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CONCENTRATION DYNAMICS IN LAKES AND RESERVOIRS, STUDIES USING RADIOACTIVE TRACERS

by

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SUMMARY

The concentration dynamics in lakes and reservoirs through which water flows can be investigated by injecting a pulse of radioactive tracer and measuring the response at the outlet or any other point of interest inside the lake. The methodology developed for this kind of investigations is presented. It was found that concentration dynamics in shallow reservoirs can be described by a model consisting of a time delay in series with one or two time constants. Procedures for the determination of the volumes of these regions are presented for reservoirs considered as either constant or variable parameter systems. The flow pattern in the reservoirs was investigated by measuring the response of the concentration through the lake and was analyzed in relation to the prevailing wind conditions. Wind induced currents have a dominant influence on the flow pattern.

CONTENTS

1. INTRODUCTION

Radioactive tracers (such as Br 82) are convenient for measuring the concentration dynamics of different systems. The purpose of the present paper is to present the methodology developed for the investigation of concentration dynamics in lakes, ponds and reservoirs through which water flows. Results of different studies are reviewed. The question of how much tracer work is needed in this type of studies is discussed.

2. METHODOLOGY OF CONCENTRATION DYNAMICS INVESTIGATION IN A LAKE THROUGH WHICH WATER FLOWS

The concentration dynamics of inert soluble matter can be investigated by injecting a pulse of radioactive tracer and measuring the response at the outlet or any other point of interest. Bromine-82 (as bromide) is a suitable safe tracer for the investigation of water systems.

2.1. Input-output response

We are interested in the impulse response (in the time domain) or the transfer function of the reservoir (in the Laplace domain), i.e., the "identification" of the system. This identification is relatively well known for time invariant systems (1,2,3). However, the reservoirs are time variant because flowrates and volumes change with time. Furthermore, these reservoirs are affected by outside parameters such as wind and temperature, which also vary with time.

When the reservoir's time constant[1] is relatively longer than the period of fluctuation of parameters affecting the reservoir, one can consider the reservoir as a constant parameter system. We arrived at this conclusion by using frequency response techniques and assuming the reservoirs to be well mixed. The reservoir's volume and flowrate can be

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[1]The average residence time, i.e. average volume divided by average flow rate.

averaged over the period of interest. For example, the Oxidation Pond described below, having a time constant of 7 days will smooth out the effect of fluctuations in temperature, flow- rate, volume and wind having a 24 h period (i.e., day-night effects).

When the time constant is of the same order or smaller than the period of fluctuation of the parameters affecting the system, one has to consider the system as a variable parameter system. Nir (4) found the impulse response $h(\phi,t)$ in mixed lakes in non-steady state:

$$h(\phi,t) = \frac{q_{in}(t-\phi)}{V(t-\phi)} \exp\left[-\int_{t-\phi}^{t} \frac{q_{in}(t')}{V(t')}\,dt'\right] \tag{1}$$

q_{in} is the inflow rate. V is the volume of the reservoir and ϕ is the time from the occurrence of the disturbance.

If the chronological time t starts at the occurrence of the disturbance,i.e., $t-\phi = 0$ or $\phi = t$, the above equation can be converted to:

$$h(t) = \frac{q_{in}(0)}{V(0)} \exp\left[-\int_{0}^{t} \frac{q_{in}(t')}{V(t')}\,dt'\right] \tag{2}$$

Let us define θ as:

$$\theta = \int_{0}^{t} \frac{q_{in}(t')}{V(t')}\,dt' \tag{3}$$

θ is a reduced time which replaces the reduced time $t/\frac{V}{q}$ for constant volume and flow rate systems.

We found that the input-output response of shallow reservoirs can be fitted to that of a plug flow region (a delay) coupled in series with one or more mixed regions. The parameters of these "mixed region models" (3), e.g., their relative volumes, are identified by minimizing a quadratic performance criterion:

$$P = \int_0^\infty (C_{calc} - C_{exp})^2 \, dt \tag{4}$$

C_{exp} is the measured specific activity in the outflow. C_{calc} is the specific activity in the outflow predicted by the model and normalized for the total activity. In the case of one mixed region, C_{calc} is computed using Eq. (2). If more regions are coupled in series, the output of the first is convoluted with the impulse response of the second, etc.

The volume of the plug flow region is obtained by integrating the inflow rate over the time delay in the occurrence of activity in the outlet stream.

Other procedures for identifying the percentage of volume corresponding to plug flow and perfect mixing are based on plotting $\ln(C_{exp})$ vs. θ or $\ln(1-F)$ vs. θ. The F function is the concentration response at the outlet of the lake to a unit step change in the concentration of the activity at the inlet. These procedures, based on regressions on $\ln(C_{exp})$ provide equal weight for low and high specific activities. They, therefore, permit a better averaging of the response over the duration of the experiment than the minimizing of P in Eq. (4).

Shallow lakes commonly exhibit relatively long time constants. One usually measures the response for at least 3 times the time constant of the system, i.e., for very long periods of time. This requires relatively high activities. However, we found that relatively short experiments, lasting very few days, can be sufficient if one performs measurements inside the reservoir and properly understands the mechanism of mixing in the lake (5,6).

2.2. Mechanism of mixing in shallow lakes

The input-output response of the tracer concentration reflects the overall mixing behavior of the reservoir. The concentration at points throughout the lake provides an insight into the actual flow pattern. It is therefore important to measure the distribution of the activity inside the reservoir as a function of time. Both lumped and distributed parameter models can be used for the interpretation of these distributions (7). The lumped parameter models are mathematically identical to the mixed region models mentioned above for input-output relations. However, an attempt is made to locate the "compartments" or "regions" of the reservoir. This might be possible if the lake is stratified, or consists of basins separated by straits, etc., which is not the case in the shallow lakes we investigated. On the other hand, the distributed parameter model, which is much closer to the actual behavior of the reservoir, is based on advection and turbulent dispersion. Such a model requires information on currents and dispersion coefficients and the distribution of both over the reservoir. It is quite tedious to obtain this information and, therefore, one is often satisfied with understanding the mechanism of mixing inside the lake, identifying the more important parameters and, whenever possible, their contribution to the overall phenomena.

The distribution of tracer concentration inside the reservoir is affected by the temperature of the incoming water as compared with the temperature of water in the reservoir, streamlines of the inflowing and outflowing water, flow rate through the reservoir and wind-induced currents. It is shown in the present paper that the latter factor is the most important one and is responsible for mixing in shallow reservoirs. It is therefore necessary to gather data on wind-induced currents, wind direction and speed for the duration of the concentration dynamics investigation.

It is very difficult to predict the lateral and vertical distribution of wind-induced currents. This distribution depends on the depth and size of the reservoir, topography of the bottom and of the surrounding area, and direction, speed and duration of the wind. For shallow reservoirs, the wind-induced current in the upper layer is generally in the direction of the wind and in the lower layer, in the opposite direction. For relatively large reservoirs located in a plain area, there is little lateral variation in the wind-induced current. For smaller reservoirs and, even more for those situated in an area of an uneven topography, it is more difficult to predict the wind-induced current from wind data.

Temperature of incoming water and temperature profiles in the reservoir are important in deeper, stratified reservoirs (5).

2.3. Experimental

Bromine 82 (as bromide) is a suitable safe tracer for the investigation of water systems. Since water contains always a few tens or hundreds ppm of chloride, no carrier has to be used. The use of a carrier would be prohibitive when studying a larger reservoir. Bromine 82 has a relatively high MPC in drinking water (100 $\mu Ci/m^3$ for year-round exposure).

