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ALGAL 'BLOOMS' IN THE LOWER TEES

- Perspectives and Prospects

Final report of preliminary projections of the  
impact on water quality of the proposed  
Tees Weir

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## 1. INTRODUCTION

This report sets out the findings of a preliminary desk-study of the potential of the lower Tees to support growths ('blooms') of planktonic algae in the impoundment resulting from the proposed construction of a weir near Newport Bridge, Middlesbrough. This report updates an earlier, provisional submission (1) in two major respects: it takes advantage of the provision of additional water-quality data, especially those relating to the phosphorus concentrations measured at Low Worsall; moreover, following the decision to obviate sea water incursion as a feature of the scheme, possibly influenced by the comments offered in (1), reference to the management problems attendant upon stratification maintained by salinity gradients is removed.

In accordance with precedents established in similar investigations (2, 3), the preliminary analysis proceeds from an assessment of likely morphometry and hydrographic constraints, the potential hydrological properties of the impounded water in relation to projected hydraulic loads, and deductions about the likely in situ rates of growth of planktonic algae inoculated with the fluvial input into the impounded lake.

## 2. MORPHOMETRIC CHARACTER OF THE IMPOUNDMENT

The proposed impoundment is to be formed by the construction of a weir across the lower Tees between Stockton and Middlesbrough, at a point (near Newport Bridge; National Grid Reference NZ 468193) approx 20 km from the sea, with its crest set sufficiently high to exclude the ingress of sea water. The raised level of the river (+ 2.5 m OD) will extend upstream to the vicinity of Low Worsall, about 18.4 km above the weir and close to the present tidal limit (NZ 384100). Geometric calculations from serial sections of the present tidal channel indicate that the impounded volume below Low Worsall will be approximately ( $V=$ )  $3.9 \times 10^6 \text{ m}^3$  under a water surface area ( $A$ ) of  $1.2 \times 10^6 \text{ m}^2$ . Taking the length ( $L$ ) as 18.4 km, the mean width of the channel ( $W$ ) is therefore about 65 m. The impounded lake will remain very much a linear basin and dominated by a mainly unidirectional, downstream flow. It is inappropriate to consider the impoundment as an integrated single system; rather it is an extension of the river to a lower point down its estuary.

The serial channel sections also permit the calculation of the greatest water depths along the impounded length, ranging from 10 m behind the weir to about 3.0 m at Low Worsall, though the mean depth of any section will be less (provisional calculation, ca. 7 to ca 2m); the mean depth of the entire basin,  $H (= V/A)$ , is 3.25 m.

## 3. HYDRAULIC LOAD

The primary source of freshwater to the impoundment will be the Tees. The nearest, fully-documented (4) discharge gauging is at Broken Scar, near Darlington (NZ 259137). A correction factor of 1.3 is suggested as a reasonable approximation of the Tees discharge at Low Moor, about 4 km above Low Worsall, and feeding the impoundment directly. The long-term mean discharge,  $Q_T$ , at Low Moor would then solve at  $22.1 \text{ m}^3 \text{ s}^{-1}$ , with mean monthly values ranging from 37.8 (January) to  $7.8 \text{ m}^3 \text{ s}^{-1}$  (July) covering 30-year minima and maxima (respectively) of 0.6 to  $100 \text{ m}^3 \text{ s}^{-1}$ ; the upper 5

percentile exceedence level is  $63 \text{ m}^3 \text{ s}^{-1}$ , the lower 95% exceedence being  $2.8 \text{ m}^3 \text{ s}^{-1}$ . The only significant tributary below Low Moor is the Leven, for which documented records are available (4) at Easby (NZ 585 087) some 30 km above the confluence with the Tees. Relevant 5% and 95% exceedence levels at Leven Bridge (NZ 431 128) near its outfall to the Tees, have been approximated as 8 and  $0.3 \text{ m}^3 \text{ s}^{-1}$  respectively, with a long-term mean ( $Q_L$ ) of  $1.2 \text{ m}^3 \text{ s}^{-1}$ . The hydraulic contribution made by direct sewage outfalls (at Yarm, Clockwood) and industrial discharges to the impoundment, together averaging some  $6000 \text{ m}^3 \text{ d}^{-1}$  ( $< 0.1 \text{ m}^3 \text{ s}^{-1}$ ), have been ignored; thus, the total 'freshwater' inputs  $\Sigma Q$  ( $= Q_T + Q_L$ ) have been assumed to normally range between 3 and  $71 \text{ m}^3 \text{ s}^{-1}$ , with a long-term mean of  $23.3 \text{ m}^3 \text{ s}^{-1}$ .

