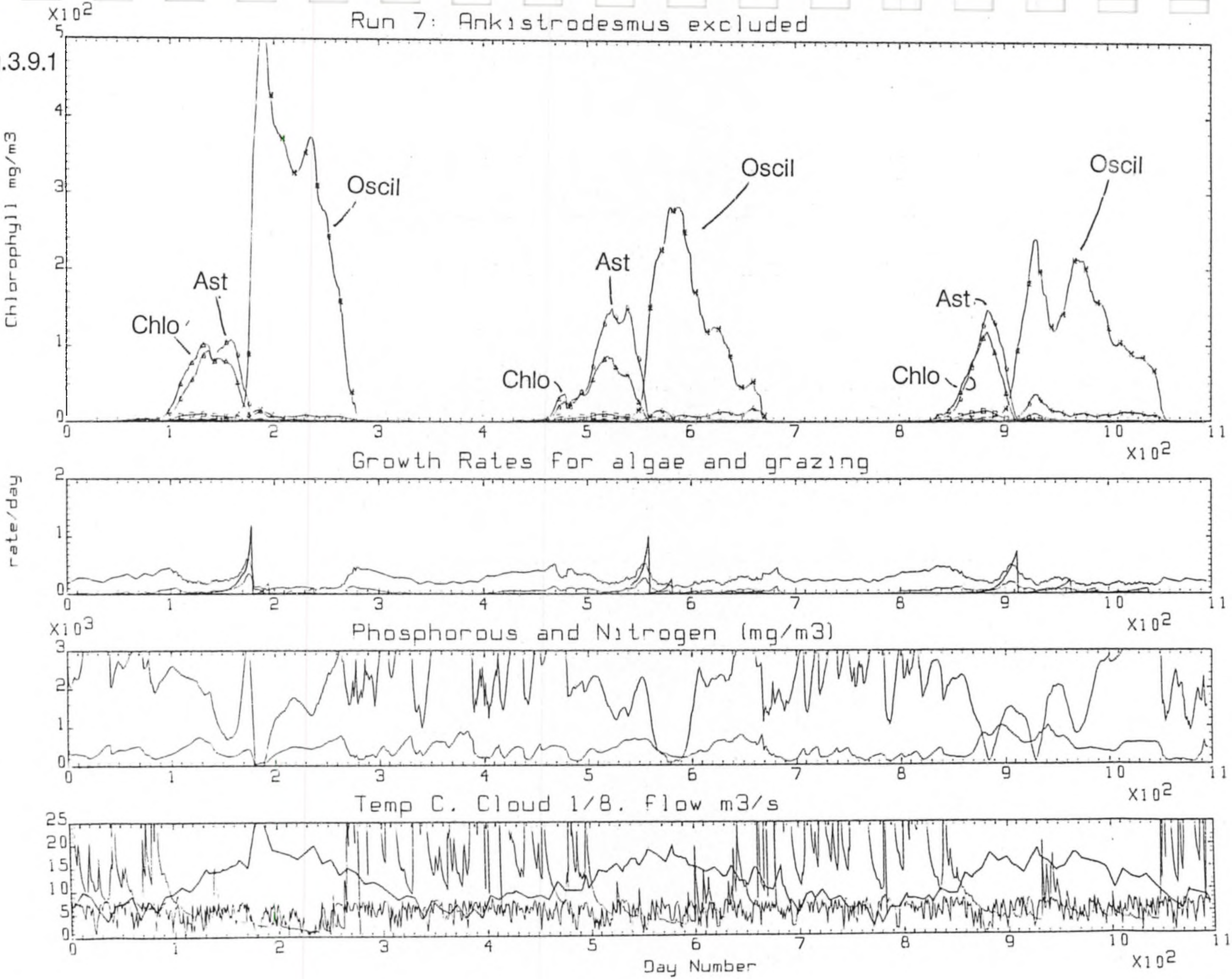

Run 7: Ankistrodesmus excluded
X10^2
Chlorophyll mg/m3
0
1
2
3
4
5
Chlo
Ast
Oscil
Chlo
Ast
Oscil
Ast
Chlo
Oscil
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
X10^3
Phosphorous and Nitrogen (mg/m3)
0
1
2
3
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Temp C. Cloud 1/8. Flow m3/s
0
5
10
15
20
25
0 1 2 3 4 5 6 7 8 9 10 11
Day Number
X10^2

Fig.3.9.2

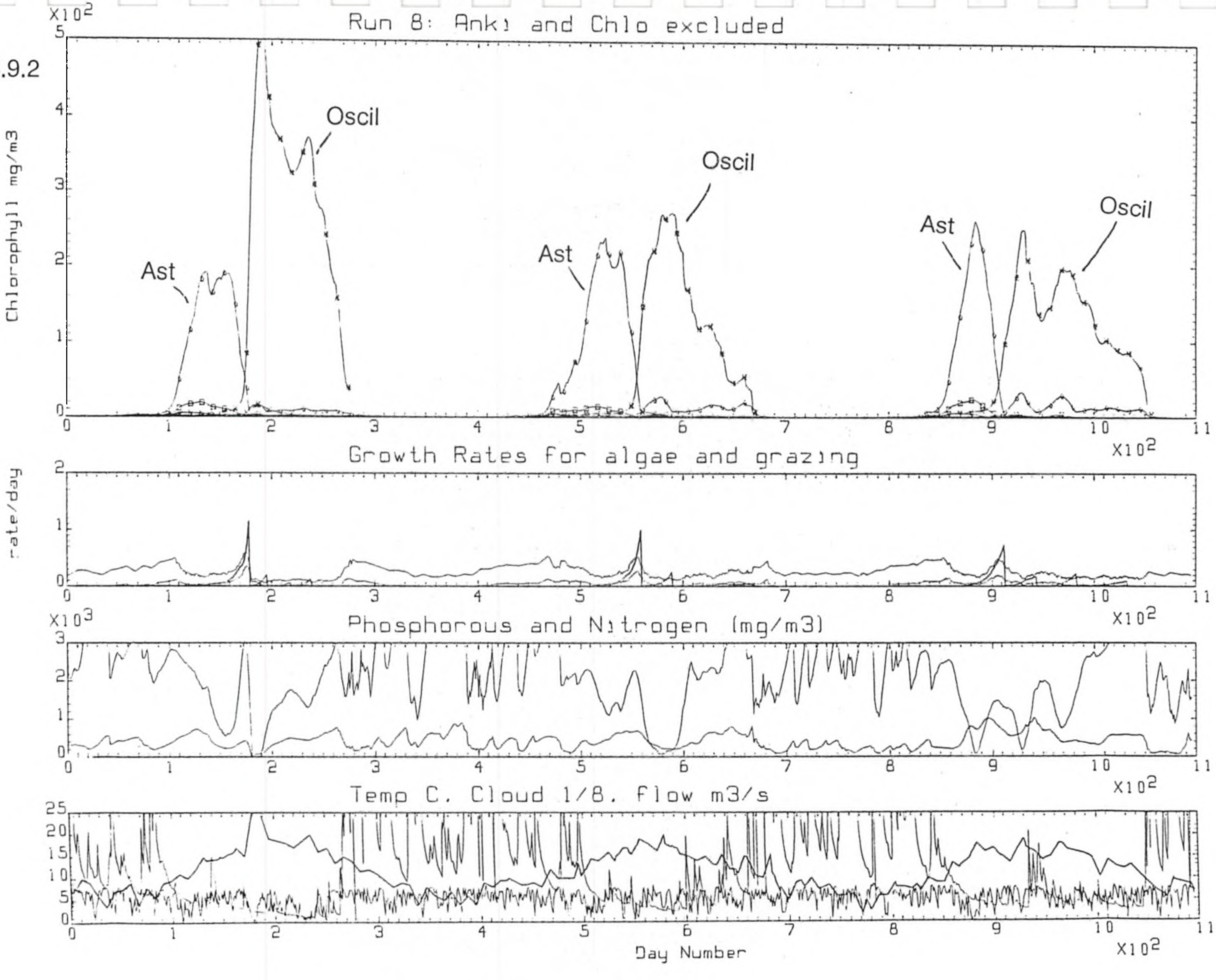

Run 8: Anki and Chlo excluded
X10^2
Chlorophyll mg/m3
5
4
3
2
1
0
Ast
Oscil
Ast
Oscil
Ast
Oscil
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Growth Rates for algae and grazing
rate/day
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
X10^3
Phosphorous and Nitrogen (mg/m3)
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Temp C. Cloud 1/8. flow m3/s
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
Day Number
X10^2

Fig.3.9.3

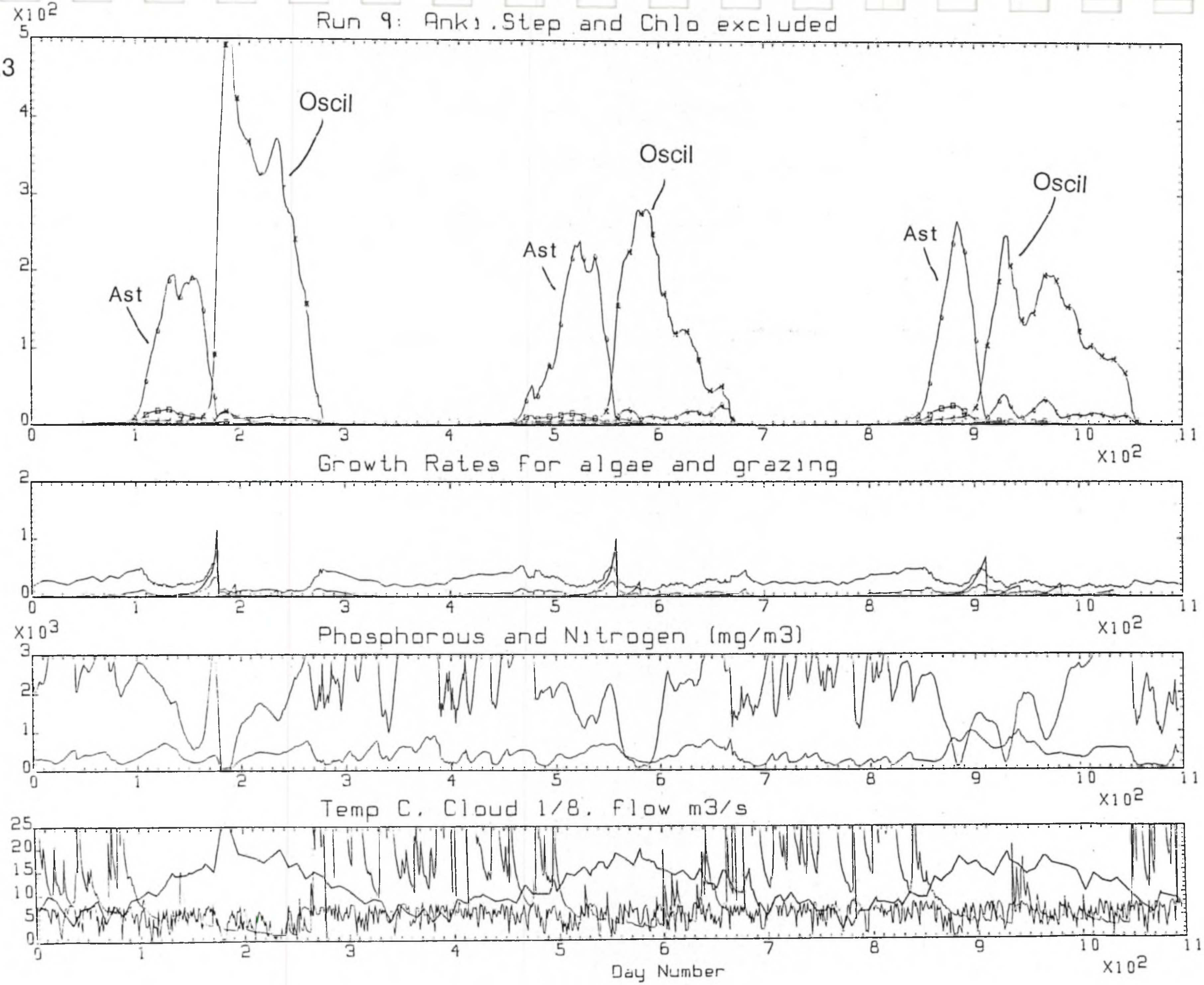

Run 9: Anki.Step and Chlo excluded
X10^2
Chlorophyll mg/m3
0
1
2
3
4
5
Ast
Oscil
Ast
Oscil
Ast
Oscil
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
X10^3
Phosphorous and Nitrogen (mg/m3)
0
1
2
3
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Temp C, Cloud 1/8, Flow m3/s
0
5
10
15
20
25
0 1 2 3 4 5 6 7 8 9 10 11
Day Number
X10^2

