Institute of Freshwater Ecology

THERMAL STABILITY AND WATER QUALITY OF THE PROPOSED MIDLANDS RESERVOIR, MAURITIUS

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Report To: Gibb Environmental
Project No: T04050u1
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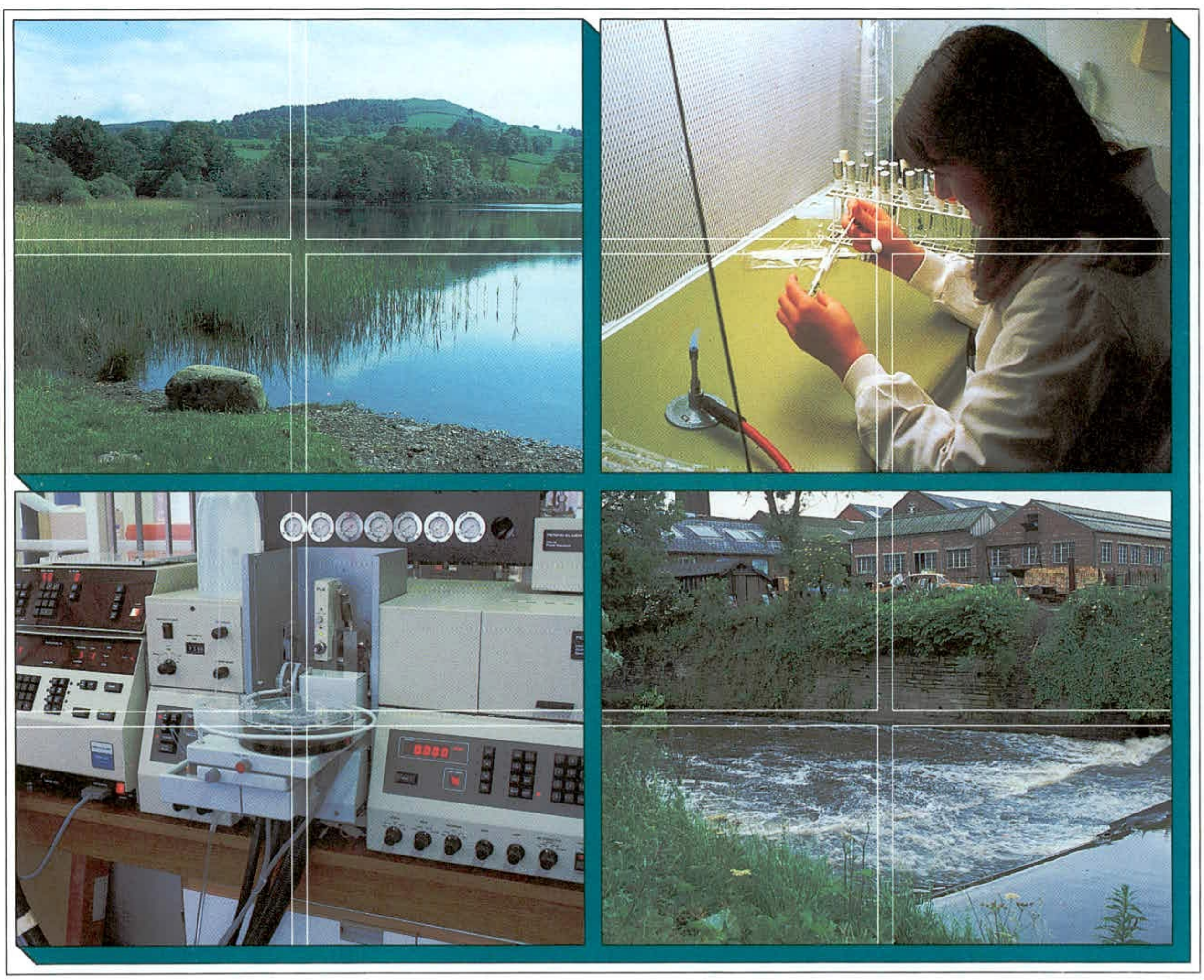

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This report makes its recommendations from a state of the art understanding of the way in which aquatic systems work and is considered to represent the best advice available at the present time. However it should be borne in mind that changes in the physical and chemical properties of water are driven by a complex interaction of biological, chemical and physical processes which are still not entirely predictable and the Institute cannot guarantee that changes will occur exactly as predicted.

