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SOME ECOLOGICAL CONSEQUENCES OF A PROJECTED DEEP RESERVOIR IN THE KABALEBO RIVER IN SURINAME

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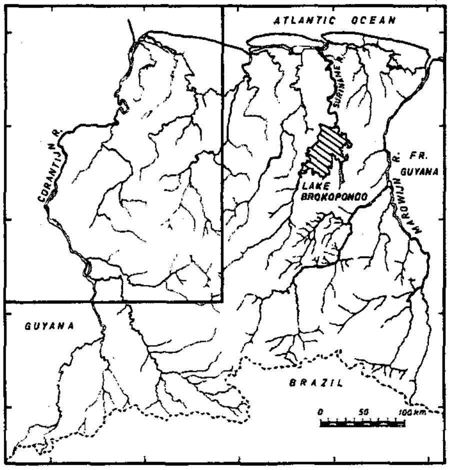
INTRODUCTION

Several years ago the Government of Suriname initiated the Kabalebo Hydro-Electric project to increase the economic activities in the Western Part of Suriname. Like the Brokopondo Hydro-Electric Project in the eastern part of Suriname, which started the forming of Lake Brokopondo in 1964 (Fig. 1a), the purpose of this project is the generation of energy for the refinement of the bauxite found in the Bakhuijs Mountains south of Apura, as well as the reduction of oil based energy production for Paramaribo by introducing hydropower.
This requirement for energy will be met by the execution of the Kabalebo Hydro-Electric Project, which includes the building of a dam in the Kabalebo River, a relatively small tributary of the Corantijn River (Fig. 1b). Because the discharge of the Kabalebo River (160 m^3/s) alone is not sufficient to fulfill the future demand for energy, a part of the Corantijn River and two smaller tributaries of this river will be diverted towards the Kabalebo River. In this way, the installed capacity can be up to 500 MW.



The Kabalebo Hydro-Electric Project can be divided in two main phases. The first phase consists of the construction of a dam in the Kabalebo River near Devis Falls and the execution of related diversion structures and ancillary items to divert the Lucie and Sisa Rivers (total discharge 200 m^3/s) to the Kabalebo River. In the second phase, the Upper Corantijn River (discharge 950 m^3/s) will be partially (maximum 80 %) diverted to the Kabalebo River. This will result in drastic changes of the hydrological conditions in the various river reaches affected.

After closure of the dam, upstream of Devis Falls, a deep man-made lake will be created with an ultimate surface area of approximately 1,250 km^2, a volume of about 14 km^3, and a maximum depth of 54 m. At present this area is covered with a dense tropical rain forest. As was clear from the construction of Lake Brokopondo in 1964, the present ecological equilibrium will be drastically disturbed in a large area. The terrestrial vegetation in the future reservoir area will die off due to inundation, whereas the amount of oxygen necessary to mineralize this organic material (leaves, twigs, trunks, etc.) might cause anaerobic circumstances, especially in the deeper parts of the reservoir. It will be clear that spilling this water into the Lower Kabalebo River will cause a bad water quality in this river, and possibly even in the Corantijn River downstream of the confluence of both rivers.

Other impacts are related to the considerable changes in the hydrological regime of the various rivers. The Middle Corantijn River will have a much smaller discharge, periodically

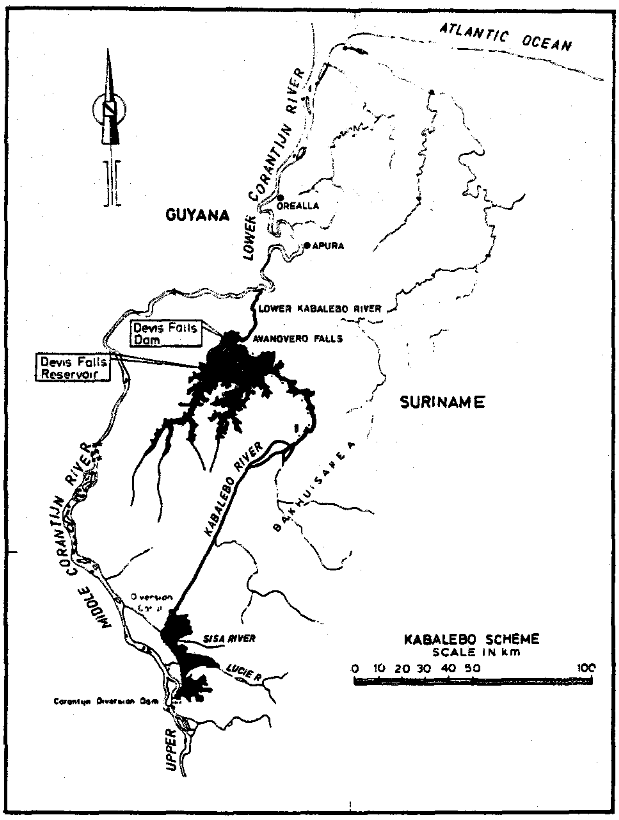


Fig. 1. Map of Suriname and the Kabalebo project area.

causing stagnant pools. The discharge of the Kabalebo River will increase from about 160 m3/s to 750 m3/s, which may induce erosion of the riverbed and banks. Due to the changed flow patterns at the confluence of the Kabalebo and Corantijn Rivers, bank erosion also occurs there. In the Corantijn estuary, the salt intrusion and morphology will change, due to changes in the river regime.

It will be clear that a large-scale project like the Kabalebo-project induces considerable hydraulic, morphological and ecological effects. These effects, and possible preventive and remedial measures should be investigated carefully. For the Kabalebo-project this has been carried out by a combination of Consultants, *e.g.* Ilaco Suriname, NEDECO and the Delft Hydraulics Laboratory (NEDECO, 1981), in cooperation with Surinam Governmental Agencies, as the Hydraulic Research Division (WL.A), the Bureau for Hydropower (B.W.K.W.), and the Surinam Forest Service (L.B.B.).

In this paper an overview will be given on some water quality aspects related to the construction and operation of the projected Devis Reservoir in the Kabalebo River.