Fig.3.9.4

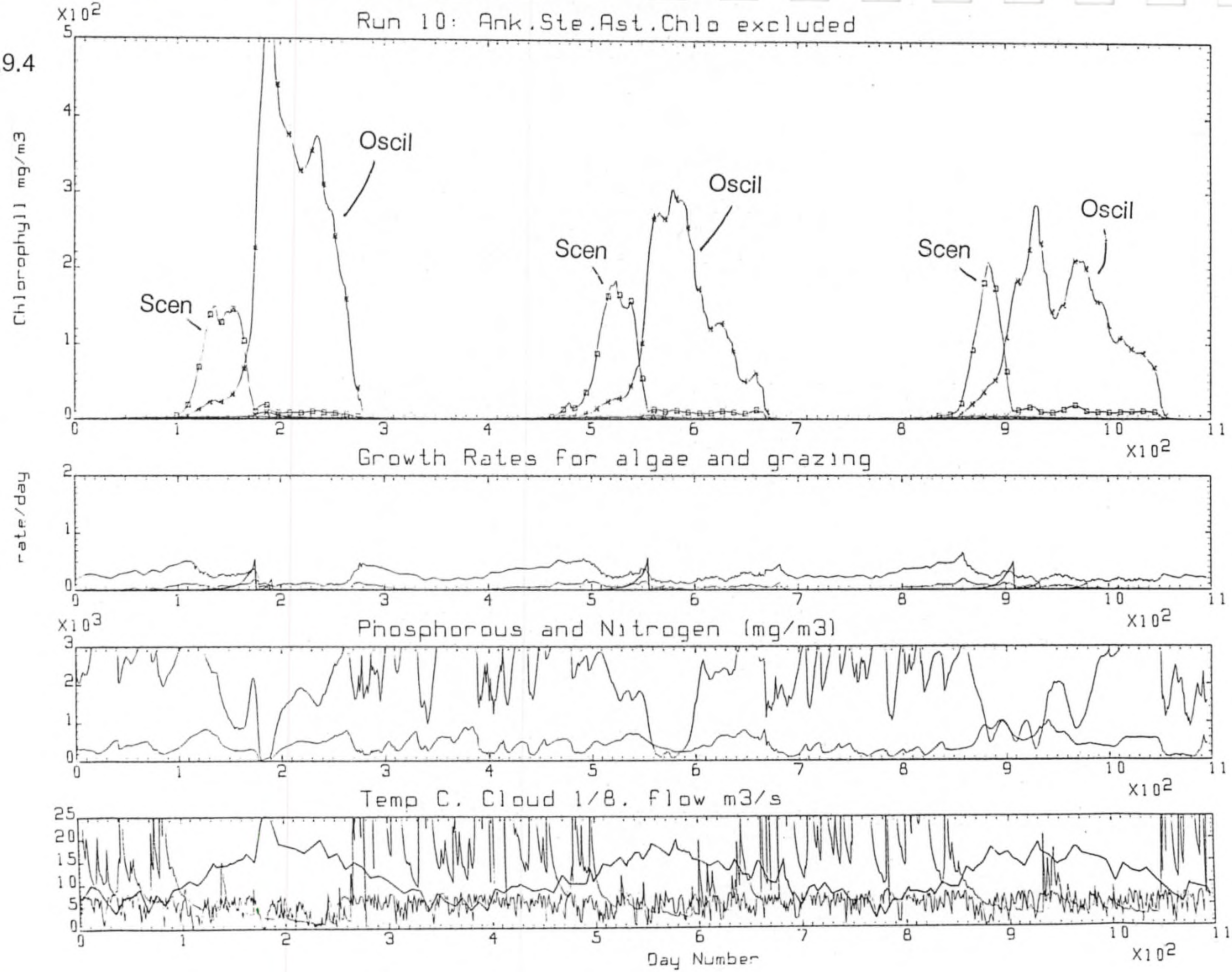

Run 10: Ank.Ste.Ast.Chlo excluded
X10^2
Chlorophyll mg/m3
5
4
3
2
1
0
Oscil
Oscil
Oscil
Scen
Scen
Scen
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
Growth Rates for algae and grazing
rate/day
2
1
0
X10^2
X10^3
Phosphorous and Nitrogen (mg/m3)
3
2
1
0
X10^2
Temp C. Cloud 1/8. flow m3/s
25
20
15
10
5
0
Day Number
X10^2

Fig.3.9.5

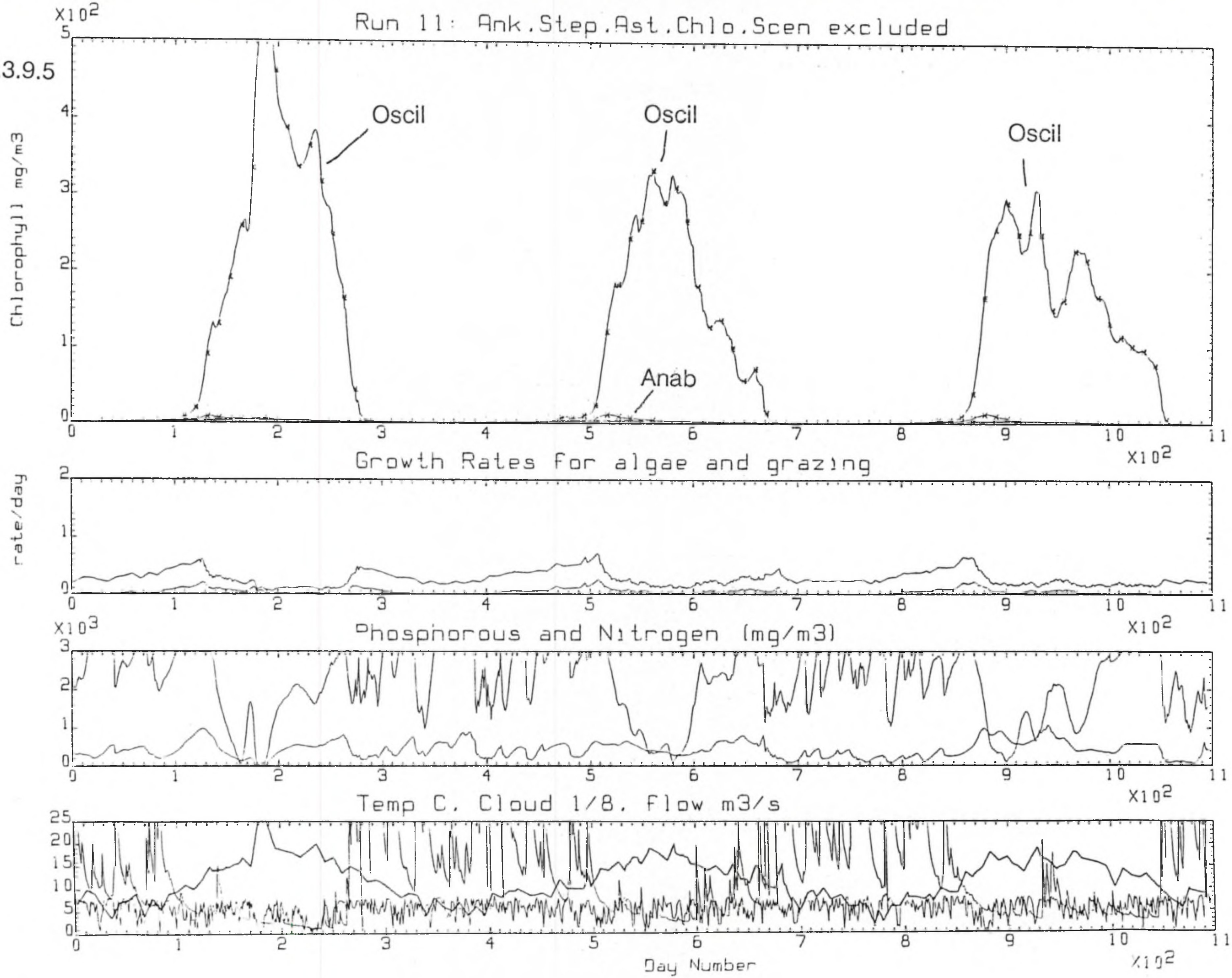

X10^2
Run 11: Ank.Step.Ast.Chlo.Scen excluded
Chlorophyll mg/m3
Oscil
Oscil
Oscil
Anab
0
1
2
3
4
5
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
X10^3
Phosphorous and Nitrogen (mg/m3)
0
1
2
3
X10^2
Temp C. Cloud 1/8. Flow m3/s
0
5
10
15
20
25
0
1
2
3
4
5
6
7
8
9
10
11
Day Number
X10^2

Fig.3.9.6

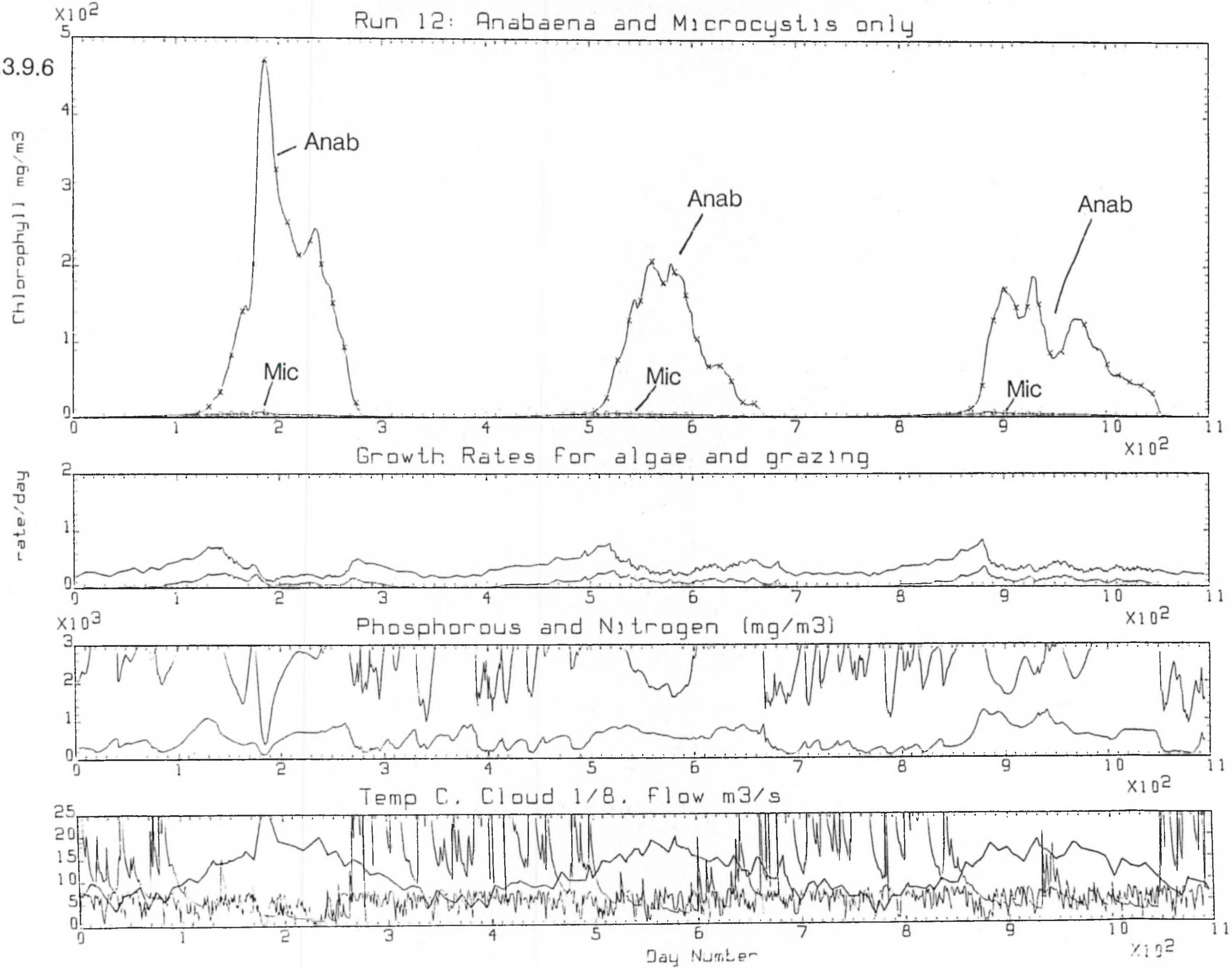

Run 12: Anabaena and Microcystis only
X10^2
Chlorophyll mg/m3
0
1
2
3
4
5
Anab
Anab
Anab
Mic
Mic
Mic
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Phosphorous and Nitrogen (mg/m3)
X10^3
0
1
2
3
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Temp C. Cloud 1/8. Flow m3/s
0
5
10
15
20
25
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Day Number

