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Main features of the Nam Theun 2 hydroelectric project (Lao PDR) and the associated environmental monitoring programmes

Principales caractéristiques de l'aménagement hydroélectrique de Nam Theun 2 (Laos) et programmes de suivi environnementaux

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Abstract – The Nam Theun 2 hydroelectric Project is located in Lao PDR on the Nam Theun River. The reservoir impoundment started in April 2008 and hydropower generation began in March 2010. The reservoir has a total volume of 3.9 billion m^3, covering an area of 489 km^2 at full supply level and 86 km^2 at the minimum operating level. The performance is 1070 MW and the annual production is 6 TWh. The reservoir is operated seasonally by storing water during the wet season. A system of tunnels and channels diverts the waters from the Nam Theun watershed to the Xe Bangfai watershed. An ambitious environmental monitoring programme of project sites was launched by EDF - NTPC in 2008 and remains operational. An on-site laboratory was established to ensure sampling and analysis in real time. The compartments studied are water quality, greenhouse gas emissions, phytoplankton, zooplankton, benthic macroinvertebrates and fish. A 3D numerical model was developed based on monitoring data to predict the long-term changes in water quality and greenhouse gas production of the reservoir. Additional research programmes have been launched to understand bio-chemical dynamics and processes.

***Key words* –** Nam Theun 2, dam, sub-tropical reservoir, impoundment, environmental monitoring

Résumé – Le projet hydroélectrique de Nam Theun 2 se situe au Laos sur la rivière Nam Theun. Le réservoir a été mis en eau en avril 2008 et la production hydroélectrique a commencé en mars 2010. Il couvre une superficie totale de 489 km^2 à la cote maximale et 86 km^2

à la cote minimale d'exploitation. Le volume total du réservoir est de 3,9 milliard de m^3. La puissance totale est de 1070 MW pour un productible de 6 TWh. L'aménagement est géré de façon saisonnière en stockant les eaux pendant la saison humide. Il dérive les eaux de la Nam Theun vers le bassin versant de la Xe Bangfai. Un programme ambitieux de suivi des effets sur l'environnement a été conduit par EDF et NTPC dès 2008. Toujours en activité, ce programme a nécessité la mise en place d'un laboratoire sur site pour assurer les prélèvements et analyses en temps réel. Les compartiments étudiés sont la qualité des eaux, les gaz à effet de serre, le phytoplancton et le zooplancton, les macro-invertébrés benthiques et les poissons. Un modèle numérique 3D a également été élaboré à partir des données du suivi afin de prévoir l'évolution du réservoir en termes de qualité des eaux et de production de gaz à effet de serre. Des programmes de recherche complémentaires ont été lancés en parallèle afin d'apporter des éléments de réponses à certains problèmes spécifiques.

Mots-clés **–** Nam Theun 2, barrage, réservoir sub-tropical, mise en eau, suivi environnemental

1 INTRODUCTION

Southeast Asian economies are developing fast and large parts of the growing electricity demand will be sourced by hydropower. The Mekong watershed was identified for numerous hydropower projects. Among the countries surrounding the Mekong basin, the Lao People's Democratic Republic (Lao PDR) harbours a high hydropower potential.

The hydroelectric potential of the Nam Theun River on the Nakai Plateau was for the first time mentioned in 1927. In 1994, the Nam Theun 2 Electricity Consortium (NTEC) was created to plan and design the Nam Theun 2 (NT2) Project. It included a comprehensive environmental and social impact assessment and was supported by the World Bank, the Agence Française de Développement, the Asian Development Bank and the Government of Laos. The NT2 Project is part of the 7000 MW electricity export programme between Laos and Thailand. By 2004, NTEC transferred the development and implementation responsibility to the newly founded Nam Theun 2 Power Company Ltd. (NTPC). NTPC is a shareholder company, owned by Electricité de France International (EDFI, 40%), Lao Holding State Enterprise (LHSE, 25%), Electricity Generating Public Company Limited (EGCO, 35%). NT2's construction works began in 2005 consecutive to the finalization of the Concession Agreement (CA). The construction was completed in 2009, the hydropower generation in March 2010 and commercial operation began in April 2010.

The CA defines environmental and social obligations, some of which last throughout the concession period. The implementation of the environmental and social programmes is monitored by various external agencies including the technical advisors of the lending agencies, the Laotian Government through the Panel of Experts and Independent Monitoring Agencies, independent consultants and multilateral development institutions (NTPC, 2004). The social and environmental safeguard standards of the World Bank and the Asian Development Bank are built into the CA to minimise and mitigate social and environmental impacts. By early 2008, the Hydro Engineering Centre of EDF (CIH) and NTPC decided to implement an environmental monitoring programme to conduct a comprehensive study of the evolution of the aquatic ecosystem consecutive to the impoundment of the reservoir.

The objective of this article is to present the NT2 Project including: (i) the main features of the project, (ii) the description of the period from impoundment to normal operation and (iii) the environmental monitoring programme of the reservoir impoundment. This article is an introduction of a series of articles included in the special issue "NT2 Environmental Studies" of "Hydroécologie Appliquée" that presents the chemical, biological and modelling results of the monitoring programme implemented by EDF CIH and NTPC.