WATER QUALITY BEHAVIOUR OF A NEW MAN-MADE LAKE

As can be learned from the construction of large reservoirs as f.i. Lake Kariba (BALON and COCHE, 1974), Lake Volta (BISWAS, 1966), Lake Brokopondo (VAN DER HEIDE *et al.*, 1976), the oxygen budget of a new man-made lake is one of the most critical factors water quality and moreover the aquatic environment of the reservoir itself and the downstream

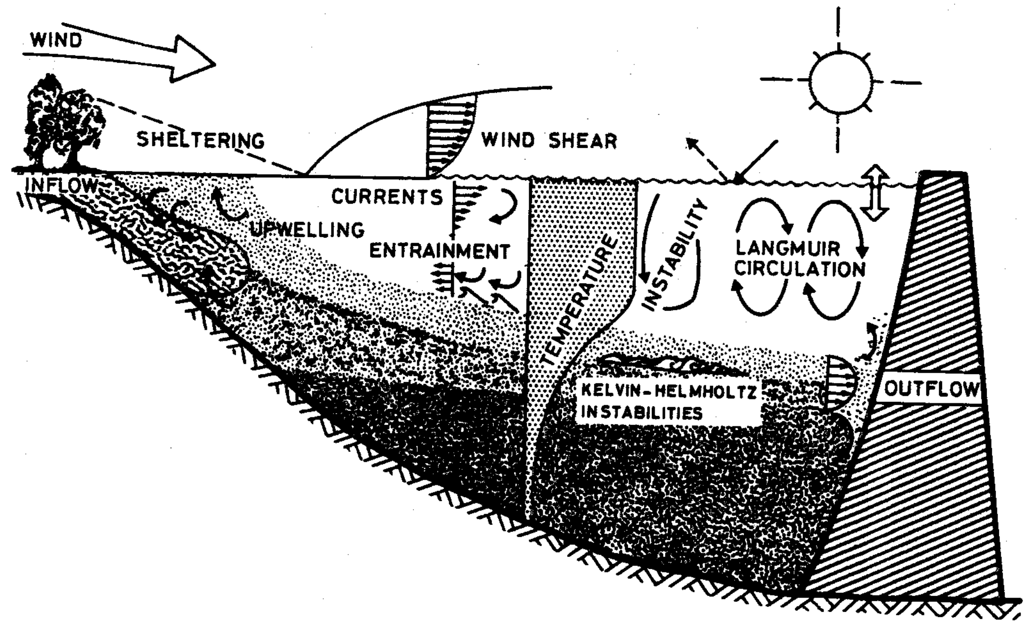


Fig. 2. Mixing processes in a reservoir (FORD, 1980).

river system. Especially during filling of a new reservoir and the first years of operation, the decay of the inundated terrestrial vegetation causes a high demand for oxygen. Other ecological problems can occur due to the nutrient supply by the decay of the original vegetation, resulting in excessive algal blooms and/or an excessive growth of water hyacinth and other floating macrophytes.

It is evident that low oxygen concentrations or anoxic conditions are fatal for the existing aquatic live and will prevent or delay the development of a new (stable) aquatic environment. In order to analyse the ecological development of a new reservoir and the ecological impacts on the downstream river system a predictive study of the oxygen budget for both the reservoir and the downstream rivers is a necessity. The oxygen budget in a reservoir is influenced by transport phenomena and various processes (kinetics).

Transport phenomena.

A brief overview of transport phenomena in reservoirs is given by FISCHER *et al.* (1979), IMBERGER *et al.* (1978), FORD (1980) and is illustrated in Fig.2. Deep reservoirs are generally stratified as a result of heat input at the water surface by solar radiation. On the one hand vertical mixing is induced by cooling at night causing instabilities (nocturnal overturn), by wind energy causing entrainment, by the breaking of internal density waves (Kelvin-Helmholtz instabilities) and by the kinetic energy of inflows and outflows. On the other hand vertical mixing is reduced due to stable density gradients over depth as a result of a thermal and/or chemical stratification. Due to density gradients over depth the inflow will penetrate at a depth which has a density in accordance to the density of the inflowing water after initial mixing.

Because of buoyancy effects, the withdrawal of water at the intake will be limited to a region determined by critical density currents. This so-called selective withdrawal allows the withdrawal of water from a region in which the water quality meets the standards as needed for the downstream river system as close as possible.