The activity is measured in situ using NaI(Tl) scintillation detectors (2 in length and 1 in diameter) submerged under water and coupled to a ratemeter and strip chart recorder. Background is about 1 cps and the sensitivity of the probe calibrated to "infinite volume" is about 50 cps/ μCi Br-$82/m^3$. Thus the sensitivity of detecting Bromine 82 is about $2x10^{-2}$ $\mu Ci/m^3$, i.e. almost 4 orders of magnitude below the MPC.

Measurement of activity can be done either at fixed locations, or from a boat towing one or several probes, or by lowering a probe from a boat at any desired location.

The injection of the tracer is usually extended over a period of few minutes. This period of time is negligible compared to the time constants of the reservoir, but still sufficient for avoiding saturation of detectors, should one be interested in monitoring the distribution of activity in the reservoir, soon after injection.

3. CONCENTRATION DYNAMICS OF SHALLOW LAKES

3.1. Oxidation pond

An oxidation pond as used by the Dan Region Sewage Reclamation Project is shown schematically on Fig. 1. The average depth in the pond is about 2.5m. The pond is fed by raw sewage at a changing flowrate, as shown on Fig. 2. The inlets are distributed and submerged. The outlets are also distributed and based on an overflow type device. The volume of water in the pond varies only very little (about 2-3% over a period of a few days) and can therefore be considered as constant.

The average time constant of the pond is about 7 days. The importance of different disturbances, such as those in flow rates (to and from the pond), temperatures of the inflowing sewage, temperatures in the pond, can be assessed by considering the frequency response of the system. It is assumed that the behaviour of the pond is closer to perfect mixing than to plug flow. The amplitude ratio of the response at the outlet to any disturbance at the inlet versus the frequency of the disturbance, i.e. a Bode plot is shown on Fig. 3, for the case of perfect mixing and a time constant of 7 days. It is seen that the pond acts as a first order filter and any disturbances having periods of less than 4.4 days are attenuated to an amplitude ratio of 0.1 or less. Thus, day-night effects (i.e. temperature fluctuations) as well as fluctuations in flowrate and wind direction and speed will be smoothed out. The inlet-outlet response of the system can be regarded as that corresponding to the average conditions prevailing during the period of interest.

The above conclusions are based on a consideration of the frequency response of the outlet concentration of a component to changes in its concentration at the inlet to the pond. It was assumed that all types of fluctuations, throughout the pond, can be represented by 'dummy' concentration changes of the same frequency at the inlet. Such shifting of the disturbances to the inlet is more justified for fluctuations in flowrate or volume than for environmental conditions distributed all over the pond. Nevertheless, the above approach provides a reasonable approximation for the latter disturbances too. It is also clear that changes occurring closer to the outlet will have a stronger effect. However, even relatively close disturbances are negligible. This can be seen from the broken line in Fig. 3, which represents the response to a disturbance as close as one tenth of the pond's volume from the outlet.

Two experiments were performed, a relatively shorter one (E1) which lasted for about 4 days and a second one (E2) which lasted for 9 days. 72 mCi of Br-82 were injected in E1 and 3.34 Ci were injected in E2. The activity was recorded at each individual outlet and monitored from time to time inside the pond from a boat, at the 28 buoys shown on Fig. 1. Wind speed and direction were measured locally and recorded during the duration of the experiments.

Fig. 4 represents the change of specific activity vs. time at the different outlets during E1 while the average specific activity is plotted vs. time on Fig. 5 for E1 and on Fig. 6 for E2. From Figs. 5 and 6 one realizes that the sharp rise in the specific activity at the beginning is followed by a relatively sharp and then a much slower decrease. The transition between the sharp and slower decreases in specific activity occurred at about 24-30 hours after injection, at which time also the activity spread out homogeneously through the reservoir. The time constant of the pond was determined from the exponential decrease of activity as a function of time on Figs. 5 and 6 and found to be 5.6 days for E1 and 6.5 days for E2.

From Fig. 5 one can also observe a very much faster time constant up to about 26 hrs from injection. This behaviour indicates a certain amount of "short circuiting". This is also the reason for the time constant during E1 being 5.6 days as compared to 6.5 days in E2.

The distribution of activity inside the pond, as measured from the boat, was mapped and plotted on cross sections such as the longitudinal ones shown for example on Fig. 7 at about 7-8 hours after injection in E1. These mappings, together with an analysis of the wind recordings were important for the understanding of the mixing mechanism in the pond. Wind conditions were different during the first hours after injection in E1 and E2. In the case of E1, the wind blew from NW and then N with an average speed of about 8 knots. At injection the speed was about 4 kn. At 7-8 hours after injection the activity was observed to be mainly in the upper layer (see Fig. 7). This stratification disappeared at about 26 hrs when the activity in the pond was found to be homogeneously mixed.

During the injection of the tracer in the experiment E2 and for about 4 hours thereafter the wind blew from W to NW, at a speed of about 5 kn. Later the direction changed to NW and also the wind speed decreased to about 3 kn. Figs. 8 and 9 display the longitudinal and transversal mappings of activity distribution with depth at about 4 hours after injection. One realizes that unlike in experiment E1, there is only very little stratification. The western part of the pond is more homogeneous than the eastern part (see Fig. 8). There is a certain tendency for the tracer to accumulate near the east bank of the pond, due to predominantly west wind. It can also be seen that the advancement of the tracer was somewhat faster along the east bank than along the west bank due to a slight northern component of the wind.. At about 26 hours after injection, this activity was homogeneously mixed through the pond.

Although under different wind regimes, the time lapse needed for achieving homogeneous distribution of the activity inside the pond is almost identical in the two experiments. In E1, the relatively strong wind blowing from N veered to S some 13 hours after the injection, thus reversing the wind induced pattern in the pond.

Based on a time delay of 4 hrs and a time constant of 6.5 days the transfer function of the oxidation pond becomes

$$\frac{C_o(s)}{C_{in}(s)} = \frac{e^{-0.02\tau s}}{1 + 0.98\tau s} \qquad (5)$$

$\tau = V/Q$, V and Q being the volume respectively the average flowrate through the pond.

Another interesting conclusion from the two experiments is that in both cases it took about 26-30 hours for the tracer to become homogeneously mixed in the pond. The behaviour of the pond during this time lapse is very much dependent on the wind direction and speed. With winds blowing from W to NW, the currents are mainly transversal from W to E in the upper layer and E to W in the bottom layer. When the northern component of the wind strengthened, the longitudinal currents (from N to S in the upper layer and S to N in the bottom layer) strengthen. It is these components that are advancing the tracer towards the outlet. In extreme cases, with a strong N wind, the tracer can "short circuit" the pond (E2).

3.2. Operational reservoir

An operational reservoir is used for regulating the sewage flowrate at an experimental sewage treatment plant. It is rather narrow (~100 m wide) and long (~300 m). It is situated in a hilly area, its inlet is at south and its outlet is at the north. The uneven topography influences the wind pattern and therefore the wind induced currents.

About 500 mCi of ^{82}Br were injected into the inflow to the reservoir. The volume of sewage in the reservoir ranged from 30,000 m^3 to about 60,000 m^3 during the experiment. This volume was V(0) = 40,000 at injection. In and outflow rates are shown on Fig. 10.

The experimental and calculated specific activities at the outlet of the reservoir are shown on Fig. 11. A model consisting of a time delay followed by a mixed region was fitted to this experiment.