2 MAIN FEATURES OF THE PROJECT

2.1 Nam Theun and Xe Bangfai Rivers catchments

The project area is located in the centre of Lao PDR (Khammouane Province) on two sub catchments of the Mekong River. It is a trans-basin project: the reservoir is located on the Nakai Plateau in the Nam Theun watershed, while electricity generation facilities and water release are in the Xe Bangfai watershed (Figs. 1 and 2).

The project area is characterised by a sub-tropical monsoon climate with three distinct seasons: warm-wet (June to October), cool-dry (November to February) and warm-dry (March to May). Most of the annual runoff occurs in the wet season (around 90%). Maximum recorded precipitation was 390 mm day^{-1} (2011) and the annual average rainfall was 2432 mm year^{-1} (1995-2013; NTPC, OMD Data). Over the period from 1987 to 2002, the average temperature recorded at the Nakai plateau was 3 °C cooler than in the Mekong valley due to the difference of altitude (SMEC, 2003). The mean annual temperature on the plateau is 22.6 °C with an average of 33.0 °C in April (hottest month) and an average of 9.6 °C in January (coldest month).

Some average and extreme discharge values of the rivers, prior to construction, are shown in Table I. The lowest mean daily discharge recorded in the Nam Theun River at the dam site was 4.4 m^3 s^{-1} in April 1986 (SMEC, 2003) and the 100 years return flood was estimated at 6134 m^3 s^{-1} (EDF-DTG, 2013). The Nam Theun River mean annual inflow is 238 m^3 s^{-1} (Tab. I), sourced by its tributaries: Nam On, Nam Yang, Nam Noy, Nam Mon and Nam Xot Rivers flowing from mountains North-East (Fig. 1). As the river discharge is directly related to precipitations, there is a high difference of inflows between the dry and the wet season (Tab. I). The total annual runoff from the catchment area at the Nakai Dam site is about 7526 million m^3 (SMEC, 2003). The NT2 Project diverts the water from the Nam Theun to the Xe Bangfai catchment. Discharge into the Downstream Channel and the Xe

