Institute of Freshwater Ecology

THERMAL STABILITY AND WATER QUALITY OF THE PROPOSED SWINDEN QUARRY REHABILITATION SCHEME

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Report To: Sir Alexander Gibb and Partners
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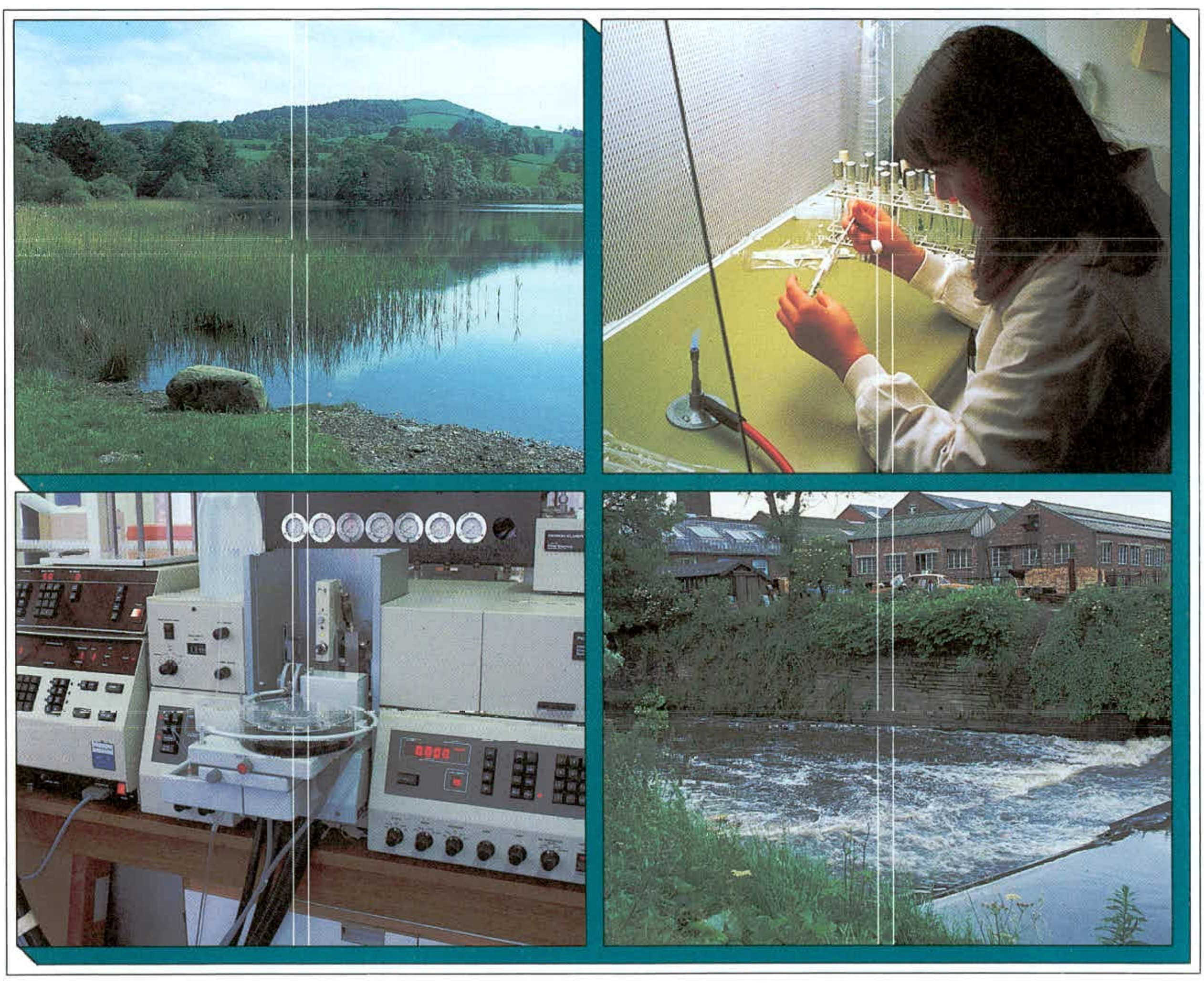

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This report makes its recommendations from a state of the art understanding of the way in which aquatic systems work and is considered to represent the best advice available at the present time. However it should be borne in mind that changes in the 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.