The delay in the occurrence of activity at the outlet was 3.5 hours. θ_d computed according to Eq. (3) was 0.30 and the $\int_0^{t_d} q_{in} dt$ was 12,500 m^3. C_{calc} is based on Eq. (2) with the volume V'(t) being the actual volume of the reservoir at t' multiplied by a constant k. k is the fraction of the volume of the reservoir that participates in mixing and is found equal to 0.6 by minimizing the performance criterion P in Eq. (4).

It is expected that

$$kV(0) + \int_0^{t_d} q_{in} dt = V(0) \qquad (6)$$

Another attempt in analyzing the results was made by plotting ln C_{exp} vs. θ, as shown in Fig. 11. According to the linear regression, about 0.60 of the total volume is well mixed. Since V(0) = 40,000 m^3 and V_d = 12,500 m^3, the value of K according to Eq. (6) is 0.69, quite close to the value of 0.6 obtained above. Thus, during the experiment 60-70% of the volume were well mixed.

The example of this operational reservoir proves that the methodology previously described in Section 2 can be efficiently used for reservoirs with widely changing parameters (volume and flowrate).

4. CONCENTRATION DYNAMICS OF A DEEP STRATIFIED LAKE

The Seletar Reservoir in Singapore (5,8) is a large (about 2 square kilometers area) artificial lake having a maximum depth of about 16 m, see Fig. 12. The average residence time of the water flowing through it is about 40 days.

The reservoir is known to be stratified, the thermocline being at a depth of about 4 m. The stability of the stratification is rather poor, due to a very small temperature difference ($\sim 2^{\circ}C$) between the epilimnion and the hypolimnion. The temperature of the epilimnion responds rather rapidly (over a few hours) to changes in ambient air temperature. Therefore cooler weather over 2-3 days can be followed by a cooling down of the epilimnion, eventually below the temperature of the hypolimnion, thus resulting in a turnover and vertical mixing over the reservoir.

Given the size of the reservoir and the relatively long average residence time, it was decided to perform first a series of "nontracer" measurements and proceed with tracer experiments only at a later stage.

Wind measurements were made at the Reservoir and correlated to wind measurements at a nearby airport, where wind statistics were available. Although not very strong (usually less than 6-8 kn), winds were observed to change direction, following a diurnal pattern. During the day, winds blow into the Sembavang arm of the reservoir, therefore the surface wind induced currents are towards the arm. At night this direction is reversed.

Current measurements were done with drogues at different depths, in order to establish the circulation pattern and correlate it with wind data. The direction of currents on the surface coincides with the direction of wind. Velocities decrease with depth. As expected, below a given depth (3-4m) the current direction is reversed (i.e. it becomes opposite to the direction of the wind).

Temperature and dissolved oxygen profiles were extensively measured in order to get a better picture about the stratification and its stability.

Two experiments were performed using radioactive tracers. In the first one (5), 100 mCi of Br-82 were injected at the Sembavang inlet to the reservoir. The activity was found to be trapped in the epilimnion and no transfer into the hypolimnion could be observed over a period of about 2 days. The injection of the tracer occurred when the wind was blowing towards the Sembavang arm. Thus the activity was observed to move towards the main body of the reservoir at a depth of 3-4m, due to the return current mentioned above. During night, the epilimnion got well mixed,due to a turn-over induced by a relative cooling of the ambient air temperature. Activity reached the intake tower (at a depth corresponding to the epilimnion) about 40 hours after the injection.

During a second experiment (8), about 1.1 Ci of Br-82 were injected at a depth of 11.5 m below the water surface, near the centre of the reservoir. The radioactive cloud was surveyed over about 4 days. Vertical mixing in the hypolimnion was very slow and no activity diffused into the epilimnion. A very slow movement of the center of gravity of the activity cloud in the hypolimnion was observed. Based on these observations, the currents in the hypolimnion were about an order of magnitude weaker than in the epilimnion. It appears as if the return currents at the bottom of the epilimnion are dragging a current in the hypolimnion.

5. CONCLUSIONS REGARDING CONCENTRATION DYNAMICS IN LAKES THROUGH WHICH WATER FLOWS

The concentration dynamics of large shallow reservoirs with water currents flowing through them can be described by a model consisting of a time delay followed by one or two time constants (mixed regions) in series. Wind-induced currents are of dominant importance in shallow reservoirs.

It is of interest to analyze the question of how much tracer work is needed in studying the concentration dynamics of inert soluble matter in lakes and reservoirs in order to reach a satisfactory state of knowledge.

It is recommended to start the analysis of the concentration dynamics in a large shallow reservoir from simple considerations on wind-induced currents. These will allow one to estimate, probably within a factor of 2 to 4, the delay in the response*. Then one could make a further assumption, that within two to four times this delay the tracer will be distributed in the reservoir rather homogeneously, both laterally and in depth. Although desirable, it is not absolutely necessary to proceed with a tracer investigation beyond this point, i.e. when homogeneity is achieved. From all these considerations, the time lapse over which the measurements have to be performed is estimated, and knowing the volume of the reservoir and the flowrate through it, one can determine the amount of activity needed for an experimental investigation. If the activity is very large and prohibitive, as might be the case in relatively large deep reservoirs, one can still perform a tracer study to investigate both lateral and depth dispersion with considerably less activity.

*A few measurements, for example with drogues, will provide additional interesting information.

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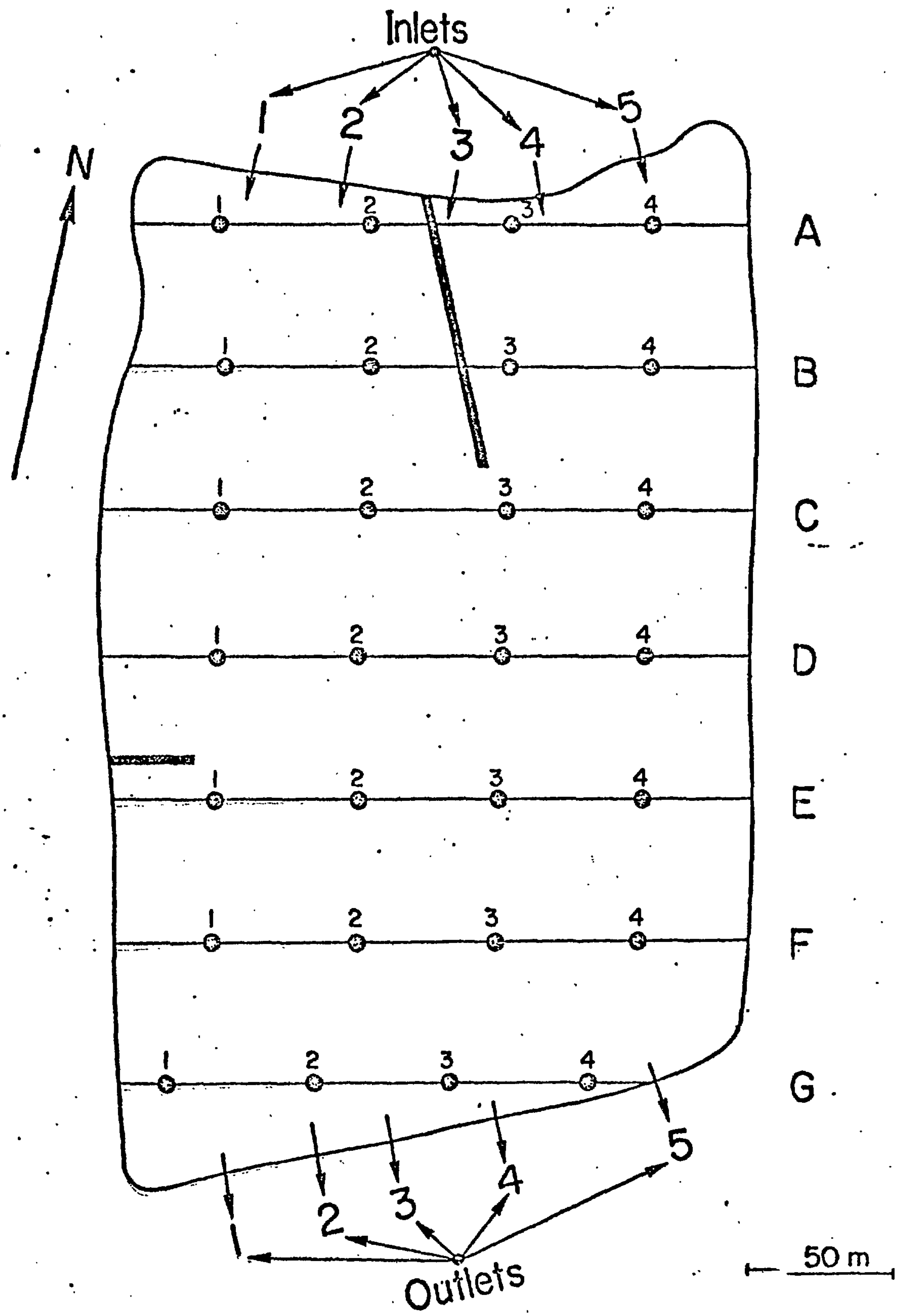