CONTENTS

EXECUTIVE SUMMARY

An analysis has been carried out of both the first and second phase of the proposed Midlands dam, Mauritius. Equations, based on fundamental physical, chemical, biological and ecological properties of standing water bodies have been used to predict the stratification behaviour and the likely algal biomass in the reservoir.

Several inconsistencies were found in the analyses of feed water. The feed water quality is very poor, being similar in chemical composition to a poor/ medium quality sewage effluent, with BOD up to 100 mg/l.

Predictions suggest that the reservoir will stratify, at least on a seasonal basis, but may even stratify permanently. The reservoir will be hyper-eutrophic. It will be phosphorus limited and, because of a low N:P ratio it will be dominated by blue green algae.

The effect of removing trees prior to flooding is discussed. A number of recommendations are made to reduce the effects of the poor quality feed water and the hyper-eutrophic status of the reservoir.

1. INTRODUCTION

1.1 The northern part of Mauritius has been facing,and continues to face, severe water shortages, which jeopardise the economic and social development of this part of the country. The creation of a dam (the Midlands dam) has been proposed to collect water from the upper reaches of the Grand River South East, a region of very high rainfall. The stored water would then be transferred via La Nicoliere feeder canal to La Nicoliere dam prior to treatment and distribution to both supply and irrigation in the North plains of the island. The dam could be raised at a later date to increase the storage capacity. The IFE was commissioned to assess the likely water quality in La Nicoliere reservoir should these two options be carried out.

1.2 The IFE study, commenced in November 1994. This report: a) assesses the general water quality in the reservoir; b)gives predictions of the likely stratification behaviour of the reservoir and c) gives predictions of the likely water quality for selected water quality parameters, mainly nutrients.

1.3 Basic data for the two phases of construction of the reservoir are given in table 1.

Table 1.1 Physical, chemical and hydrological properties of the Midlands reservoirs.

Location	**20° 00'S, 57° 35'E**	
Catchment Area (Km^2)	**17**	
	phase 1	phase 2
Full Supply level (FSL) (m)	394.5	399.5
Lake volume FSL(m3)	25500000	42000000
Lake area FSL (m2)	3000000	3840000
Maximum depth FSL(m)	~21	~26
Mean depth (m)	8.5	10.9
Maximum length (km)	1.93e	2.05e
Maximum width (km)	1.33e	1.78e
estimated thermocline depth (m)	3	3
Estimated epilimnion volume (m^3)	7982000	10487000
estimate mean epilimnion depth (m)	2.66	2.73
Annual inflow (m3/a)	43000000	
Inflow P conc (mg/m3 as P)	280	
Inflow N conc (mg/m3 as N)	490	
P load (t/a)	12.04	
N load(t/a)	21.07	
All calculated values below		
mixed lake retention time (y)	0.59	0.98
mixed lake retention time (d)	216	356
epilimnion retention time (y)	0.19	0.24
epilimnion retention time (d)	67	89
Areal load P(as P)(g/m2/a)	4.01	3.14
Areal load N(as N)(g/m2/a)	7.02	5.49

e - estimated from figure 4, North Mauritius Water Supply, Dec, 1993.

2. FEED WATER QUALITY

2.1 The available data are given in table 2.1. There are a number of data which are anomalous. There is confusion as to whether the data in row three are suspended solids or dissolved solids. Either way a nil result on the second sampling occasion is unlikely. Similarly a nil result for total phosphorus in the second sample is impossible since dissolved phosphate, alone, is reported as o.442 mg/l. The chlorophyll data cannot be correct as reported. Chlorophyll b is always less than chlorophyll a. (typically Chl a:chl b = 3:1). Either the Chlorophyll a and b data have been systematically inverted, or the methodology is incorrect. In the latter case there are at least two potential causes. It appears that the laboratory is using the classical Strickland and Parsons trichromatic method. One possibility is that the spectrophotometer wavelength scale is not correctly calibrated. An alternative is that there are a large number of chlorophyll degradation products present (such as pheophytin) which interfere with the method. In a hot climate the rapid breakdown of organic matter makes the latter a distinct possibility.

2.2 The water is essentially circum-neutral. The conductivity is relatively low (=100 uS/cm), typical of run of from highly leached soils. This is to be expected as the rainfall is very high at the Midlands dam site, so that run-off speeds will be high leaving little time for the water to interact with, and dissolve minerals in the catchment.