Fig.3.9.7

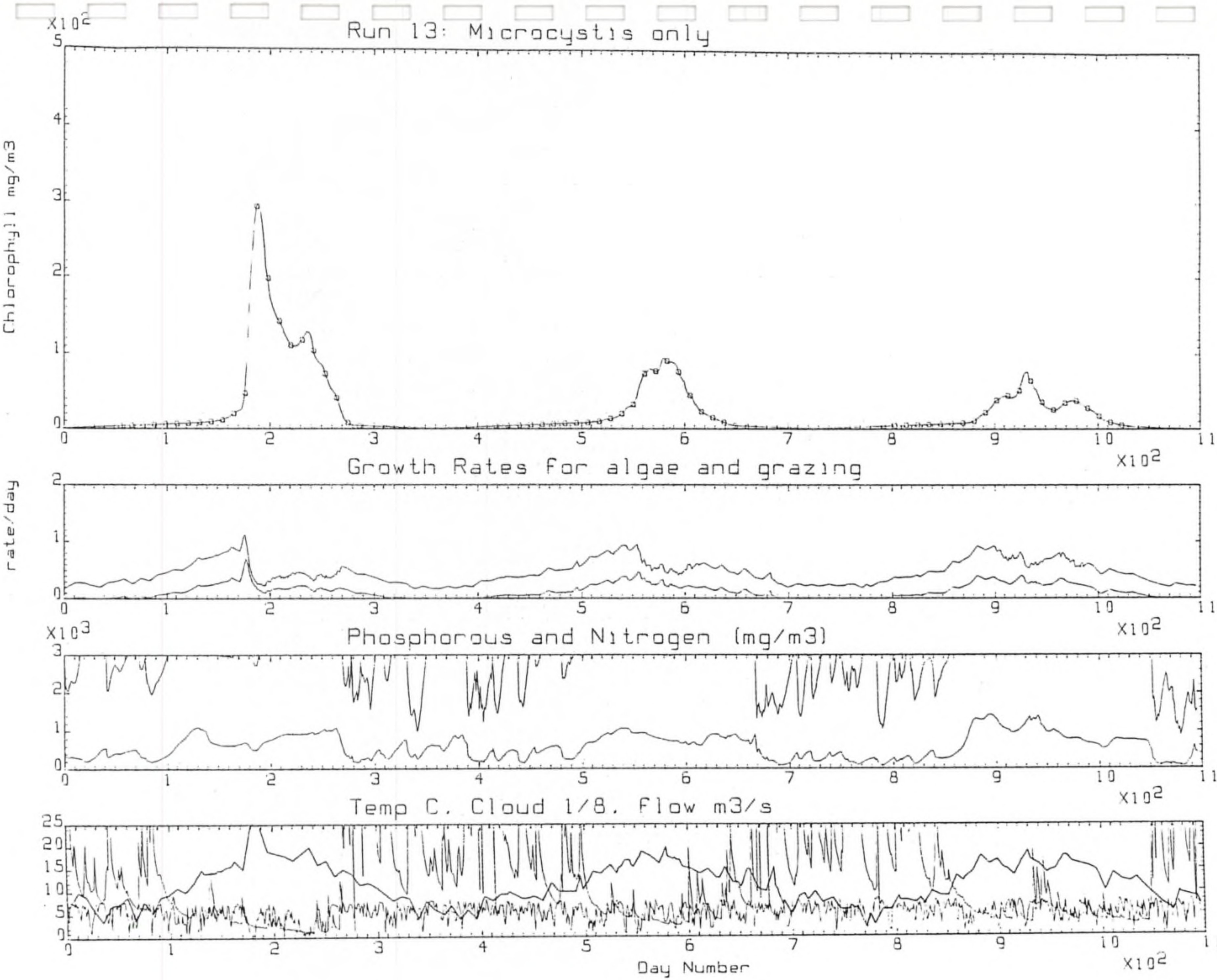
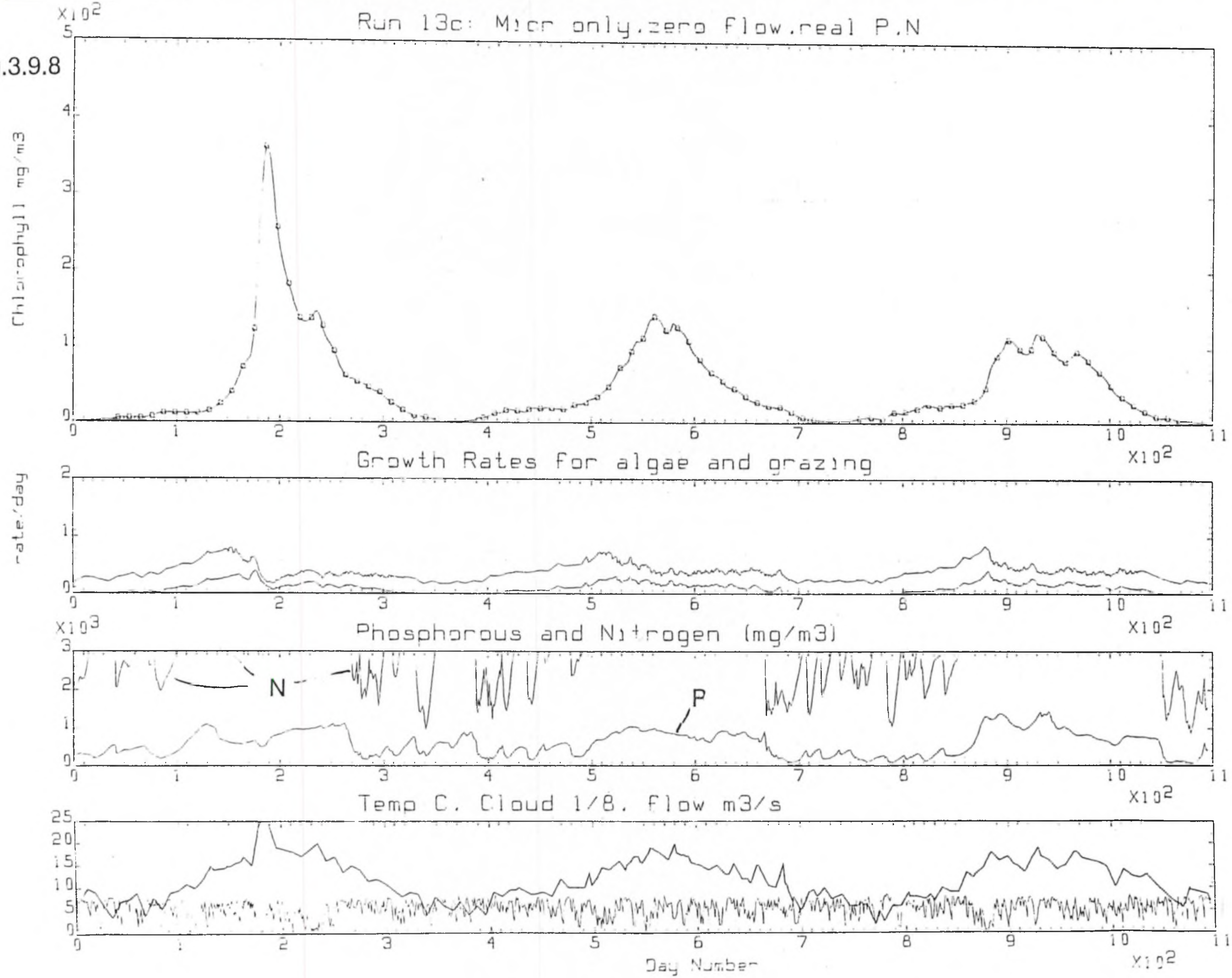

Run 13: Microcystis only
X10^2
Chlorophyll mg/m3
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
X10^2
Phosphorous and Nitrogen (mg/m3)
X10^3
0
1
2
3
X10^2
Temp C. Cloud 1/8. Flow m3/s
0
5
10
15
20
25
Day Number
X10^2

Fig.3.9.8



Run 13c: Micr only.zero flow.real P.N
X10^2
Chlorophyll mg/m3
0
1
2
3
4
5
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
X10^2
X10^3
Phosphorous and Nitrogen (mg/m3)
N
P
0
1
2
3
X10^2
Temp C. Cloud 1/8. flow m3/s
0
5
10
15
20
25
Day Number
X10^2

