Joule Africa Ltd

Yiben HEP Project

Pilot Forecasts of Likely Trophic Status and Eutrophication Risk of Yiben Reservoir – a Proposed Hydro-power Impoundment on the Seli River (Sierra Leone)

A predictive Eutrophication Risk Assessment

ecotone
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I, Michiel Jonker, as duly authorised representative of Ecotone Freshwater Consultants CC (Ecotone), hereby confirm my independence (as well as that of Ecotone, its members, employees and sub-consultants) as a specialist and declare that neither I nor Ecotone have any interest, be it business, financial, personal or other, in any proposed activity, application or appeal in respect to the proposed Yiben HEP Project, other than fair remuneration for work performed.

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ABBREVIATIONS AND ACRONYMS

BOD	Biological Oxygen Demand
COP	Chemical Oxygen Demand
DO	Dissolved Oxygen
EC	Electrical Conductivity
ERA	Eutrophication Risk Assessment
FSL	Full Supply Level
HABs	Harmful Algae Blooms
ITCZ	Intertropical Convergence Zone
MEI	Morpho Edaphic Index
MOL	Minimum Operating Level
MPL	Maximum Permissible Loadings
NTU	Nephelometric Turbidity Units
OECD	Organization for Economic Co-operation and Development
POM	Particulate Organic Matter
TDS	Total Dissolved Solids
TN	Total Nitrogen
TP	Total Phosphorus
TSI	Trophic State Index
TSS	Total Suspended Solids

GLOSSARY

Alkaline:	Having the properties of an alkali, or containing alkali; having a pH greater than 7.
Autotroph:	An organism that can form nutritional organic substances from simple inorganic substances such as carbon dioxide.
Benthic:	The benthic zone is the ecological region at the lowest level of a body of water such as a lake, including the sediment surface and some sub-surface layers.
Biological Oxygen Demand:	Biochemical Oxygen Demand is the amount of dissolved oxygen needed (i.e. demanded) by aerobic biological organisms to break down organic material present in a given water sample at certain temperature over a specific period.
Chemical Oxygen Demand:	Chemical Oxygen Demand is a measure of the capacity of water to consume oxygen during the decomposition of organic matter and the oxidation of inorganic chemicals such as Ammonia and nitrite.
Cladocerans:	The Cladocera are an order of small crustaceans commonly called water fleas.
Curvilinear:	Contained by or consisting of a curved line or lines.
Cyanobacteria:	Cyanobacteria, are a phylum of bacteria that obtain their energy through photosynthesis, and are the only photosynthetic prokaryotes able to produce oxygen.
Dinoflagellate:	The dinoflagellates are a large group of flagellate eukaryotes that constitute the phylum Dinoflagellata. Most are marine plankton, but they also are common in freshwater habitats.
Eutrophic:	A water system rich in nutrients and so supporting a dense plant population.
Eutrophication:	Process of nutrient enrichment in a lake or other body of water, frequently due to run-off from the land, which causes a dense growth of plant life.
Holomictic:	Holomictic lakes are lakes that have a uniform temperature and density from top to bottom at a specific time during the year, which allows the lake waters to completely mix.
Hydrophyte:	A plant which grows only in or on water.
Hypsographic:	A branch of geography that deals with the measurement and mapping of the varying elevations of the earth's surface above sea level.
Lacustrine:	Related to or associated with lakes.
Nektonic:	Nektonic animals are those that swim and migrate freely. Planktonic organisms, usually very small or microscopic, have little or no power of locomotion and merely drift or float in the water.
Oligotrophic:	An oligotroph is an organism that can live in an environment that offers very low levels of nutrients. They may be contrasted with copiotrophs, which prefer nutritionally rich environments. Oligotrophs are characterized by slow growth, low rates of metabolism, and generally low population density.

Particulate Organic Matter: Particulate Organic matter (macro-organic matter, or coarse fraction organic matter) is defined as organic matter between 0.053 mm and 2 mm in size.

Plankton: The small and microscopic organisms drifting or floating in the sea or fresh water, consisting chiefly of diatoms, protozoans, small crustaceans, and the eggs and larval stages of larger animals. Many animals are adapted to feed on plankton, especially by filtering the water.

Protistan: Any eukaryotic organism that has cells with nuclei and is not an animal, plant or fungus. The protists do not form a natural group, or clade, since they have no common characteristic origin, but, like algae or invertebrates, they are often grouped together for convenience.

Thermal stratification: Lake stratification is the separation of lakes into three layers: Epilimnion: the top of the lake. Metalimnion: the middle layer, which may change depth over time. Hypolimnion: the bottom layer. The thermal stratification of lakes refers to a change in the temperature at different depths in the lake, and is due to the change in water's density with temperature

Thermocline: An abrupt temperature gradient in a body of water such as a lake, marked by a layer above and below which the water is at different temperatures.

Total Dissolved Solids: Dissolved solids refer to any minerals, salts, metals, cations or anions dissolved in water. Total Dissolved Solids comprise inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulphates) and some small amounts of organic matter that are dissolved in water.

Total Suspended Solids: Total Suspended Solids are solids in water that can be trapped by a filter. It can include a wide variety of material, such as silt, decaying plant and animal matter, industrial wastes, and sewage.

Trophic Chain: A food chain is a linear network of links in a food web starting from producer organisms and ending at apex predator species, detritivores, or decomposer species.

Trophic structure: Trophic structure refers to the way in which organisms use food resources to get their energy for growth and reproduction, and is often referred to in simple terms as the “food web” or “food chain”.

Turbidity: Turbidity is the cloudiness or haziness of a fluid caused by large numbers of individual particles that are generally invisible to the naked eye, like smoke in air. The measurement of turbidity is a key test of water quality.

Vascular plants: Vascular plants, also known as tracheophytes and also higher plants, form a large group of plants that are defined as those land plants that have lignified tissues for conducting water and minerals throughout the plant.

EXECUTIVE SUMMARY

An overview is given of the regional setting of the Seli River drainage basin upstream of its confluence with the Rokel River, outlining the local climate, geology, hydrology, vegetation and land-use practices in its catchment. General water quality characteristics of the river are considered.

The cause and consequences of eutrophication are sketched, to contextualize the potential implications of this threat, the severity of which can be quantified in terms of the reservoir's trophic status or nutrient content level, in relation to trophic status classification norms provided herein.

Hydrological features are considered in relation to basic morphological and bathymetric attributes of specific importance to the ecological functioning of the future reservoir and its vulnerability to eutrophication.

Predictive methods used to forecast trophic status are described. Shortcomings and limitations in the data needed to ensure reasonably secure forecasts for Yiben Reservoir are outlined. Notwithstanding, predictions were made for Yiben Reservoir, using a multi-method scenario-modelling approach to span inherent deficiencies in the input data and information base.

Under the most likely plausible conditions tested, forecasts strongly suggest that the trophic status of Yiben Reservoir will remain oligotrophic, with eutrophication very unlikely to exceed tolerable levels. This modelled output is predicated on the relatively low nutrient export capacity inherent to the Yiben Reservoir catchment. The transient phenomenon of 'trophic upsurge' that is generally observed in newly impounded reservoirs during and after they first fill is considered likely to be muted in Yiben Reservoir, predominantly due to the low background soil nutrient levels and relatively high flushing rate for the Yiben Reservoir.

Some follow-up procedures are suggested to examine various conclusions reached in this pilot assessment and test their validity.

1. INTRODUCTION

1.1. BACKGROUND

Sierra Leone's development hinges, in large measure, on an increased and assured, externally-independent supply of locally-produced electric power. To meet this demand, various hydro-electric schemes, exploiting the potential use of renewable 'green' hydro-power were investigated nearly half a century ago. For western Sierra Leone, the Bumbuna Hydroelectric Project (BHP) on the Seli River was identified as the most favourable option in 1970/1971 (Nipon Koei *et al.*, 2005a). The first phase of this 5-stage scheme plan was a 'run-of-river' storage reservoir - Bumbuna I, operationally commissioned in 2010. The following report is contextually based on the proposed phase II of the overall BHP, specifically the Yiben or Bumbuna II Reservoir, an impoundment planned on the Seli River upstream of Bumbuna I (**Figure 1-1**) (Lahmeyer International GmbH, 2013a). To obviate any name confusion between the two Bumbuna reservoirs, the future Bumbuna II Reservoir is hereafter referred to as Yiben Reservoir.