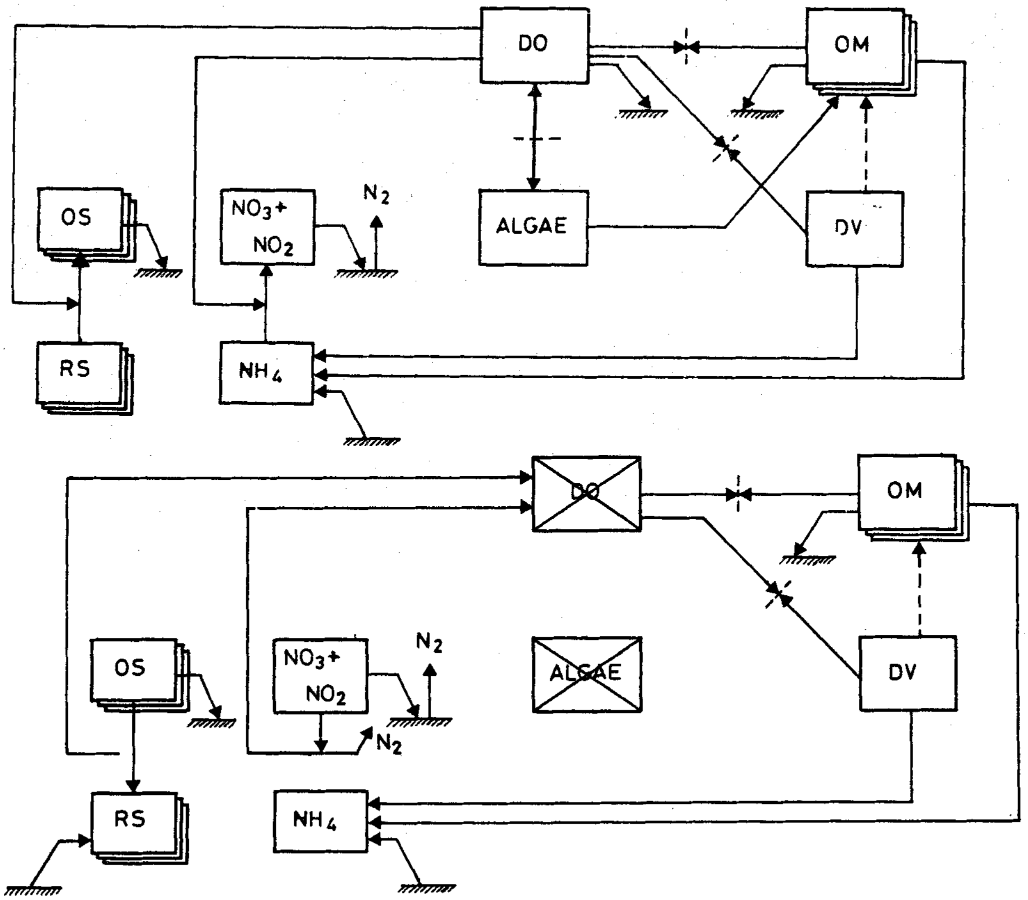


Fig. 3. Kinetics in relation to the oxygen budget for (a) aerobic and (b) anaerobic conditions.
DO dissolved oxygen;
OM dissolved and suspended organic matter;
DV drowned vegetation;
OS oxidized substances;
RS reduced substances.

Kinetics.

Besides transport phenomena the oxygen budget is influenced by various physical, (bio)chemical and biological processes, including (1) atmospheric exchange; (2) decay (biodegradation) of dissoved and suspended organic matter; (3) benthic respiration and decay of drowned vegetation; (4) photosynthesis by algae and macrophytes; (5) respiration by algae and other living organisms; (6) oxidation of reduced nitrogen (nitrification), and (7) chemical oxidation of anaerobic decomposition products. Fig.3a shows a schematic overview of the interrelations between these processes.

It will be clear that if the supply of oxygen by transport phenomena (inflow, vertical mixing, etc.), by atmospheric reaeration and by photosynthesis is insufficient in relation to the use of oxygen by the processes (2), (3), (5), (6) and (7), this will result in anaerobic conditions. The processes (4), (5), (6) and (7) will be absent then, whereas the decay of organic matter, represented by the processes (2) and (3), will be continued producing anaerobic decomposition products.

Specific processes for anaerobic conditions are (8) reduction of nitrate (denitrification), and (9) forming of reduced substances (Mn^{2+}, Fe^{2+}, H_2S, CH_4). An overview of relevant processes for anaerobic conditions is presented in Fig.3b. For anaerobic conditions the decay of organic matter is based upon the reduction of nitrate, iron, manganese, sulfate, whereas anaerobic decomposition products as ammonia, reduced iron, reduced manganese, hydrosulfide and methane might be formed. They will consume oxygen as soon as it comes available, causing a more or less direct demand for oxygen.

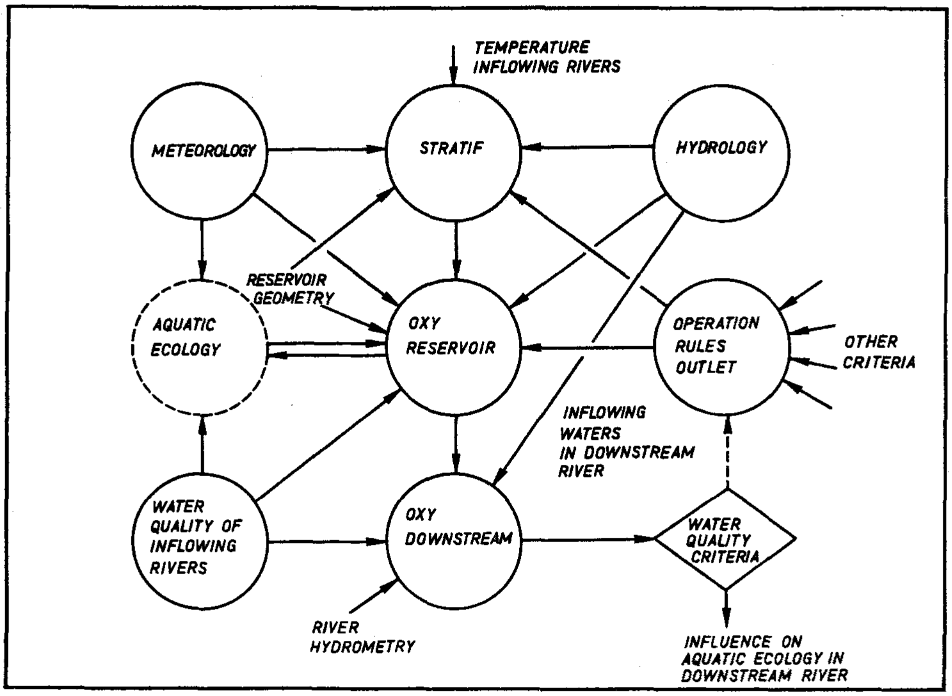


Fig. 4. Mathematical tools for water quality predictions in a reservoir and the adjacent downstream river basin.

MODELLING APPROACH TO WATER QUALITY PREDICTION

Mathematical tools and their interrelations.

Because of reasons mentioned earlier, the modelling approach to water quality prediction is primarily directed to the calculation of the oxygen budget. Since the oxygen budget is rather complicated, a set of numerical models, called STRATIF and OXY, has been developed to analyse the influence of different scenarios with respect to hydrology, meteorology, filling strategy and reservoir operation (KLOMP *et al.*, 1980).