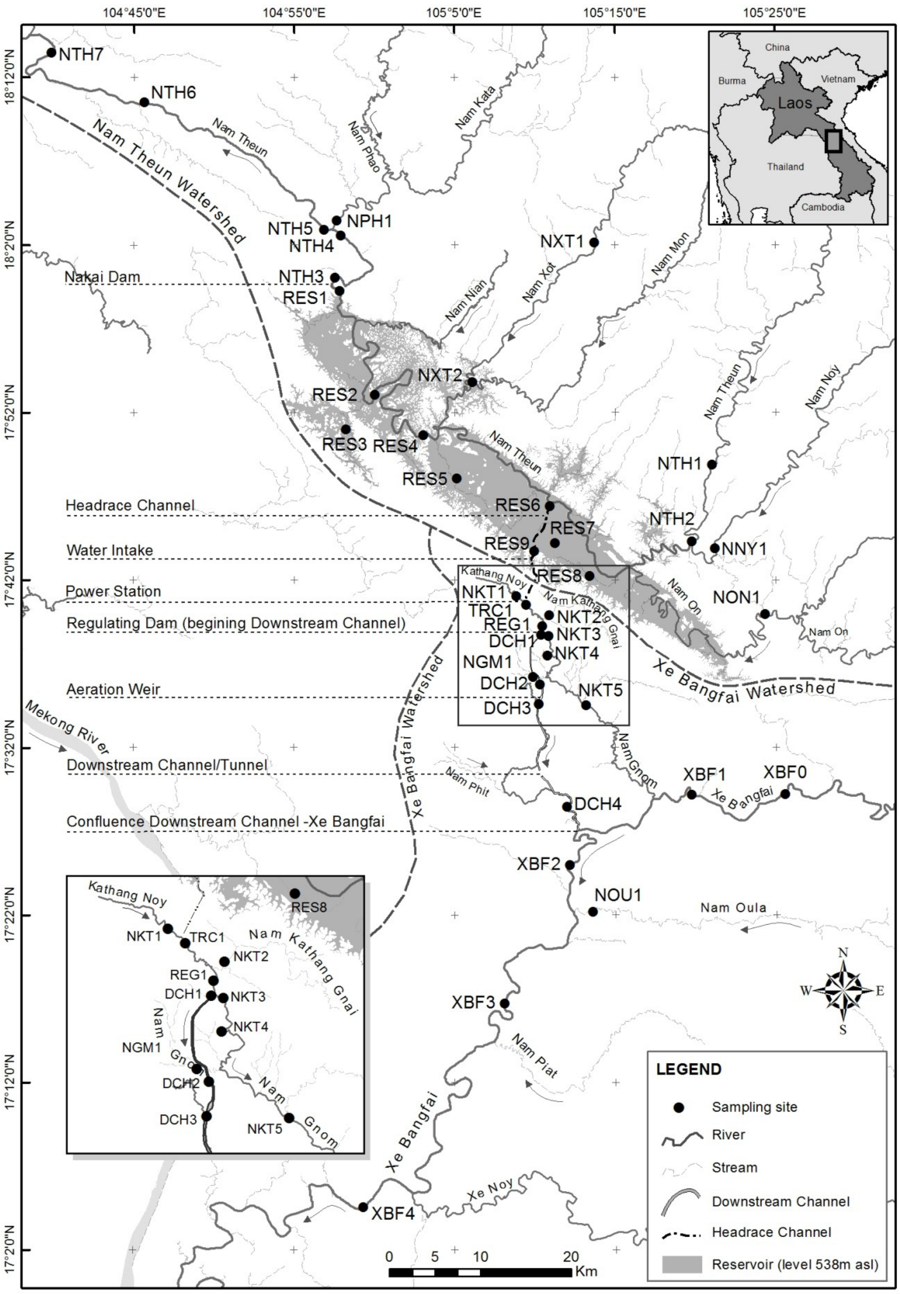

Fig. 1. Location of the NT2 site and monitoring stations.

Fig. 1. Cartographie du site de NT2 et des stations de suivi.

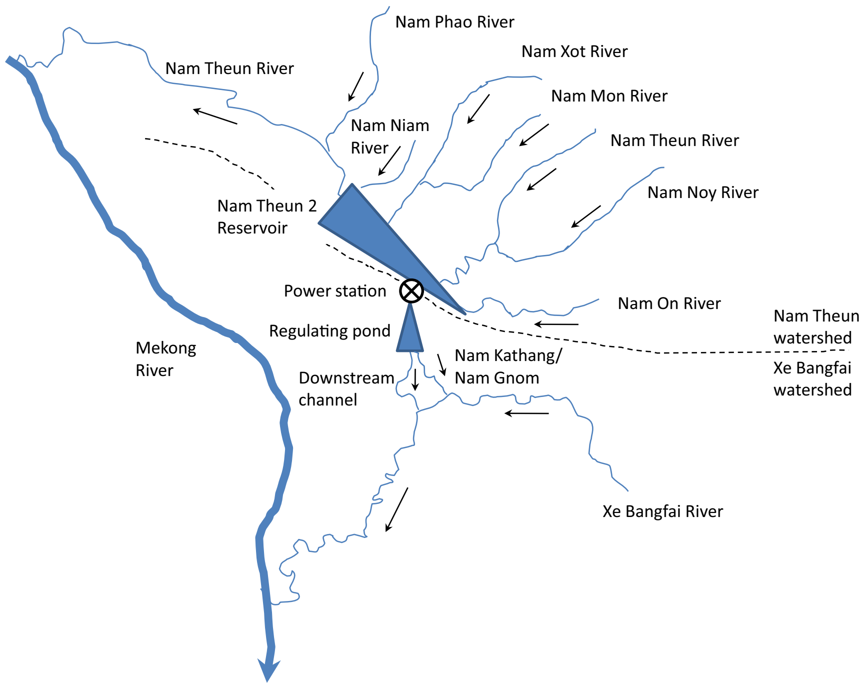

Fig. 2. Hydraulic scheme of the Nam Theun and Xe Bangfai bassins.
Fig. 2. Schéma hydraulique des bassins de la Nam Theun et de la Xe Bangfai.

Table I. Characteristics of the rivers, discharges presented are in $m^3\ s^{-1}$ (NTPC, 2004).
Tableau I. Caractéristiques des rivières en $m^3\ s^{-1}$ (NTPC, 2004).

Stations	Data series	Mean annual discharge	Mean driest month	Mean wettest month
Nam Theun at the Dam site	1950-2002	238	31.9 (Apr)	734.7 (Aug)
Nam Kathang at the Regulating Dam	1994-2002	10.2	0.3 (Apr)	38.5 (Sept)
Xe Bangfai at Mahaxai	1989-2002	265.4	12.7 (Apr)	921.2 (Aug)
Mekong after the confluence of the Xe Bangfai	1922-1992	6960	1552 (Apr)	21453 (Aug)

Bangfai River depends on the power generation and ranges from 0 to 333 $m^3\ s^{-1}$. The Nam Kathang Noy and Ngai flow into the Regulating Pond downstream of the Power House and are small tributaries of the Nam Gnom River. The latter is itself a tributary of the Xe Bangfai and its confluence is located upstream of the Downstream Channel confluence.

2.2 Reservoir characteristics

The closure of the Nakai Dam on the Nam Theun River led to the inundation of 195 km of rivers and to the formation of a 489 km² reservoir, at full supply level, 538 m above sea level (asl) (EDF-DTG, 2012). The total storage capacity is of 3.9 billion m^3 with an active volume of 3.6 billion m^3. At Nakai Dam, the Nam Theun watershed is about 4039 km².