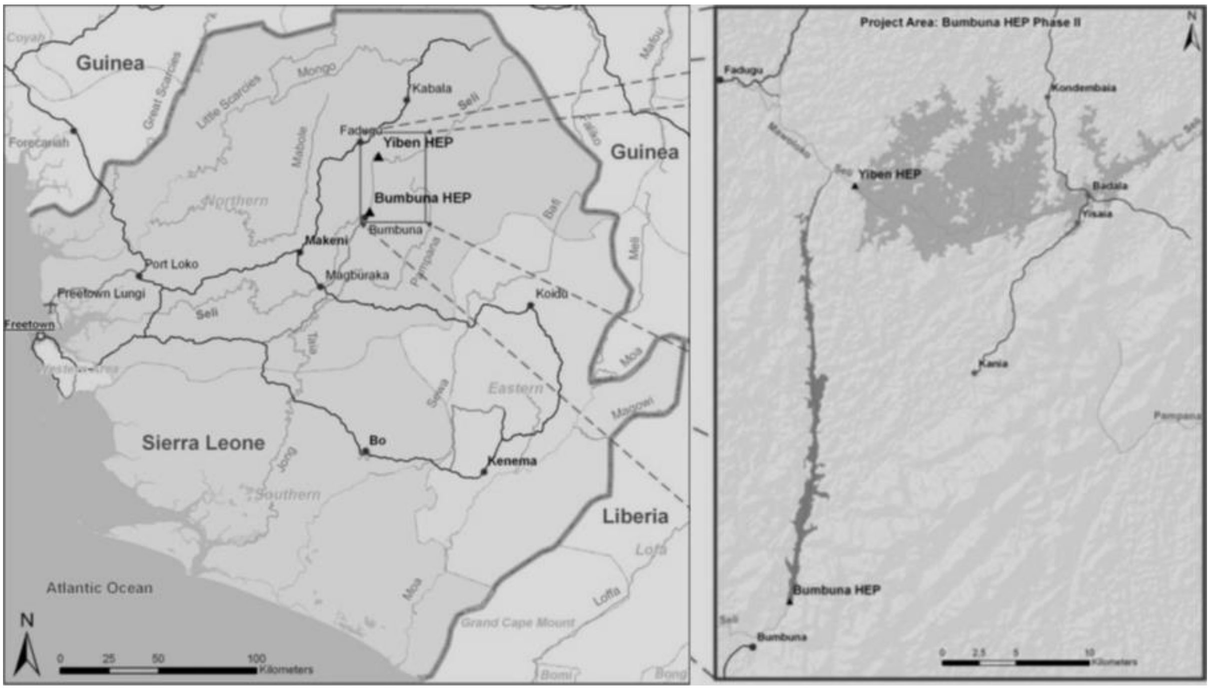

Figure 1-1: Map of Sierra Leone with enlarged sectional view of Bumbuna and Yiben Reservoir HEP sites (from Lahmeyer International, 2013).

1.2. PURPOSE OF THE YIBEN RESERVOIR

The proposed Yiben Reservoir is planned primarily for hydro-electric power generation, with a designed capacity to produce 23 MW (‘firm’ - assured output) and maximum of 66 MW (Lahmeyer International, 2013). In this context, eutrophication poses little or no **direct** risk.

Tentative suggestions have been made to develop a fishery on the reservoir to improve protein availability for residents, and/or provide a product for economic trade. Since levels of biological productivity relate directly to water fertility, eutrophication is directly relevant and within limits, largely beneficial. The feasibility of developing a fishery project will require separate enquiry, as the focus of this study is to elucidate an eutrophication risk.

1.3. CONTEXTUAL OUTLINE OF EUTROPHICATION – CAUSES AND CONSEQUENCES

Eutrophication, literally meaning nutrient enrichment, results in ubiquitous biological, recreational, health, economic, aesthetic and water quality problems, and is accordingly recognized as a severe chronic global threat to human and ecosystem health and water security (Smith and Schindler, 2009). Broadly speaking, reservoir construction has obvious direct impacts on water quality, through conversion of a flowing riverine system to a ‘standing’ water environment, in which river-borne chemicals can accumulate. Reservoirs are susceptible to eutrophication because of the relatively large drainage basins from which enriching nutrients originate. Furthermore, various physical conditions in the ‘still water’ lacustrine environment favour the development and growth of planktonic biota, which, as predominantly small organisms, grow relatively faster than their larger bottom-dwelling (benthic) and strong-swimming open-water (nektonic) counterparts.

To grow, photosynthetic organisms (autotrophs) require light, water, and various nutrient elements, any or all of which can be limiting, individually or in combination. In aquatic environments, water is obviously no constraint. Light is generally adequate at the water surface, although radiant energy declines exponentially underwater. Among the rage of the chemical elements essential for autotroph growth, Nitrogen (N) and particularly Phosphorus (P) are most commonly in shortest supply in aquatic ecosystems, and thereby function as the primary growth-limiting factors for aquatic vascular plants, protistan algae, and cyanobacteria.

The source of nutrient responsible for enrichment (‘fertilization’) allows for distinction between natural and/or anthropogenic eutrophication, with N and P arising respectively either from natural weathering and leaching processes, or from man-induced agricultural fertilization, sewage effluent disposal, etc. Natural eutrophication is a gradual, millennium-scale process, whereas anthropogenic eutrophication is generally much faster – taking one or several decades, depending on its severity (rate of enrichment). Reduction or removal of chemical limitation stimulates autotroph growth, commonly resulting in the proliferation of hydrophytes and/or planktonic algae (both protistan and/or blue-green cyanobacteria), often to ‘excessive’ levels. Thereafter light availability often becomes the primary growth limiting factor.

The consequences of such ‘excessive’ growth are both direct and/or indirect, resulting in adverse alterations to aquatic biotic composition and foodweb structure, and the degradation of water quality. On this basis, eutrophication was identified as a major focus of international concern, leading to a status report on its assessment 3½ decades ago (OECD, 1982).

To elaborate briefly. The elevated primary production induced by high nutrient concentrations results in large pools of autotroph biomass, and thus of Particulate Organic Matter (POM) that sinks into and decomposes in deeper water, resulting in rising Biological and Chemical Oxygen Demands (BOD, COD) and thereby reducing or depleting oxygen content of the water. Various alterations in the food-web structure, particularly the disruption of the customary functional ‘grazing chain’, exacerbate oxygen depletion, permitting up to 10-fold more autotroph biomass to enter the decomposition cycle directly rather than amounts that remain after grazer-depletion (based on the nominal 10 % trophic chain efficiency level). At an ecosystem level, disruptions of the ‘natural’ food-chain structure generally lead to concomitant losses of species diversity, dominated by a small number of opportunistic species, and an overall decrease in ecosystem complexity and stability.

Disruptions of the grazing chain arise from various factors – primarily related to the types of autotrophs that predominate in eutrophic waters – *inter alia* cyanobacteria (blue-green ‘algae’) and dinoflagellates (collectively widely termed as ‘harmful algae’), which are mostly too large, unpalatable, nutritionally deficient, noxious or even toxic, for consumption by typical zooplankton grazers, particularly *Daphnia*-type cladocerans. Blooms of algae and cyanobacteria commonly develop, especially in summer, when higher temperatures permit faster autotroph growth rates, often resulting in ‘harmful algal blooms’ (HABs) that can produce cyanotoxins under certain conditions.

Reduction of nutrient limitation can result either in proliferation of planktonic autotrophs underwater or at the water surface, and/or of submerged, floating or emergent macrophytes. Floating vascular hydrophytes like water hyacinth (*Eichornia*), water lettuce or water cabbage (*Pistia*), or ferns like Kariba weed (*Salvinia*) potentially pose a greater risk for hydro-electric schemes than do planktonic autotrophs, although lake-derived cyanotoxins can be carried downstream to impact on the riverine environment.

1.4. TROPHIC STATUS CLASSIFICATION

The extent to which water is enriched determines its **trophic status** – literally a measure of its ‘nourishment’ or ‘fertility'. **Table 1-1** summarizes the internationally accepted norms for trophic status classification, based on three criteria: the causal driver – nutrient concentration (of P and/or N – only P values listed here) and two their consequential outcomes (Chlorophyll concentration and water transparency). In so far as Yiben does not yet exist, no *in situ* determinations of any of these parameters can be made. However, it is possible to forecast probable nutrient content levels in the future lake, values of which can in turn be related to Chlorophyll concentration – a measure of phytoplankton abundance. As phytoplankton particles affect underwater light penetration, Secchi depth transparency provides a very simple and inexpensive proxy measure of algal abundance. But projected forecasts of water transparency are not justified here, since suspended sediment particles confound the abundance-transparency relationships and negate this proxy measure in sediment-laden waters.

Table 1-1: International (OECD 1982) fixed boundary norms for trophic status classes

Annual mean values of:	**Total Phosphorus (µg/ℓ ≡ mg/m^3)**	**Chlorophyll-a (µg/ℓ≡ mg/m^3)**	**Secchi depth transparency (cm)**
Ultra-oligotrophic	≤ 4	≤ 1.0	> 1 200
Oligotrophic	≤ 10	≤ 2.5	> 600
Mesotrophic	10 – 35	2.5 – 8	600 – 300
Eutrophic	35 – 100	8 – 25	300 – 150
Hypertrophic	≥ 100	≥ 25	< 150

Apart from ultra-oligotrophy (which is generally restricted to waters in high latitude or high montane regions), oligotrophy is the optimal trophic status category reflecting a desirable water quality condition. As such, **oligotrophy serves as the baseline reference condition of acceptability for this Yiben Reservoir eutrophication risk assessment**. Mesotrophic waters remain tolerable, but sub-optimal. Eutrophy and hypertrophy constitute progressively more undesirable water quality states.

Other measures of trophic status exist. The Trophic State Index (Carlson, 1977) is a direct reflection of general lake productivity, while the Morpho-Edaphic Index (Ryder, 1982) specifically estimates potential fish yield, which depends on productivity of fish, and thereby indirectly reflects trophic status.