Fig. 1 - The Oxidation Pond. 28 buoys were located on 7 lines and 4 rows.

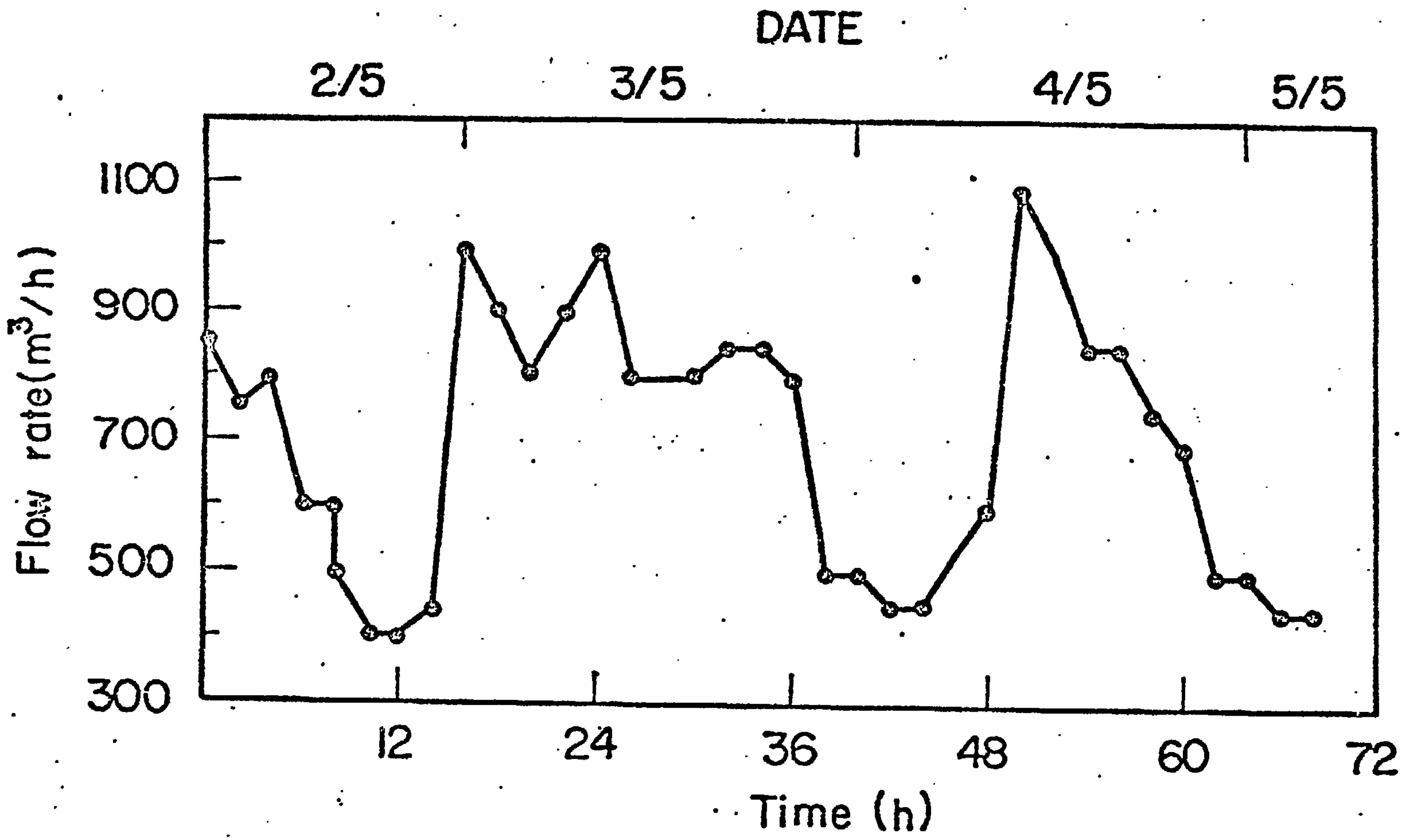

Fig. 2 - Inflow rate to the Oxidation Pond. Experiment E1.

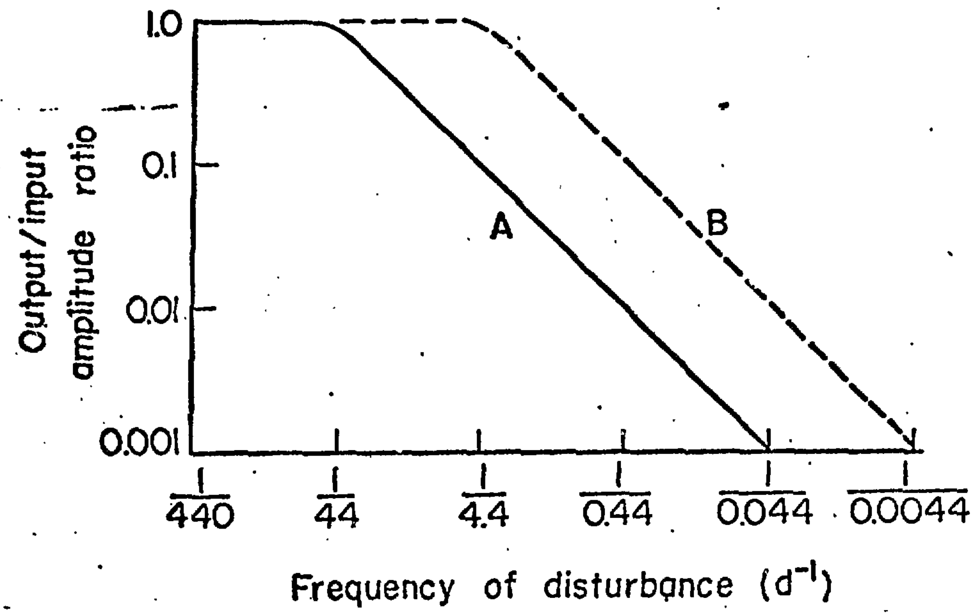

Fig. 3 - Frequency response of the oxidation pond.