The bedrock mainly consists of fine to medium grained micaceous, quartzose red-brown and grey sandstone and brown-red to brown mudstone and siltstone. In the central area upstream of Ban Thalang, late tertiary alluvial deposits can be found. The Nam Theun River meandered through this area where soils are composed of soft to very stiff, silty clays and loams. Right along the river, more recent alluvium material, consisting of fine to coarse sands were present (NTPC, 2005).

The reservoir is located on the Nakai Plateau where the water is captured at the Intake, channelled through the Pressure Tunnel, the Power House, the Regulating Dam and the 27 km long Downstream Channel and finally released to the Xe Bangfai River about 30 km south of the Power House (Fig. 2).

The NT2 Reservoir is a narrow water body of approximately 80 km long and 5 km large. The reservoir is highly dendritic and relatively shallow with an average depth of 8 m (maximum depth of 39 m; Chanudet *et al.*, 2012). It is characterized by a maximum water level range of 12.5 m (NTPC, 2005), which results in a drastic reduction in the reservoir surface area at the end of the dry season. The NT2 Reservoir is managed on a seasonal basis: incoming waters are higher than the production capacity during the wet season and water is stored in the reservoir. During low inflows, the installed capacity is higher than incoming water flow and the level of the reservoir decreases. The reservoir surface fluctuates from 86 km² at the minimum operating level, to 489 km² at the full supply level and from 525.5 m asl to 538 m asl, respectively (DTG, 2012).

The NT2 Reservoir is characterized as a warm monomictic lake, i.e. completely mixed once a year during the cool dry season (Chanudet *et al.*, 2012). The water residence time is estimated to be 6 months.

Prior to impoundment, 69% of the total reservoir area was covered by dense, medium and light forests, 13% was covered by agriculture land and wetlands (the remaining 18% was covered by degraded and riparian forests, water and roads). The mean carbon density was estimated at 115±15 tC/ha (for a soil thickness of 30 cm), corresponding to a total flooded organic carbon stock of 5.1±0.7 MtC (Descloux *et al.*, 2011).

The NT2 Reservoir can be divided into 2 zones: (i) the South-East zone with a shallow reservoir and initially mainly covered by agricultural soils and swamps, receiving the main tributary inflows and (ii) the North-West zone with a higher water depth and initially covered by forest. During normal operation (after commissioning), the residence time in this area is longer than in the South-East zone due to low outflows at the Dam site.

2.3 Project design

The Nakai Dam (Figs. 1 and 2) is 439 m long and 39 m high and includes five radial gates to evacuate floods (up to 16000 m^3 s^{-1}). The reservoir is surrounded by 13 saddle dams (for a total length of 4.4 km) on the south and west side walls to close the reservoir. A riparian release (i.e. the environmental flow) of 2 m^3 s^{-1} is released at the Nakai Dam to the Nam Theun River. A multi-level off-take allows the riparian release to be selectively taken from the reservoir oxygenated surface water. This riparian release is then discharged through an aeration cone valve.

The Headrace Channel is located in the upstream zone of the reservoir (near RES9; Figs. 1 and 3). It is 4 km long and reaches a maximum depth of 34 m at the Intake. It ensures that the reservoir water mass can reach the Intake, even when the water level in the reservoir is low. Further downstream of the Intake, water enters the Headrace Tunnel (1500 m in length and 9.2 m in diameter), then goes to the Pressure Shaft (vertical drop of 220 m, diameter of 8.8 m) and finally descends to the Pressure Tunnel (1142 m in length and 7.15 m in diameter; Fig. 3). There is a surge shaft of 109 m in height and 8.8 m in diameter. The Power House is located 360 m below the Nakai plateau. It shelters four "Francis" (total of 996.5 MW) and two "Pelton" turbines (total of 75 MW). The total performance is 1070 MW and the mean production capacity is approximately 6000 GWh $year^{-1}$. The ratio of flooded lands is therefore 2.2 W m^{-2}.

Downstream of the Power House, water is conveyed to a Regulating Pond through a 340 m long Tailrace Channel with a 345 m^3 s^{-1} capacity (NTPC, 2004). With a capacity of 8 million m^3, the Regulating Pond buffers the turbinated flows on a daily and weekly scale. It is closed by a dam of 531 m in length (concrete dam 135 m long and earth dam 396 m long) and receives natural tributaries of the Nam Kathang River (Nam Kathang Noy and Gnai). Downstream of the Regulating Pond, two outflows have been constructed: (i) a riparian release to the Nam Kathang with an outflow corresponding to the natural inflow (minimum environmental flow of 0.2 m^3 s^{-1}). The Nam Kathang flows into the Nam Gnom River approximately 5 km from the Regulating Dam, (ii) the main release (water from PWH) through a 27 km long Downstream Channel towards the Xe Bangfai River (Figs. 1 and 3). The Downstream Channel is composed of rocks and soil and can evacuate a maximum flow of 330 m^3 s^{-1}. An Aeration Weir (labyrinth type) was built in the mid zone of the Downstream Channel to provide a maximum aeration capacity. The structure includes a U-shaped weir constructed of reinforced concrete walls which are 6 m high and approximately 160 m long (+10 m on each side of the channel), giving a total overflow crest length of approximately 340 m. Sub-horizontal perforated wooden plates are attached to the downstream edge of the crest to divide the flow over the weir into multiple discharges, thereby maximizing aeration. In its course, the Downstream Channel finally crosses a