STRATIF calculates the characteristics of thermal behaviour of the reservoir as a function of hydrological and meteorological conditions. The output of STRATIF can be used to quantify the rate of vertical mixing and the region of inflows and outflows as needed for the calculation of the oxygen budget of the reservoir and the quality of water discharged from the reservoir.

OXY can be divided into a model for calculating the oxygen budget of a new man-made lake (OXY-reservoir), and a model to calculate the oxygen budget on the adjacent tailwaters (OXY-downstream). Both models can be used seperately or in combination, whereas OXY-reservoir provides the upstream boundary for OXY-downstream by calculating the oxygen budget of outflow of the reservoir. OXY-downstream calculates the oxygen recovery due to reaeration and dilution in the Lower Kabalebo River and the Lower Corantijn River. An overview of this modelling approach, including the inputs for these models and the inter-relationships is schematized in Fig.4.

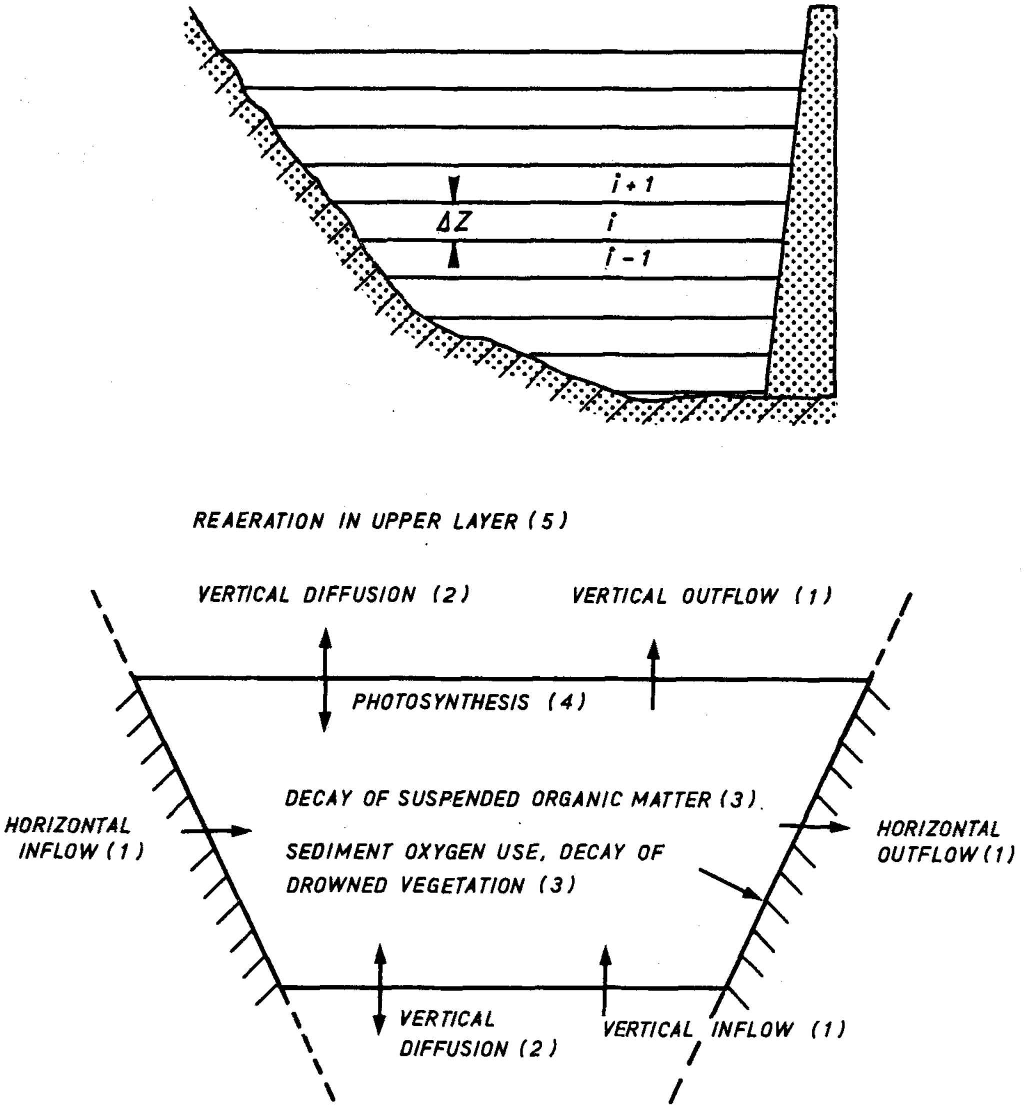


Fig. 5. Schematisation of a multi-layer system for modelling the oxygen budget in a deep reservoir.

STRATIF.

The presence of a thermal stratification in a reservoir is strongly related to the transport of mechanical and thermal energy from the water surface to greater depth. A thermally stratified reservoir is in general composed of a turbulent upper layer (epilimnion) and a quiescent lower layer (hypolimnion). Between these layers a thermocline region can be defined characterized by a more or less sharp decline of temperature over depth. The position of the thermocline follows from an energy balance between the total kinetic energy induced by wind and inflows, and the total potential energy in the epilimnion as a result of buoyancy induced by the net atmospheric heat flux, the inflows and outflows and reduced by the vertical mixing (entrainment). In accordance to PHILLIPS (1966), TURNER (1973) and VERHAGEN (1974) the ratio between kinetic and potential energy can be defined as a Richardson-flux number (Rif) which equals unity at the thermocline depth.

Although the thermal behaviour of Lake Brokopondo (VAN DER HEIDE, 1978) indicates that a continuous well mixed surface layer can be absent for most of the year as a result of daily heating, the calculation of the thermocline-depth based upon Rif = 1, provides a quantification of the surface region where vertical mixing is induced by nocturnal overturn and turbulences caused by wind.

The input for STRATIF is related to hydrological conditions as inflows and outflows, and to the driving meteorological forces for the heat budget, as global radiation, evaporation, wind speed, wet and dry bulb temperature, air temperature, vapour pressure, cloudiness and relative humidity. The output of STRATIF comprises the occurence of stratification, the characteristic depth of the thermocline and the temperatures in the turbulent upper layer and quiescent lower layer.