Fig.3.9.9

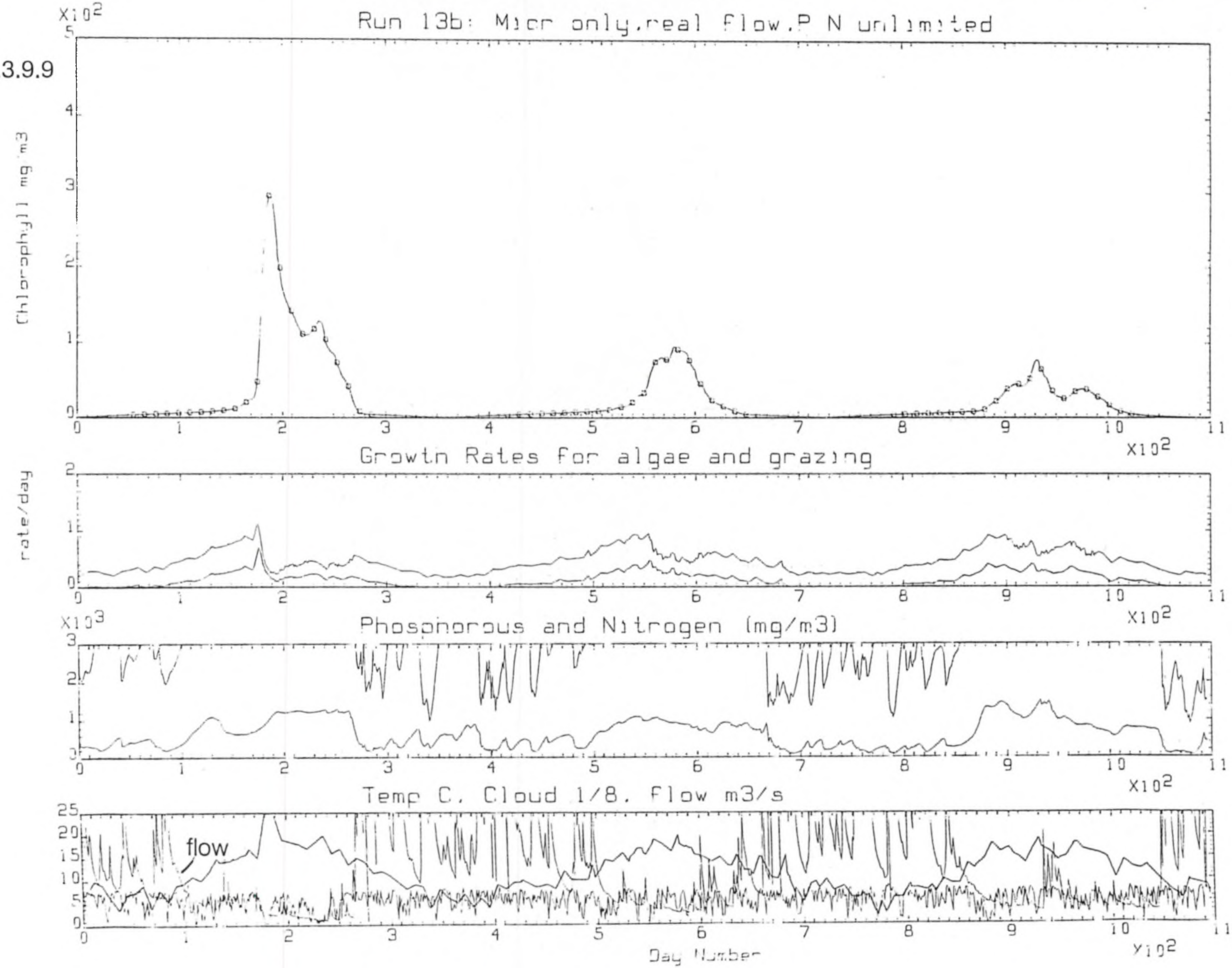
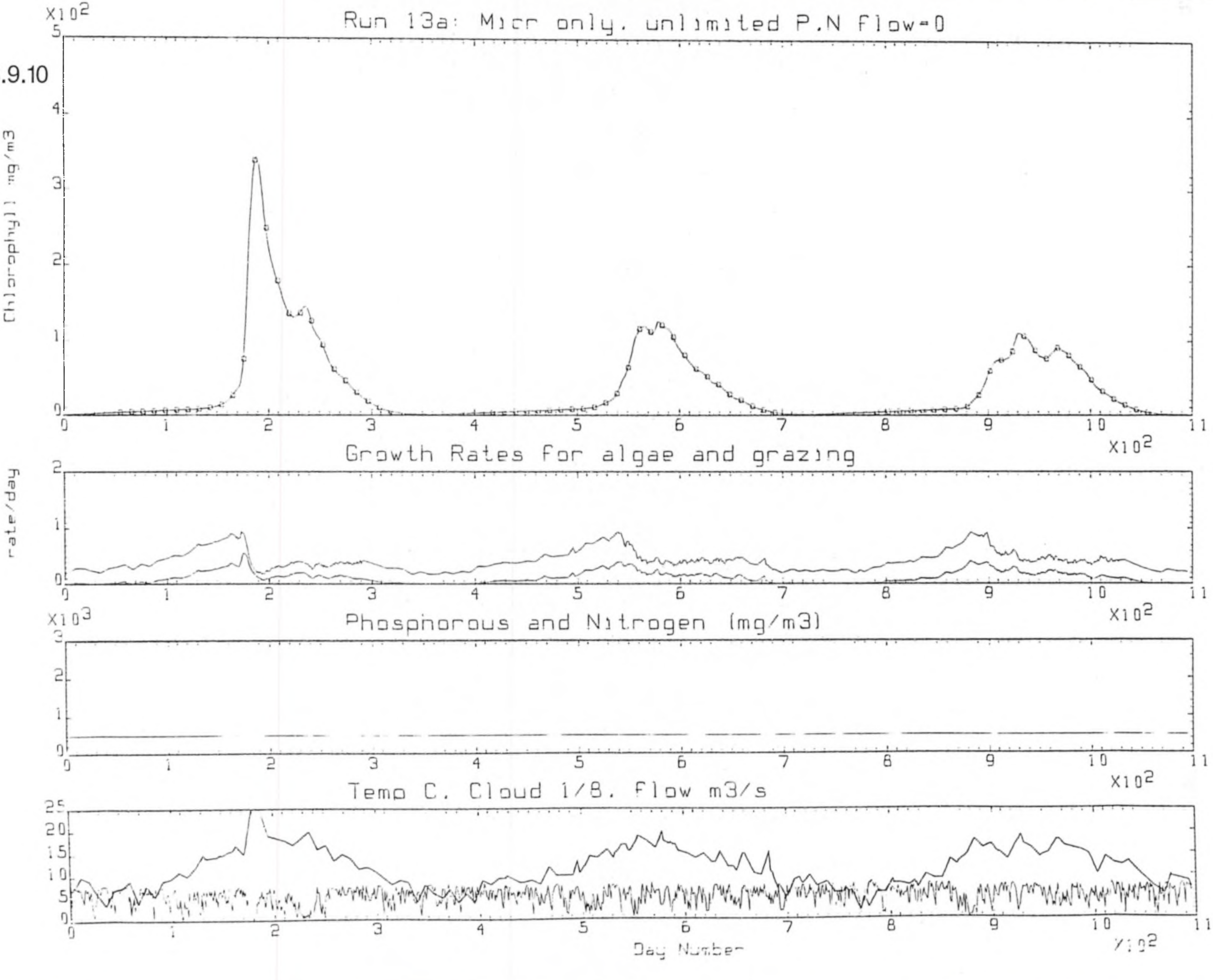

Run 13b: Micr only, real flow, P N unlimited
X10²
Chlorophyll mg/m3
0
1
2
3
4
5
0
1
2
3
4
5
6
7
8
9
10
11
X10²
Growth Rates for algae and grazing
rate/day
0
1
2
X10²
Phosphorous and Nitrogen (mg/m3)
X10³
0
1
2
3
X10²
Temp C, Cloud 1/8, Flow m3/s
0
5
10
15
20
25
flow
Day Number
X10²

Fig.3.9.10


Run 13a: Micr only. unlimited P.N flow=0
X10^2
Chlorophyll mg/m3
0
1
2
3
4
5
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
X10^3
Phosphorous and Nitrogen (mg/m3)
0
1
2
3
Temp C. Cloud 1/8. Flow m3/s
0
5
10
15
20
25
Day Number
X10^2

Other selective and controlling mechanisms

3.10.1. Nitrogen limitation and *Anabaena*. The evidently strong selection against potential scum-forming blue-green algae could be reversed in the event of significant nitrogen limitation developing while phosphorus remained sublimiting (1). In this case, the ability to fix gaseous nitrogen would give an undoubted selective advantage to *Anabaena*. In Fig. 3.10.1, nitrogen is artificially reduced (as if by stopping at source, on the same premise followed in 3.8) by 50% between April and September (inclusive): the sequence is again an alternative between low (winter) biomass, *Ankistrodesmus* and, finally, *Oscillatoria*; a modest population of *Anabaena* was constituted in the summer months, though always < 50 mg chlorophyll m^{-3}.

3.10.2. 80% removal of dissolved inorganic nitrogen yielded a weaker response of other species and, in some years, allowed a brief phase of *Anabaena* increase to a dominant maximum of ≤ 130 mg chlorophyll m^{-3}.

Fig.3.10.1

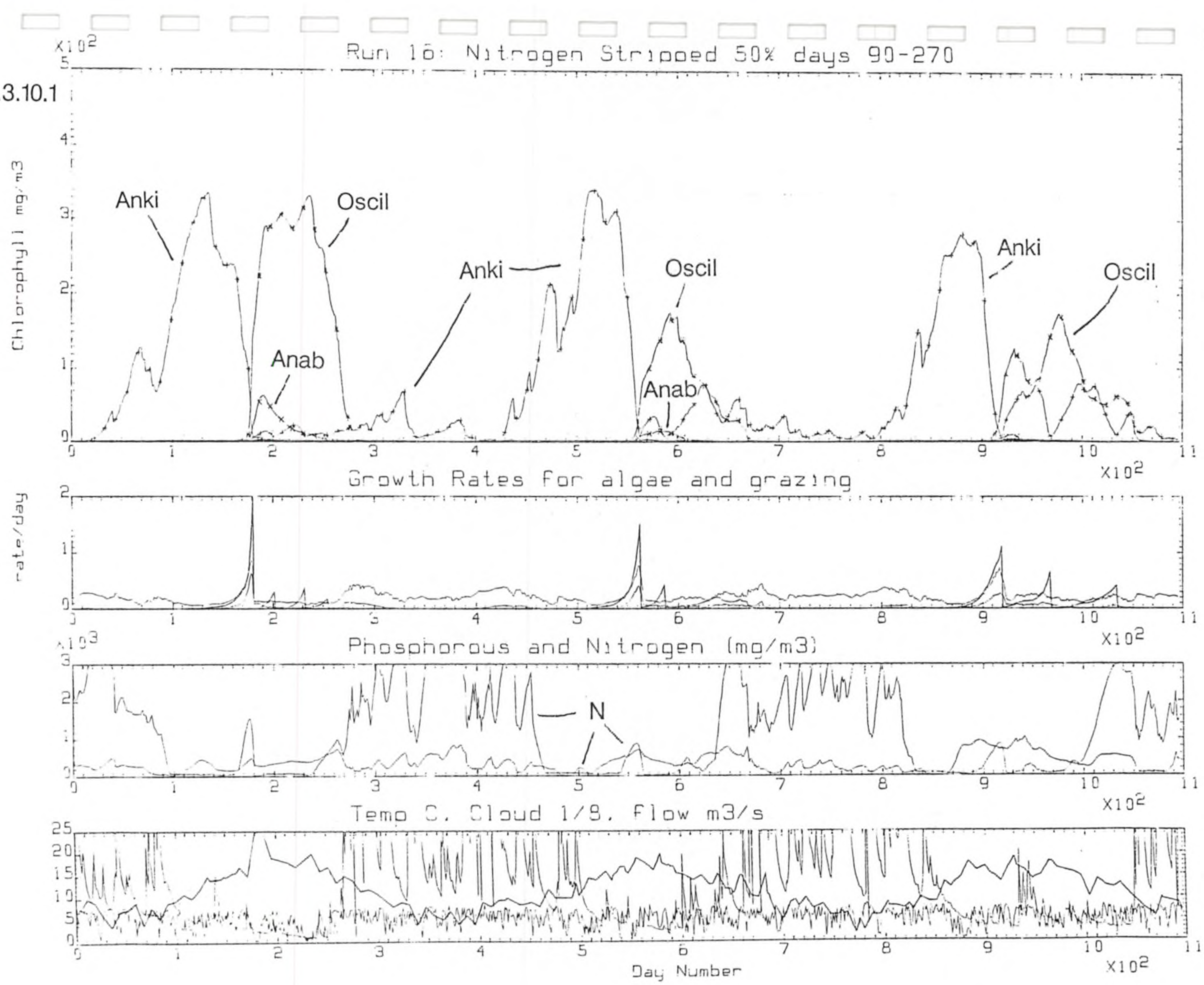
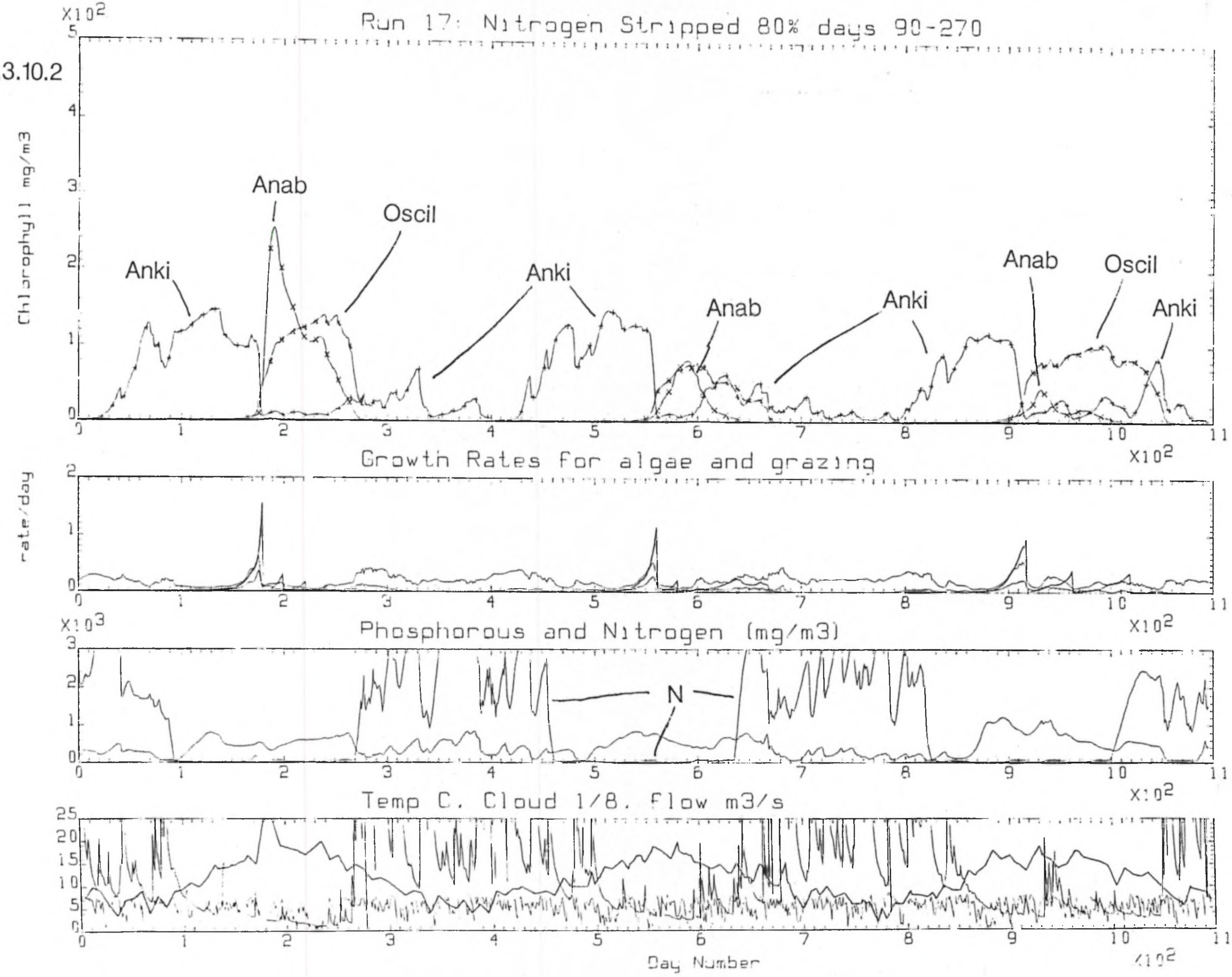