#### 4. RETENTION AND TRAVEL TIMES

The crudest calculation of mean residence time in an instantaneously uniform impoundment is the quotient  $V/\Sigma Q$ : i.e.  $3.9 \times 10^6 \text{ m}^3 / 23.3 \text{ m}^3 \text{ s}^{-1} = 167\,382 \text{ s}$  or just under 2 d (with 90% of cases in the range 0.6 - 15.5 d). However, owing to the previously advanced view that channel forces will continue to predominate in the impoundment, a more useful calculation is of the mean time of travel. Let us assume the mean cross-sectional area of the impoundment (C) is given from  $V/L$  ( $3.9 \times 10^6 \text{ m}^3 / 18.4 \times 10^3 \text{ m}$ ) as  $212 \text{ m}^2$ , then the mean velocity (U) of  $\Sigma Q$  through C, given by  $\Sigma Q/C$ , is  $23.3/212 = 0.11 \text{ m s}^{-1}$  and the time (t) to traverse the entire length, L, is given from  $t = L/U \approx 2\text{d}$ . Mathematically, the solution is identical to the calculated retention time but the difference to the extrapolation of algal growth potential is that the opportunity for increase becomes a basic, zero-order function of linear travel time, rather than a first-order reaction involving retention time as a negative exponent of the natural logarithmic base (e.g. 5). The problem is that the mean velocity does not apply uniformly down the whole channel and it is compounded by the fact that, through any given cross-section, velocity is infinitely variable within a range 0 - 1.25 U.

These complications would have been further compounded by constricted flows caused by non-moving saline lenses (see 1). However, these are no longer likely to arise in an impoundment from which sea water is excluded. The remaining instances of density stratification would be entirely due to surface warming proceeding faster than the heat income can be dissipated by mechanical energy, due to water flow and to wind action on the water surface. Under conditions of intense solar heating, minimal flow and no wind, the water column develops a temperature gradient, the structure of which may intensify, with further insolation, or weaken, as surface cooling and convection occurs or is subject to wind mixing. The balance between buoyancy generation and dissipative forces can be expressed as a ratio, as in (e.g.) the calculation of Wedderburn Number,  $W$  (Imberger & Hamblin, 1982; Ref. 6):

$$W = \frac{g(\Delta\rho) h^2}{\rho (u^*)^2 L}$$

where  $g$  = gravitational acceleration ( $9.81 \text{ m s}^{-2}$ ),  $\rho$  is the density of the water and  $\Delta\rho$  is the difference in the densities of the top and deeper water;  $(u^*)$  is the friction velocity of the motion,  $L$  is the length scale over which the motion is effective (the distance of 'fetch') and  $h$  is the equilibrium depth of the mixed layer. The numerator corresponds to the buoyancy forces, the lower to the dissipative energy. When  $W=1$ , the opposing forces are in balance and the structure is stable. In order to decide the permanency of a given structure under conditions of variable buoyancy generation and variable dissipation, it is helpful to rearrange the Wedderburn equation when  $W=1$  to determine  $h$ , the depth beneath the surface at which the structure may survive a new episode.

$$h = \sqrt{\frac{\rho(u^*)^2 L}{g \Delta \rho}}$$

This may be solved for a series of cases representing successive stages in the spring warming and subjecting them to different stresses. Stratification is extremely transient in lakes when the surface temperature is in the range 0-10°C. Dry-weather flow ( $< 3 \text{ m}^3 \text{ s}^{-1}$ ) when the water is still only 10°C could permit near-surface stratification whilst there is no wind, the given values of  $u^*$  being attributable entirely to the fluvial flow; winds across the lake ( $L = 65 \text{ m}$ ), or, especially, funnelled down the lake ( $L = 18400 \text{ m}$ ) are clearly effective in bringing about substantial mixing (see Table 1).