OXY-reservoir.

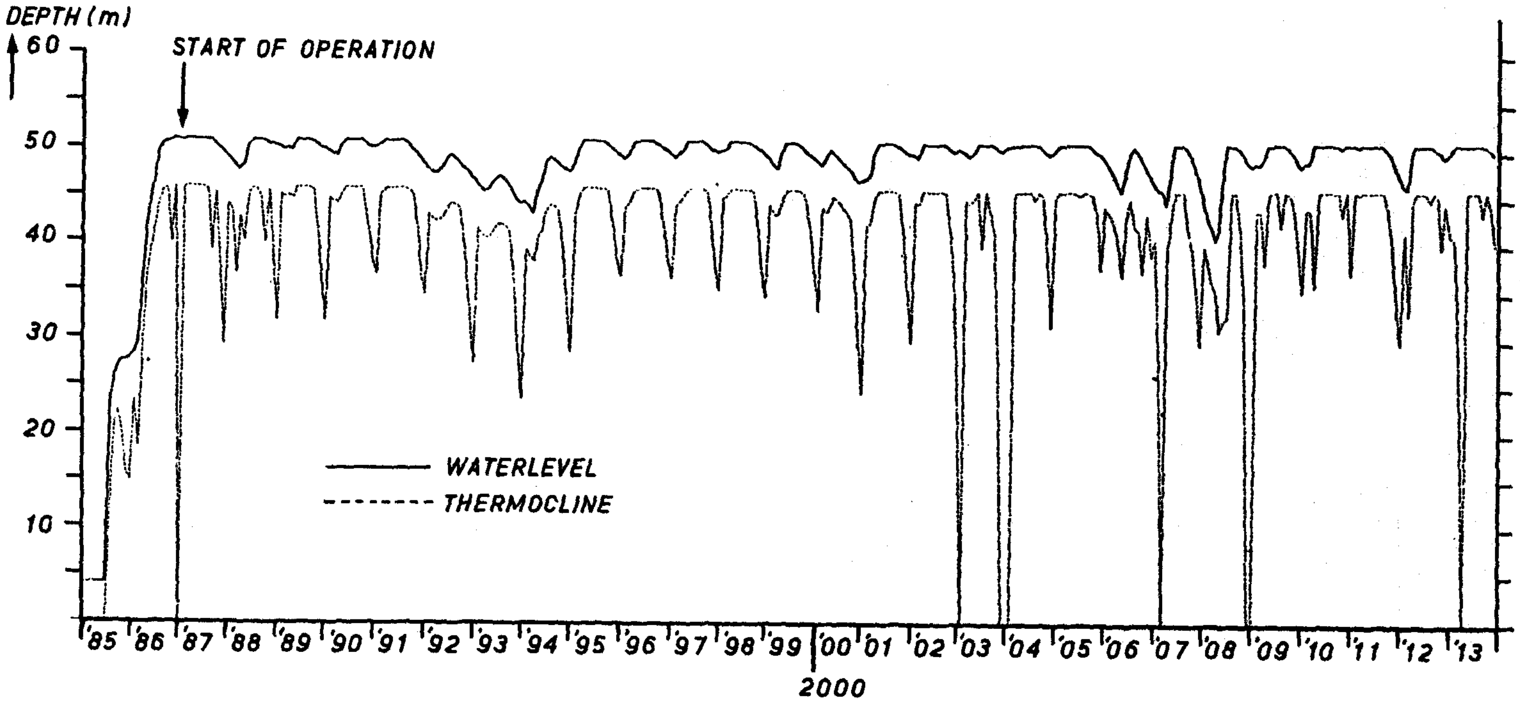
Based upon the description of water quality behaviour of new man-made lakes, as presented above, a numerical model has been developed to calculate the oxygen concentration and oxygen demands in a new man-made lake during filling and the first years of operation. The model is based on a one-dimensional schematisation by which the oxygen concentration and direct oxygen demand is calculated over depth for each step of time.

The numerical structure of the model is based on a multi-layer system (Fig.5a). For each layer a mass balance is formulated, based upon the assumption that the layer can be considered as completely mixed. The accumulation of oxygen in a layer depends on (1) transport of oxygen by inflows and outflows in both horizontal and vertical direction, (2) transport by vertical dispersion (because of the one-dimensional approximation it is better to speak of dispersion than diffusion), (3) use of oxygen for the decay of drowned vegetation and suspended biomass, (4) production of oxygen by photosynthetic growth of phytoplankton, and (5) atmospheric exchange at the surface layer. An overview of the various processes influencing the oxygen budget within a layer is given in Fig.5b.

The distribution over depth of river inflows, outflows at the dam and the vertical dispersion coefficient, are calculated based upon the calculated thermal behaviour by STRATIF, the geometrics of the reservoir and hydrological and meteorological conditions. The atmospheric exchange depends on wind speed and surface temperature (VAN PAGEE, 1978). The rates for primary production, the decay of organic matter and the decay of drowned vegetation are derived from the model application on Lake Brokopondo for an almost 10 years period (NEDECO, 1981). The output of OXY-reservoir includes for each depth and specified time interval the calculated oxygen concentrations in the aerobic zone and the calculated direct oxygen demands by reduced substances in the anaerobic zone. The direct demand, expressed in negative oxygen values, indicates the amount of oxygen to be consumed more or less immediately as soon as oxygen comes available. The calculated oxygen budget of the outlet water is also expressed in negative oxygen values, if this water is anaerobic.

OXY-downstream.