Run 16: Nitrogen Stripped 50% days 90-270
X10^2
Chlorophyll mg/m3
Anki
Oscil
Anab
Anki
Oscil
Anab
Anki
Oscil
0
1
2
3
4
5
Day Number
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
X10^2
Phosphorous and Nitrogen (mg/m3)
X10^3
N
0
1
2
3
X10^2
Temp C. Cloud 1/8. Flow m3/s
0
5
10
15
20
25
0
1
2
3
4
5
6
7
8
9
10
11
Day Number
X10^2

Fig.3.10.2



Run 17: Nitrogen Stripped 80% days 90-270
X10^2
Chlorophyll mg/m3
0
1
2
3
4
5
Anki
Anab
Oscil
Anki
Anab
Anki
Anab
Oscil
Anki
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
X10^2
X10^3
Phosphorous and Nitrogen (mg/m3)
0
1
2
3
N
X10^2
Temp C. Cloud 1/8. Flow m3/s
0
5
10
15
20
25
Day Number
X10^2

3.11 Increased turbidity.

One of the more speculative input components in the original assessment (1), namely, the vertical extinction coefficient ($\epsilon = \epsilon_w + \epsilon_p + n\epsilon s$), was evaluated at a 'worst case' level at which ($\epsilon_w + \epsilon_p$) = 0.2 m^{-1} and algal chlorophyll was alone responsible for enhancement of ϵ. In the present simulations, a new value, based on a recent determination (Welsh Water, unpublished) that ($\epsilon_w + \epsilon_p$) = 0.73 m^{-1} (and which reduced the maximum estimates of standing crop by 70 mg chl m^{-3}. In order both to simulate the effect of rather higher background extinctions (due to river-transported seston or resuspended bottom sediment) and to show that artificial increase of turbidity due to non-living, suspended particles might be considered as an artificial biomass-control. In 3.11.1, ($\epsilon_w + \epsilon_p$) is raised to 1.8 m^{-1}; in 3.11.2, it is raised to 3.0 m^{-1}. An approximate linear response, in terms of maximum biomass (110–230 mg m^{-3} chlorophyll LESS), with reduced light is strongly indicated.

Fig.3.11.1

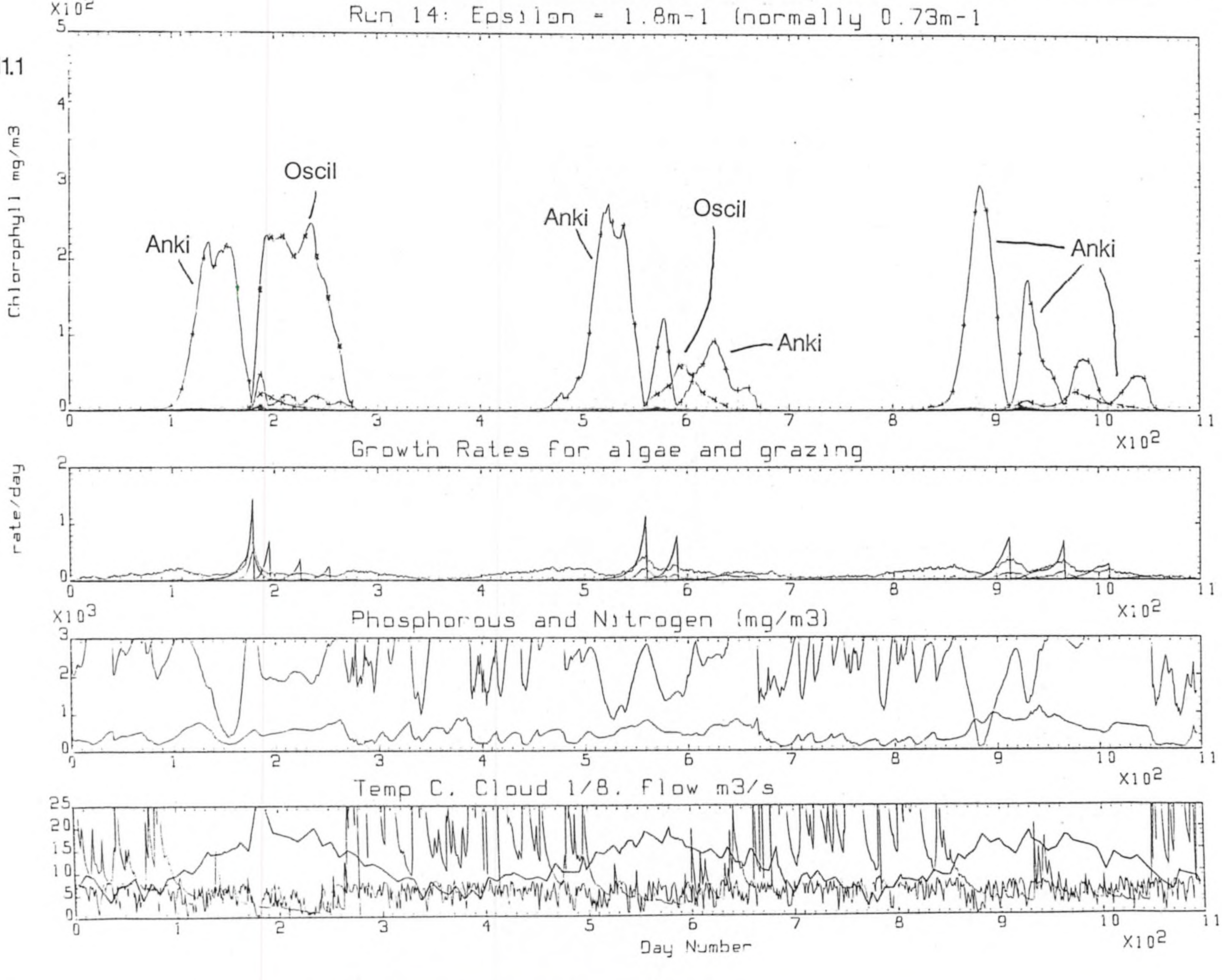
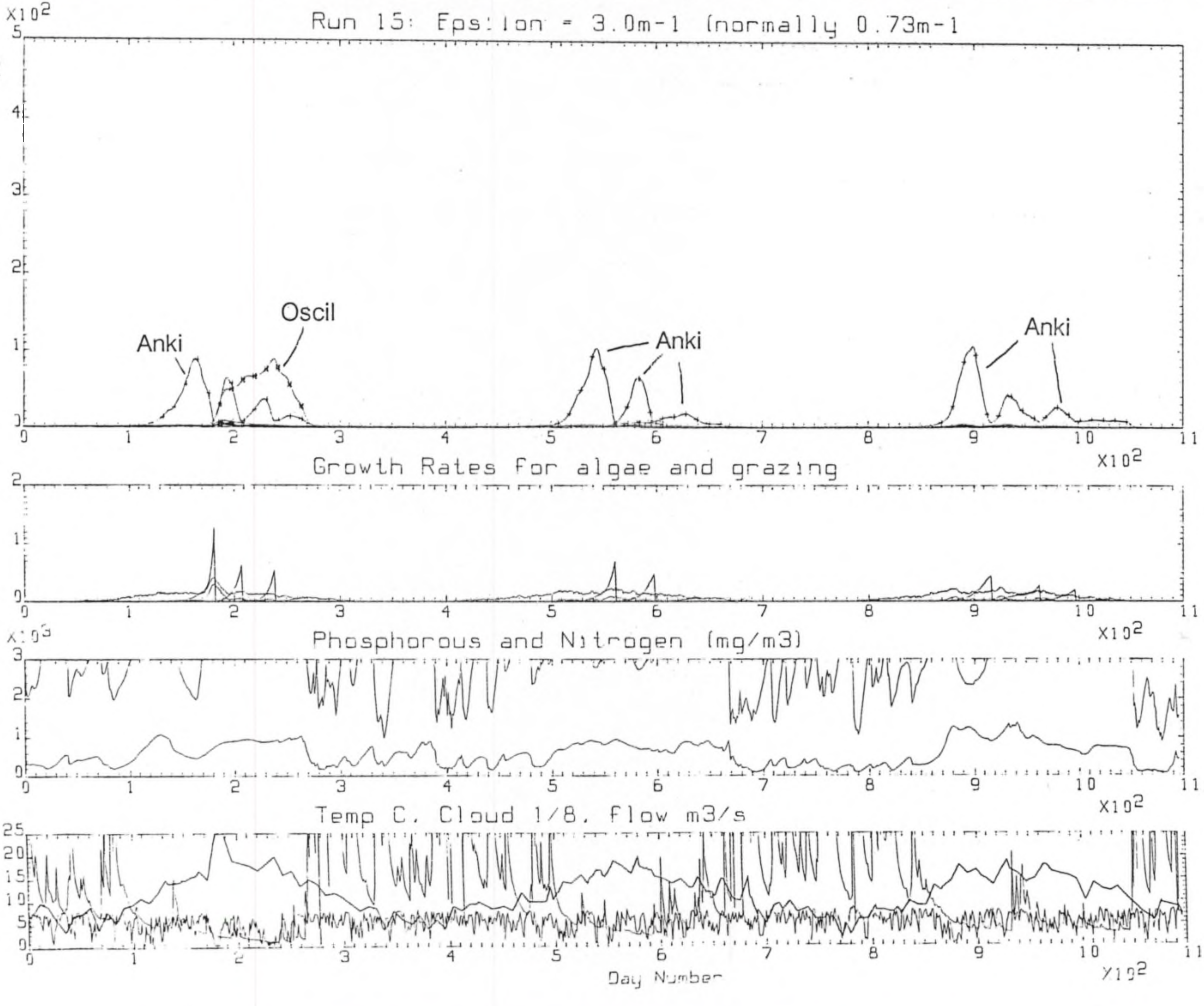

X10^2
Run 14: Epsilon = 1.8m-1 (normally 0.73m-1
Chlorophyll mg/m3
0
1
2
3
4
5
Anki
Oscil
Anki
Oscil
Anki
Anki
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
X10^2
X10^3
Phosphorous and Nitrogen (mg/m3)
0
1
2
3
X10^2
Temp C. Cloud 1/8. Flow m3/s
0
5
10
15
20
25
Day Number
X10^2

Fig.3.11.2



Run 15: Epsilon = 3.0m-1 (normally 0.73m-1)
X10^2
Chlorophyll mg/m3
5
4
3
2
1
0
Anki
Oscil
Anki
Anki
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Growth Rates for algae and grazing
rate/day
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
X10^3
Phosphorous and Nitrogen (mg/m3)
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Temp C, Cloud 1/8, Flow m3/s
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
Day Number
X10^2

3.12 Flow manipulations

We have run three simulations employing altered inflow arrangements. In the first, the take-off of Taff discharge to the Dock Feeder (1 m^3s^{-1}) is 'discontinued' and diverted directly to the barrage lake (3.12.1). Only minor detail differences are detected with respect to the standard solution (3.1). Diverting flow away from the lake, at an average of -4 (3.12.2) and -11 m^3s^{-1} (3.12.3) have quite a profound effect, however: the basic sequence is unchanged but the production of crops of 30-200 mg m^{-3} is extended in time but flattened in amplitude. This effect is the outcome of a complex of responses: the growth periods are lengthened because the period of outwash losses is truncated considerably but the reduced supply of nutrients during times of low fluvial discharge appear to be critical to the development of large maxima.