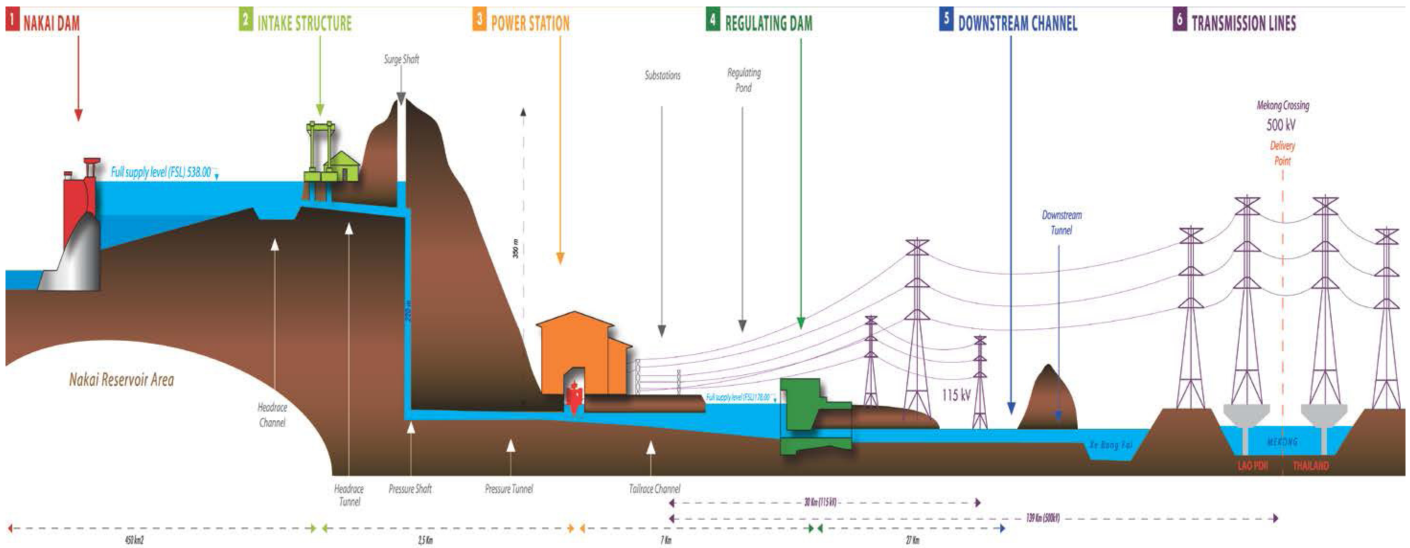

Fig. 3. Hydraulic scheme of the Nam Theun 2 Project. (1) Nakai dam, (2) intake structure, (3) power station, (4) regulating dam, (5) downstream channel, (6) transmission lines.

Fig. 3. Schéma hydraulique du Projet Nam Theun 2. (1) barrage de Nakai, (2) prise d'eau, (3) usine de production, (4) bassin de démodulation, (5) chenal aval, (6) lignes de transmission.

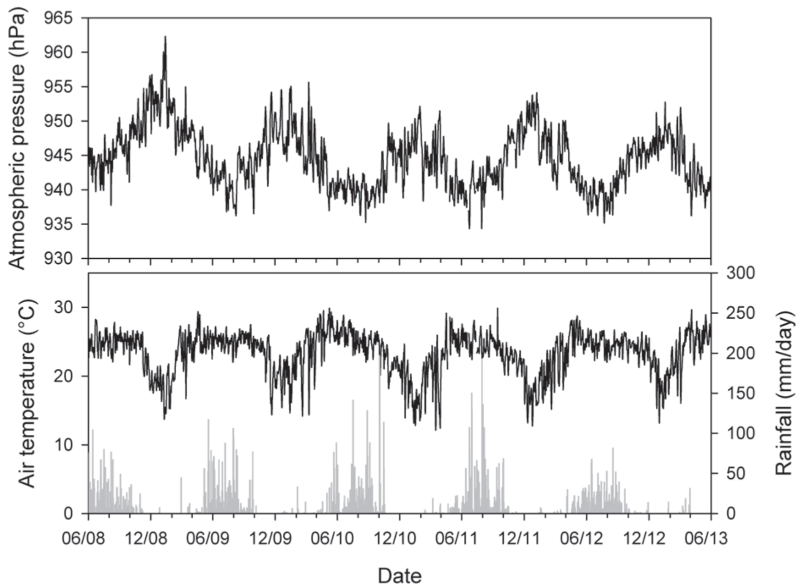

Fig. 4. Atmospheric pressure (hPa), air temperature (black line in °C) and precipitation (grey line in mm day^{-1}) at the meteorological station at Ban Thalang during the study period (2008 – 2013).