Based upon a one-dimensional mass-transport equation for a river system, OXY-downstream calculates the oxygen concentration at various locations downstream of the reservoir. The geometry of the river is represented by flow depended functions for the stream velocity and depth. Processes


DEPTH (m)
60
50
40
30
20
10
START OF OPERATION
WATERLEVEL
THERMOCLINE
'85
'86
'87
'88
'89
'90
'91
'92
'93
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'95
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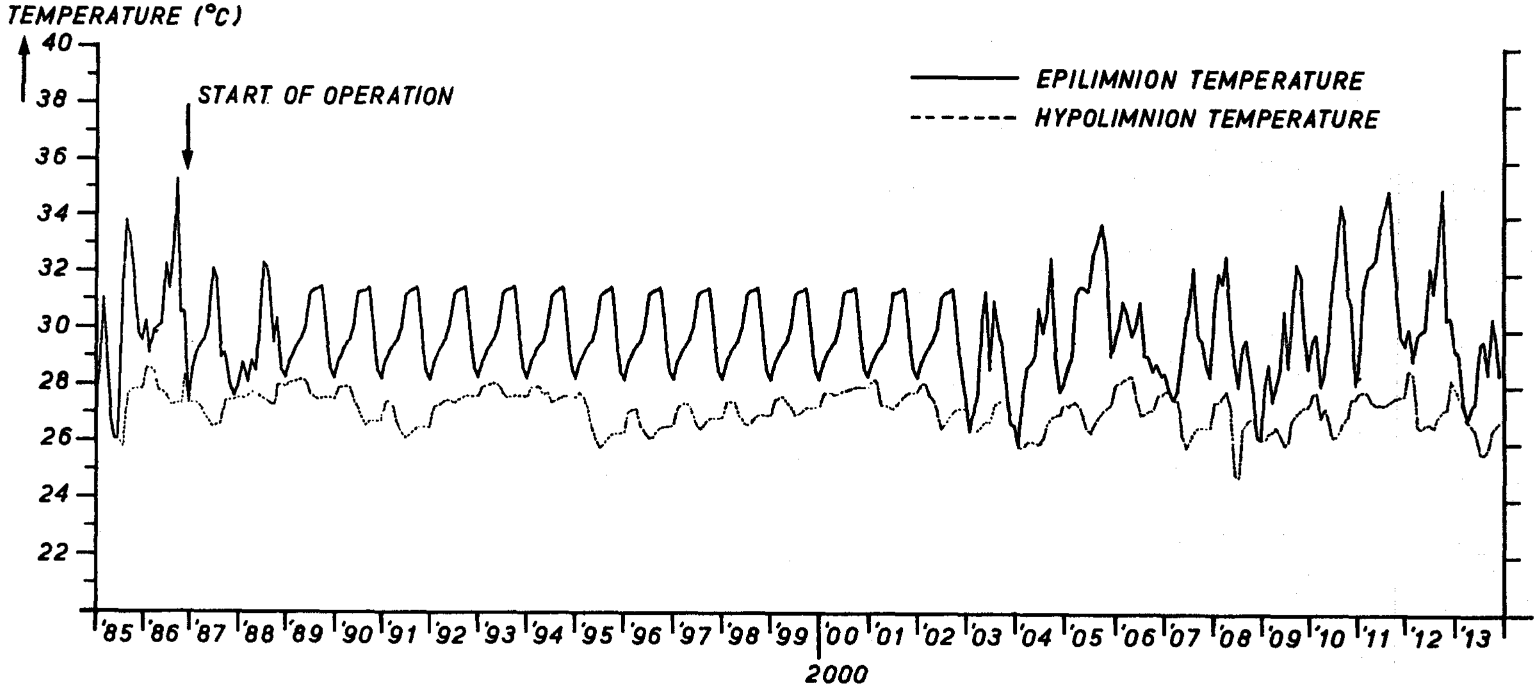

Fig. 6. Simulation of the thermal situation in the projected Devis Reservoir.

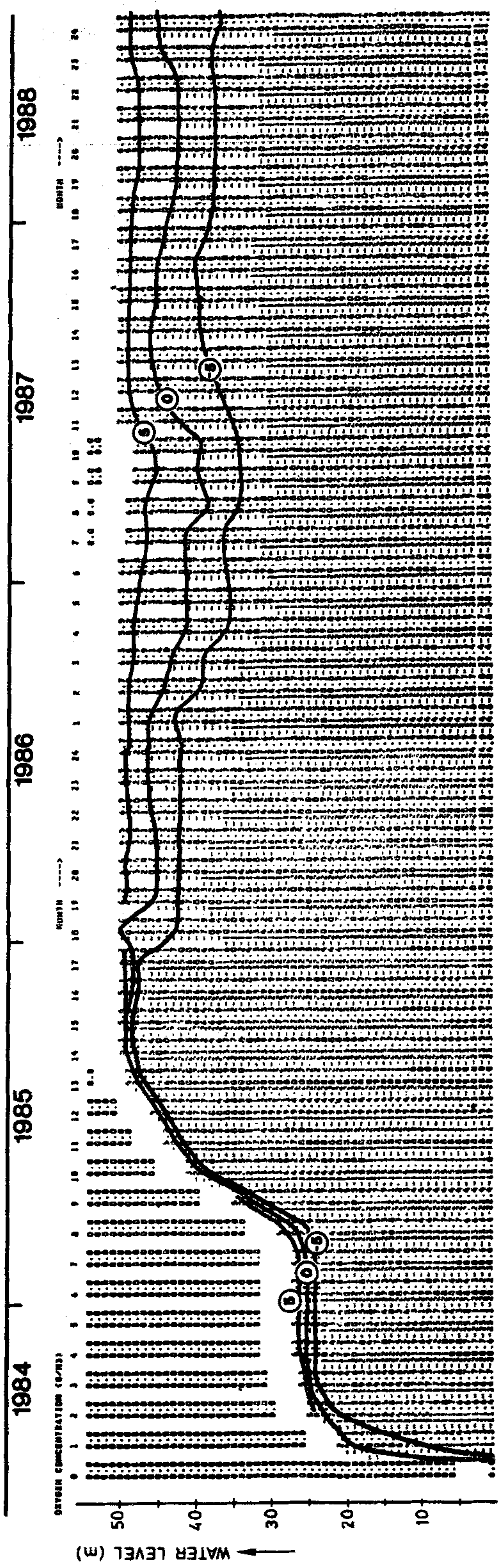

Fig. 7. Simulation of the dissolved oxygen concentration (+) and the direct oxygen demand (—) in the projected Devis Reservoir.

considered are the reaeration by Avanovero Falls, the reaeration by the river itself, the mineralization of dissoved and suspended organic matter released from the reservoir, the benthal oxygen demand, and the dilution by the Corantijn River.