EXECUTIVE SUMMARY

A study has been made of the likely physical and chemical behaviour of the lake created by the, proposed, rehabilitation of the Swinden quarry. Calculations were made for the lake at periods through its 10 year filling stage, using either ground water or stream (beck) water as the filling medium. Similar calculations were also made for the full lake when rain water would be the feed medium.

Results from the heat balance models show that the lake, at all its stages of filling, is likely to stratify during the summer and be completely mixed in the winter. Thermal stability will be strong with a possibility that the mean thermocline depth could be only a few metres below the water surface.

A number of different models of predicting algal productivity have been used to assess the likely trophic status of the proposed lake. In all stages of filling the phosphorus concentrations will limit the growth of algae. In the stratified system summer mean chlorophyll concentrations will be around 15 µg/l with maximum summer levels approaching 55 µg/l. Blue green algae are unlikely to dominate.

The water quality of the proposed lake is likely to be good with relatively small algal blooms and insignificant deoxygenation of the bottom water.

CONTENTS

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 it 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 lake 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 ability of the wind to mix the incoming heat throughout the water body prior to stratification, and the latter predicting the ability of the wind to overcome the stabilising effect of a density difference after stratification has occurred.

3.2 At a latitude of 54.054°N the solar flux is about 6 MJ m^{-2} d^{-1} in December/January rising to about 42 MJ m^{-2} d^{-1} in June/July. 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. There are further losses due to black body radiation from the water surface to the atmosphere and a gain of heat due to long wave radiation from the atmosphere to the water. The sum of these gains and losses gives the total heat input for a day in each calendar month. For both the Monin-Obukov and Wedderburn estimates it is assumed that the water temperature is the mean of the air temperatures for the previous two months. This is a simple approximation to allow for the thermal capacity of the water in the lake. The initial Wedderburn calculations assume that prior to the beginning of each month no stratification has taken place.

3.3 A rearrangement of the Monin-Obukov equation allows an estimate to be made of the minimum wind speed required to fully mix the lake for a given heat input. Estimates for the different filling periods are given in table 2. The Wedderburn depth is the same for all four lake sizes less than 80 m since the determining parameter is the maximum length which is the same for all these situations. The Wedderburn depth for the full lake is different since the maximum length is larger.

3.4 Comparison of the minimum wind speeds with the percentage frequency of occurrence of winds in different speed bands suggests that, for all stages of filling, the minimum wind speed required from November to April is exceeded at least 25% of the time. Hence the lakes will be completely mixed for all of this period. A similar analysis shows that from July to October in the first 20 m stage; June to October in the second and third stage lakes and from May to October for the fourth stage and the full lake, the minimum wind speed for mixing is only exceeded for less than 5% of the time. Since these higher wind speeds tend to occur in a number of events and not in a single time period it is unlikely that the wind speed will remain high enough for long enough to develop a lake circulation system and mix the lake completely during these occasions, i.e. the lakes will stratify over these periods.

3.5 This is consistent with estimates of the possible mixing depth (Wedderburn mixing depth) which could be achieved with the most frequent wind speeds. With no assumption of stratification in the month prior to calculation, estimates suggest that at all stages the lake will stratify from May to September. The predicted thermocline depth of 1-3 m suggests that the system will be highly stable once stratification has developed.

3.6 The wind data are for a nearby site since there are no wind data available for the site itself. The site itself is very sheltered due to surrounding hills so that wind speeds will generally be lower than the values used. This effect will be enhanced at the early stages of filling as a result of the steep walls, which surround the quarry, increasing protection from the wind. Hence the thermal structure which is likely to develop will be much stronger than the estimates given here. However it is clear that at all stages of filling the lake will stratify during the summer period and become completely mixed during the winter.

Table 2. Data on the likely stratification of the Swinden Quarry lake at different stages of filling.