2.3 The water at the dam has a relatively high BOD (Biochemical oxygen demand), which is consistent with the COD (Chemical oxygen demand) value. The latter is slightly higher, as would be expected. However, the high BOD/COD ratios (62 and 80% respectively) suggest that the dissolved organic matter is highly degradable. The water at this point is, in fact, equivalent to a medium/ poor quality sewage effluent with a high potential for removing oxygen from the water column. Further conformation of the rapid degradation of organics is given by the proportion of nitrogen in the form of ammonia (~80%) and the oxygen level at 70% of the saturation concentration (8.58 mg/l @23°C). An alternative explanation is that the water contains natural organic matter, which at the high temperatures in the static pool at the sampling site decays very quickly. However, it is unlikely that decaying vegetation would produce so much phosphate or nitrate/ ammonia. Hence an alternative source of these nutrients would need to occur.

2.4 The over-riding probability is that water of this quality, which is retained in a semi-static state by a dam, will rapidly become deoxygenated throughout its depth, irrespective of stratification, with a resultant significant reduction in water quality typified by major increases in iron, manganese and probably even sulphide, as well as ammonia, which is already apparent. A survey should be carried out to try an ascertain the source of the carbon and nutrients in the catchment.

Table 2.1. Water chemistry of the Grand River S.E. at the dam site.

parameter	**13/10/94**	**27/10/94**
pH	6.62	6.76
Conductivity (mS/m)	10.2	9
Total susp. solids (mg/l)	7.6	nil
Dissolved oxygen (mg/l)**	6.0	5.2
Temperature (°C)**	23	23.5
Nitrate as N (mg/l)	0.12	0.134
Ammonium as NH_4^+ (mg/l)	0.47 (0.37^{+})	0.496 (0.39^{+})
Phosphate as P (mg/l)	0.28	0.44
Total phosphorus (mg/l)	0.38	N/D
COD (mg/l)	65	147
BOD (mg/l)	40	118
Iron as Fe^{2+} (mg/l)	1.06	0.78
Manganese as Mn^{2+} (mg/l)	0.06	<0.02
Chlorophyll a (mg/m^3)	6.94	0.54
Chlorophyll b (mg/m^3)	53	353
Chlorophyll c (mg/m^3)	0.05	N/D

** in situ measurement at time of sampling.
+ concentration in mg/l as N.

3. Stratification

3.1 Standing water bodies receive heat from the sun at different rates throughout the day and throughout the year. They are also exposed to winds of different speeds and directions which vary over similar time scales to the heat input. The incoming heat will be absorbed by and hence, preferentially warm the upper layer of the water body. The warmer water will expand and become less dense. As a result the warmer, less dense water will tend to float on top of the cooler, more dense bottom water, and so isolate the bottom water from further heat inputs. The wind, on the other hand, transfers kinetic energy to the water, creating turbulent movements which try to disperse the heat throughout the whole water body. Hence the thermal structure of a water body results from a complex balance, with the kinetic energy of the wind trying to overcome the buoyancy provided by the net heat input. The likelihood of stratification occurring in a reservoir can be inferred from estimates of the Monin-Obukov length (Spigel, Imberger and Rayner, 1986) and the Wedderburn number (Imberger and Hamblin, 1982). These two measures make different assumptions and are therefore independent estimates, the former predicting the relative stability of the buoyancy effects compared to the wind energy, and the latter predicting the depth of mixing for a given density difference.

3.2 At a latitude of 20°S the solar flux is about 24 MJ m^{-2} d^{-1} in June/ July rising to about 42 MJ m^{-2} d^{-1} in December/ January. About two thirds of this, at most, reaches the ground due to absorption and scatter by the atmosphere. Of this a further ~15% is lost by reflection at the water surface. For both the Monin-Obukov and Wedderburn estimates it is assumed that the water temperature equals the mean air temperature for the previous two months. Because of the thermal capacity of the water in the reservoir the water temperature will lag behind the air temperature so that use of this assumption will slightly underestimate the water temperature in January and slightly overestimate the temperature in July. This will tend to reduce the stability in June/ July while making little difference to the stability in December/ January. The initial Wedderburn calculations assume that prior to the beginning of each month no stratification has taken place.

3.3 By rearranging the Monin-Obukov equation it is possible to estimate the minimum wind speed required to fully mix the lake for a given heat input. Estimates of the minimum wind speed suggest that speeds of 11- 12 knots would be required at any time of the year to fully mix the phase 1 reservoir, and 12-13 knots to mix the phase 2 reservoir. Since normal wind speeds on the island are typically between 3-7 knots. The predictions suggest that the lake could be permanently stratified.