The dimensionless Carlson (1977) Trophic State Index (TSI) is derived from log-transformed values of empirical in-lake measurements of P_{total} (TP, µg/l), Chlorophyll (CHL, µg/l), or Secchi disk transparency (SD, metres), using the following equations:

$$TSI = 4.15 + 14.42Ln(TP)$$

$$TSI = 30.6 + 9.81Ln(Chl)$$

$$TSI = 60 - 14.41Ln(SD)$$

TSI values rise from 1 to 100 as fertility increases, with class boundaries for oligotrophy (< 38), mesotrophy (38-48), eutrophy (49-61) and hyper-eutrophy (> 61) used by Fuller & Jodoin (2016). It is considered to be a useful index for phosphorus-limited systems, but not for nitrogen-limited and/or turbid water systems (Holren *et al*., 2001).

Ryder's simple Morpho-Edaphic Index (MEI) is merely the quotient of total dissolved solids (TDS, mg/l) or electrical conductivity (µmhos/cm) to mean depth (metres):

$$\text{MEI} = \frac{TDS}{mean\ depth} \quad \text{or} \quad \frac{Conductivity}{mean\ depth}$$

where the numerators (TDS and conductivity) serve as a surrogate measure of likely nutrient content. However, no trophic status categories are assigned directly to MEI values, the upper limit of which is indefinite.

1.5. DIRECT IMPACTS OF EUTROPHICATION ON HYDRO-ELECTRIC SCHEMES AND DOWNSTREAM RIVERS

In general, **potential** direct impacts of eutrophication on hydro-electric schemes include (*inter alia*):

1. Mechanical fouling of turbines by aquatic macrophytes - highly unlikely for the Yiben HEP, designed with a deep water turbine offtake (15 or 20 m below the water surface at reservoir full supply level).
2. Premature clogging of turbine intake filters and grids resulting from algal blooms (Bunea *et al*., 2012).
3. Corrosion of structural components resulting from precipitation reactions of iron and manganese in anaerobic water (Bunea *et al.*, 2012), and by sulphate-producing bacteria (Enning & Garrelfs, 2014).

However, more certain effects of eutrophic reservoirs generally, and eutrophic systems, relate to the negative environmental effects on the downstream riverine ecosystem resulting from discharge of stored water. Where 'deep' storage water is released to drive generating turbines (as planned for the Yiben HEP), decreased water temperature is the commonest and most significant negative physical factor. Negative chemical features relate to reduced oxygen content of deep water in eutrophic systems, with resulting prospects of hydrogen sulphide and/or methane production, and elevated pH levels.

2. GENERAL REGIONAL-SCALE CHARACTERISTICS APPLICABLE TO THE YIBEN CATCHMENT

2.1. GEOLOGY

The geology of the Bumbuna Reservoir catchment area (3 920 km^2), of which the Yiben drainage basin is a large component (72.8 % of total), is dominated by igneous rocks, which dissolve only slowly in rainwater. Ionic strength and the associated buffering capacity of the surface and ground-waters is consequently low, with potentially high variability in pH levels and in turn, significant consequences on water quality particularly under conditions of low oxygen concentration (p 228 - Nippon Koei *et al.,* 2005c).

2.2. CLIMATE

Located in an equatorial zone, climate around the Yiben area has been classified as typical West African 'tropical savannah', characterized by distinct wet and dry seasons resulting from the seasonal migration of the Intertropical Convergence Zone (ITCZ) – the convergence of warm dry continental air masses developed over the Sahara (the harmattan) and humid south westerly monsoon air mass over the equatorial Atlantic Ocean (the Guinea monsoon).

The slightly cooler wet season (May to October) is characterized by heavy cloud cover, usually continuous rainfall, and high humidity. The dry season (November to April) is generally warmer and drier, with virtually no rain in February and March, mostly because of intermittent, warm, dry and dust-laden harmattan winds (Lahmeyer International GmbH, 2013).

Summary meteorological records specific for the region (**Table 2-1**) reflect the typically warm to hot temperatures (annual mean = 26.3˚C) in and around the Yiben drainage basin, with high but distinctly seasonal rainfall (annual mean = 2 500 mm). Wettest (Aug-Oct) and driest (Dec-Mar) quarters respectively accord with the coolest (Jul-Sep) and warmest (Feb-Mar) quarters of the year.

2.3. HYDROLOGY OF THE SELI RIVER AT THE YIBEN DAM SITE

Hydrological records indicate that the Seli River flow pattern accords closely with the rainfall pattern (**Table 2-1**). This implies that surface runoff predominates – an understandable outcome of the hilly terrain and regional geology (low permeability), probably aggravated further by land-use in the catchment (see **Section 2.4**). Accordingly, it is likely that groundwater contributes minimally to the water budget.

Table 2-1: Summary of climate-indicative statistics recorded from meteorological stations in or adjacent to the Yiben catchment, and related flow data for the Seli River at the Yiben Dam site (Lahmeyer International GmbH, 2013). The three hottest, wettest and highest-flow months of the year are emphasized in bold font, while the three coolest, driest and lowest-flow months are highlighted in italic bold font.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (°C)													
Avg. max	32.7	34.8	35.0	33.4	31.5	29.6	28.0	27.7	28.8	30.2	31.1	31.4	31.2
Avg. min	16.7	19.2	21.0	21.2	21.5	20.9	20.7	20.7	20.5	20.3	19.5	16.4	19.9
Mean	26.8	**28.7**	**28.9**	**28.5**	26.8	25.2	***24.3***	***24.2***	***24.6***	25.6	25.9	25.9	26.3
Rainfall (mm)													
Avg. max	70	42	124	270	356	475	564	610	745	513	289	69	3 129
Avg. min	0	0	2	20	101	228	174	326	332	235	5	0	2 047
Mean	***6***	***8***	29	94	202	326	396	**487**	**464**	**356**	119	***16***	2 503
Evaporation (mm)													
A Pan	169	**176**	**218**	**181**	154	135	***99***	***82***	***92***	111	129	148	1 694
Lake surf.	135	**141**	**174**	**145**	123	108	***79***	***66***	***74***	89	103	118	1 355
Monthly flow data of Seli River (m^3/s) (10^6 m^3/yr) (Mm^3)													
Max	23.8	11.7	5.3	7.0	15.8	63.0	105.9	171.0	178.6	173.2	85.4	39.1	1 678
Min	6.5	4.0	1.3	0.6	2.3	6.7	20.2	65.1	69.5	79.4	37.3	14.7	890
Mean	11.1	***5.6***	***2.4***	***2.5***	7.2	25.2	53.3	**92.2**	**124.2**	**116.4**	47.9	22.1	1 348

2.4. VEGETATION AND LAND USE

The general vegetation can be described as an equatorial forest-savannah mosaic. Because of low soil fertility, the predominant land use over the larger Bumbuna drainage basin is slash-and-burn agriculture. Most farmers grow rice (either dry upland and/or wet lowland varieties), while other food crops also grown include cassava, potato, yam, and fruits like bananas, pineapples, oranges, grapefruits, mangoes etc. Population density in the area is low.

Artisanal gold mining occurs widely within the catchment and have presumably been taken place for some time. Artisanal mining involves localised disturbance of the soil and vegetation. Mining predominately occurs seasonally on river bed and banks.

A quantitative analysis for two lower sub-catchments of the Yiben drainage basin (**Figure 2-1**) shows the predominance of undeveloped and low-intensity land usage, with little development (**Table 2-2**). However, greater land transformation is evident in these sub-catchments than in the remainder of the entire Yiben drainage basin. Google Earth imagery reveals an overall lower agricultural land-use intensity for the overall catchment, for the present risk assessment these data can be safely extrapolated as conservative estimates for the entire catchment.

Substantial rainfall levels (mean = 2 503, range = 2 047-3 129 mm/yr) falling on a catchment with predominantly slash-and-burn agricultural practice result in highly eroded and well-leached soils; in concert with the predominant igneous rock geology, nutrient release is likely minimal. By implication, localised disturbances in soil due to agricultural induced erosion or artisanal mining will not result in a significant nutrients source which will influence the risk of eutrophication.

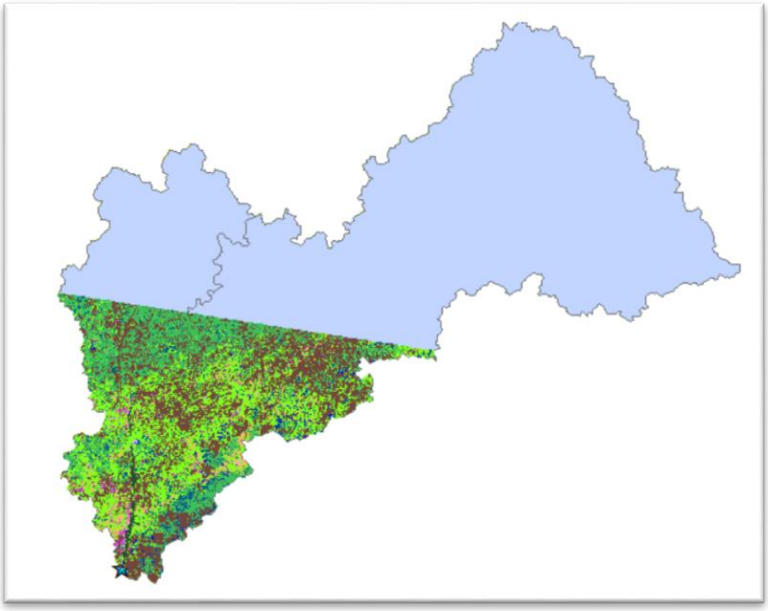

Figure 2-1: Outline map of the Yiben catchment, showing the distribution of different land types (colour-coded, no key provided) determined in its B1 and B2 sub-catchments.

