Annex G: Water Quality Modelling Assumptions and Results

The Center for Water Research of the University of Western Australia, in collaboration with Sinclair Knight Metz, made quantitative predictions of the expected water quality in the proposed Nakai Reservoir. The development of the Nakai Reservoir water quality model was based on several assumptions and data input from previous analyses summarized below. The water quality model used is a calculation-based model, used to predict water quality in a number of reservoirs in the world where many of the assumptions initially made have been verified. Further details are available in "Prediction of the Water Quality Characteristics of the Proposed Nam Theun Reservoir Basin" by Winters *et al.* prepared in 1997, and in "Review of Prediction of Nam Theun 2 Reservoir Water Quality", Part 1 – Numerical Modelling, and Part 2 – Assessment of Reservoir Water Quality, by Romero *et al.*, prepared in 2000.

Assumptions for Developing the Water Quality Model

Parameters & Assumptions

Reservoir bathymetry: based on the predicted reservoir volumes and probable surface area.

Meteorological data: compiled from a number of climatic stations situated on the Nakai Plateau and at Nakhon Phanom in Thailand.

Stream inflows to the impounded area: based on results derived from a daily drainage basin rainfall/run-off model developed by SMEC.

Quality of water coming into the reservoir: constant with the exception of total nitrogen and total phosphorus, whose concentrations were determined from measurements of suspended solids.

Water temperature: five-day moving average of the average daily air temperature.

Dissolved oxygen: fully mixed and saturated in the inflowing water.

Residual above ground biomass in the reservoir: 65 tonnes/ha by April 2000 (scenario A, only prior logging, updated to 60 tonnes/ha in 2001), and 58 tonnes/ha (scenario B, logging and removal of vegetation by communities).

Above ground carbon biomass: 40 percent of residual biomass, or between 26 and 23 tonnes/ha.

Below ground carbon biomass: obtained from soil samples.

Calibration

Calibration of the 1-D model was based on a review of literature describing ecological parameters for tropical and sub-tropical lakes and experience with the water quality model in existing lakes and reservoirs, such as the Prospect Reservoir, North Pine Dam, and Lake Julius, Australia. Main outputs of the model, chlorophyll a and dissolved oxygen concentrations, can be expected to be within 25 percent of measured values.

The 1-D model (DYRESM Water Quality) combines a process based on a hydrodynamic model with numerical descriptions of phytoplankton production, nutrient cycling, and the oxygen budget and particle dynamics. The **hydrodynamics** is free from calibration, which ensures that it is readily transferable to other lakes and reservoirs. It also allows for the identification of the specific hydrodynamic processes that influence water quality.

The **water quality component** consists of 13 variables which may include up to three algal groups, BOD, dissolved oxygen and four other components of the dissolved oxygen budget, nutrients (PO_4-P, NO_3-N, NH_4-N, TP and TN) and inorganic particles. The particle mode stimulates settling and flocculation/deflocculation of up to seven different size classes of particles. The hydrodynamic, water quality and particle models interact on a daily time step.

The **ecological components** require calibration for each new application through adjustments of several different biological and chemical parameters. Literature values for these parameters are wide, but provided that the process description is correct, many of the parameters can be validated with measured data. Such a validation was undertaken for Prospect Reservoir, Sydney, Australia. Schladow and Hamilton (1997) assigned a range to each of the parameters used in the ecological component of the DYRESM water quality model based on the values found in the literature. The sensitivity of the model to changes in these parameters was determined by individually adjusting parameters to maximum or minimum of their assigned ranges while keeping all other parameters at their assigned means. The effects of these changes were quantified through the mean, the vertical distribution and the temporal variation in chlorophyll a and dissolved oxygen concentrations over a 200-day period, using data from the Prospect Reservoir.

Parameters that influenced kinetics of phosphorus by phytoplankton, the minimum internal concentrations, the half saturation constant and the maximum uptake rate, were among the more important determinants of all three measures of chlorophyll a. These parameters were also important determinants of the mean concentrations and the vertical distribution of dissolved oxygen resulting from photosynthetic oxygen production.

Sediment oxygen demand has a significant effect on the mean concentration and vertical distribution of dissolved oxygen. Phytoplankton density altered the vertical distribution of chlorophyll a and rates of phytoplankton growth, respiration and mortality influences the mean concentration of chlorophyll a. The model parameters were calibrated for the 200-day period and model was validated over the additional 306 days.

In this case, simulated nutrient concentrations (PO_4-P, NO_3-N, NH_4-N, total phosphorus and total nitrogen) reflect the general temporal and spatial trends in the measured data from Prospect Reservoir.