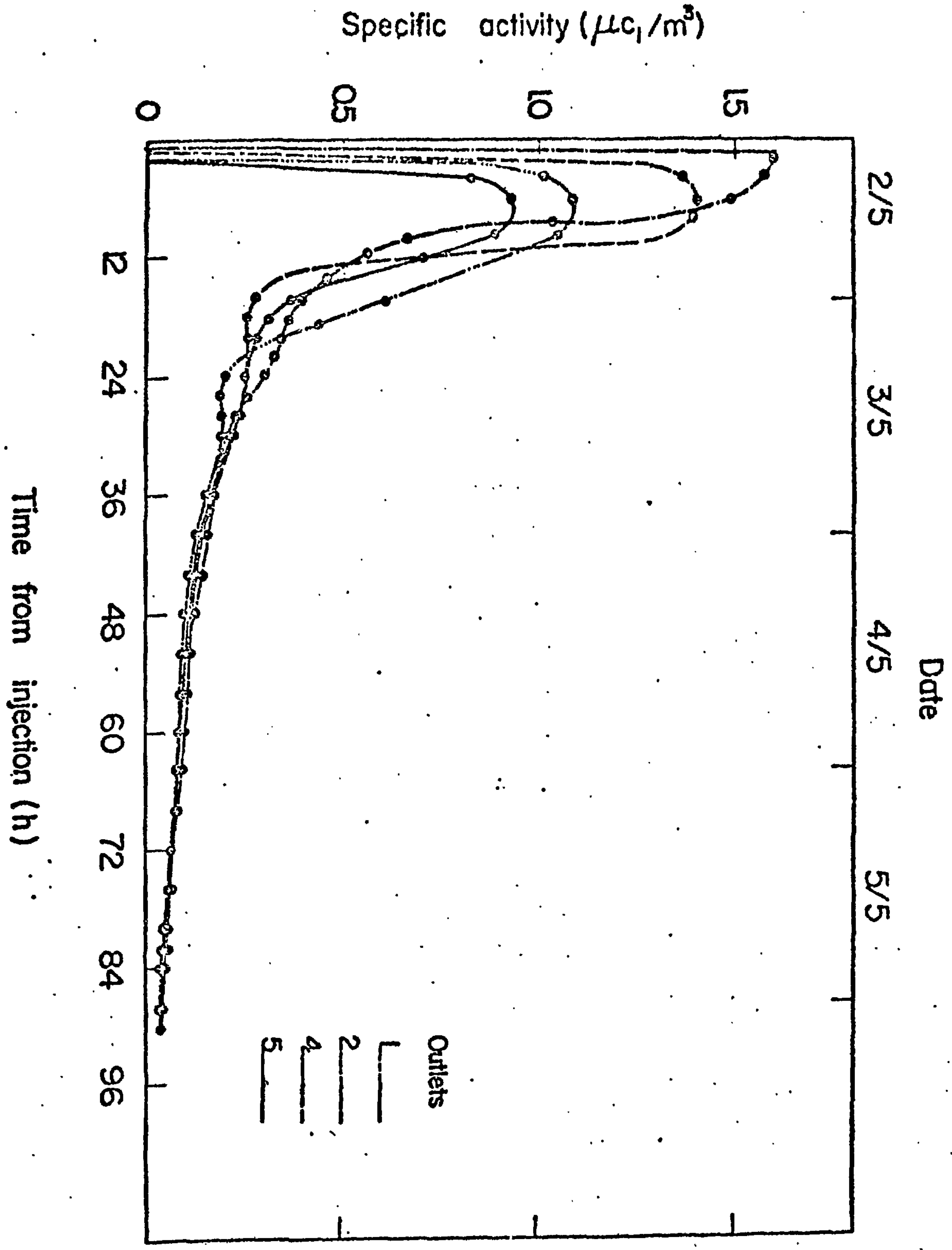

Fig. 4 - Specific activity vs. time at the various outlets of the Oxidation Pond. Experiment E1.

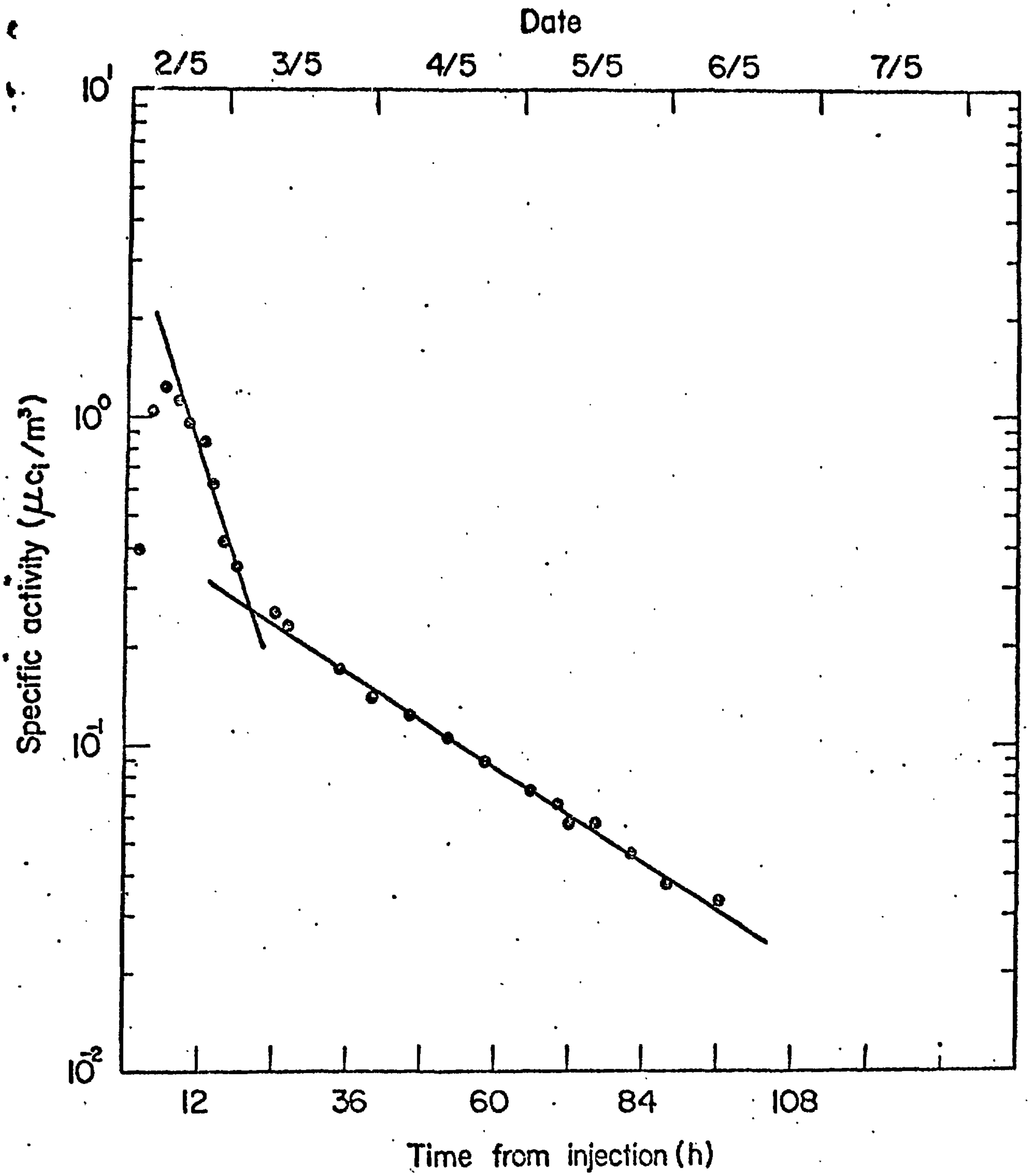

Fig. 5 - Average specific activity vs. time. Experiment E1.