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Table 1. Critical depth of mixing ( $h$ , in m) under selected combinations of mechanical energy and buoyancy forcing, assuming  $W = 1$ .

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	no wind	wind $3 \text{ m s}^{-1}$		wind $8 \text{ m s}^{-1}$	
		across lake	down lake	across lake	down lake
$0.3 \text{ kg m}^{-3}$	0.04	0.56	9.4	1.49	25.0
$0.6 \text{ kg m}^{-3}$	0.03	0.39	6.6	1.05	17.7
$1.5 \text{ kg m}^{-3}$	0.02	0.25	4.2	0.66	11.2

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Equally, persistent calm conditions might allow a more stable structure to differentiate ( $1.5 \text{ kg m}^{-3}$  would represent the difference in density between top water at 20°C and bottom water still at 10°C). Only a strong wind, down the lake would be adequate to integrate the full depth, once stratification had begun to establish. The portion of the lake liable to stratify would be confined to the area of the deepest water, just behind the dam; however, in

most years, brief phases of stratification might follow warm sunny spells and a dearth of westerly winds but they would scarcely resist subsequent strong winds. The incidences would appear likely to persist only when floods and storms are infrequent from the spring on and, even then, only in the near-weir bottom waters where the absolute depth exceeds 4 m.

Assuming the instances of density stratification to be rare or localised, they may be reasonably ignored in the deduction of travel-times through the impoundment, at various mean discharges (Table 2).

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Table 2 Mean times of travel of freshwater through the Tees weir impoundment under different possible discharge régimes.

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$\Sigma Q =$	Mean travel time (in days) assuming H = 3.25 m	Discharge Corresponding to
$100 \text{ m}^3 \text{ s}^{-1}$	0.5	30-yr maximum monthly discharge
71	0.6	5% exceedence level
39	1.2	Mean wettest-month flow
23.3	1.9	Overall mean
7.8	5.8	Mean driest-month flow
3.1	14.6	95% exceedence level
0.6	75.3	30 yr minimum monthly discharge

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The importance of these values is that they set an approximate time window in which planktonic algae, delivered in the fluvial input at the head of the impoundment, will have the opportunity to grow and divide. Later sections define those opportunities more objectively. Nevertheless, it is clear that

algae requiring 0.5 to 5 days to double their biomass will, generally, have that opportunity only during dry weather flows. Thus, we should go on to consider the other factors influencing algal doubling times.

## 5. NUTRIENTS

A full catalogue of determinands in Tees water, analysed by NWA, was made available. Of the relevant chemical constituents it is sufficient to note that the concentrations of dissolved inorganic nitrogen species ( $\text{NH}_4^-$ ,  $\text{NO}_3^-$  and  $\text{NO}_2^-$ -N) in the Tees at Worsall rarely fall below  $2 \text{ mg N l}^{-1}$ , and are frequently as high as  $7 \text{ mg N l}^{-1}$ . The contribution of the Tees to the impoundment is between  $4000$  and  $11000 \text{ kg N d}^{-1}$ . The three sewage works and two industrial concerns with monitored inflows contribute only a small part of the load on the barrage (Table 3).

Table 3 Mean daily contributions to the N-load on the completed barrage

<u>Source</u>	<u>Volume</u>	<u>Concentration</u>	<u>Daily load</u>
R. Tees, L. Worsall	$2.00 \times 10^6 \text{ m}^3 \text{ d}^{-1}$	$2-7 \text{ g m}^{-3} \text{ N}$	$4000 - 14\ 000 \text{ kg d}^{-1}$
Yarm STW	$1200 \text{ m}^3 \text{ d}^{-1}$	37.8	45
Clockwood STW 1	780 "	32.2	25
Clockwood STN 2	1128 "	20.8	23
H.J. Hird effluent	455 "	230	105

With regard to phosphorus, often supposed to be the key nutrient in assessments of biological aspects of water quality, the tentative deductions and assumptions in (1) may now be justified. A series of over 60 water



samples, drawn from the Tees at Low Worsall, was analysed between January 1980 and December 1988 (data of NWA, supplied on request). This series shows a remarkably good inverse correlation between P concentration and discharge; ignoring one pint, owing to aberrant findings, (n =) 62 analyses were used to derive a flow-dependent prediction of phosphorus concentration, viz:

$$\log [P] = -0.382 - 0.012 Q$$

where Q is the average daily discharge at Low Worsall.