Table 2-2: Aggregated empirical areal land cover by vegetation and land-use types in two Yiben sub-catchments (sample area – see Figure 2-1). Land transformation has been greater in the sample area than in the remainder of Yiben catchment, but has been extrapolated to the entire catchment. Nutrient load estimates are accordingly likely to be inflated even when derived from more conservative export coefficient values (see Scenarios in Table 5-2).

Land type	Yiben sample area (ha)	Sample Area (%)	Yiben total area (ha)
Mountainous scrubland	42 263	33,44	95 438
Pre-cultivated barren	37 490	29,66	84 650
Clear mountainous	29 713	23,51	67 098
Barren scarred land	7 353	5,82	16 610
Intensive Farming	4 183	3,31	9 447
Other natural vegetation	2 264	1,79	5 109
Miscellaneous others	3 124	2,47	7 049
Total	**126 391**	**100,00**	**285 400**

2.5. GENERAL PHYSICAL AND CHEMICAL WATER QUALITY ATTRIBUTES OF THE SELI RIVER

A synopsis of water quality information, derived from various reports and on-site sampling, is provided in Table 2-3. This reflects the paucity of empirical data, both in terms of spatial and particularly temporal coverage. Notwithstanding these limitations, it appears reasonable to conclude that Seli River water quality is generally good, particularly upstream of the proposed Yiben Dam site.

Although the Seli River is low in total ionic content, no unusual features are evident in its overall ionic composition that are directly relevant here. River water is near-neutral to marginally alkaline (pH ± 7.5), and well-oxygenated (saturation mostly > 100%). In line with the relatively insoluble granitic geology of the catchment, and well-leached soils resulting from high rainfall, both ionic conductivity (average ± 13 µS/cm) and content of Total Dissolved Solids (average TDS ± 34 mg/l) are low. **Table 2-3** affirms the expectation of such waters as being characteristically nutrient-poor. The most analytically reliable and consistent determinations indicate that both Nitrogen and Phosphorus were below limits of detection (respectively < 0.25 and <0.08 mg/l) during low-flow conditions prevailing in April 2018. The veracity of substantially higher values in the historical record (≤ 9 and ≤ 1 mg/l) is uncertain. While these possibly reflect seasonal tendencies, inadequate data are available to explore the existence of any seasonal trend.

Normal altitude-related increases in temperature are longitudinally evident along the water-course (Payne *et al.,* 2010). However, somewhat peculiar longitudinal changes were evident, notably for dissolved oxygen, conductivity, and pH. A curvilinear pattern was evident in values of these parameters, ascending from lower values in the upper river to reach a peak in mid-altitude reaches before declining again along lower reaches of the river (Nippon Koei *et al*., 2006). Apart from these, no major longitudinal differences in water quality are evident; likewise, no long-term trends are evident over a 24 year observation period.

The only negative attribute of water quality relates to the considerable turbidity level reflected in many locality photographs (Nippon Koei *et al.*, 2005a, 2005b; Nippon Koei *et al.*, 2006; Lahmeyer International GmbH, 2013), and affirmed in various records of water transparency (Secchi depth visibility, SD) collated in **Table 2-4**. The identity of the suspended particles responsible for this turbidity remains uncertain, but is visually consistent with that associated with suspended sediment, the level of which likely varies seasonally with rainfall and runoff. The low quantitative Nephelometric Turbidity Unit values determined in April 2018 (~ 30 NTU on average), with correspondingly low Total Suspended Solids content (< 21 mg/l TSS) plausibly relate to the low-flow conditions. Quantitative NTU/turbidity values cannot be expressed in SD value equivalents without site-specific inter-calibration.

Table 2-3: Synopsis of general water quality attributes of the Seli River above Bumbuna (Ecotone Freshwater Consultants and various other sources). Sample sites within date-specific sub-sets are listed in downstream sequence. The location of April 2018 sample sites is mapped in Annex 1

Sample dates	Sample sites	Temp.	Dissolved Oxygen		Water Trans.	EC	TDS	pH-*in situ*	pH-lab	TSS	NO_2 - N	NO_3 - N	NH_4 - N	Total N	PO_4 - P
	Units	ºC	mg/l	% sat	NTU	mS/m	mg/l	-	-	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
May 1994	Dam	28,5	7,20	~ 94	#	60,0	35,8	7,4	#	#	2,07	*	0,24	2,31	0,93
Oct 1994	Dam	25,0	#	#	#	55,0	34,1	7,4	#	#	#	#	0,19	0,19	1,00
Aug 2004	Bumbuna	#	#	#	#	#		7,6	#	200	#	8,8	#	8,8	#
July 2016	R1	24,5	#	#	#	#	22,4	8,7	#	#	#	#	#	#	#
	R2	26,0	#	#	#	#	19,5	7,5	#	#	#	#	#	#	#
	R3	28,5	#	#	#	#	22,8	7,8	#	#	#	#	#	#	#
April 2018	SL1	28,6	#	#	298	5,3	40	7,3	6,6	*	*	*	0,08	0,08	*
	SL2	27,5	#	#	3,5	6,6	40	7,3	7,0	*	*	*	0,07	0,07	*
	SL3	22,7	#	#	17,9	9,5	65	7,2	6,7	*	*	*	0,43	0,43	*
	SL4	26,0	#	#	7,3	4,7	45	7,9	6,8	*	*	*	0,08	0,08	*
	Dam 1	31,5	6,14	85,8	10,9	5	50	7,3	6,9	*	*	*	0,12	0,12	*
	Dam 2	31,1	8,2	114	3,0	3,7	35	8,2	7,0	*	*	*	0,09	0,09	*
	Dam 3	30,9	7,22	98,3	1,4	3,3	30	7,7	7,0	*	*	*	0,04	0,04	*
	Dam 4	31,0	8,5	111,7	1,8	3,0	40	9,0	7,5	*	*	*	0,07	0,07	*
	Dam 5	31,8	8,4	112,2	1,3	3,1	30	9,1	8,3	*	*	*	0,08	0,08	*
Upper Sei	Median	28,5	7,71	111,7	3,5	6,6	35,4	7,6	7,0				0,08	0,09	0,97
April 2018	SL5	25,2	~	~	5,9	3,2	30	7,3	6,1	*	*	0,04	0,03	0,03	*
	SL6	~	6,3	80,6	40,5	3,1	25	7,7	7,0	*	*	0,05	0,02	0,02	*
	SL7	29,4	~	~	57,0	3,0	25	7,6	6,9	*	*	0,05	0,02	0,02	*
	SL8	31,2	7,84	104,4	11,1	3,0	25	7,6	7,0	*	*	0,04	0,02	0,02	*
	SL9	29,8	6,6	87,6	2,6	3,0	30	7,2	6,9	*	*	*	0,01	0,01	*
	SL10	30,0	6,98	92,6	1,8	2,9	25	7,7	7,1	*	*	*	0,02	0,02	*
Seli above Bumbuna	Min	22,7	6,1	80,6	1,3	2,9	19,5	7,2	6,1			0,04	0,01	0,01	0,93
	Max	31,8	8,5	114	298	60	65	9,1	8,3			8,8	0,43	8,8	1,0
	Mean	28,4	7,4	99,9	29,2	13,2	33,6	7,7	7,0	200	2,07	3,0	0,10	0,7	1,0
	Median	28,55	7,22	101,35	4,70	4,85	30,0	7,6	7,0	200	2,07	0,05	0,08	0,08	0,97
	# Not determined	* Undetectable				Detection limit =					**21**	**0,20**	**0,03**	**0,01**	**0,08**

Table 2-4: Measurements of water transparency (cm Secchi Depth visibility) in the Seli River at and above Bumbuna Bridge during 2006. (Nippon Koei et al., 2006)

Site	Altitude	January	April	July	September
Fadugu	296	40-50	-	10-15	-
Kafogo	258	50-60	-	10-15	10-15
Above Bumbuna Dam	171	50	-	10-15	-
Below Bumbuna Dam	163	15	10-15	10-15	10
Bumbuna Falls	130	20-30	40-50	5-10	5-10

While high suspended sediment load is often construed as an adverse aspect of water quality, it has positive benefits in mitigating the potential threat of eutrophication. Adsorption, back-scattering and reflectance of light by suspended sediments attenuates light penetration, thereby reducing underwater light availability for autotrophs. Nutrient availability can also be reduced through sequestration on particle surfaces (depending on the mineral and chemical nature of the suspended sediment). Two essential requirements for autotroph growth are accordingly reduced. On this account, eutrophication symptoms often do not manifest in clay-laden waters despite substantial nutrient loadings.

3. RESERVOIR CHARACTERISTICS

3.1. LOCATION

The wall of the proposed Yiben Dam is located north of the Equator at 9.325848o N, and west of the Greenwich Meridian at 11.683489o W.

3.2. RESERVOIR FEATURES

Summary hydrological, morphometric, bathymetric and related features of direct significance to this eutrophication risk assessment are given in **Table 3-1**. Their discussion is reserved to relevant subsequent sections of this report.