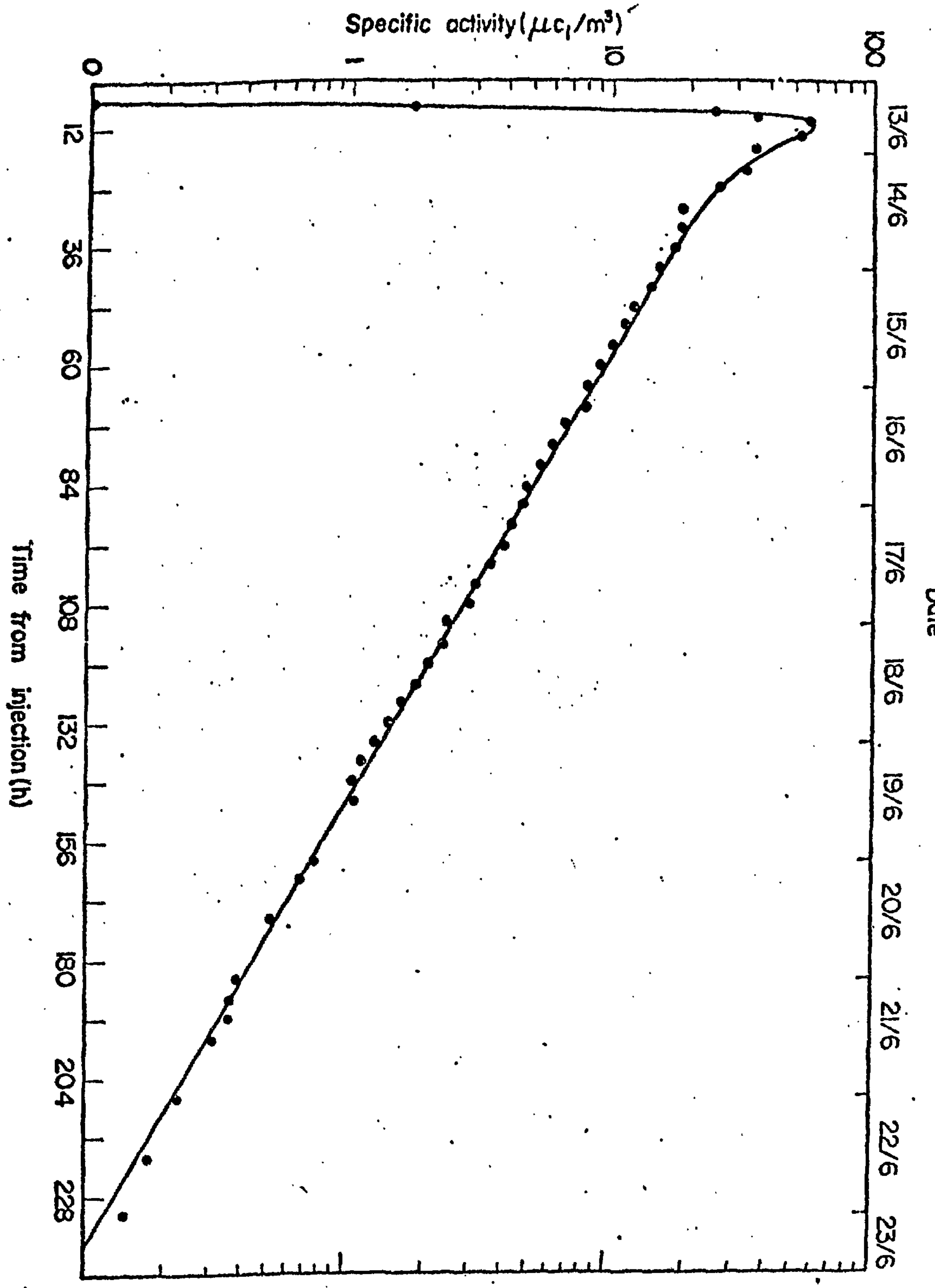

Fig. 6 - Average specific activity vs. time. Eexperiment E2.

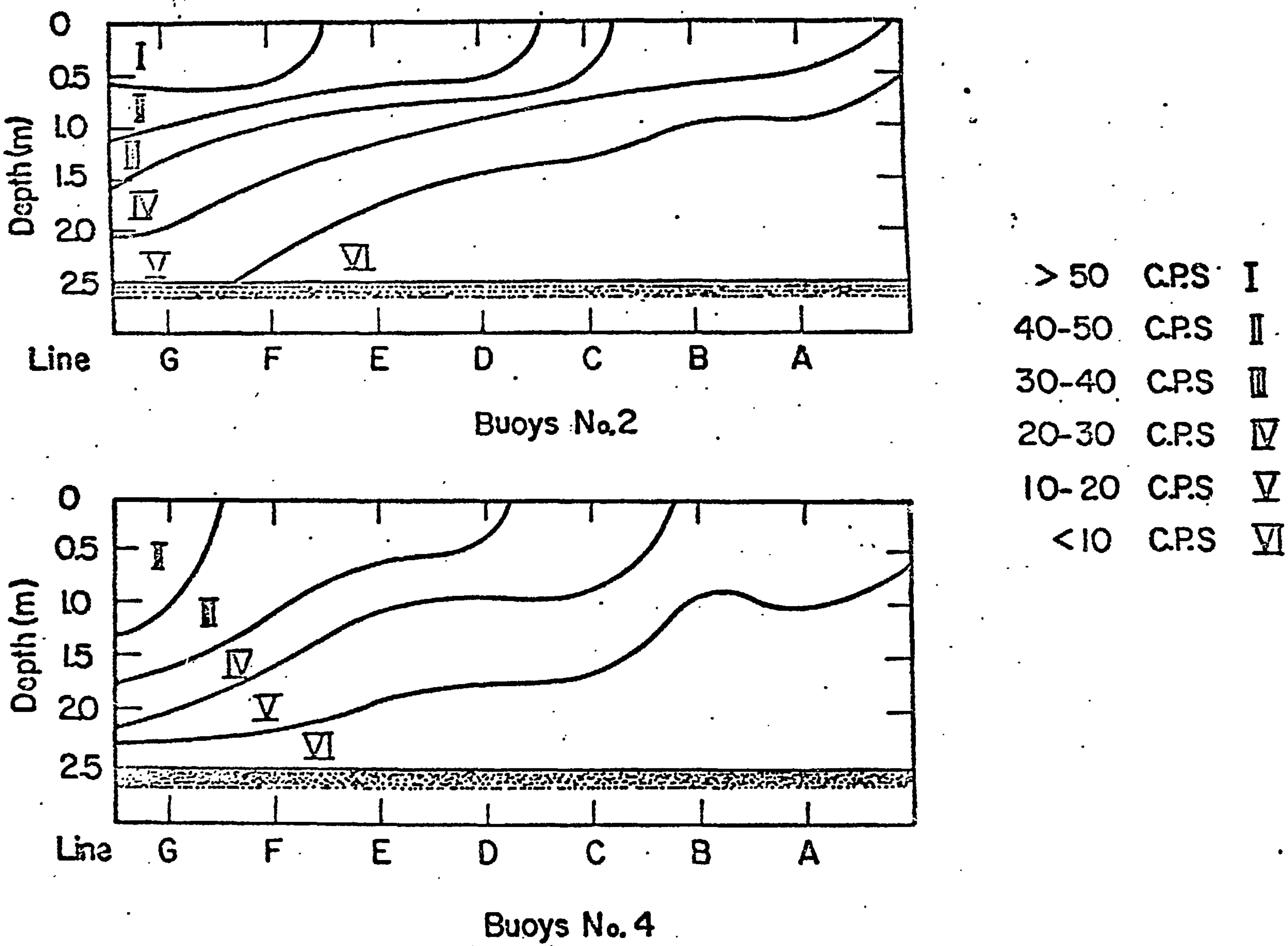

Fig. 7 – Mapping of activity in the Oxidation Pond at 7-8 hours after injection, longitudinal sections. Experiment E1.