SIMULATION RESULTS AND IMPACT ANALYSIS

For the analysis of the future situation of Devis Reservoir and the rivers downstream, various scenarios consisting of alternative operational schemes and meteorological and hydrological time series were established as input data for STRATIF, OXY reservoir and OXY downstream.

The simulations with STRATIF showed that the thermal situation in Devis Reservoir has the same characteristics as Lake Brokopondo, and is hardly influenced by the various alternative operational schemes, but mainly by the meteorological circumstances. In the first ten years the yearly chance for destratification is about 60 %, while afterwards overturn will occur almost every year. Cooling of the surface layer during the 'cold' season (December-March) is the main cause of destratification, whereas mixing by wind is of minor importance. The depth of the epilimnion is therefore mainly determined by the depth of the nocturnal overturn and varies from 5 -20 metres (Fig.6).

The development of the oxygen budget of the Devis Reservoir after the start of filling (for the presented simulation projected in July 1984), is characterized by a small (1-2 m) aerobic upper layer during filling and an increasing thickness of the aerobic layer during the first years of operation (5 -10 metres) (Fig.7). During highly stratified conditions the oxygen values in the aerobic surface layer are mainly determined by photosynthetic oxygen supply, resulting in concentrations close to the oxygen saturation value (approximately 7 mg O_2/l). In the anaerobic layer reduced substances are formed with a more or less direct oxygen demand up to more than five times the oxygen saturation value. Because of this high demand in the deeper part of the reservoir, an increased vertical mixing during the 'cold' season can result in anaerobic conditions over the whole water column (see f.i. January 1986), despite the relative small volume of the deeper part of the reservoir.

The hydropower production was assumed to start at full reservoir conditions (January 1986). As shown in Fig.8a the outlet water was calculated to be completely anaerobic during the first 4.5 years. Although temporary improvements can occur as a result of spilling of aerated surface water in the wet season (May-August), the calculations show a direct oxygen demand up to two times the oxygen saturation value. The calculated 'oxygen' recovery in the Lower Kabalebo by the reaeration of Avanovero Falls just downstream of the reservoir dam and the river itself is in the order of 2-7 mg O_2/l. This recovery, however, is insufficient to create aerobic conditions in the downstream stretch of the Lower Kabalebo River (see Fig.8a).

The dilution of the water from the Lower Kabalebo River with the unaffected water of the Corantijn River significantly improves the conditions for the Lower Corantijn River downstream of the confluence (Fig.8a). However, it must be emphasized that the minimum dissolved oxygen (DO) criterion of 2 mg O_2/l for fish to survive could not be guaranteed for this river stretch. Especially during the dry and cold season (December-February), the oxygen concentration at the confluence can be most critical. This is caused by the low dilution capacity of the Corantijn River in this period and by the most unfavourable conditions in the reservoir to withdraw the best water.

Based upon these results remedial measures (including an alternative intake design, filling and operation strategy) were formulated in order to minimize the chance for critical oxygen values in the lower Corantijn as much as possible. It was shown that a more gradual filling of the reservoir, f.i. by maintaining a through-flow during filling, by delaying the diversion of upstream rivers towards the Kabalebo River, or by a start of power production at a lower water level, will be favourable for the oxygen budget of the reservoir and the outlet water, especially during the first (critical) years of operation.

Simulations with different intake heights have shown that a high intake is preferable with respect to the improvement of the oxygen budget of the outlet water and the adjacent tail