Table 3-1: Summary of morphometric and bathymetric features of the future Lake Yiben in relation to hydrological features influencing its functional attributes and likely trophic status

Parameter	Units	Value	Comments
Catchment area	km^2	2 854	Nested within 3 990 km^2 Bumduna I catchment
Surface area	km^2	86.1	At Full Supply Level (FSL)
Storage capacity	Mm^3	2 085.3	At FSL
Surface elevation	m asl	320	At FSL
Perimeter length	km	314.6	Excluding islands
Shoreline development	-	9.56	Excluding islands
Maximum length	km	~ 22.9	
Maximum breadth	km	~ 11.7	
Maximum depth	m	~ 79.0	
Average depth	m	24.2	
Seli River inflow volume	Mm^3/yr	1 348	Average
		1 678	Maximum (also reported as 1797.3 and 1791 in Lahmeyer International GmbH, 2013)
Water retention time	yr	1.547	Average – at average inflow/yr
		1.243	Shortest – at maximum inflow/yr
Flushing rate (FSL volume replacement)	per yr	0.645	At average inflow
		0.805	At maximum inflow
Water discharge depth	m asl	≤ 292	≥ 28 m below reservoir surface at FSL

4. ANTICIPATED LIMNOLOGICALLY RELEVANT CHARACTERISTICS OF YIBEN RESERVOIR

4.1. HYDROLOGICAL FEATURES

Considerable fluctuations in water level are expected to result both from natural factors (rainfall and inflow seasonality) and operational needs for hydro-power generation. With design criteria for the HEP indicating an optimal Minimum Operating Level (MOL) of 305 (but also 300) m asl – drawdown of up to 15 (or 20) m from FSL (320 m asl) can be expected **(Figure 4-1)**. Depending on prevailing annual rainfall levels, this drawdown cycle however, will not necessarily occur on a regular annual time-scale. (The simulated cycle inexplicably reflects greatest drawdown during cooler, wetter months when river flows are highest).

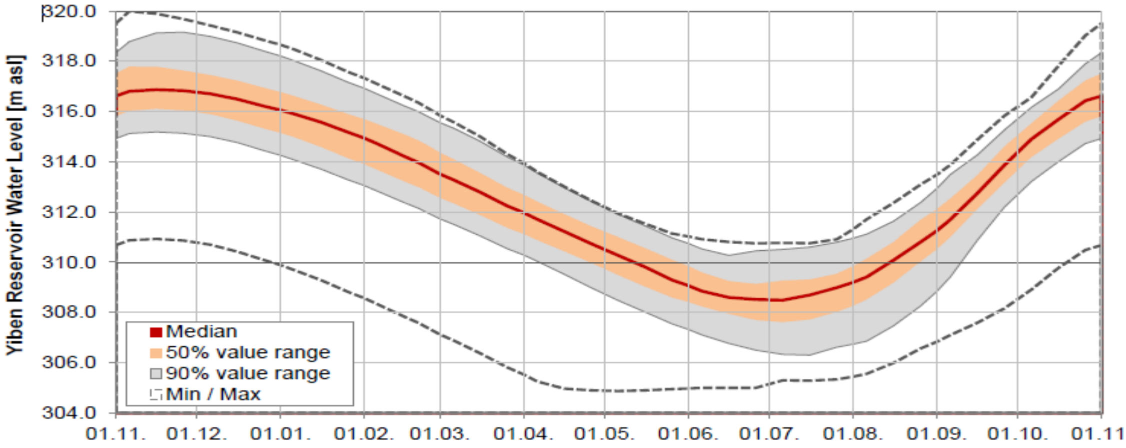

Figure 4-1: Simulated water level range for Yiben Reservoir (Lahmeyer International GmbH, 2013)

Water level fluctuations strongly influence the establishment and stability of beds of rooted emergent and/or submerged hydrophytes around the margins of the reservoir. Given the high shoreline development ratio (**Table 4-1**), these marginal areas will be relatively expansive in Yiben, as reflected in the hypsographic (surface area to depth) data for Yiben (**Table 4-1**). Drawdown by 5 m will expose some 12.4 km^2 (~14.4 % of FSL area), while drawdown to MOL will reduce lake area by 34 km^2 (~ 39.5 % of FSL area).

Table 4-1: Hypsographic relationships for Yiben Reservoir, at the FSL datum (Lahmeyer International GmbH, 2013). *(MOL shown as 20 m in Fig. YIB-0123)

Depth (m)	Volume (Mm³)	Area (km²)	Area (% FSL)	Areal change (km²)	Areal change (%)	Σ areal change (%)	Mean Depth (m)
FSL 0	2 085.3	86.1	100.0	0	-	-	24.2
5	1 676.6	73.7	85.6	12.4	14.4	14.4	22.7
10	1 326.6	62.4	72.5	23.7	13.1	27.5	21.3
*MOL 15	1 030.7	52.1	60.5	34.0	12.0	39.5	19.8
20	782.3	43.3	50.3	42.8	10.2	49.7	18.1
25	582.8	34.9	40.5	51.2	9.8	59.5	16.7
30	421.3	28.9	33.6	57.2	7.0	66.4	14.6
35	288.0	23.4	27.2	62.7	6.4	72.8	12.3
40	201.1	16.5	19.2	69.6	8.0	80.8	12.2
45	112.4	11.3	13.1	74.8	6.0	86.9	9.9
50	63.3	6.8	7.9	79.3	5.2	92.1	9.3
55	34.6	3.5	4.1	82.6	3.8	95.9	9.9
60	19.3	2.4	2.8	83.7	1.3	97.2	8.0
65	9.1	1.5	1.7	84.6	1.0	98.3	6.1
70	2.7	0.7	0.8	85.4	0.9	99.2	3.9

Flushing rates of Yiben Reservoir will be determined by the prevailing ratios of inflow to storage volumes, which can be expected to vary from year-to-year. As nutrient loading estimates are modified by flushing time (see **Section 5.4**), such variations will consequently influence this eutrophication risk assessment.

4.2. MORPHOLOGICAL FEATURES

With average and maximum depths of 24.2 and ~79 m at FSL, and an average depth of 19.8 m even at MOL, Yiben Reservoir can be expected to function as a ‘deep’ lake. Thermal stratification accordingly seems highly likely during the hot season, although in the absence of seasonal information on wind strength and direction, no prediction can be made regarding the depth at which stratification is likely to occur. Wind-rose data at Cape Sierra Leone (**Figure 4-2**) indicate the almost exclusive dominance of SSW to WSW winds, peaking at ~ 20 km/h. Very speculative extrapolation of this pattern ± 250 km inland to Yiben implies that wind run could align obliquely with the lake’s longitudinal axis (**Figure 4-2**), and thus deepen the thermocline depth.

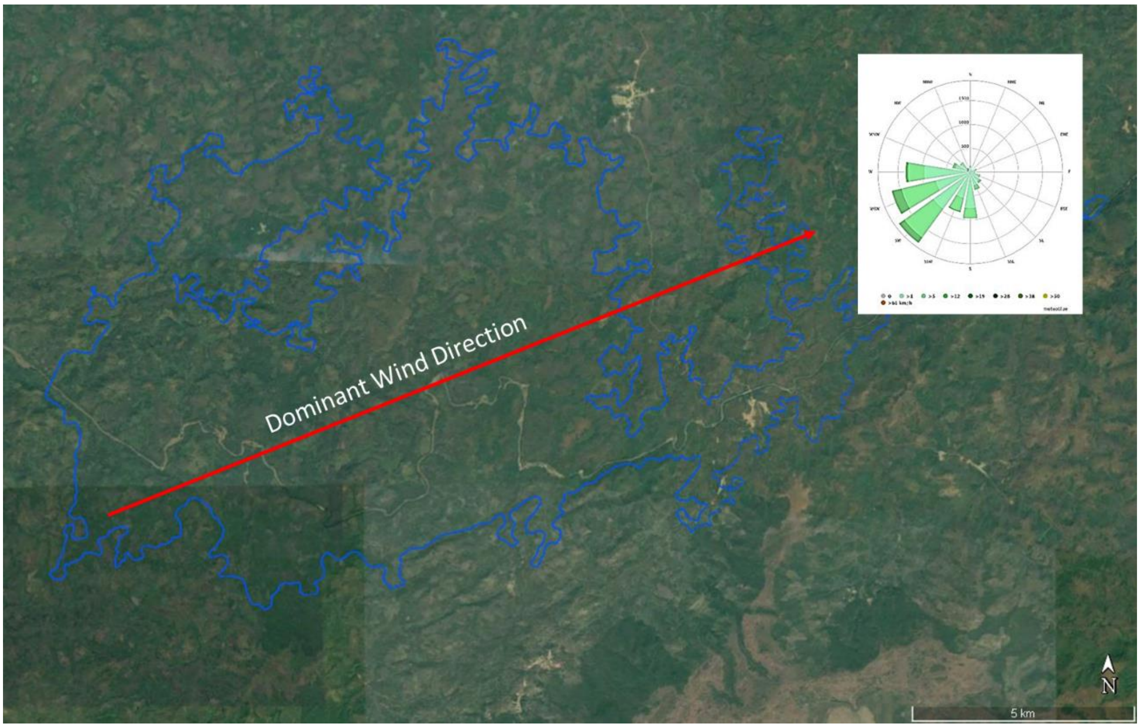

Figure 4-2: Wind rose for Cape Sierra Leone (presumed to reflect an annual composite), extrapolated to the FSL outline of Yiben Reservoir.