Sensitivity of Results to Sediment Nutrient Release Rates

The long-term effect on water quality of sediment nutrient release was evaluated on a sensitivity basis. Alternate concentrations of above and below ground biomass were used in the model to gain some understanding of the potential impacts to water quality for the long-term. The concentration of dissolved oxygen, both within and released from the reservoir, will depend on a number of factors, including the quantity and composition of the vegetation inundated and the organic content of the soils. Two scenarios were considered in the study of 1997: A first scenario with a residual biomass of 65 tonnes/ha, if timber harvest is completed only to the stage of removing logs prior to impoundment and a second scenario, involving more extensive clearing prior to filling the reservoir, with a residual biomass of 58 tonnes/ha.

In addition, it was assumed that all of the organic material of the first five cm of soil participates in the mineralization process and would be involved in the sediment oxygen demand and nutrient release. This gives, based on data acquired in 1997, an equivalent of 30 tonnes (C) /ha (using a soil density of 2.37 g cm^{-3} and a carbon content of 2.5% by dry weight).

Approximately 47% of this carbon should be consumed in methane production (Wetzel, 1983) and another 15-20% of the total should be degraded anaerobically to carbon dioxide (David Hamilton, pers. communication, 1997). This leaves about 35%, or 1037 g of carbon requiring oxygen for mineralization. Using the previously referenced stoichiometric ratio, the oxygen demand is thus 2764 g per square meter. Assuming the oxygen demand is spread over 15 years, gives a daily demand of 0.5 g/m^2/day. This estimate is consistent with reported values for lake sediments that are relatively low in organic and nutrient content (Snodgrass, 1987; Hamilton *et al.*, 1995). Given typical ratios for carbon, nitrogen and phosphorus measured at the Project site in 1997, the corresponding rates of nutrient release can be calculated.

The following values represent upper limits for the effects of below-ground biomass in the Nakai Reservoir:

- Oxygen demand, 0.5 g/m^2/day,
- Phosphorus release, 0.1 mg/m^2/day,
- Nitrogen release, 1.0 mg/m^2/day.

The base sediment oxygen demand and nutrient release parameters discussed above were increased to the following values:

- Oxygen demand, 5.0 g/m^2/day,
- Phosphorus release, 1.0 mg/m^2/day,
- Nitrogen release, 10.0 mg/m^2/day.

These increases by ten fold e.g. from 34 tons of Carbon to 340 tons of Carbon were used to determine the effects of large amounts of below ground biomass. Similar increases were also used for nitrogen and phosphorus.

The simulated water quality results were found to be sensitive to ascribed sediment release rates. Increased sediment nutrient release rates of an order of magnitude greater than that estimated to be present in the impoundment significantly lowered the dissolved oxygen concentrations in the reservoir.

Anoxic conditions in the near surface layers were found to occur infrequently for short durations during the rainy season under a low sediment release scenario. This is in contrast to the high sediment release scenario, which shows extended durations of limited dissolved oxygen concentrations through depth in the rainy season. Increased phosphorus and nitrogen sediment release rates are also shown to increase the production of chlorophyll a during the onset of the rainy season.

At the exception of dissolved oxygen concentrations, other parameters of quality of water discharged through the power station is relatively unaffected by the increased sediment nutrient release rates. Under base-case four turbine, high discharge conditions, the dissolved oxygen concentration of discharged water varies between 5 and 9 mg/l with an average of 7 mg/l. Increased sediment nutrient release rates reduce the average dissolved oxygen concentration of discharged water to approximately 5 mg/l with significant seasonal fluctuations from 2 mg/l to 9 mg/l. The water quality of the dam spills and environmental releases show similar dissolved oxygen concentration trends to those predicted for water discharged through the Power Station.

Results of the Water Quality Model

Impact of High Flow Relative to Low Flow Decades

Using a ten-year moving average on the monthly inflow data provided by EDF, a low and high flow period was selected. The low flow period corresponds to January 1986 to December 1995 and the high flow period, July 1958 to June 1968.

Inflow volumes affect the reservoir storage volume and consequently the water surface level. The depth of radiation penetration (and consequently temperature) is a function of the reservoir depth. The extent of thermal stratification is similar under both flow regimes.