3.4 This is consistent with estimates of the possible mixing depth (Wedderburn mixing depth) which could be achieved with average wind speeds. With no assumption of stratification in the month prior to calculation, estimates suggest that the reservoir will, at least stratify from November to April. Assumption of stratification in November, i.e. fixing the hypolimnion temperature to the temperature in November, suggests that stratification will be maintained all year round, with a mean thermocline depth of about 3m from the surface for both the phase 1 and phase two reservoirs.

3.5 These analyses assume that the reservoir is kept full all year round. This will not be the case and the presence of low levels at the end of the summer would probably allow de-stratification to occur. However, the impression is of a reservoir with potential for continuous stratification. This is reasonable, given the very high solar heat input, the low wind speeds and the relatively greater stability of thermal density gradients at high temperatures, compared to lower temperatures. With this scenario, the hypolimnion would be continuously anaerobic with very poor quality water containing high concentrations of ammonia, dissolved iron, dissolved manganese and probably sulphide.

4. EFFECTS OF ALGAL GROWTH ON WATER QUALITY

4.1 The growth of algae in water is influenced by many things. Research carried out over many years has established that, for temperate lakes, reasonably reliable estimates of the size of algal crops can be made by considering five main factors: the amount/ concentration of available nutrients; the relative balance between different nutrients; the residence time in the lake; the light environment; the wind patterns. In this report several equations will be used to estimate algal biomass in the Midlands reservoirs. These equations were originally developed for northern temperate lakes. However, in spite of observed differences between temperate and tropical/ sub-tropical lakes and reservoirs, present evidence supports the belief that control of eutrophication in the tropics can be considered in essentially the same manner as in temperate zones (Ryding and Rast, 1989). In the absence of other means the normal predictive equations will be used, but it is likely that, because of the higher temperatures and consequent faster growth rates and nutrient turn over, algal crops will be slightly higher than those predicted by equations based on the effects of nutrient limitation.

4.2 Physical and chemical data used for the estimation of likely water quality in the phase 1 and enlarged, phase 2, reservoir are given in table 1.1. Estimates of P and N loadings and concentrations are given in table 4.1. Chlorophyll a concentrations have been estimated for different depths of completely mixed surface water when either different nutrients or light are assumed to limit growth.

4.3 The mean concentrations of dissolved phosphorus and nitrogen (nitrate + ammonia) in the reservoir are estimated at 0.28 and o.49 mg/l respectively, i.e. the same as in the inflow. On the basis of the dissolved inorganic nitrogen the reservoir would be classed as mesotrophic. However, on the basis of total phosphorus (0.38 mg/l) the reservoir would be considered as hyper-eutrophic (OECD, 1982). These assessments are based on training sites located in the northern temperate zone. In the tropics, trophic status would be expected to higher. Hence these are under estimates.

4.4 There are a large number of empirical equations which can be used to predict chlorophyll concentrations from either total (or soluble reactive) phosphorus or total nitrogen (or nitrate) concentrations (Ryding and Rast, 1989). They all make different assumptions and predict different descriptors of algal biomass. The following discussion will use four measures which have been widely used in predictive situations. Vollenweider's equation (OECD, 1982) has been used to predict the mean annual chlorophyll a concentration which could be attained for a given P loading. Dillon and Rigler's equation (1974) can be used to estimate the mean summer chlorophyll a levels assuming P limitation and Sakomoto's equation (1966) gives the equivalent assuming N limitation. Reynolds' equation is a predictor of maximum summer chlorophyll a assuming P limitation (Reynolds, 1991). Reynolds has also given the equations for calculating the maximum algal biomass sustainable for a given light intensity, assuming that nutrients are not limiting (Reynolds, 1991).

4.5 With the mean hydraulic residence time of both phases exceeding 200 days, there will be plenty of time for algal biomass to develop to its full potential. The average standing crop of algae in the reservoir could reach about 35 µg/l chlorophyll-a when the reservoir is well mixed throughout its full volume. Maximum biomass concentrations could reach at least 170 µg/l. The mean phosphorus loading is so large that the Dillon and Rigler equation for mean summer chlorophyll estimation appears to be unreliable. It is included for comparison with the Sakamoto estimate which assumes nitrogen limitation. Predictions show that the nitrogen concentrations in the fully mixed reservoir are only capable of maintaining annual mean biomass levels of 18 µg/l. Hence blue green algae, which can obtain nitrogen directly from the atmosphere, would dominate.