From this relationship it is apparent that the greatest daily loads of phosphorus from the Tees catchment has been around  $480 \text{ kg P d}^{-1}$  when the river has been close to its winter mean flow. The load dwindles with lower flows but is still capable of achieving additional plant production (the plankton), under favourable growing conditions. At  $Q = 3.1 \text{ m}^3 \text{ s}^{-1}$ , for example, the Tees is expected to load some  $0.085 \text{ g m}^{-2} \text{ d}^{-1}$  of P over the impoundment ( $\approx + 26 \text{ mg m}^{-3} \text{ d}^{-1}$ , sufficient to sustain the development of a light-limited phytoplankton within a matter of 20 days, and without resort to the inevitably large contributions of soluble and reactive P supplied from the treated-sewage effluents. By any standards, it must be considered to be an environment favouring algal growth, rarely, if at all, limited by the main nutrients available. They will not be considered further at the present time.

## 6. OTHER ASPECTS OF THE CHEMICAL ENVIRONMENT

So far as it is possible to judge, the general ionic environment, pH and oxygenation state are not prejudicial to algal growth, while no potential toxic effects of heavy metal content or any organic derivative is evident.

## 7. LIGHT ENVIRONMENT

Within the chemical capacities of freshwaters, algal growth is most liable to be governed by the perceived input of light energy. There are generally two aspects to this : one is the quality and quantity of light falling on the water

surface; the other is the underwater distribution and attenuation of photosynthetically-active radiation (PAR, roundly 'visible' electromagnetic radiation in the spectral range 400-700 nm), especially in relation to the depth of the circulation. For this assessment, we require to derive the impact of these factors upon algal growth rates and upon light-limited algal carrying capacity, using components interrelated in the following equation:

$$\Sigma nP = \frac{nP_{\max} \cdot 0.7 T \cdot \ln(I/0.5I_k)}{\epsilon} \quad (1,7)$$

where  $n$  is the algal population,  $P$  is the rate of photosynthetic production,  $T$  is the day-length in hours and  $\epsilon$  is the vertical extinction coefficient of PAR;  $I$  is the surface irradiance received at the lake surface, calculated from the black-body radiation constant above the atmosphere, corrected for zenithal angle for the day of the year, for atmospheric absorption and cloud scatter and converted from  $W m^{-2}$  to  $mol \text{ photons } m^{-2} s^{-1}$  by the use of the relation  $218 \text{ kJ} \equiv 1 \text{ mol photon}$ .  $I_k$  is a property of the alga, being the light intensity at which its photosynthetic rate is saturated by light; the use of the half- $I_k$  value alludes to an underwater photosynthetic capacity equivalent to a trapezium of area  $0.5 \times I_k \times P$  (see 7). Because the extinction,  $\epsilon$ , is exponential, the area of production is also a logarithmic function (for a full explanation, see 7). It may be, noted, however, that  $I_k$  varies interspecifically and, in time, intraspecifically, as a function of the organism's photosynthetic efficiency. This character has been successfully modelled and is included in the present components (see, for instance, 2).

No information is to hand about  $\epsilon$ . Following precedence, we assume  $\epsilon$  is componentised, viz.  $\epsilon = \epsilon_w + \epsilon_p + n \cdot \epsilon_s$ , where  $\epsilon_w$  is the mean spectral absorption of pore water across the PAR-band, averaging about  $0.12 m^{-1}$ .  $\epsilon_p$  is the absorbance due to non-living tripton. Our recent work in turbid systems (8) established a rough relation between absorption and suspended-solid

concentration, viz.  $\epsilon_p \sim 20 \text{ m}^2 \text{ kg}^{-1}$ . The suspended load in the Tees is variable but generally falls within a range  $4\text{-}10 \text{ mg l}^{-1}$  ( $= \text{g m}^{-3}$ ); thus,  $\epsilon_p$  is taken to be  $> 0.08$  and usually  $< 0.2 \text{ m}^{-1}$ . Finally,  $\epsilon_s$  is a species-specific property of algae, being the projected area of chlorophyll as presented in a given cell arrangement (individual values fall in a range  $0.004 - 0.02 \text{ m}^2 \text{ mg}^{-1}$  chlorophyll). Then the specific population,  $n$  (expressed in  $\text{mg chl m}^{-3}$ ), affords an extinction component in comparable units (i.e.,  $\text{m}^{-1}$ ).