Assuming that Yiben Reservoir will broadly conserve the water temperature range measured in the influent Seli River (Nippon Koei *et al*. 2006; Payne *et al*., 2010), the derived temperature-elevation regressions presented in that study indicate a likely temperature range for Yiben Reservoir of 19.4 to 26.2 ˚C (based on an elevation of 300 m - 20 m below its FSL elevation) – rather conservative compared with the corresponding air temperature range of 24.2 to 28.9 ˚C. Presuming the cool season temperature of 19.4 ˚C will pertain during full mixing (holomictic isothermy), and persist below waters heated up to 26.2 ˚C, at the surface, a moderately high Brunt-Väsäilä stability value (N^2/s – equation below) of 0.01568 can be expected, certainly sufficient to maintain moderate to strong thermal stratification.

$N^2 = (-g/\rho o)(\partial\rho/\partial z)$ where
$g = 9.81\ \mathrm{m/s}$, and $\partial\rho/\partial z = \text{density gradient of water column of mean density } \rho o$.

For comparative purpose in support of this contention, it is relevant to note that stratification occurs in two other man-made lakes in West Africa (Lake Kainji in Nigeria, and Volta Lake in Ghana) (**Table 4-2**). These waterbodies are both much larger and topographically more exposed than Yiben, and receive major inflow pulses from their much large feeder rivers. Both wind fetch and strength, along with water inflows differing in density from a recipient lake generally influence the development, depth and intensity of thermal stratification. In Lake Kainji, thermal discontinuity was strongest between 5-10 and 15 m. The

N^2 values for Lake Kainji interpolated from its temperature-depth isopleth plot (Henderson 1973) are comparable to the projected value for Yiben (**Table 4-2**). Data was not accessible to run a parallel simulation for Lake Volta, although it shows thermal stratification (Viner 1970) within its seasonal water temperature range of roughly 27.8-31.8 °C (Amakye 2001).

Table 4-2: Comparative temperature-depth (m vs T) profiles and corresponding Brunt-Väsäilä stability values (N^2 x 10-3). The Yiben profile is a constructed 5 m interval simulation using the maximum-minimum temperature range (not all values tabulated*); profiles for Lake Kainji reflect mid-month measurements interpolated from Henderson (1973 - Figure 4-2)

Yiben Reservoir* Hypothetical		Lake Kainji							
		Dec 1969		Mar 1970		Oct 1970		Feb 1971	
m	T*	m	T	m	T	m	T	m	T
0	26.2	0	27.8	0.0	28.5	2.7	28.0	0.0	26.5
5	25.8	10	27.5	2.7	28.0	5.2	27.5	0.6	26.0
10	25.3	20	27.5	5.2	27.5	7.6	27.0	1.2	25.5
15	22.9	30	27.5	7.6	27.0	10.7	26.5	2.1	25.0
20	20.1	40	27.5	10.7	26.5	13.4	26.0	3.4	24.5
30	19.8	50	27.5	13.4	26.5	15.0	25.5	5.2	24.0
40	19.6			15.0	25.5	26.0	25.0	15.3	23.5
50	19.4			26.0	25.5			30.5	23.0
Mean °C	21.6		27.5		26.8		28.5		24.8
N^2 x 10^{-3}	**15.68**		**0.00**		**9.39**		**5.59**		**8.74**

The design indicates placement of the turbine intake tower at 292 m asl – 28 m below FSL and 15 m (or 20 m) below MOL (Lahmeyer International GmbH. 2013b). Should thermal stratification develop at depths below about 15 m, water take-off for power generation is thus likely to disrupt or destabilize stratification.

Thermal stratification is potentially also influenced by river inflows to Yiben Reservoir. The density of inflow water depends on its temperature, dissolved solid and suspended sediment content, and relative to the contemporaneous density of water in the recipient lake water, results in various inflows ranging between three characteristic patterns. Inflows can sink to the lake bed as deep plunging plumes, overly the lake in surface overflow plumes, or penetrate as interflow plumes at a particular depth. Interflows are the most likely to disrupt established thermoclines. At this point, however, no realistic forecast can be made regarding which inflow pattern is likely to occur.

4.3. CHEMICAL WATER QUALITY ATTRIBUTES

The Seli River serves as a reasonable proxy for the water quality (**Table 2-3**) likely to prevail in Yiben Reservoir. Conservative chemical features such as its low TDS and conductivity are certain to persist in Yiben Reservoir, implying that its total nutrient content will also be low. Thermal stratification can be expected to affect certain parameters such as dissolved oxygen content, with a cascading influence on chemical components that are influenced by prevailing redox potentials.

Nutrient chemistry is of central contextual relevance for this eutrophication risk assessment. Probable concentrations of nutrients, particularly phosphorus, are examined in **Sections 5.3** and **Section 5.4** below.

5. EUTROPHICATION RISK ASSESSMENT

5.1. ASSUMPTIONS AND LIMITATIONS

The validity of any risk assessment depends on the availability, reliability and accuracy of pertinent data used in predictive models. For the Yiben Reservoir, uncertainty exists in the empirical data available – which is limited, either spatially and/or seasonally. Contradictory statements regarding nutrient status exist within and between various reports, which often provide little or no factual data for independent consideration of conflicting opinions. For example, compare excerpts a) and b) with c):

a) "The **low concentrations** of salts and **plant nutrients** occur despite heavy runoff in the wet season, because …. land in the catchment is low in fertility, as soluble and insoluble components have been leached out by rainfall and rainfed agriculture, and erosion of soil from areas cleared to provide land for agriculture" (page 76 - Nipon Koei et al., 2005b).

b) "Results from the various analyses (Table 7.2.8-1) show that water quality in the [Seli] river is relatively good throughout its length, with the main characteristics being **low concentrations** of dissolved salts and **plant nutrients** (page 149 -Nipon Koei et al., 2005b, – whose Table 7.2.8-1 provides no recent indicative data for phosphorus).

c) "The chemical analysis that is available for the inflowing water suggests **high concentrations of phosphate** and low concentration of inorganic Nitrogen. High concentrations of phosphate from granitic rocks would normally be accompanied by high concentrations of silicate…" (page 228 - Nippon Koei *et al*., 2006c); bold emphases added by present author.

Since various hydrological data are required to estimate eutrophication risk, disparate data values specified regarding annual inflow volumes into Yiben (**Table 4-1**) contribute further uncertainty.

In the present case, predictive modelling projections of possible trophic status (nutrient levels), and thereby eutrophication risk for the presently non-existent Yiben Reservoir, are necessarily based on uncertain, presently unverifiable (and empirically untestable) input data. This has required the use of various interpolations and extrapolations, along with experience-based assumptions (informed by long-standing personal practice). Predictive modelling aims to accomplish the statistical and biological criteria of simplicity, reality, generality, and accuracy (Gilpin & Ayala 1973). In practise, however, it is widely recognized that only two of the three foremost ideals – generality, reality and accuracy – are generally simultaneously achievable within the constructs of a single model.

For the following risk assessment, it is accordingly essential to recognize resulting inherent limitations – primarily reflecting limitations and uncertainties of available data as requisite inputs for the predictive models selected for use here.

5.2. BASIC METHODOLOGY FOR TROPHIC/NUTRIENT STATUS PREDICTIONS

Trophic status assessments are customarily based on empirical values determined for an existing waterbody, perhaps most commonly employed as *post-hoc* tests of the efficacy of various interventions undertaken to mitigate the severity of eutrophication and/or to determine what nutrient levels can be 'assimilated' by a system, the Maximum Permissible Loading (MPL per specified time unit) before it is likely to manifest the undesirable symptoms of nutrient pollution.

Advance prediction of trophic status is nonetheless founded on similar conceptual notions – essentially that input-output flux and overall balance determines the outcome (nutrient concentration). Input and output assessments are addressed in the following two sections.

5.3. NUTRIENT EXPORT COEFFICIENTS – INPUT LEVEL PREDICTION

The prediction of lake/reservoir nutrient content rests on a simple and logical approach – the determination of input loads of the nutrient element of concern – generally Phosphorus and Nitrogen. Such inputs derive mostly from surface runoff from drainage basins, although atmospheric precipitation (deposition of organic ash) sometimes makes a significant contribution to the total. While the origin of loadings in catchment runoff are generally of a 'diffuse' nature, 'direct point source' contributions arising from anthropogenic discharges of various effluents are rising sharply because of rising population size, and associated development.

Since diffuse loading rates are related to land forms (geology, soil, etc.), vegetation types (forest, scrub, grasslands, marshlands etc.) and land use practices (dryland or irrigated croplands – fertilized or not, extensive or intensive livestock rearing, etc.), nutrient export coefficients derived for catchment-specific vegetation types and agricultural practices are required to estimate total nutrient load accurately. In the absence of catchment-specific values, as is widely the case, various generic values are used to estimate total nutrient loading rates. Application of this generic proxy approach depends on the regional applicability of the coefficients used (see Wilson 2005). Lamenting the absence of regionally-specific coefficient values derived specifically for African conditions, Thornton & Harding (2003) and Harding (2008), among many more practitioners, have had to resort to using coefficient values determined elsewhere, with or without modification. In this regard, it is important to justify the selection of a particular value (Wilson 2005). The export coefficients applied here (see **Table 5-2**) were compiled from various sources (*inter alia* Holdren *et al*., 2001, Thornton & Harding 2003, Wilson 2005, Harding 2008).