Fig. 4. Pression atmosphérique (hPa), température de l'air (courbe noire en °C) et précipitations (courbe grise en mm jour^{-1}) à la station météorologique de Ban Thalang pendant la période d'étude (2008 – 2013).

karst mountain through a 600 m long tunnel.

3 THE NT2 PROJECT SINCE 2008

3.1 Hydro-meteorological data

Atmospheric pressure is heavily correlated with precipitation. Pressure is low during the warm-wet season (938 ± 3 hPa) and high during the cool-dry season (954 ± 3 hPa; Fig. 4). The annual hydrologic cycle is precipitation-driven and the peak rainfall event was recorded in 2011 with 390 mm day^{-1}. The annual average rainfalls recorded in the meteorological station of Ban Thalang (RES4) were 2580 mm, 2502 mm, 3162 mm and 2162 mm respectively in 2009, 2010, 2011 and 2012. 2009 and 2010 represented average rainfall years, whereas 2011 was a very wet year and 2012 was a very dry year. Air humidity was high with a mean value of 80.9% (± 8.5%) over the study period (Air humidity means were 85.8 ± 6.9%, 77.7 ± 8.2% and 76.5 ± 7.0% respectively for the warm-wet, cool-dry and warm-dry seasons). Since 2008, air temperatures ranged from 12 to 30 °C with an average value of 23.21 °C (Fig. 4). Wind speed is generally low throughout the year with an average value of 1.96 ± 0.9 m s^{-1} over the study period (Fig. 5). Wind direction is also influenced by the

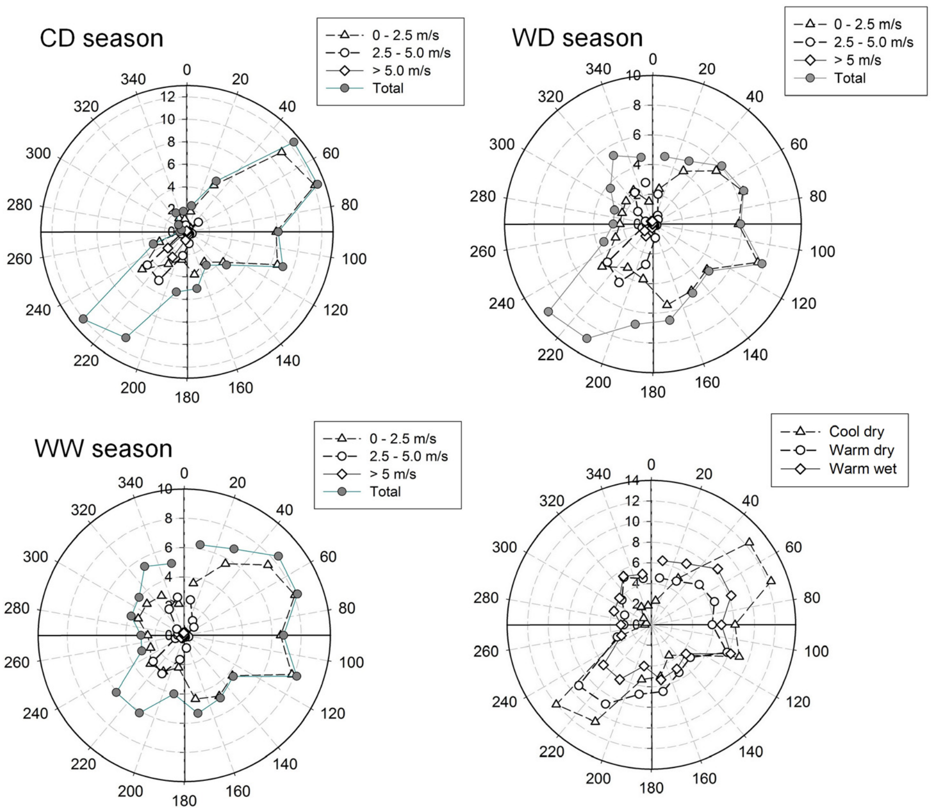

Fig. 5. Wind speed (m s^{-1}) at the meteorological station at Ban Thalang during the study period (2008 – 2013).

Fig. 5. Vitesse du vent (m s^{-1}) à la station météorologique de Ban Thalang pendant la période d'étude (2008 – 2013).

southwest and northeast monsoon. Over the period 2008 to 2013, maximum wind speed was recorded during the cool-dry season (8.5 m s^{-1} over 10 minutes in December 2008) whereas the lowest values were recorded during the warm-wet season.