Fig.3.12.1

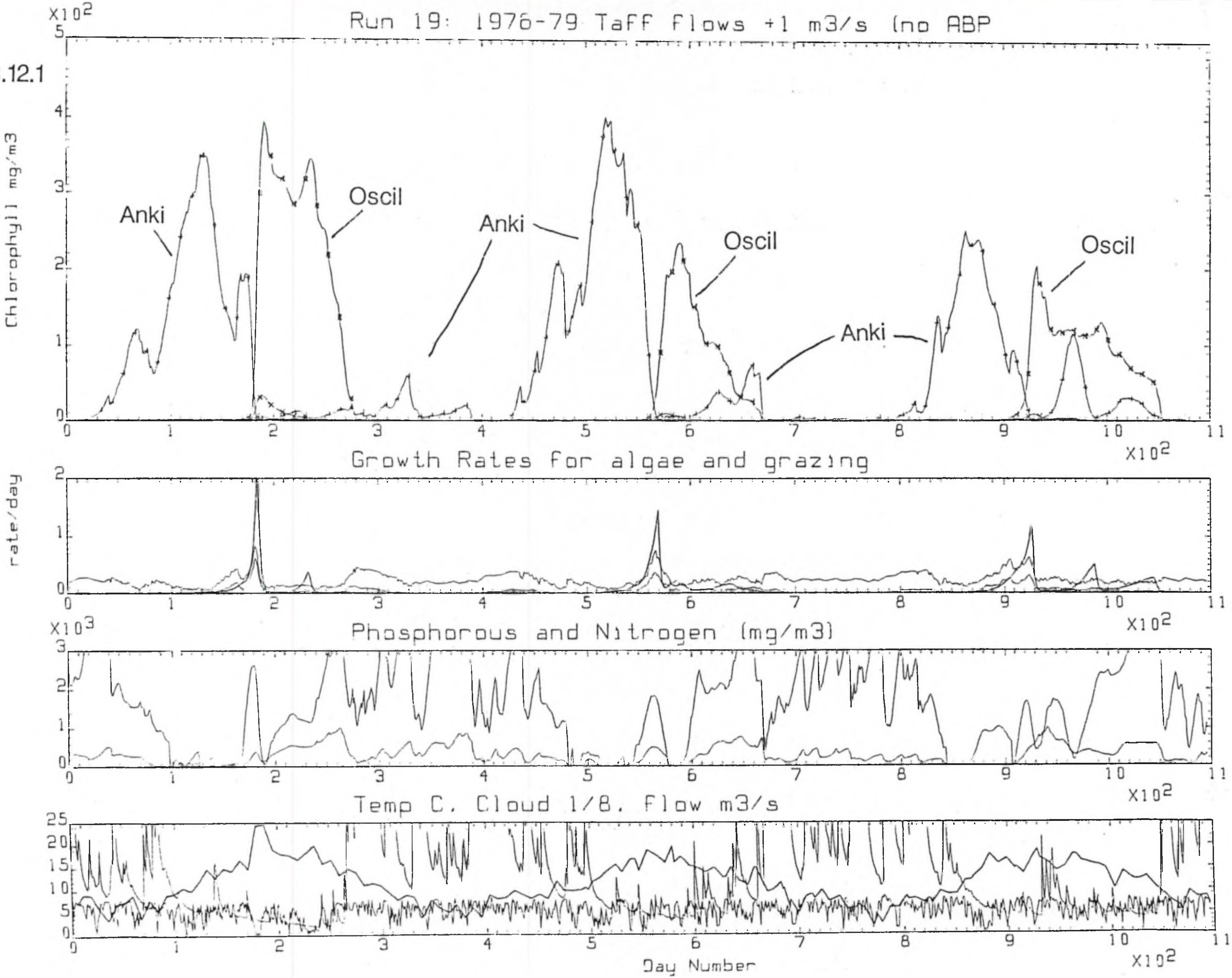

Run 19: 1976-79 Taff Flows +1 m3/s (no ABP
X10^2
Chlorophyll mg/m3
0
1
2
3
4
5
Anki
Oscil
Anki
Oscil
Anki
Oscil
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
X10^2
Phosphorous and Nitrogen (mg/m3)
X10^3
0
1
2
3
X10^2
Temp C. Cloud 1/8. Flow m3/s
0
5
10
15
20
25
0
1
2
3
4
5
6
7
8
9
10
11
Day Number
X10^2

Fig.3.12.2

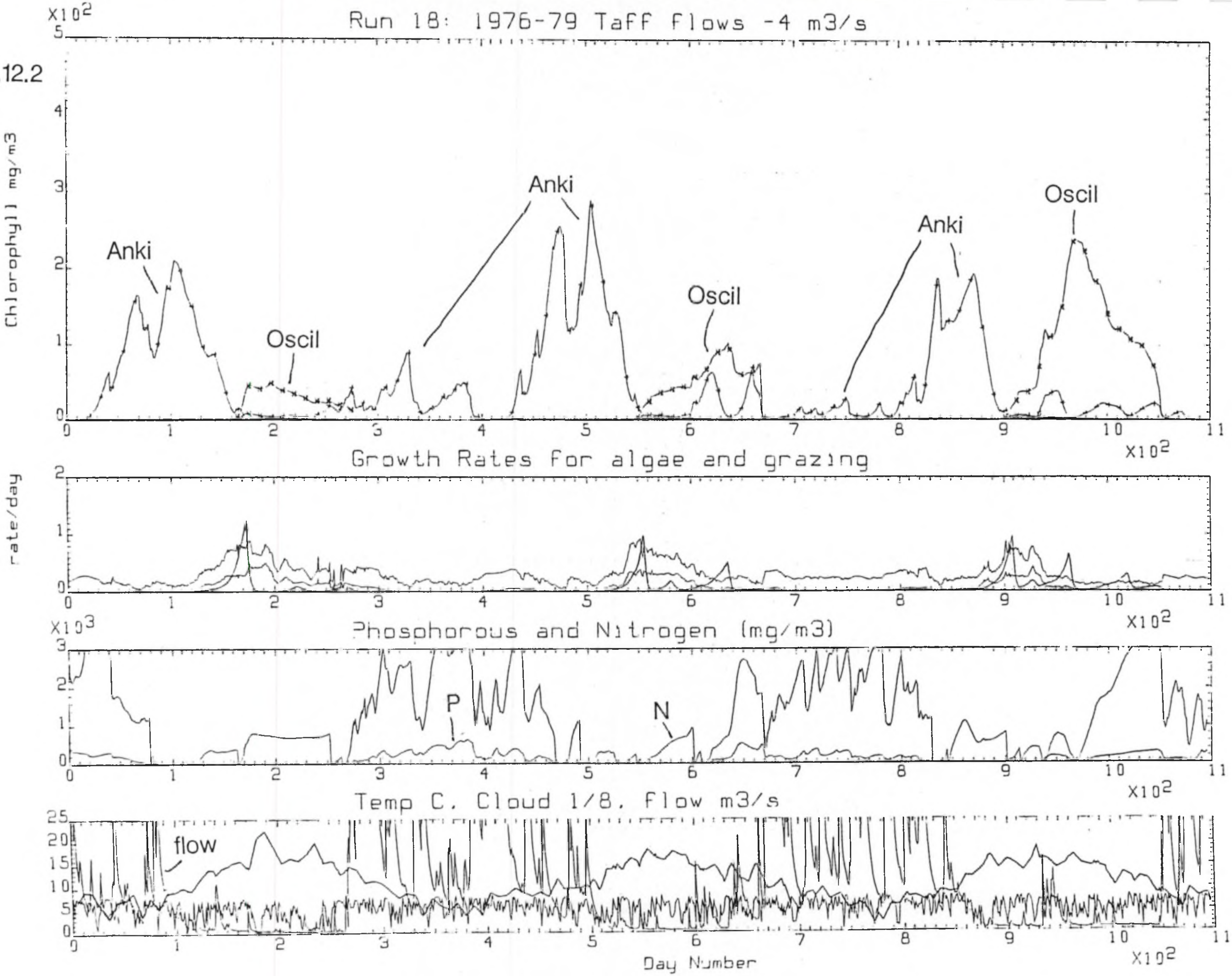
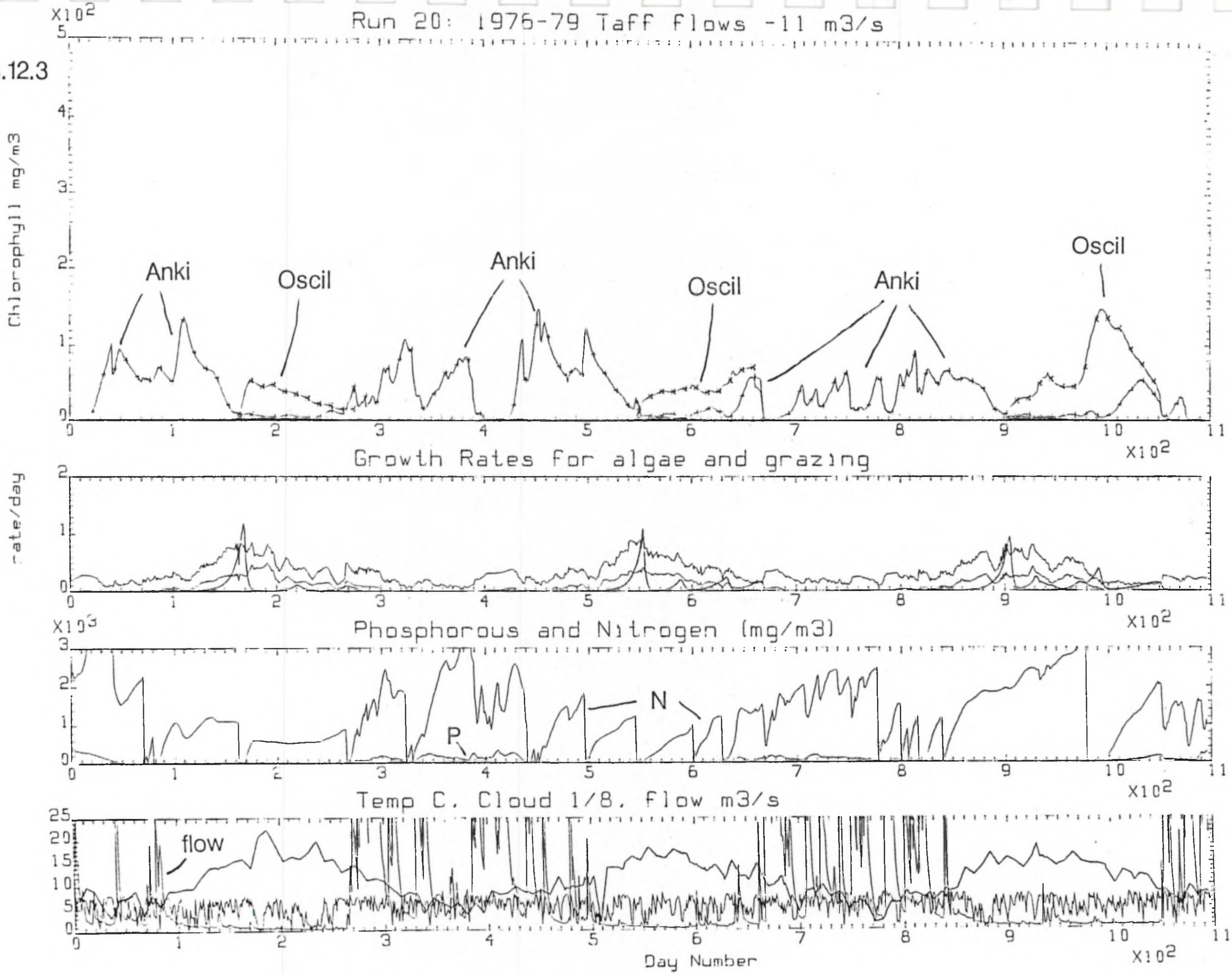