Overall, the water quality of the water discharged through the Power Station is affected by seasonal variations in inflow volumes. **Total phosphorus** concentrations tend to be higher in the high flow period (5-10 µg/l) with concentrations similar in latter years for both periods. **Chlorophyll a** concentrations in water discharged through the Power Station tend to be higher in the low flow period for the 10-year period. These concentrations reach a maximum of 20 µg/l and average in the order of 10 µg/l throughout the 10-year period. Slightly lesser concentrations of chlorophyll a are found in the high flow period. **Ammonia** concentrations are higher in the high flow period (15-20 µg/l) than in the low flow period (10 µg/l) for the first five years with concentrations stabilizing for the remainder of the ten-year period. A similar trend occurs for **total nitrogen**. Under a four turbine configuration, **dissolved oxygen** concentrations are less in the first year during the low flow period than during the high flow period. The dissolved oxygen concentration is approximately 3 mg/l for a period of 30 days. Overall, water discharged through the Power Station has dissolved oxygen concentrations that are low in the first year of operation when inflow to the reservoir is low. **Nitrate concentrations** in the discharge waters during the high flow period for the first three years will be slightly greater than that predicted for the low flow period. **Dissolved Reactive Phosphorous** concentrations in the high flow period are higher (5-10 µg/l) for the first 1.5 years than those in the low flow period, then concentrations are similar for both flow regimes.

The volume of inflow affects the frequency of dam spills. Simulation results derived for the four turbine configuration indicates that the variations in water quality of dam spills between high and low flow periods is negligible with dam spills occurring more often during high flow periods.

Three Dimensional Simulations of Circulation Patterns

Three-dimensional simulations of the circulation patterns resulting from wind stress and large inflows were conducted. Wind forcing was found to be ineffective at transporting deep, relatively poor quality water toward the power intake, in agreement with Winters *et al.* (1997). Advective transport to the power intake is dominated by flows through deep channels and sub-basins. Large inflows to the upstream basin should flow directly to the Power Intake. This result further emphasizes the importance of effective basin management, as this will ultimately determine the characteristics of the inflowing waters.

Maximum **dissolved phosphorus** (PO_4-P) concentrations occurred in the bottom waters (0.1-0.2 mg/l) during the first several years when sediment release rates were high from the mineralization of the inundated terrestrial biomass. Otherwise (PO_4-P) concentrations ranged from 0.03 mg/l during high inflows to 0.005 mg/l when the reservoir is stratified. Concentrations of PO_4-P decreased rapidly in the surface waters because of the uptake by phytoplankton.

Total phosphorus concentrations of the bottom waters were high during the first several years because of the elevated PO_4-P sediment release rates. **Total phosphorus** also increased in winter during high inflows when riverine concentrations increased. Concentrations decreased thereafter from settling because most of the riverine **total phosphorus** enters the reservoir as particulates.

Seasonal variations of **NO_3-N** are caused predominately by inputs from high inflows when reservoir concentrations of approximately 0.1 mg/l **nitrogen** are similar to riverine concentrations (0.1 mg/l **nitrogen**). Algal uptake reduces NO_3-N concentrations in the surface waters while at mid-depths, nitrification of NH_4-N occurs throughout the water column. A mid-depth maximum developed during stratification because of low phytoplankton uptake at the middle depths. A trend of lower NO_3-N concentrations over the ten-year simulation results because of the decrease in NH_4-N and hence a lower source of ammonium for nitrification to NO_3-N.

Clearly, the mineralisation of inundated organic matter yields quite large sediment NH_4-N fluxes resulting in concentrations in excess of 0.5 mg/l during periods of prolonged thermal stratification in the very bottom waters. After the initial years, maximum NH_4-N was approximately 0.01-0.05 mg/l at depth during prolonged stratification and <0.01 mg/l in the surface waters.

The maximum concentrations of **total nitrogen** occurred in the bottom 5 m of the water column because of the high NH_4-N attained during this period. Otherwise, similar to **total phosphorus**, the maximum **total nitrogen** concentrations occurred during rising lake level from riverine-derived loading with concentrations of ca. 0.2 mg/l. Conversely, minimum values of **total nitrogen** were present during the dry season with values on the order of 0.05 mg/l. Similar to **total phosphorus** concentrations in the surface waters, **total nitrogen** concentrations were low during thermal stratification (<0.05 mg/l **nitrogen**) because of algal uptake of dissolved concentrations and settling of the particulates.