Monthly average air temperature (°C)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
3	4	5	9	11	15	16	16	13	10	6	5

Minimum wind speed required to keep the lake totally mix the lake (m/s).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
first 20m	3	1	3	3	6	7	8	9	9	8	6	4
second 20m	4	1	3	4	7	9	10	11	10	9	8	6
third 20m	5	1	4	4	8	10	11	13	12	11	9	6
forth 20m	5	1	4	5	9	12	13	14	14	12	10	7
full	5	1	4	4	8	10	12	13	13	11	9	6

Depth of thermocline developed for most frequent wind speed each month (m)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Bottom 80m	M	M	M	M	2	1	1	1	2	M	M	M
Full lake	M	M	M	51	3	2	1	1	3	M	M	M

Swinden Quarry wind speed data. Percentage total time at given wind speeds

Metre/ sec		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
calm	calm	0.13	0.12	0.16	0.08	0.03	0.14	0	0.08	0.21	0.08	0.25	0.02
0.52	1.55	13.98	13.55	10.24	14.51	15.35	14.56	11.45	14.85	16.76	18.03	15.83	13.12
2.06	3.09	16.3	15.08	17.97	20.01	22.77	23.14	19.57	20.66	20.33	18.33	19.15	14.05
3.61	5.15	21.94	23	28.23	30.96	35.86	33.77	33.21	34.05	29.85	27.79	29.14	18.28
5.67	8.24	25.56	26.1	27.73	27.5	21.26	19.21	23.19	26.09	24.93	22.82	24.81	26.14
8.76	10.82	14.02	11.59	9.99	5.94	3.52	1.95	2.72	3.86	5.15	4.83	7.99	12.36
11.33	13.91	6.13	5.54	3.8	0.93	0.6	0.17	0.15	0.36	1.26	2.03	2.61	4.24
14.42	17.00	1.57	1.38	0.59	0.04	0.13	0.03	0	0.01	0.004	0.15	0.13	0.86
17.51	20.60	0.19	0.12	0.12	0	0	0	0	0	0	0.01	0	0.13
21.12	24.21	0.01	0.04	0	0	0	0	0	0	0	0	0	0.01
24.72	28.33	0.01	0	0	0	0	0	0	0	0	0	0	0
28.84	32.45	0	0	0	0	0	0	0	0	0	0	0	0
>32.5	>32.5	0	0	0	0	0	0	0	0	0	0	0	0
Total		99.84	96.65	98.83	99.97	99.56	93.21	90.37	100	98.75	94.12	99.97	89.43

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 Swinden quarry lake.

4.2 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).

4.3 Vollenweider's equations were developed on flowing systems and uses retention time as one of the estimation parameters. During the filling stage no water will exit the lake, hence retention times will approach infinity. Under these circumstances Vollenweider's equations are not applicable. Results for calculations using this equation will only be given for the case of the full lake with rainfall input. Because the other algal biomass estimators require only the predicted nutrient concentration as inputs, the predicted biomass will be the same for all five stages of filling. Hence, the results are only reported for the bottom 20 m.

4.4 Physical and chemical data used for the estimation of likely water quality are given in table 1. Estimates of P and N loadings for and concentrations are given in table 3 for ground water and stream inflow for the bottom 20 m with no outflow and for rainwater inflow to the full lake with residual outflow. On the basis of these data, 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.

Table 3.

	first 20 m	full	
estimated thermocline depth (m)	1	2	
Estimated epilimnion volume (m^3)	291 100	540 000	

	Ground water first 20m	Becks first 20m	Rain full lake
P load (t/a)	0.105	0.028	0.032
N load(t/a)	4.59	0.52	0.12
All calculated values below			
lake retention time (y)	inf	inf	99
Areal load P(as P)(g/m2/a)	0.72	0.41	0.01
Areal load N(as N)(g/m2/a)	31.55	4.16	0.45

4.6 The mean concentrations in the lake of dissolved phosphorus and nitrogen (nitrate + ammonia) are given in table 1, and are the same as in the appropriate inflow. On the basis of dissolved phosphorus (<0.040 mg/l) the lake would be considered as mesotrophic. On the basis of the dissolved inorganic nitrogen the lake would be classed as meso (beck water) or eutrophic (rain and ground water) (OECD, 1982). However, phosphorus is generally the limiting nutrient in fresh waters so the rating of mesotrophic is the more reliable rating. The analytical data quote values of phosphorus in all the sources as less than values, hence the predictions made here will be upper estimates of algal standing crop concentrations.