'Carrying capacity' is determined by the point at which a given water column contains sufficient algae to shade each other until their photosynthetic gain balances respirational losses in the dark; i.e.,

$$\frac{n P_{\max} \cdot 0.7T \cdot \ln(I_0/0.5I_k)}{(\epsilon_w + \epsilon_p + n\epsilon_s) 24 n RH} = 1$$

where  $R$  is the chlorophyll-specific respiration rate (generally  $0.05 P_{\max}$ ) and  $H$  is the height of the mixed column, assumed in the present case of the Tees Weir impoundment to be  $3.25 \text{ m}$ .

Then, by rearrangement,

$$n = \frac{1}{\epsilon_s} \frac{20 \cdot 0.7T \cdot \ln(I_0/0.5I_k)}{24 H} (\epsilon_w + \epsilon_p)$$

Solving for midsummer ( $T = 16 \text{ n}$ ;  $I = 56 \text{ mol m}^{-2} \text{ d}^{-1}$ ) and a well-adapted planktonic alga like *Asterionella* ( $\epsilon_s = 0.016 \text{ m}^2 \text{ mg}^{-1}$ ;  $I_k = 100 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$ ) in the fully-mixed depth ( $H = 3.25 \text{ m}$ ), in which background extinction attributed to water ( $0.012 \text{ m}^{-1}$ ) + particulates ( $0.008 \text{ m}^{-1}$ ), we find:

$$n = 530 \text{ mg chl m}^{-3}$$

This is an ultimate, if somewhat notional, maximum; at all other times of the year (shorter day, less than cloudless conditions), the capacity is

correspondingly less. Moreover, the capacity will be higher upstream because of the lesser depth (if  $H = 1 \text{ m}$ ;  $n = 1720 \text{ mg chl m}^{-3}$ ), whereas near the weir ( $H$  nearer  $5 \text{ m}$ ;  $n = 334 \text{ mg chl m}^{-3}$ ), it would be lower. The decrease in capacity is counter to the anticipated downstream increase in biomass. The question of algal dynamics then assume considerable importance.

#### 8. OPTIMAL GROWTH KINETICS

Well before the onset of light compensation, species-specific growth rates depend upon the supply of resources and the temperature-mediated rate of assimilation. These capacities have been found (7) to be well-described by a relatively simple algorithm:

$$r_{(\theta, I)} = \frac{(r_{\theta} T/24H) \cdot \ln(2I_0) \cdot 0.257(\text{ms}/v)^{0.236}/r}{\epsilon}$$

where  $r_{(\theta, I)}$  is the growth rate at a given mean temperature and mean PAR-irradiance level,  $r$  is the light-saturated growth rate at that temperature;  $m$  is the maximum linear dimension of the algal cell (in  $\mu\text{m}$ ),  $s$  is its surface area and  $v$  is its volume. Note that in clear water where  $I$  received at the bottom of the column nevertheless exceeds  $I_k$  (i.e. column compensation is exceeded), there is no light limitation and

$$r_{(\theta, I)} = (r_{\theta} T)/24$$

Table 4 sets out a series of growth rate scenarios embracing derived growth rates under maximal irradiance conditions at the appropriate time of the year (cloudless, dry conditions). The selection illustrates the shifting growth-rate opportunities during the year, regardless of possible variations in discharge. The calculations refer to algae reported to be common in the lower Tees (9). Doubling times transferred to Table 5 are calculated from  $\ln 2/r_{(\theta, I)}$ , and are directly comparable with the times of travel under seasonally-variable discharges. Thus, even under the optimum conditions of below-average flows and capacity-growth rates, the opportunities for significant algal increase are limited to warm-weather, drought conditions.

Table 4 Simulated growth rates of selected planktonic algae (Asterionella, Cyclotella, Chlorella and Scenedesmus under seasonally differing growth conditions in the Tees.