The main natural reservoir inflow comes from the Nam Theun River. Daily average discharge (Fig. 6) was highly correlated with rainfall. An absence of peak flows was observed in 2008 and 2012 contrary to 2010 and 2011 where high flows occurred several times a year. The Nam Kathang River is a stream with contrasting hydrologic conditions among seasons. For instance, the river bed can completely dry up during the dry seasons (Fig. 6). The Xe Bangfai River also exhibits seasonal flows; although this river did not run dry during the study period, it had low flows

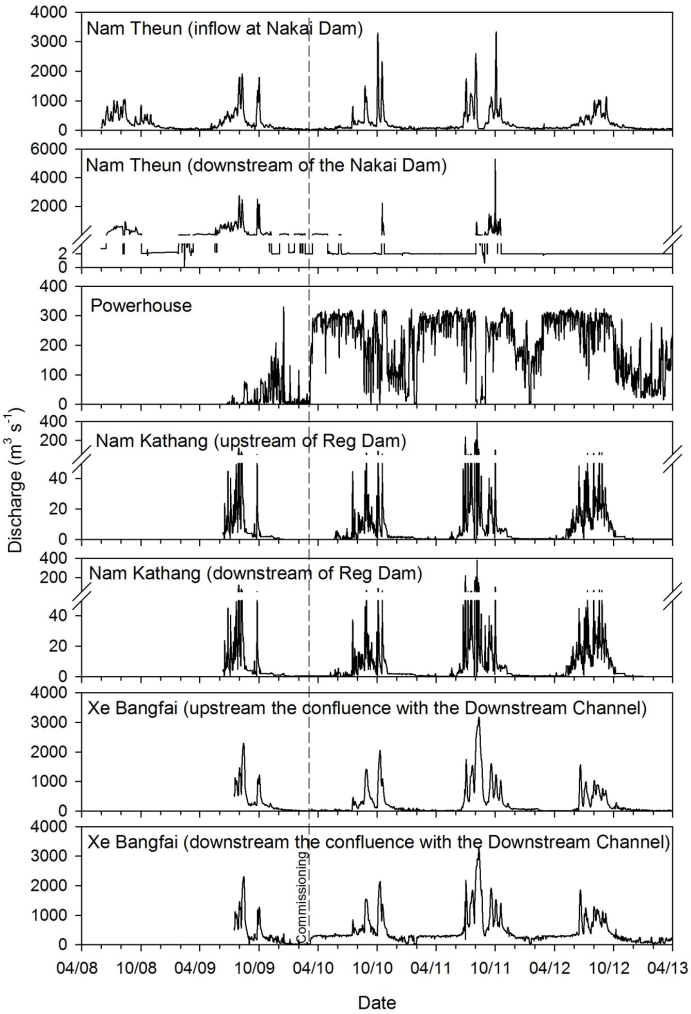

Fig. 6. Average daily discharges in the Nam Theun, Nam Kathang and Xe Bangfai Rivers (in $m^3\ s^{-1}$).
Fig. 6. Débits moyens journaliers dans les rivières Nam Theun, Nam Kathang et Xe Bangfai (en $m^3\ s^{-1}$).

(approximately 50 $m^3\ s^{-1}$) during the dry season (Fig. 6).

3.2 Impoundment details and normal operation

The first filling of the reservoir started in April 15th 2008 (Fig. 7). The water level increased gradually until November 2008 to 537 m as a result of high inflows during the wet season. The reservoir was maintained at this level for 44 weeks and slowly increased to 538 m (full supply level) in the second week of October 2009. By the end of the 2009 wet season, inflows