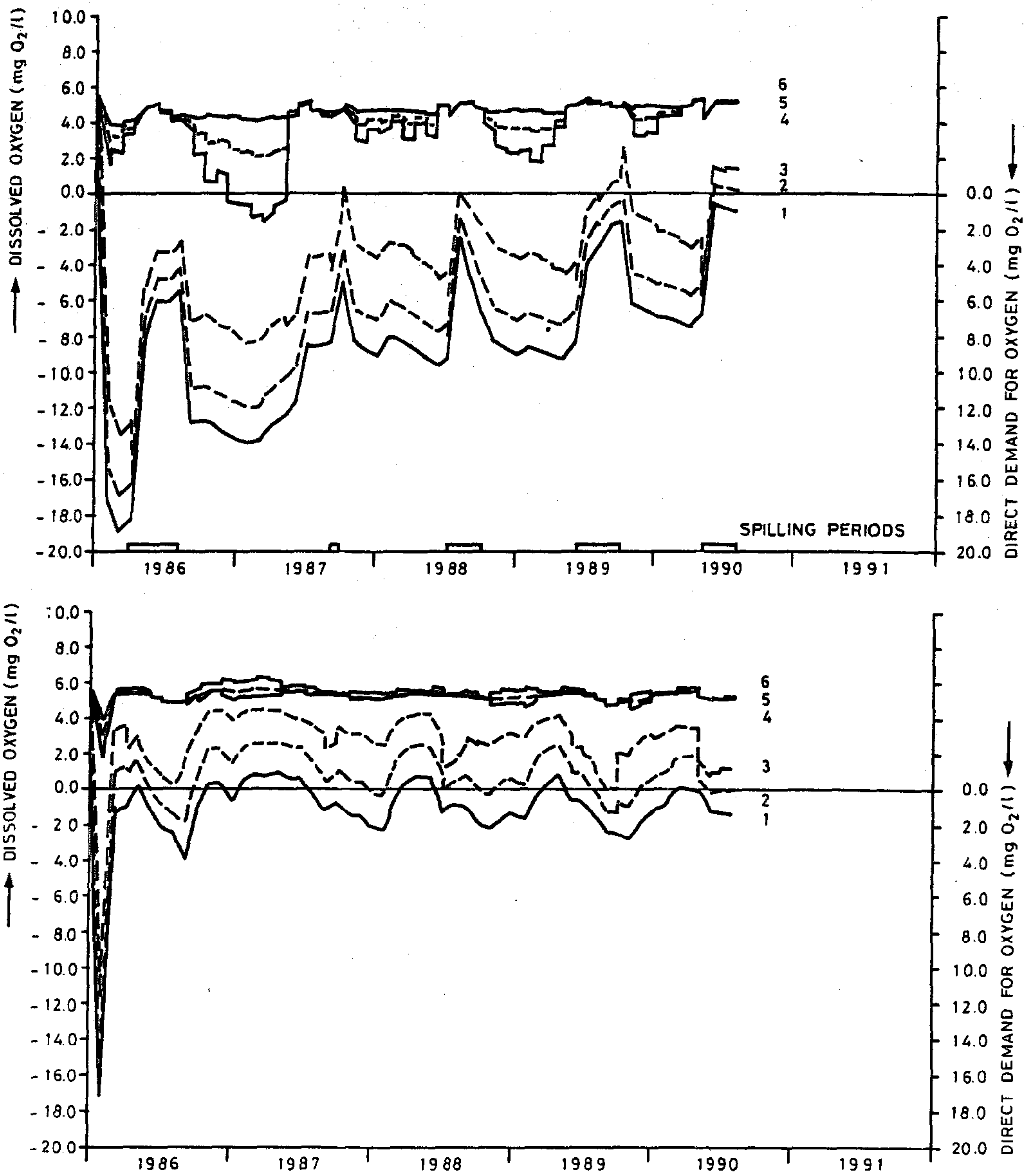

Fig. 8. Simulation of the dissolved oxygen concentration (+) and the direct oxygen demand (–) in the rivers downstream of the projected Devis Reservoir; (a) original planned intake structure; (b) alternative high intake.

1. Outlet water at the dam;
2. lower Kabalebo downstream of Avanovero Falls;
3. lower Kabalebo before the confluence with the Corantijn;
4. lower Corantijn downstream of the confluence with the Kabalebo;
5. lower Corantijn near Apura;
6. lower Corantijn near Orealla.

waters (Fig.8b). The use of a high intake, however, delays the recovery of the oxygen budget of the whole reservoir, since only the best water is withdrawn. Although in general this delayed recovery of the reservoir has a negligible effect on the oxygen budget of the outlet water, it must be realized that during extreme conditions (sudden destratification, inclination of the thermocline) the selective withdrawal of surface water can be disturbed. The probability of such extreme conditions is the highest during the dry season (December-March) when the dilution capacity of the confluence of Kabalebo and Corantijn is limited. During less critical periods downstream a lower intake position should temporarily be used to improve the oxygen budget of the reservoir. Also the spilling height can be used for this purpose by manipulating the spillway and the bottom spill-outlet. A well-balanced combination of the use of a high intake for power production and a bottom outlet for spilling can improve both the oxygen budget of the reservoir and the outlet water.

Although destratification of the reservoir will ultimately improve the oxygen budget of the reservoir, the first weeks of destratification will be unfavourable for the outlet water also if a high intake is used. This is caused by the reduction of the oxygen concentration in the surface layer due to increased vertical mixing and by the reduction of the possibilities of selective withdrawal due to the absence of vertical density gradients.

With a high intake the chance of violating the DO criterion at the confluence has become almost zero after two years of operation. However, during each of the first two years of operation there is a chance of 50 - 60 % that the DO criterion at the confluence is not met due to sudden destratification of the reservoir (in the most critical months December, January, February). Oxygen concentrations below 2 mg/l will not occur downstream of Apura.

Fish mortality as a result of severe oxygen depletion or anaerobic conditions at the confluence might occur during dry periods in the first 2 years of operation. It is expected however, that no fish kills will occur downstream of Apura.

It has to be mentioned that the results of simulations as described above are mainly based on the assumption that the diversion of the Upper Corantijn will not take place during the considered 6 years period. Simulations of scenarios including an immediate diversion and a diversion after two years of operation indicate that it is preferable, from a water quality point of view, to postpone the diversion of the Corantijn until at least 5 years after the start of the operation.

DISCUSSION

The realization of a large-scale water resources project means, directly or indirectly, a drastic and rather abrupt change in the environmental conditions in the reservoir area and the downstream river basin. In order to guide the development of the new reservoir ecosystem optimally and to minimize negative effects with respect to the downstream ecosystem, the following points require further attention.

a. Although the monitoring of water quality development of Lake Brokopondo as carried out by P. Leentvaar, J. van der Heide (see VAN DER HEIDE *et al.*, 1976), the Hydraulic Reservoir Division (WL.A), and Suralco was of incalculable value for the present study, additional field surveys in this lake are necessary to allow more reliable predictions using more sophisticated modelling techniques. In this respect special attention has to be paid to daily variations, the nutrient budget, the primary production by phytoplankton and the composition of anoxic water.

b. Because of the dominant role of phytoplankton in the later stage additional field surveys are necessary to quantify the nutrient load on the projected Devis Reservoir, by the inflowing rivers and creeks.

c. To enable a well founded operational management of the Devis Reservoir and the related diversion works, a careful evaluation of management options should be carried out based upon an integrated approach of (1) the final planning for reservoir construction, (2) the requirement for energy, (3) a stochastic analysis of meteorological and hydrological conditions, and (4) a prediction of water quality behaviour in the reservoir and adjacent downstream river basin. Special attention should be given to short term water quality variations and a related probabilistic analysis of the downstream water quality in relation to fish kills.

SUMMARY

The construction of a deep reservoir for hydropower generation and the consequent inundation of a tropical rain forest will drastically disturb the ecological equilibrium in the Kabalebo River basin. Mathematical modelling techniques are used to predict the water quality in the new Devis Reservoir and the adjacent downstream river. Special attention is given to the oxygen budget being the most critical factor in water quality during the first decennium after the start of filling. In order to minimize the ecological impacts of the reservoir construction, an alternative intake design and a delayed filling period are the most promising remedial measures.

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