X10^2
Run 18: 1976-79 Taff flows -4 m3/s
Chlorophyll mg/m3
0
1
2
3
4
5
Anki
Oscil
Anki
Oscil
Anki
Oscil
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Growth Rates for algae and grazing
rate/day
0
1
2
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
X10^3
Phosphorous and Nitrogen (mg/m3)
0
1
2
3
P
N
0 1 2 3 4 5 6 7 8 9 10 11
X10^2
Temp C. Cloud 1/8. Flow m3/s
0
5
10
15
20
25
flow
0 1 2 3 4 5 6 7 8 9 10 11
Day Number
X10^2

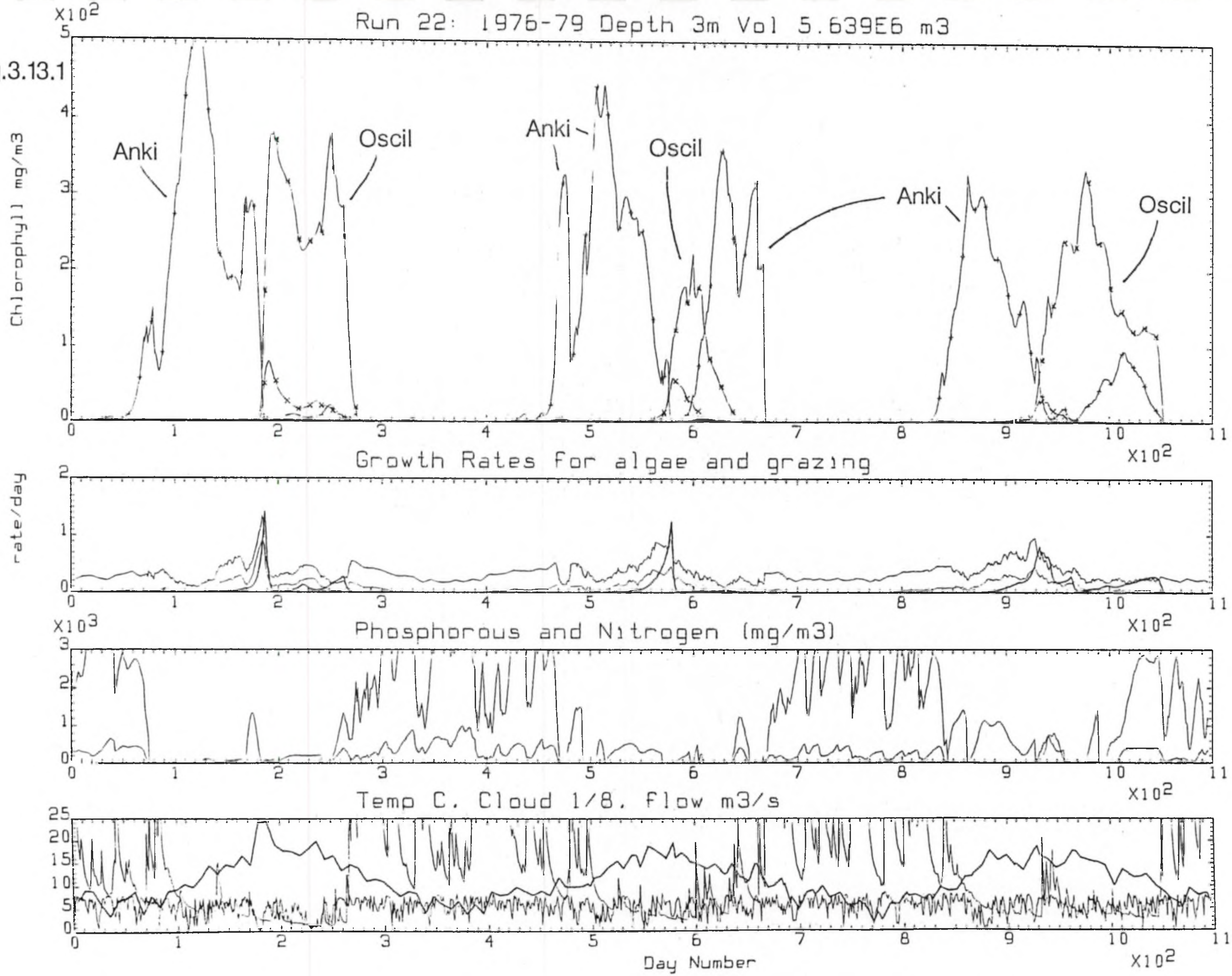
Fig.3.12.3


Run 20: 1976-79 Taff flows -11 m3/s
X10^2
Chlorophyll mg/m3
Anki
Oscil
Anki
Oscil
Anki
Oscil
Growth Rates for algae and grazing
rate/day
Phosphorous and Nitrogen (mg/m3)
X10^3
N
P
Temp C, Cloud 1/8, flow m3/s
flow
Day Number
X10^2

3.13 Changing the depth of the basin

Although the design criteria have been provisionally agreed, we carried out two further runs to test the effect of a much shallower average depth, whilst leaving all other factors of discharge- and nutrient-loads unaltered. The principal effects of reducing mean depth to 3 m (3.13.1) or even 2 m (3.13.2) are to narrow the bases of the peak crop in time but to raise the level of the attainable peaks, giving the 'spikier' appearance of the plots with respect to the baseline run (3.1). These effects are interpreted as being due to a longer period of effective washout but permitting a higher concentration of biomass to be averaged over the truncated lake depth. Deepening the lake would presumably lead to reciprocal effects, analogous to the reduction of inflow volume (3.12.2, 3.12.3).

Fig.3.13.1



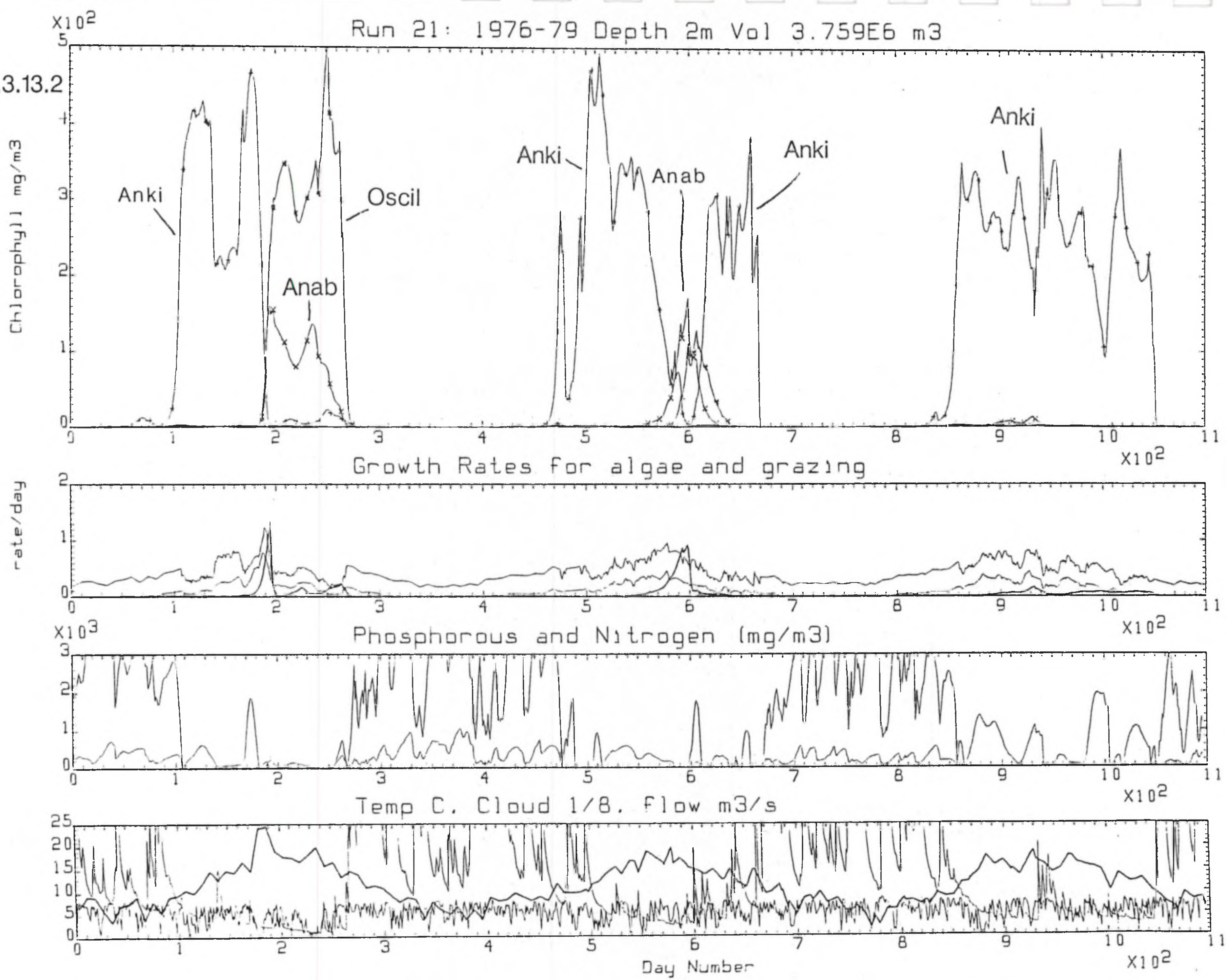
Run 22: 1976-79 Depth 3m Vol 5.639E6 m3

Growth Rates for algae and grazing

Phosphorous and Nitrogen (mg/m3)

Temp C. Cloud 1/8. Flow m3/s

Fig.3.13.2


Run 21: 1976-79 Depth 2m Vol 3.759E6 m3
X10^2
Chlorophyll mg/m3
Anki
Anki
Anki
Anki
Anab
Anab
Oscil
0
1
2
3
4
5
6
7
8
9
10
11
X10^2
Growth Rates for algae and grazing
rate/day
Phosphorous and Nitrogen (mg/m3)
X10^3
Temp C. Cloud 1/8. Flow m3/s
25
20
15
10
5
0
Day Number

3.14 Other tests

Model simulations have also been run using a horizontal-division into sequential segments, each receiving and feeding water, nutrients and biomass carryover to the next. 2-, 3-, 4- and 5-segment models have been constructed. In addition, we have experimented using different timesteps. The effects of removing the Elai flows have also been tested. In general, the outcome of each of these simulations is very much in line with the standard 'baseline' and are not illustrated (output plots are available if required). In the case of reducing the Elai loads, the effect was always similar to reducing the inflow from the Taff (3.12).

4. DISCUSSION & GENERAL CONCLUSIONS

4.1 Trends in biomass production

The various simulations described herein lend graphic support to the worst-case prognoses laid out in the original report (1). That they should tend to compound the original views expressed is heartening though not really surprising: the simulations merely evaluate the same components but the computational power provides for exhaustive extrapolations of those components through time that were otherwise lacking. It is emphasised that the system is oversimplified and that the interaction of the various components follows first-approximation pathways. These are nevertheless based on predicted maximal capacities for growth and so generate 'worst-case' solutions for the potential extent of the response. Actual responses need not involve the species cited (though similar organisms would be so involved with a high probability of incidence), they will not necessarily attain capacity biomasses nor need they do so in such time periods. While the capacity remains, however, the possibility that all contributory variables might 'match up' simultaneously to produce the simulated levels of biomass cannot be excluded.