For this pilot eutrophication risk assessment, export coefficients for TP (kg/ha/yr) were applied to aggregated vegetation types and land-use practices (**Table 5-2**), and summed across categories to provide area-weighted TP loads from the entire catchment (kg TP/yr). Given the inherently limited soil fertility in the region (**Section 2.1**), more conservative lower coefficients were selected as the most appropriate, although different loading values were applied to predict outcomes in a range of alternative loading scenarios (**Table 5-2**).

5.4. PREDICTING LAKE NUTRIENT CONCENTRATIONS AND RELATED TROPHIC STATE CLASSIFICATION

A wide array of empirical models exists to predict in-lake nutrient content from total nutrient load levels, variously adjusted for system-specific hydrological and morphological attributes of the receiving waterbody. Collectively, these are often termed Vollenweider-OECD models.

Many alternative predictive models, largely derived from the original Vollenweider concept, have arisen from attempts to incorporate specific regional features and other 'special cases'. Harding (2006 – **Table** 2-2) lists 13 such variants.

No empirical data exist to test (validate) the respective predictions of any model for a non-existent water body. Accordingly, respective predictions of three widely-used 'default' models, namely the Vollenweider (1975) Lake Model, the OECD Combined Model (1982), and the Walker (1987) Reservoir Model were compared empirically. Their resulting outputs were sufficiently similar for application in this pilot eutrophication risk assessment (**Table 5-2**). Their predictive formulas for calculating average nutrient concentration are specified below for Phosphorus (P), although, they are applicable to other nutrient elements of interest (N, Si, etc.).

1. Vollenweider General Lake Model:

$$[\mathrm{P}] = \mathrm{L}/(\mathrm{qs}\ (1 + \sqrt{\mathrm{Tw}})) \qquad \text{or} \quad [\mathrm{P}] = \mathrm{L}/(10 + \mathrm{zRw})$$

2. Combined OECD Model:

$[\mathrm{P}] = 1.55(\mathrm{Pj}/(1+\sqrt{\mathrm{Tw}}))^2$ or $[\mathrm{P}] = \mathrm{L}/(10+\mathrm{zRw})$

3. Walker reservoir Model:

$$[\mathrm{P}] = (\mathrm{L\ Tw}\ (1-\mathrm{R}))/\mathrm{z}$$

Where $\mathrm{R} = 1 + (((1-\sqrt{((1+4\ \mathrm{Nr})))}/(2\ \mathrm{Nr}))$

$$\mathrm{Nr} = (\mathrm{K_2 L}\sqrt{\mathrm{Tw}})/\mathrm{z}$$
$$\mathrm{K_2} = (0.17\ \mathrm{qs})/(\mathrm{qs}+13.3)$$

[P] = average in-lake concentration (mg P/m3)
Pj = mean annual inflow concentration (mg P/m3)
L = annual areal loading of Phosphorus (mg/m2/yr)
qs = annual areal water loading rate (m/yr)
Tw = hydraulic retention time (years)
Z = mean depth of water body
Rw = storage volume/inflow (per time unit)

Table 5-1 shows the resulting predictions of concentrations, based on different export coefficient values, and hydrological regimes. The estimates firmly indicate that the desirable low trophic status level of oligotrophy (< 10 mg/m^3 class boundaries in **Table 1-1**) can be expected when realistic export coefficients are used (Scenario 1 and 2). Substantially elevated export coefficients (Scenario 3) predict only mesotrophic waters (< 35 mg/m^3). Only the worst-case model (Scenario 4), based on highly improbable nutrient export coefficient maxima, predicts an entry into the unacceptably high level of eutrophy; the least tolerable condition of hypertrophy is not approached.

All model predictions are closely similar in Scenarios 1 and 2. In the higher export coefficient scenarios, most conservative predictions result from the Walker reservoir model, while the Vollenweider general lake model makes the highest predictions. The influence of hydrological variation on trophic status was examined using the Walker model. The results indicate that predicted inlake [P] are not greatly different across the range of inflows (**Table 5-2**).

The export coefficient represents the input driver of nutrient loading to the reservoir (i.e nutrients from the catchment entering the reservoir), and bears no relation to nutrient output from the reservoir. The dominant driver of an eutrophication risk within the reservoir relate to nutrient input (i.e. the capacity of the catchment to provide significance sources of nutrients. In this regard, the more realistic scenarios in **Table 5-1** predicts a low nutrients exports capacity for the catchments in question.

Models prediction presume that vegetation biomass within the inundation zone will remain intact. The removal of vegetation within the inundation zone, is not expected to result in a significance nutrient source or nutrient build-up. An initial nutrient upsurge is likely as herbaceous and woody matter decomposes (see **Section 5.7**) but it is unlikely that this will result in an increase in the trophic status classification of the reservoir.

Similarly, the low background nutrient levels associated with the soil, renders any subsequent disturbance of the soil (for instance through increased erosion rates or artisanal mining) as a low nutrient source risk This notion is consistent with the existing observation of low nutrient levels is oligotrophic in Bumbuna I reservoir despite historical and ongoing artisanal mining.

Table 5-1: Scenario modelling: application of different export coefficients, different predictive models, and different hydrological inflow regimes. *Disparity* based on assumed instream [P] of 2 mg/m^3 (below measured values in Table 3-1). ‡ Dilution estimate determined as quotient of total export load and Yiben volume at FSL

Scenario:	**1 MIN**	**2 MTDL**	**3 MIDPT**	**4 HIGH**
Land-use category	**Export coefficients applied kgP/ha/yr**			
Scrubland	0.02	0.04	0.345	0.67
Barren cultivated farmland	0.02	0.04	0.345	0.67
Clear mountain	0.02	0.04	0.345	0.67
Barren Land	0.02	0.04	0.345	0.67
Intense Agric	0.05	0.075	0.5	0.75
Other Land	0.02	0.1	0.2	0.25
Rain	0.1	0.1	0.1	0,1
Total load (kg P/yr)	14 601	21 086	98 164	195 477
Export/stream [P] disparity	5.4	7.8	36.4	72.5
Phosphorus concentration (mg/m^3) Predicted at mean Seli River inflow				
‡ 'Dilution' estimate of stream [P]	8.1	11.7	54.6	108.8
Vollenweider prediction	4.8	7.0	32.5	64,6
OECD prediction	5.6	7.6	26.9	47,3
Walker prediction	5.9	7.5	19.4	28.6
Walker predictions of [P] under different inflow regimes				
Seli River inflow (Mm3/yr) Mean: 1 348	5.9	7.5	19.4	28.6

	Max: 1 797	5.1	6.6	17.5	26.2
	Min: 890	7.3	9.1	22.5	32.8
Max: Min ratio		1.43	1.38	1.29	1.25
Mean flow [P] prediction model		**Chlorophyll predicted from [P]**			
Vollenweider		0.9	1.4	6.3	12.6
OECD		1.1	1.5	5.3	9.2
Walker		1.2	1.5	3.8	5.6

5.5. CHLOROPHYLL CONCENTRATION PREDICTIONS

Relationships between Chlorophyll and Phosphorus are well established, and described in the generic OECD equation:

$$\text{Chlorophyll} = 0.37([P]/(1 + \sqrt{tw}))0.79$$

Assuming this equation is suitable for Yiben Reservoir, predicted Chlorophyll values across the range of Phosphorus concentrations tested align directly with the corresponding trophic state level classification based on Phosphorus (**Table 5-1**). However, as Chlorophyll is contextually irrelevant to hydro-power production, it is not considered further in this eutrophication risk assessment.

5.6. CRUDE 'VALIDATION' OF EXPORT COEFFICIENTS THROUGH BACK-EXTRAPOLATION OF RIVER NUTRIENT VALUES

Given the uncertainty of the export coefficient values applied, a crude 'hind-cast' order of magnitude test of their likely aggregate representability was planned, using direct back-calculations from Phosphorus concentration values measured in the Seli River (**Table 2-3**). However, as too few measurements were available for this purpose, 2 mg/m^3 was applied as an approximation. Results of this crude analysis labelled '*Export/stream [P] disparity*' in **Table 5-1** indicate that back-extrapolated approximations of total nutrient load are 5 to 8-fold lower than input nutrient loads determined for the more plausible Scenarios 1 and 2 export coefficients. The differences, although quite substantial, reconcile with causally attributable nutrient attenuation known to result from biological and chemical sequestration that occurs during down-stream overland, in-stream or underground passage of water.

5.7. POST-IMPOUNDMENT CHANGES IN TROPHIC STATUS – TIME-LINE PROJECTIONS

Some ‘trophic upsurge’ can be expected during the reservoir filling phase and can be expected to persist for some time thereafter. This results from the release of nutrients (either organically-bound or inorganic) from drowned soils. However, trophic upsurge is not expected to be pronounced in Yiben, for various reasons:

a) soils in the inundation area are likely to be as inherently nutrient poor as in the catchment generally;
b) larger woody vegetation in the inundation area is planned to be harvested and removed for use elsewhere;
c) and more importantly, flushing time is relatively short (~ 1.5 vs. > 4 years for Kariba (Magadza 2010)). On the latter basis, Yiben Reservoir is likely to experience an accordingly relatively short ‘stabilization’ phase before attaining a resulting ‘mature’ phase, when trophic status will be determined by future catchment conditions (presently unforeseeable land-usage and development state).

5.8. NITROGEN SUPPLIES AND INFLUENCES OF N/P RATIOS

Nitrogen is recognised as being a potentially stronger autotroph growth-limiting factor than Phosphorus in tropical inland waters. While analyses of Nitrogen input loads and in-lake retention can be made using approaches broadly in line with those applied above to Phosphorus, such determinations were not made, mostly since even less information is available regionally for Nitrogen than for Phosphorus.