	Mid-winter (Jan)	Spring Equinox (Mar)	Summer Solstice (Jun)	Autumn Equinox (Sep)
(c)	2	5	15	12
T (h)	9	12	16	12
I (mol m <sup>-2</sup> d <sup>-1</sup> )	12	36	56	36
$r_{,I}$ :				
<u>Asterionella</u>	0.118 d <sup>-1</sup>	0.208 d <sup>-1</sup>	0.675 d <sup>-1</sup>	0.390 d <sup>-1</sup>
<u>Cyclotella</u>	0.050	0.096	0.425	0.224
<u>Chlorella</u>	0.135	0.235	0.726	0.426
<u>Scenedesmus</u>	0.094	0.166	0.597	0.337

Table 5 Comparison of species-specific doubling times at different times of the year (from Table 4) with selection of travel times (t) under different discharge conditions (Q).

	Q (m <sup>3</sup> s <sup>-1</sup> )	t (d)	doubling times (d) of			
			Asterionella	Cyclotella	Chlorella	Scenedesmus
Midwinter, mean	39.0	1.2	5.9	13.9	5.1	7.4
Spring equinox, mean	30.0	1.5	3.3	7.2	3.0	4.2
" " 95 percentile	3.1	14.6	"	"	"	"
Summer solstice, mean	8.3	5.4	1.0	1.6	1.0	1.2
" " 95 percentile	3.1	14.6	"	"	"	"
Summer solstice minimum	0.6	75.3	"	"	"	"
Autumnal equinox mean	14.1	3.2	1.8	3.1	1.6	2.1
" " 95 percentile	3.1	14.6	"	"	"	"

## 9. INOCULA, POPULATIONS

The Tees is one of a small number of British rivers with a modicum of published information about its phytoplankton. Besides the classical study of Butcher, Longwell and Pentlow (10), there is a more recent and useful summary of observations made in 1977 by Holmes & Whitton (9). This study showed that the plankton of the Tees was fairly typical in supporting populations of diatoms and certain green algae, in generally slightly elevated numbers downstream, but that seasonal fluctuations occurred also. Diatoms were relatively most abundant in spring, especially Asterionella, Cyclotella, Navicula and Nitzschia species, together with such typically epipelagic forms as Achnanthes and Cymbella; the green algae Chlorella, Scenedesmus and Chlamydomonas were relatively more abundant during the middle part of the year.

Of particular interest is the fact that, at the lowest point of their observations (Low Middleton : NZ 363106 and barely 5 km above Low Worsall), none of the populations was recorded in numbers significantly greater than 1000 cells ml<sup>-1</sup> (10<sup>9</sup> m<sup>-3</sup>) and most of the diatom species occurred at less than 100 cells ml<sup>-1</sup> (10<sup>8</sup> m<sup>-3</sup>). These provide a good guide to the typical populations of river phytoplankton introduced into the proposed impoundment. Except under favourable summer conditions, (Table 5) there would appear to be very little opportunity for more than a doubling or two. Because the best approximation of the chlorophyll content of the phytoplankton that would have been inoculated in 1977 is in the region of 1 to 2 mg chlorophyll m<sup>-3</sup> as diatoms and a similar quantity as summer 'greens', then it is difficult even to sustain a case for expecting large chlorophyll concentrations (say = 100 mg chl a m<sup>-3</sup>; 5 cell divisions!) to develop except under drought (i.e. < mean summer flow) conditions. Allowing for a substantially increased inoculum during drought, the circumstances that would lead to the production of chlorophyll concentrations > 100 mg chl m<sup>-3</sup> would be encountered proportionately sooner.

There is little reason to expect the formation of floating blooms of planktonic cyanobacteria. Not only are the usual travel times less than the typical doubling times of these relatively slow-growing species but there are no obvious sources of inocula. This could change in time, once the 'lake' becomes established, but the populations would remain small in all but the driest years.

#### 10. CONCLUSIONS

From the starting point of basin morphometry, hydraulic loads and travel times, the view has been developed that algal growth is unlikely to become a serious drawback to the creation of an impoundment behind the proposed Tees weir. Significant growths are likely to occur only in the summer months of the driest years and even these are unlikely to be dominated by floating, scum-forming cyanobacteria at any time. These predictions are made in the knowledge of the high nutrient loadings and in the belief that salt water incursions will be excluded.

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