Summarizing the simulations applying to the proposed barrage, it may be re-asserted that:

i) The lake would continue to be dominated by flushing. Significant growth of biomass is possible only when growth components less outwash are positive. The model runs suggest that the presence of large algal biomass persists for longer than the "transient" periods suggested in (1). This is due, in part, to the absence from the model of a death term, save grazing and washout. Worse, the sustained high biomass levels (100-200 days) typically embrace the summer period.

ii) Nitrogen and phosphorus are unlikely to limit biomass and rarely to determine limitation of growth rate. Even a 60% reduction in P-loading appears to make little impact on base-line predictions. Biomass may be produced until light limits any further net biomass recruitment.

iii) Nuisance-algae, the scum-forming blue-green algae (Anabaena, Microcystis) would have produced significant (5-10 mg m^{-3}) crops only in the two drought summers (1976, 1984) of the twelve-year period considered. Had nitrogen (but NOT phosphorus) fallen to severely low concentration (< 80 mg N m^{-3}), the abundance of Anabaena would have been considerably more serious.

iv) Grazing appears to be the major factor to overcome the dominance of small green algae. Oscillatoria, which is not normally grazed extensively, becomes dominant in summer (when outwash is low), mainly by virtue of its superior qualities of light harvesting in a turbid mixed water-column.

v) It remains probable that the lake would have been subject to large populations (≥ 400 mg m^{-3} chlorophyll in most years) of small chlorophytes and/or diatoms in spring (declining flows, still-cool water temperatures and inactive grazers) and of Oscillatoria (or filamentous and colonial diatoms) during lower summer flows, initially as a result of herbivores having removed the smaller, grazeable species.

4.2 Perception of nuisance

Concern has been expressed, both by the Development Corporation and by scientists at the Welsh Water Authority, about the scale of likely algal production in the lake and the public perception thereof. No attempt has been made to disguise the fact that, at times, the planktonic biomass will be very large and well above the guide lines of acceptability advised by OECD (10). It is difficult to make rational predictions about public perception and opinion. There is no doubting that surface scums would attract adverse comment, especially when driven into compact, lee-shore aggregations. This perceived nuisance could be manifest at quite low concentrations of the relevant organisms and in-lake concentrations of ≥ 5-10 mg chlorophyll m^{-3} would present a "high-risk". Fortunately, these same species would seem to grow so slowly for most of the year that the critical range is apparently approached in only the driest summers. Relatively larger populations of algae that normally remain well-dispersed in the water, (including Oscillatoria) could be tolerated. However, concentrations ≥ 80-100 mg m^{-3} will certainly impart a bright green or brownish coloration to the water that will be evident to the casual observer. A bright, grass-green or a sombre golden-brown associated with concentrations of chlorophyll in the range 100-400 mg m^{-3} will be correspondingly more apparent and, hence, more likely to be unacceptable in the eyes of a discerning public. It would be far from the expectations of developers and public alike of a clear, pristine water body, reflecting a deep blue under a cloudless sky.

To judge from experiences elsewhere, high algal concentrations are not necessarily viewed adversely: some examples of water systems where algal growth is said to be troublesome are listed on Table 1. In fact, in none of these examples is the 'nuisance' attributed to algal abundance per se, save in the case of the North American Great Lakes. It is usually some secondary consequence that is the perceived nuisance. This perception is aggravated by rapid (within a few years) deterioration of the water quality: "this lake used to be so clear ..." Whilst there is no previous condition against which the public will judge the ambient condition of the newly-constructed barrage, beyond that most people may consider a lake better than the blackish muds presently exposed at low tide, it must be remembered that the simulations anticipate wide fluctuations of clarity and colour on a time-scale of weeks, rather than years. These visible, rapid changes seem likely to invoke popular adverse comment and for which the answer, "it will all be washed out in the winter", may be insufficient. The model runs lend graphic support to a view that the likely frequency and persistence of large planktonic crops may be more contentious than was indicated earlier (1). It may be advisable that the proposals be reviewed in order to determine whether artificial constraints upon phytoplankton development are desirable. In this context, the outcome of the modelling permits a clearer assessment of the options to be made.

4.3 Control options

Apart from the alternative of the 'status quo' (i.e. construction as proposed, despite possibly more persistent plankton crops), the options that might be considered appear to be as follows.

1) Phosphate-stripping of summer inflows. Significant reduction in potential biomass would require the removal of some 85% of the phosphorus supplied to the lake by typical fluvial loads. This is probably expensive to achieve, and effectiveness is subject to weather; low flows appear to be critical. Apart from high investment costs for suitable plant, running costs may prove unacceptably high.

2) Artificial increase of non-living turbidity. Raising the background light extinction due to resuspended silts and muds, artificial enhancement of the content and its impact on light availability reduce the potential production

Table of algal biomass, composition and alleged nuisance in productive systems elsewhere.

Lake	Maximum chlorophyll	Main species	Nuisance
Lake Ontario	80 mg m^{-3}	Diatoms, flagellates greens	Loss of clarity
Lake Erie, W Basin	120 mg m^{-3}	Diatoms, phyto-flagellates, greens. Occasional blue-greens only	Hypolimnetic oxygen deficit. Impact on fishery.
Lake Mendota	150 mg m^{-3}	Aphanizomenon) blue- Anabaena) greens Microcystis)	Copious blooms in summer months
Slapton Ley, Devon	150-200 mg m^{-3}	Mostly very low in this flushed coastal lagoon. Summer growth of Peridinium (dino-flagellate) and Anabaena-Gloetrichia (N_2-fixing blue-greens in summer)	Blooms rare; discoloration reputedly damaging to fishing but no scientific evidence to support.
Lough Neagh, Northern Ireland	150 mg m^{-3}	Diatoms, Oscillatoria	Aesthetic deterioration, allegedly poorer fishing.
Shropshire/ Cheshire Meres	250 mg m^{-3}	Dinoflagellates; Anabaena, Microcystis (blue-greens)	Blooms; treated locally as traditional. Fishing "said to be poor"
Lower Thames	250-300 mg m^{-3}	Diatoms, small greens Blue greens recorded in 1976 drought.	High coloration and turbidity. Removal of algae from abstracted reservoir water.
Wolderwijd, Veluwemeer Drontermeer (Polder lakes, Netherlands)	400 mg m^{-3}	Almost continuous dominance by Oscillatoria (blue-green)	High colonisation and turbidity. No blooms. Main corrective treatment is high flushing rate.
Norfolk Broads	600 mg m^{-3}	Centric diatoms, small flagellates. Filamentous blue-green (Oscillatoria) when flushing rate low: Prymnesium events.	Discoloration and Prymnesium toxicity. No blue-green blooms. Main perceived problem is loss of macrophytes.

rates and equilibrium biomass that may be maintained. Some turbidity can be predicted as a result of sediment resuspension but deliberate disturbance or introduction of particulates would be needed if the principle were to be exploited as a realistic control mechanism. The question would have to be faced whether high turbidity due to suspended sediment was any more or less acceptable than a bright-green turbidity due to suspended algae.

3) Construction of a shallower or deeper basin. Two opposite principles are invoked here. A lesser depth for the same area of lake and some throughput volume MUST reduce residence time and, hence, the time-window available for algal growth. On the other hand, the lesser depth and the enhanced supply of nutrients per unit volume, raise the concentration capacity during dry-weather flows. No clear case for seeking significantly more or significantly less than a mean depth of 5 m or so can be defended.

4) Direct flow regulation. The simulations emphasise the important regulation of algal growth imposed by high discharges. Any move towards controlling discharge into the lake so that the period of critical throughflow is maintained for longer would be desirable. One way of achieving this might be to retain flood waters upstream of the lake in a 'cascade' of pre-lakes. Even if enough water could be held back to augment low summer flows, the problem of algal growth would simply be moved upstream, with the result that algal inocula to the barrage lake would be greater. To employ reservoir storage in headwater regions is presumbly not practicable.

5) Indirect flow manipulation. Another strategy might be to re-design the barrage lake such that most of the fluvial flow by-passed the barrage lake, so that river water did not pass directly through the lake. A weir-arrangement would maintain the lake level, with respect to sea- and river-level, yet allow flood-water in autumn and winter to recharge and flush the lake. Input from the Elai could feed into the by-pass and avoid the lake altogether. Such a scheme would then gain the advantage of flushing afforded by high winter discharge but remove the augmentation of nutrients into the lakes furnished by low summer discharges. As shown in Figs 3.12.2 and 3.12.3, the effect would be to permit earlier annual development of the algal population in the lake but to suppress the size of the population maxima to the order of 100 mg chlorophyll m^{-3} and to reduce the relative contribution of cyanobacteria, including Oscillatoria. From the point of view of water quality, this option has many attractions. On the negative side, the design and engineering work represents

a substantial, additional cost and there may well be disadvantages in terms of navigational access. Unfortunately, none of the options advanced is self-evidently beneficial overall but this fifth scheme seems most likely to satisfy the objective of achieving modest algal production at all times.

4.4 Conclusions

The outcome of the model simulations generally confirms the assessment in (1) that phytoplankton production in the proposed barrage lake will be regulated principally be throughflow but that it will nevertheless be capable of achieving proportions in the order of 300-400 mg chlorophyll m^{-3} for substantial periods of the year, coinciding with low fluvial flows. It may be predicted, with a reasonable level of confidence, that the lake is likely to support significant populations of the scum-forming blue-greens like _Anabaena_ and _Microcystis_ only in a very dry, arm summer, but the filamentous (non-bloom-forming) _Oscillatoria_ is likely to figure prominently in the lake. Surface algal-scums are unsightly, usually foul-smelling and injurious to leisure pursuits. These do more than any other single factor to give lake-enrichment (especially) and rich lakes, even, its notorious reputation.

Whether large (300-400 mg m^{-3} chlorophyll), but dispersed, populations of green algae or _Oscillatoria_ are intrinsically more acceptable to a casual but increasingly critical public is a matter of opinion; there is clearly a case to be made for containing these so far as possible. The report suggests ways in which episodes of 'green water' could be ameliorated in intensity and in time as indicated by the model simulations. These provide strategy-options aimed at overcoming potential algal concentrations of $\geq$ 100 mg chlorophyll m^{-3} in the lake.

In summary, then, the model simulations largely confirm what has been said already: without further modification, construction of the proposed barrage lake will inevitably permit high algal populations in dry summers but that periods of enhanced river flows will always bring about their dissipation. If artificial controls to alleviate the problems of copious algal growth are to be considered desirable, then the exploration of flow regulation should be given a high priority.

5. LITERATURE CITED

1) Freshwater Biological Association, 1987. Algal growth in the proposed Cardiff Bay Barrage. Report to Hydraulics Research Ltd, Wallingford.

2) Vollenweider, R.A., 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem. Ist. ital. Idrobiol. 33, 58-83.

3) Reynolds, C.S., 1984. Phytoplankton periodicity: the interactions of form, function and environmental variability. Freshwat. Biol. 14, 111-142.

4) Reynolds, C.S., 1986. Experimental manipulations of the phytoplankton periodicity in large limnetic enclosures in Blelham Tarn, English Lake District. Hydrobiologia 138, 43-64.

5) Reynolds, C.S., 1987. The response of phytoplankton communities to changing lake environments. Schweiz. Z. Hydrol. 49, 220-236.

6) Reynolds, C.S., 1988. Physical determinants of seasonal change in the species composition of phytoplankton. In: Sommer, U. (ed.) Determinants of seasonal succession in phytoplankton. Science Publishers, Madison (in press).

7) Vollenweider, R.A. (ed.), 1974. A manual on methods for measuring primary production in aquatic environments, 2nd edition. (IBP Hb. 12), Blackwell, Oxford.

8) Reynolds, C.S., 1988. Functional morphology and the adaptive strategies of freshwater phytoplankton. In: Sandgren, C.D. (ed.) Growth and survival strategies of freshwater phytoplankton (in press). Cambridge Univ. Press, New York.

9) Ferguson, A.J.D., Thompson, J.M. & Reynolds, C.S., 1982. Structure and dynamics of zooplankton communities maintained in closed systems, with special reference to the algal food supply. J. Plankton Res. 4, 523-543.

10) Organisation for Economic Co-operation & Development, 1982. Eutrophication of waters: monitoring, assessment and control. OECD, Paris.

C.S. Reynolds
Windermere, January, 1988