4.6 If the lake stratifies on an annual basis, i.e. a single period stratified followed by a single period fully mixed, the retention time will probably stay about the same but the phosphorus is available to a smaller volume of the lake and will sustain higher biomass levels in the summer. Conversely, if the reservoir is continuously stratified biomass estimates reduce, since the retention time is significantly lowered, reducing the chances that the algae can utilise the P before it flows out of the reservoir. However, it would still maintain average biomass levels higher than the fully mixed reservoir.

4.7 A comparison of the estimates of biomass concentrations which can be sustained under light limitation and under P limitation is given in table 4.1. Under all assumptions of limitation for a given mixed depth, the biomass estimates for light limitation are significantly greater than estimates of mean biomass levels. Only on a few occasions during the summer could the maximum, P-limited biomass exceed the light limited levels. As a result, light is unlikely to be a growth limiting factor, except occasionally during the periods of highest growth in the summer. Under these circumstances, efficient light utilising or light intercepting algae (blue green algae) will dominate, and capture light.

4.8 There is evidence from two directions that blue-green algae will be dominant for some part of the year. Since they can often float, they rise to the surface and form unpleasant scums which can reduce recreational use of the lake and create the possibility of algal toxin formation which can be lethal to livestock and can cause skin rashes and upset stomachs in humans. Chlorophyll concentrations of over a 1000 µg/l in the top metre or so of the reservoir could occur under these circumstances.

4.9 Because light is not generally limiting, the total algal biomass cannot be controlled by mixing. If the reservoir were to be artificially destratified, then the turbulence created by the mixing would overcome the weak buoyancy forces developed by blue green algal arresting the development of surface scums. Dominance by potentially toxin producing blue green algae would be removed.

4.10 If destratification is not used, or if the equipment fails for short periods of time (a few days) then highly concentrated algal scums created during the frequent calm periods in summer would be prone to concentration at the down wind end of the reservoir. This occurs particularly when light breezes occur after a calm period. As a result consideration should be given to the location of the draw off tower so as to minimise any problems which are bound to arise.

4.11 Because of the high algal productivity and highly organic rich feed water, which is expected to occur in the Midlands reservoir, it is very likely that the hypolimnion will rapidly deoxygenate very soon after stratification (or be permanently anoxic if permanent stratification occurs). This will result in a major deterioration in water abstracted from the hypolimnion, ie below about 3 m, on average. The water will have no oxygen and have high concentrations (tens, possibly hundreds of mg/l) of ammonia, iron, manganese and sulphide. This will reduce it's acceptability for irrigation purposes and it will increase treatment costs for potable supply. In addition it will create a major oxygen demand on La Nicoliere feeder canal.In its own right it will also constitute a significant quantity of substances toxic to both aquatic biological species and to man and animals.

Table 4.1a Calculated nutrient and chlorophyll concentrations assuming different limitations to growth.

Phase 1	**Nitrogen**	**Phosphorus**
areal loading ($g/m^2/a$)	7.02	4.01
in-lake concentration (mg/m^3)	490	280

Chlorophyll a concs under nutrient limitation		
mean annual (µg/l)[1]	37	mixed
mean annual (µg/l)[1]	106	annual stratify
mean annual (µg/l)[1]	45	permanent stratify
mean summer (µg/l)	18[2]	258[3]
max summer (µg/l)[4]		171

Chlorophyll a (µg/l) assuming		light limitation		P limitation	
		June/July	equinox	Dec/Jan	OECD[1]
Fully mixed	70	86	102	37	
mean stratified depth (3)	234	281	325	106(45)	
mean stratified depth (1m)	741	884	1014		

(1). OECD; 1982; (2). Sakamoto, 1966;
(3). Dillon and Rigler, 1974; (4). Reynolds, 1991

Table 4.1b Calculated nutrient and chlorophyll concentrations assuming different limitations to growth.