4.7 A hydraulic residence time of (theoretically) infinity in the filling scenarios and 99 years in the full lake, gives plenty of time for algal biomass to develop to its full potential. Although it is not possible to use the Vollenweider equation for the system when it is filling, it is likely that the mean annual chlorophyll concentrations will be similar to those in the full, rain replenished system, since the P levels are the same and the retention in the full system is very high. Irrespective of the source of water, maximum chlorophyll concentrations are unlikely to exceed about 55 and mean summer levels will be about 15 µg/l. However, if beck water alone is used the Sakamoto estimate is very close to the Dillon and Rigler estimate. Hence, there is a possibility that nitrogen will become limiting and blue-green, buoyant algae may become dominant causing unsightly scums. This would not occur if ground water alone were used to fill the lake. Since there will be no way of stopping the ground water also contributing to the filling of the lake if the beck sources are chosen, then the higher nitrogen levels in the ground water will provide sufficient extra nutrient to stop blue green algal dominance.

1. INTRODUCTION

1.1 Sir Alexander Gibb and partners have been commissioned to assess the feasibility of rehabilitating a former limestone quarry at Swinden, Yorkshire. The proposal is to allow the quarry to fill with water from either underlying ground water or from two nearby streams. The IFE was commissioned to assess the likelihood of stratification of the new water body and to assess the likely water quality in the new lake should the rehabilitation occur.

1.2 The IFE study commenced in April 1995. This report: a) gives predictions of the likely stratification behaviour of the lake, and b) gives predictions of the likely levels of selected water quality parameters, mainly nutrients and algal biomass.

2. BASIC DATA

2.1 It has been calculated that the lake will take ten (10) years to fill, irrespective of the source of water (ground water or streams). After this the level will be maintained by rainfall alone. The period has been split into five sub-periods. Estimates made by Gibb suggest that the lake will fill at the following rates:

	Ground water		Eller and Crook Becks	
Filling stage	Average inflow (m^3/d)	time (days)	Average inflow (m^3/d) (days)	time
Lower 20m	7188	405	1918 (Ell)+2192 (Cr)	708
next 20m	6247	466	1918 (Ell)+2192 (Cr)	708
next 20m	5253	554	1918 (Ell)+2192 (Cr)	708
next 20m	3905	746	1918 (Ell)+2192 (Cr)	708
upper 20m	2290	1272	1918 (Ell)+2192 (Cr)	1060

2.2 Basic data for the site and for the proposed lake through the five phases of filling are given in table 1. The typical nutrient content of rainwater from a nearby site at Cow Green has been reported as 20 mg/m^3 of dissolved phosphorus (Allen); 350 mg/m^3 dissolved nitrate; 392 mg/m^3 ammonia giving 742 mg/m^3 total dissolved nitrogen (AEA). These concentrations were delivered in the 1200 mm/y of rain which falls in the area. However, 600 mm/y of water are lost each year through evaporation. Hence the nutrient levels reported in table 1 are concentrated by a factor of 2 to give the concentration in the remaining 600 mm/y of rainfall left.

Table 1 Physical, chemical and hydrological properties of Swinden Quarry

Location Grid ref. = 3980E 4615N Latitude = 54.054 N; Longitude = 2.000 W
Final lake level = 193 m AOD

	Volume (m^3)	Area (m^2)	Length (m)	Width (m)	Mean depth (m)
Bottom to 80m :	11 644 000	145 550	510	285	80
each bottom 20m:	2 911 000	145 550	510	285	20
top 20m :	4 356 000	270 000	900	300	20
total volume	16 000 000	270 000	900	300	59.25

Input source	flow rate (m^3/a)	Diss. P mg/m^3	NO_3-N mg/m^3	NH_4-N mg/m^3	Tot-N mg/m^3
Full lake					
Rainwater	0.6 x 270 000	40	700	784	1484
All stages					
Eller Beck	700 000	40	700	47	747
Crook Beck	800 000	40	50	54	104
flow weighted mean		40			404
lower 20m					
Ground water	2 624 000	40	1300	450	1750
second 20m					
Ground water	2 280 000	40	1300	450	1750
third 20m					
Ground water	1 917 000	40	1300	450	1750
fourth 20m					
Ground water	1 425 000	40	1300	450	1750
final stage					
Ground water	834 000	40	1300	450	1750