Algal Growth

The 2000 modelling study simulated three algal groups. The three groups had the broad ecological characteristics of blue-green algae, green algae and diatoms of temperate regions. The water quality coefficients of the blue-green algae were set for optimal conditions at high temperatures, low nitrogen concentrations and high phosphorus concentrations whereas diatoms were configured optimally for cooler temperatures with high nitrogen concentrations. Thus, during the initial several years when nutrients were high, both green algae and diatoms bloomed. However, nitrogen limitation and high temperature adaptation favoured blue-green algal dominance with peak summer biomass of ca. 10 μg-chlorophyll a/l and minimum winter biomass of ca. 1 μg-chlorophyll a/l. This is not to say *a priori* that blue-green algal blooms will occur in the Nakai Reservoir, as undoubtedly the local species of diatoms, green algae and other algal groups in the Project catchment are likely to adapt to high temperatures. However, if nitrogen is the limiting nutrient, blue-green algae may be dominant during the summer months when river inputs of nitrogen are low. The results of this study were relatively insensitive to: i) the different discharge schedules for different power station configurations; and ii) relatively high-inflow versus low-inflow decades, and are in agreement with Winters *et al.* (1997). The results were sensitive, however, to the assumed sediment and nutrient characteristics of the inflows as found by Winters *et al.* (1997). Nutrient levels during the wet season, particulates and algal biomass was predicted to be higher than baseline predictions.

Increased Periods of Anoxic Conditions in the Nakai Reservoir

An increased period of anoxic conditions in the Nakai Reservoir than what is predicted in the water quality model should lead to enhanced sediment nutrient releases and potential increases in phytoplankton production in surface waters. There is also the possibility that upon overturn, low levels of dissolved oxygen may occur in surface waters, leading to possible fish kill. This phenomenon is rarely reported in the literature for large lakes, probably because in such lakes there are a sufficient number of refugia available for fish to escape to, should low oxygen concentrations be present. Fish would generally avoid these anoxic waters at the surface. If low levels of dissolved oxygen should occur, it would likely be only for several days. Re-aeration of surface waters by wind mixing is likely to occur rapidly.

Changes in Surface Water Temperatures

There is the possibility that surface water temperatures may be several degrees higher or lower than that predicted by the water quality model. Higher surface water temperatures will increase algal productivity, which in turn may increase fisheries production. Additionally, turnover rates of dissolved nutrients should increase as well as increased bacterial decomposition of the organic fraction within the water column. Water will be at a temperature close to the one of the riverine lowland ecosystems, where it will be released. Lower water temperatures may result in a decrease in both bacterial activity and algal production in the reservoir. They may impact upon the aquatic ecology of the Xe Bang Fai, though it is expected that the water temperatures should equilibrate with local air temperatures rapidly.

The estimated temperature of the reservoir water ranges from 18°C in the dry season to approximately 20°C-25°C from the hypolimnion and 30°C from the surface waters in the wet season (Winters et al., 1997). This water will be diverted to the Xe Bang Fai, whose temperature ranges from 21°C to 32°C. The difference in temperature between the reservoir water and the water in the Xe Bang Fai will be reduced by warming in the Regulating Pond and in the 27 km Downstream Channel to the Xe Bang Fai. The retention time of the diverted water from the Power Station to the confluence of the Nam Phit with the Xe Bang Fai is approximately six hours. The average monthly air temperatures on the Gnommalat Plain range from 22°C to 32°C.

In the dry season, the temperature difference between the diverted water and the water in the Xe Bang Fai is expected to be no greater than 3.5°C. In the wet season, the differential will be less, and will be buffered by the equal or greater quantities of water in the Xe Bang Fai. Because of this, sudden temperature changes in the Xe Bang Fai are not expected during the wet season. In the dry season, the Xe Bang Fai flow will be mostly comprised of the discharged water and it will largely take on the characteristics of the water discharged through the Downstream Channel to the Xe Bang Fai. The water releases and spills from the Nakai Dam into the Nam Theun will be of a similar temperature to the receiving water.

Summary of Water Quality Predictions

In conclusion, the water quality predictions are:

- The Nakai Reservoir is likely to thermally stratify each year from late spring to autumn, and following the rainy season should be nearly homogenous and cool.
- Periodic episodes of anoxia are likely to occur, typically lasting one to three months at the end of the dry season. The thermal stratification will be driven by light absorption of riverine introduced suspended solids into the surface waters of the

reservoir, increasing the thermal stability of the surface layer. Anoxic conditions will likely occur only in the lower 6-8 m of the reservoir, below the level of withdrawal.

- During the initial several years after dam construction, high decomposition rates of inundated biomass is likely to lead to low dissolved oxygen concentrations of approximately 2-3 mg/l. However, seasonal minimum dissolved oxygen concentrations, less that 5 mg/l may occur occasionally after the initial several years period of high decomposition rates.
- Outflows should have seasonally high particulate concentrations during peak flows in the wet season. Further, environmental releases from the surface of the reservoir should have a strong interannual signal, dependent upon the magnitude of peak flow events.