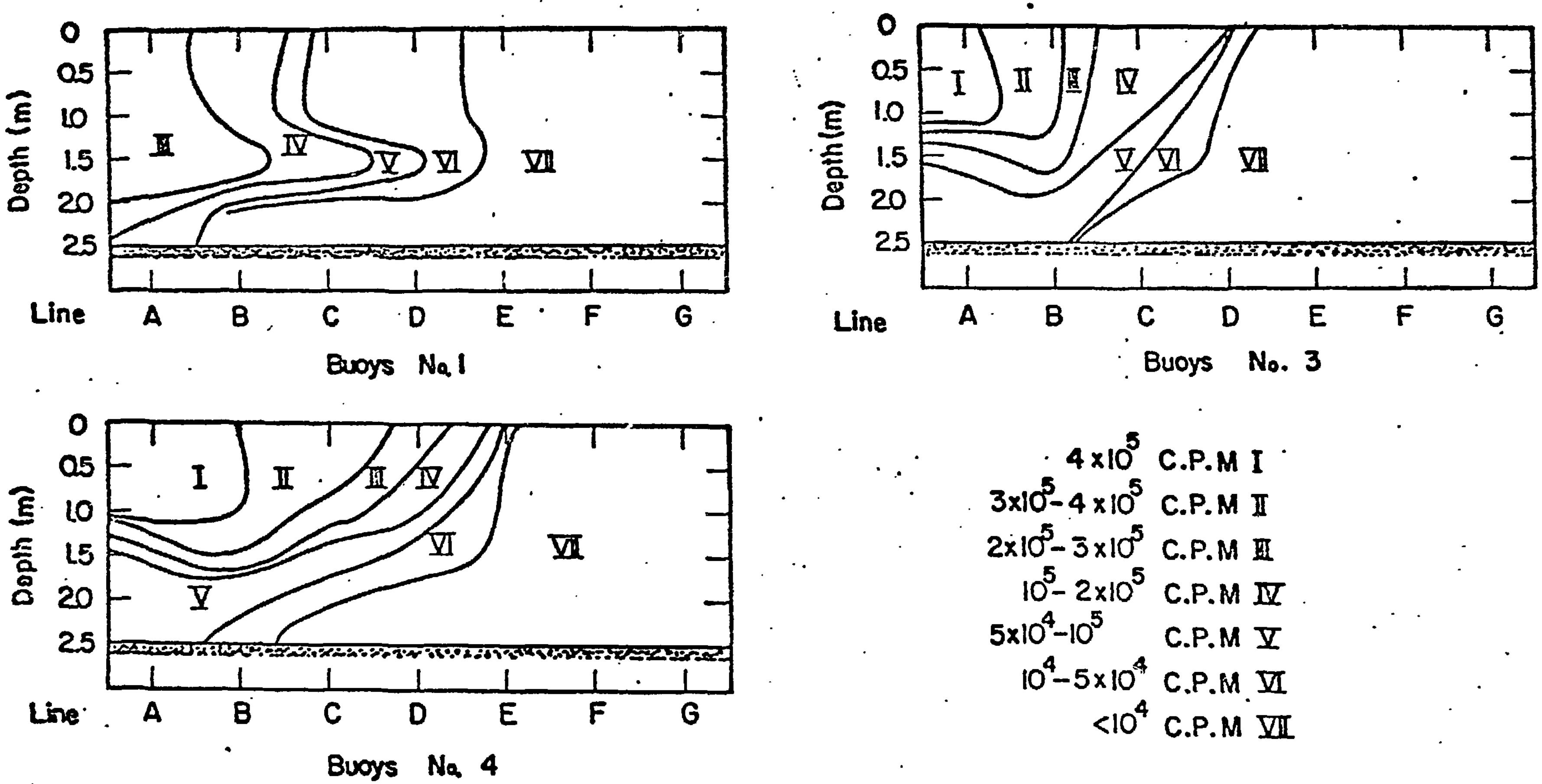

Fig. 8 - Mapping of activity in the Oxidation Pond at 3.5-4.5 hours after injection, longitudinal sections. Experiment E2.

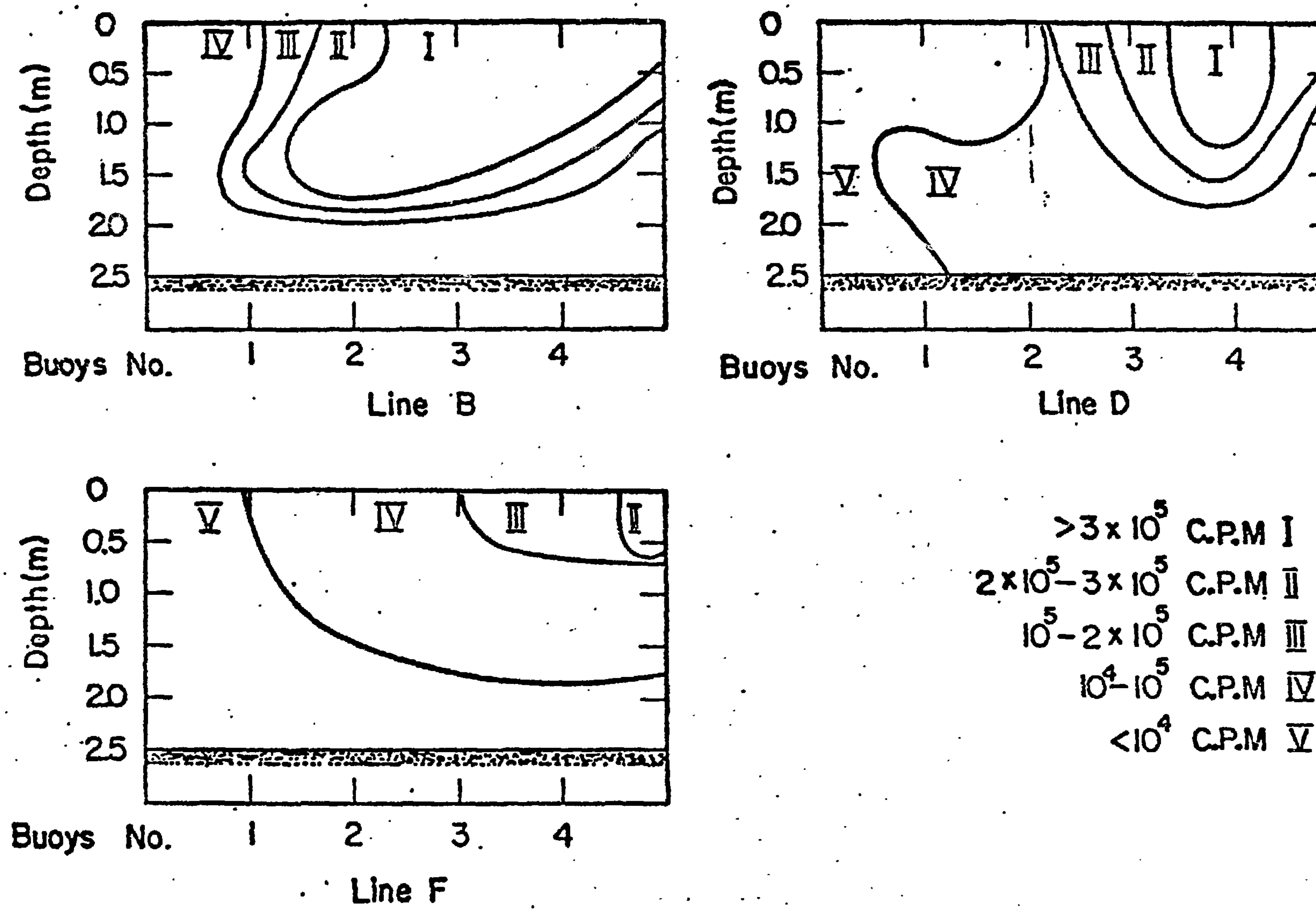

Fig. 9 - Mapping of activity in the Oxidation Pond at 4.5-5.5 hours after injection, transversal cross sections. Experiment E2.