Phase 2	**Nitrogen**	**Phosphorus**
areal loading ($g/m^2/a$)	5.49	3.14
in-lake concentration (mg/m^3)	490	280

Chlorophyll a concs under nutrient limitation			
mean annual (µg/l)[1]		33	mixed
mean annual (µg/l)[1]		117	annual stratify
mean annual (µg/l)[1]		43	permanent stratify
mean summer (µg/l)	18[2]	258[3]	
max summer (µg/l)[4]		171	

Chlorophyll a (µg/l) assuming	light limitation			P limitation
	June/July	equinox	Dec/Jan	OECD[1]
Fully mixed	50	63	75	33
mean stratified depth (3m)	234	281	325	117(43)
mean stratified depth (1m)	741	884	1014	

(1). OECD; 1982; (2). Sakamoto, 1966;
(3). Dillon and Rigler, 1974; (4). Reynolds, 1991

5. REMOVAL OF VEGETATION PRIOR TO FILLING THE DAM

5.1 This is a contentious issue with protagonists for and against. In my opinion it basically depends if net fishing is to be encouraged in the new reservoir, or not. The flooding of new land will leach out nutrients from the soil and increase the productivity for the first few years. The nutrients in the terrestrial plant biomass are unlikely to make much difference to the observed trophic status in the first few years compared to the former source of nutrients. The reservoir will then fall back to "normal" levels driven by the external sources of nutrients. The wood, etc will increase the organic loading to the reservoir and reduce the oxygen in the bottom water if it is allowed to stratify. But in the first few years one would expect strong deoxygenation of the hypolimnion, in any case, as a result of the high algal productivity. The most important factor is the requirement for net fishing. If this is to be encouraged then trees and shrubs should be removed, otherwise nets become entangled and fishing is ineffective. If fishing is not to be encouraged then the cost benefit is probably in favour of not removing the trees.

6. CONCLUSIONS

6.1 In the feed water analyses data:

a) suspended solids and dissolved solids are confused.
b) a nil result for total P in the second sample is impossible.
c) Chlorophyll a and b level cannot be as reported.

6.2 The feed water has a low ionic strength and a neutral pH.

6.3 The feed water has a high BOD, COD, ammonia and dissolved P content and is consistent with a sewage effluent. It will rapidly deoxygenate the water column when retained by a dam.

6.4 Both the first and second phase dams will behave essentially in the same way with respect to stratification and algal biomass.

6.5 The reservoir is likely to stratify from November to April and may well remain permanently stratified with a mean thermocline depth of 3m below the water surface.

6.6 Given the poor quality of the feed water, the hypolimnion of a stratified reservoir will rapidly deoxygenate, creating water with no oxygen and high ammonia, dissolved iron, dissolved manganese and sulphide.

6.7 The reservoir will be hyper eutrophic.

6.8 The retention time in a fully mixed reservoir will be greater than 200 days allowing algae to take full advantage of the high nutrient levels.

6.9 The mean biomass in a fully mixed reservoir is likely to be 35 mg m^3 with maximum summer levels up to 170 mg m^3.

6.10 If the lake stratifies seasonally, algal biomass will be much higher than in the fully mixed case.

6.11 If the lake stratifies permanently algal biomass will be about 30% higher than in the fully mixed case.

6.12 Algal biomass in the reservoir will normally be limited by P. Reductions in biomass will only be reduced by reducing the P load.

6.13 Because light will not normally be limiting, mean biomass levels cannot be controlled by mixing.

6.14 Nitrogen levels are low relatively to P levels so that N-fixing blue green algae will dominate.

6.15 Light will become limiting at times during the summer, encouraging blue green algal dominance.

6.16 In calm periods, surface blue green algal concentrations could reach 1000mg m^3.

6.17 Blue green algae have the potential to produce toxic substances which can be harmful to animals and man.

6.18 Destratification would reduce the likelihood of blue green algal dominance.

6.19 During calm periods and/ or breakdowns of destratification equipment, blue-green scums will form at the down wind end of the reservoir.

6.20 The high productivity of the reservoir will rapidly create deoxygenation of the hypolimnion in a stratified lake, with a resultant significant drop in water quality.

6.21 Trees and shrubs in the flooded area will probably add little to the level of early eutrophication in comparison to other sources.

6.22 Submerged tree will snag fishing nets.

7. RECOMMENDATIONS

7.1 The methodology and accuracy of the analytical results should be checked.

7.2 Sources of high BOD, COD, and ammonia in the catchment should be located and a strategy developed to reduce them and improve the feed water quality.

7.3 Provision should be made to include destratification equipment at an appropriate stage in the construction or early operation of the dam should the predictions of stratification and blue green algal dominance be confirmed in operation.

7.4 Sources of P in the catchment should be located and reduced to limit algal productivity.

7.5 The location of the draw-off tower should be considered with respect to the build up of algal scums downwind.

7.6 Trees and shrubs need only be removed from the flooded area if net fishing is to take place.

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