Nonetheless, it should be noted that the composition of autotroph communities can be influenced by the Nitrogen to Phosphorus (N/P) ratio, often favouring cyanobacteria, many of which can fix atmospheric Nitrogen, and thereby predominate where N/P < 8. While the composition of the planktonic autotroph assemblage that arises has little contextual relevance on power-generation, it can threaten the potability of water. In this regard, the production of cyanotoxins by some cyanobacteria under certain conditions is singularly relevant. If carried downstream, such cyanotoxins potentially have a detrimental influence on riverine biota.

5.9. FACTORS POTENTIALLY REDUCING EUTROPHICATION RISK

The trophic status classification resulting from this analysis (**Section 1.4**) may be 'unfavourably' biased by application of export coefficients that plausibly over-estimate nutrient input levels derived from well-flushed low nutrient level soils. A related potential bias arises from the extrapolation of land-type distributions in the more intensively used sub-catchment 'sample area' to the entire drainage basin. Such errors are indirectly 'covered' superficially in the scenario modelling undertaken.

Whether or not in-lake nutrient concentration is over-estimated, predicted values are unlikely to translate directly into commensurate levels of autotroph growth (**Section 5.7**) because of light-limiting impacts of suspended mineral particles. The settling time of such particles is related inversely to size. Presuming these are mostly small (clay colloid-like), they are more likely to remain suspended than to settle fully within the ~ 1.5 years reservoir flushing time.

5.10. EUTROPHICATION RISK PROBABILITY (SUBJECTIVE RATING)

On balance, the risk of eutrophication occurring to any significant degree in Yiben Reservoir appears negligible or marginal. While this subjective rating derives from limited and intrinsically uncertain data, as indicated in **Section 5.1**, the assessment is considered reasonably secure. The compilation of forecast values shows that in the most likely cases examined (Scenarios 1 and 2), predicted [P] levels will lie well within the OECD's oligotrophic class boundaries. TSI forecasts, based on Phosphorus, are understandably similar, while values of MEI are likewise remarkably low (**Table 5-2**).

Table 5-2: Synopsis of derived forecast values, illustrating clear concordance in predicting the likelihood of low 'infertile' trophic status for Yiben Reservoir. MEI estimates cover a nominal conductivity level range of 5 to 50 µS/cm

	[P]	TSI	MEI
Oligotrophy: upper limit	10.0	38.0	n/a
Vollenweider	4.8 - 7.0	26.9 - 32.2	0.21 to 2.07
OECD	5.6 - 7.6	29.1 - 33.4	
Walker	5.9 - 7.5	29.7 - 33.3	

6. MANAGEMENT CONSIDERATION

Several future determinations are suggested, mostly to 'validate' the interpretations and conclusions presented here.

6.1. WATER CHEMISTRY

Ahead of Yiben Reservoir construction, determined efforts should be made to acquire reliable and accurate measurements of Total Phosphorus and Total Nitrogen content in the Seli River near the planned Yiben Reservoir wall. Determinations should be made at quarterly intervals to discern any underlying seasonal pattern that may exist.

Corroboration of the findings (above) made for river water through parallel determinations on water collected from various depths in the Bumbuna Reservoir itself (near-surface, midwater and deep water) would be very beneficial, and even more so if accompanied by parallel determinations of Chlorophyll in surface/sub-surface zone of Bumbuna. Three locations are recommended for sampling in Bumbuna Reservoir (below river inflow, near dam wall, and roughly mid-way along the length of Bumbuna).

6.2. THERMAL STRATIFICATION

The reality of projections regarding the development of thermal stratification cannot be tested until Yiben Reservoir is a reality. Nevertheless, vertical profiling of water temperature in the Bumbuna Reservoir may hint at the prospects of its development in Yiben Reservoir, although the morphological features, and particularly the hydrological management of Bumbuna will be confounding influences. Examination of thermal profiling records, if undertaken as previously recommended (Nippon Koei, 2005c), could pre-emptively assist in optimizing the time-scheduling of further measurements.

Design specifications for Yiben (Lahmeyer International GmbH, 2013) anticipate that thermometers will be incorporated with strain gauge instrumentation at various depths in the dam wall, or otherwise as independent installations at 319.8, 315.0, 310.0, 300.0 and 280.0 m asl on the upstream face. Periodic, or at least once-off or cross-calibration of these temperature readings with closer-interval temperature-depth profiling in unsheltered, deep-water sites in Yiben Reservoir would assist in the future management of the dam, particularly with regard to its environmental flow releases.

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8. APPENDIX A: *PROFESSIONAL RÉSUMÉ: R. C. HART*

Date of birth 21 July 1947

Qualifications

1967 – BSc (University Natal, Pietermaritzburg) - majoring in Botany and Zoology
1968 – BSc (Hons) Zoology (University Natal, Pietermaritzburg)
1974 – PhD (Zoology, Rhodes University, Grahamstown)
1994 – DSc (Zoology, University of Natal, Pietermaritzburg)

Positions held

2007 to date	Professor Emeritus, Honorary Researcher, University of KwaZulu-Natal
1994 to 2007	Professor, Department of Zoology & Entomology, University of Natal and thereafter University of KwaZulu-Natal
1992	Research Fellowship, Max Planck Institute of Limnology, Germany
1990 to 1993	Associate Professor, Department of Zoology & Entomology, University of Natal
1987 to 1989	Senior Lecturer, Dept of Zoology & Entomology, University of Natal
1984/1985	Visiting Professor, Royal Holloway College, University of London
1982 to 1987	Professor of Limnology (Endowed Chair), Rhodes University
1978 to 1981	Senior Research Officer, Institute for Freshwater Studies, Rhodes University
1975	Postdoctoral Fellow, DALHOUSIE UNIVERSITY, Halifax, Canada
1973 1977	Research Officer, Institute for Freshwater Studies, Rhodes University
1969 1972	Lake Sibaya Research Fellow, Institute for Freshwater Studies, Rhodes University
1971 to date	Member of various CSIR, WRC, NRF/FRD and various university research and/or evaluation panels and research steering committees.

Professional expertise as general Biological Scientist and specialized Aquatic Ecologist

Nearly 50 years' experience in fundamental biology and ecology of aquatic biota (mostly planktonic and benthic organisms), and ecosystem functioning and management (with special focus on coastal lakes and reservoirs). Work in various research projects on fundamental biology and ecology of specific organisms and ecosystems, investigating a range of practical and applied ecological issues and problems, including:

- impacts and consequences of high turbidity (suspended particles) and of high nutrient loading (eutrophication) on ecological structure and functioning of such ecosystems and their biota;
- determinants of plankton periodicity in warm-water/subtropical systems;
- special focus on biology and ecology of planktonic algae and crustaceans (as well as freshwater shrimps), and their role in food webs and ecosystem productivity.

Ecosystems investigated include:

- Coastal subtropical lakes (Sibaya, Bhangazi South in RSA; Chidenguela lakes in Mozambique; Macae lakes in Brazil);
- African Great Lakes (Malawi, Victoria);
- River reservoirs (Laing and Bridle Drift Dams – Buffalo R.; Midmar, Albert Falls and Nagle Dams – Umgeni R.; Hartbeesport Dam – Crocodile R.; Rietvlei Dam – Hennops R., Spioenkop Dam – Thukela R.; Wagendrift Dam – Bushmans R.); and
- Wetlands (Okavango Delta).

Diverse lecturing portfolios, including: – Structural and functional biology of invertebrates; General population, community and ecosystem ecology; African inland waters; Conservation biology and ecology; Biological and ecological experimentation and data analysis (principles and practices); Theoretical and practical limnology.

Academic Honours:

- NRF B-rating (international recognition of scientific research contributions and endeavours) between 1997 and 2009, preceded by NRF C-rating since ca. 1985, and since 2010.
- DSc (Senior Doctorate, based on published outputs).
- Fellow, University of KwaZulu-Natal (2005).
- Professor Emeritus, University of KwaZulu-Natal (2007).
- Gold Medal award of Southern African Society of Aquatic Sciences (2017).

Academic Outputs and Services:

- Approximately 110 peer-reviewed journal articles, 5 book chapters, 1 co-authored book, 15 published reports, 22 published book reviews and popular articles dealing with aquatic ecosystems and environmental issues.
- Regular (roughly annual) attendance and presentations (including plenary addresses) of local and international (overseas) conferences.
- Supervision of 5 MSc and 1 PhD candidates, and co-supervision of 5 MSc candidates.
- External examiner of local and international PhD and MSc dissertations.
- Referee (at different times) for 20 national and international journals; editorial board member and services on various international journals (e.g. Limnology (Berlin), Limnologica, Aquatic Ecology, Freshwater Reviews).

Professional Membership

- Registered with South African Council for Natural Scientific Professions as Professional Natural Scientist (Pr.Sci.Nat. 1163/83) in 1983. Registration allowed to lapse in 1992 view of its practical irrelevance for a University academic.
- Membership of: Southern African Society of Zoology (ZSSA); Southern African Society of Aquatic Scientists (SASAqS); International Limnological Society (SIL); Royal Society of South Africa (Roy Soc SA). Sometime member of: Freshwater Biological Association (FBA); World Association of Copepodologists (WAC); Natal Evolutionary Biology Society (NEBS).