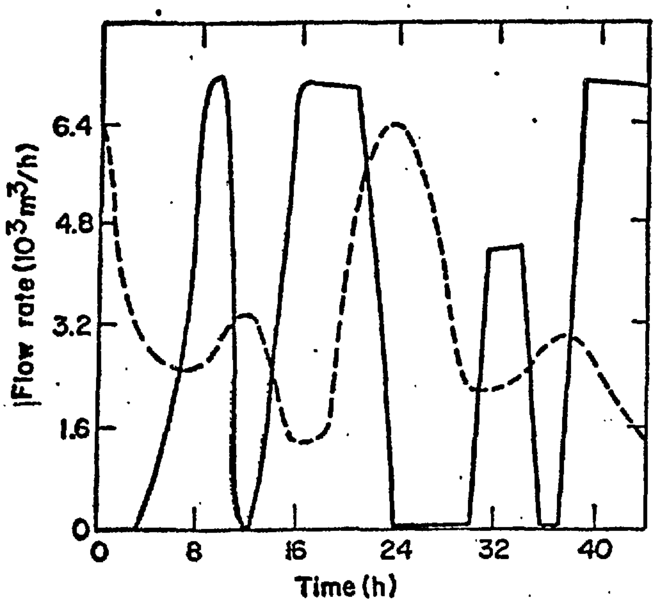

Fig. 10 - Flowrates at the operational reservoir

------------ inflow rate

———————— outflow rate

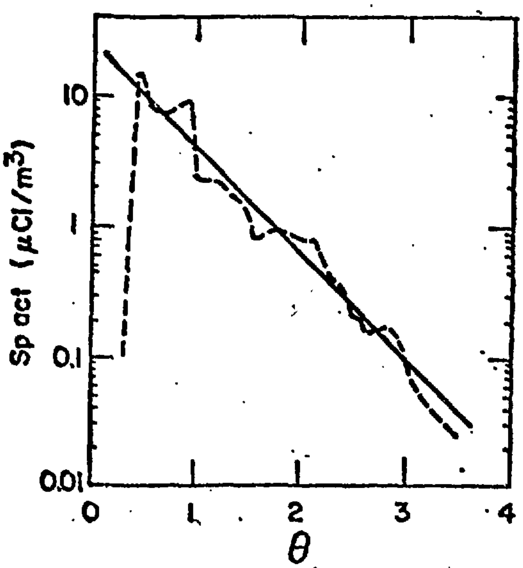

Fig. 11 - Specific activity at the outlet of the operational reservoir as a function of reduced time θ.

------------ experimental

———————— calculated by linear regression of $\ln(C_{exp})$ vs. θ.

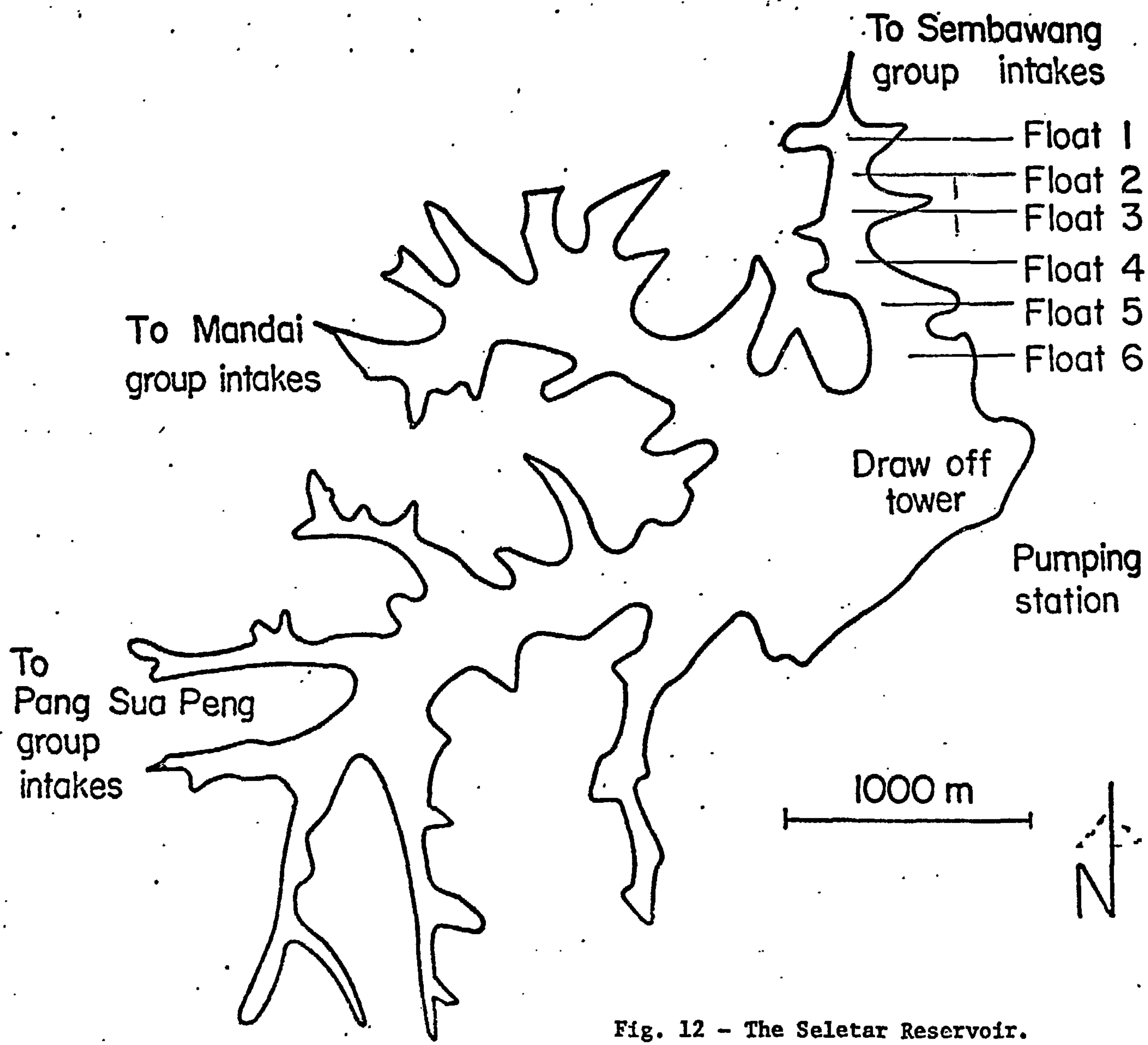

Fig. 12 - The Seletar Reservoir.