4.8 If the lake were well mixed throughout its full volume all year and replenished with rain water, the average annual standing crop of algae in the lake will be very small (1 µg/l = mg/m^3 chlorophyll *a*). If the lake achieves the very stable, predicted stratification with a thermocline at a few metres from the surface (a slightly larger value of 3 m has been taken for algal predictions rather than the predicted thermocline depth of 2 m) an annual mean chlorophyll level of 26 µg/l would result. Maximum biomass concentrations could reach 55 µg/l. These are not large values. The mean summer chlorophyll, assuming nitrogen limitation to growth is likely to be 15 µg/l. A comparison with the Sakamoto estimate of 89 µg/l, which assumes nitrogen limitation, suggests that there will always be sufficient nitrogen to maintain the algae. Hence blue green algae will not have an ecological advantage due to nitrogen limitation.

4.9 A comparison of the estimates of biomass concentrations which can be sustained under light limitation is given table 4. The biomass estimates which would be allowed if growth were limited by the light conditions for mixed depths less than about 40 m are significantly greater than estimates of mean summer biomass levels. Since the lake is likely to stratify with a mixed depth less than this the algal standing crop concentrations will be determined by phosphorus levels, not by light, light is unlikely to be a growth limiting factor.

4.10 The picture given by the model predictions is of a lake with relatively low algal populations. Hence, even though the lake will stratify the carbon flux to the bottom water will be small, particularly when considered in the light of the large oxygen reservoir contained in the large volume of isolated bottom water.

Table 4. Calculated nutrient and chlorophyll concentrations assuming different limitations to growth.

Chlorophyll *a* concentrations under nutrient limitation

	Full Rain water		Bottom 20m Beck water		Ground water	
	mixed	stratified	mixed	stratified	mixed	stratified
mean annual (µg/l) (OECD-P)	1	26	NA	NA	NA	NA
mean annual (µg/l) (D & R - P)	15		15		15	
mean annual (µg/l) (Sakamoto - N)	89		13		112	
max summer (µg/l) (Reynolds - P)	55		55		55	

Chlorophyll *a* (µg/l) assuming	light limitation		
	June/July	equinox	Dec/Jan
Mean mixed depth (3m)	395	269	101
Mean mixed depth (20m)	42	23	0
Mean mixed depth (40m)	11	2	0
Mean mixed depth (60m)	0	0	0
Mean mixed depth (80m)	1	0	0
Mean mixed depth (59.2m)	1	0	0

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

5. CONCLUSIONS

5.1 During its filling stages and when full the lake will stratify thermally from about May to September.

5.2 The average thermocline depth could rise to within a few metres of the surface during both the filling stages and when full.

5.3 Estimates of thermal stability are likely to underestimate the effect as the lake is sheltered from the wind.

5.4 The retention time in the lake is long.

5.5 Phosphorus concentrations in the lake will determine the maximum algal populations which occur.

5.6 Neither light nor nitrogen are growth limiting.

5.7 Chlorophyll levels in a continuously mixed lake would be very low.

5.8 Annual mean chlorophyll levels could approach 26 µg/l with maximum summer levels up to 55 µg/l.

5.9 Nitrogen fixing blue green algae will not be a problem when the lake is full.

5.10 If beck water alone is used to fill the reservoir occasional problems may occur with nitrogen fixing blue-green algae becoming dominant and forming scums.

5.11 Algal populations are likely to be over-estimates as phosphorus concentrations in the inflows were only reported as being <40 µg/l.

6. RECOMMENDATIONS

6.1 The client should not consider water quality due to algal growth as a potential problem with respect to the rehabilitation of the rehabilitation of the quarry in the manner outlined to contractor.

6.2 Filling of the lake should not be carried out using beck water alone but even a small mixture with ground water seepage would alleviate any potential problems with blue-green algal dominance.

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