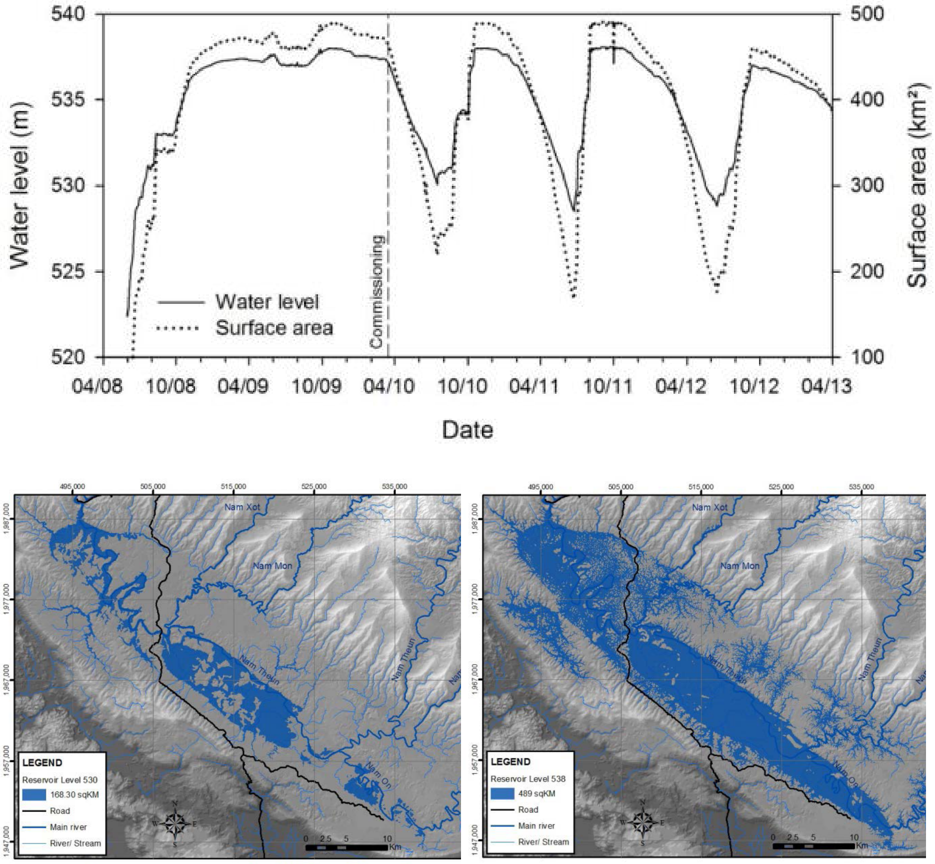

Fig. 7. Evolution of the reservoir water level (m) and of the flooded area (km²) for a reservoir water level of 526 to 538 m during the study period (2008 – 2013). The pictures represent the surface of the reservoir at a low level (530 m asl – left picture) and at the full supply level (538 m asl – right picture).

Fig. 7. Évolution du niveau d'eau du réservoir (m) et de la surface noyée (km²) pour un niveau d'eau du réservoir entre 526 et 538 m pendant la période de suivi (2008 – 2013). Les images représentent la surface du réservoir à un niveau bas d'exploitation (cote 530 m – image de gauche) et au niveau maximum d'exploitation (cote 538 m – image de droite).

had filled up the reservoir and were flushed between June and October 2009. As shown in Figures 6 and 7, flows were spilled at the dam site through the flood gates. During this event, outflows were slightly higher than inflows. As a consequence, the water level decreased and facilitated the flush. The objective of the 'fill and flush' operation was to export dissolved elements from the water body and thus to accelerate the improvement of the water quality. Soils and vegetation were totally flooded by the end of October 2009 when the maximum of the reservoir surface was first reached. The water level of the reservoir was nearly constant from October

2009 to March 2010 and remained unaffected by the turbine test runs during this period.

The NT2 hydropower plant started electricity production in March 2010 and began its commercial operation in April 2010. Since this date, the water level of the reservoir follows an annual cycle under normal operation (Figs. 6 and 7), with a mean annual water level fluctuation of 8.6 m (min 7.6 m in 2010 and max 9.5 m in 2011), still far from the maximum water level range of 12.5 m at the minimum operating level. The year 2010 was an average hydrological year, whereas 2011 was a very wet year with a spill of 6337 m^3 s^{-1} on the 1st of October to the Nam Theun River. 2012 was a dry year with no spilling and a filling level of 1 m below full supply. The Power House discharges show a similar annual pattern over years with a maximum of turbinated waters during the dry season and a minimum during the wet season. Water discharge ranged from 0 to 333 m^3 s^{-1} and the annual average turbine discharge is 220 m^3 s^{-1} (Fig. 6).

Since April 2008, the water release into the Nam Theun River is 2 m^3 s^{-1}, corresponding to the minimum required riparian release (environmental flow). Short periods of higher discharges were recorded each year during flood events, except in 2012 where no spill occurred (Fig. 6).

The Downstream Channel feeds into the Xe Bangfai River at Mahaxai village (Figs. 1 and 6). Xe Bangfai high flows occur in the wet season between July and November and peaked at 3260 m^3 s^{-1} in August 2011. In Mahaxai, the annual average of the Xe Bangfai River natural flow is around 238 m^3 s^{-1}, whereas the annual average of turbinated waters release is around 220 m^3 s^{-1}. As a consequence, the doubling of the Xe Bangfai annual flow maintains a constant high flow in the river, even during the dry season. This change in hydrology creates a back water effect 15.5 km upstream of the confluence with the Downstream Channel.

The Nam Kathang River inputs and outputs from the Regulating Pond (Fig. 6) show a similar pattern, where discharges generally ranged from 0.2 to less than 100 m^3 s^{-1}, but a flood event in 2011 resulted in a discharge of up to 1278 m^3 s^{-1} (not shown in Fig. 6). The Project has no effect on the Nam Kathang River discharge as the concession agreement defines that outflows from the Regulating Pond to the Nam Kathang must match the inflows from the two tributaries, the Nam Kathang Ngai and Noy (except during extreme floods, where the Downstream Channel can be used to evacuate natural inflow).

4 ENVIRONMENTAL PROGRAMME

The NT2 Aquatic Environment Laboratory (AE Lab) was established in April 2008, a few weeks before the first impoundment of NT2 Reservoir. The AE Lab was initially setup as an NTPC independent unit under a joint-venture agreement between EDF and NTPC. By 2011, the AE Lab was integrated into the NTPC Environmental Management Office (EMO). A service agreement between NTPC and EDF was elaborated in which NTPC (through the AE Lab) provided monitoring and analytical services to EDF and its research partners. Once installed, AE Lab progressively took over all tasks to fulfil NTPC's obligations in terms of water quality and biological monitoring as defined in the CA.

The water quality and hydrobiology monitoring programme was implemented to understand the evolution of the entire NT2 hydrological system, but also to provide data to develop a predictive model of reservoir water quality. This model, implemented by EDF-CIH, helps to define scenarios of the evolution of the water quality over the medium term (30 years). Greenhouse gases (GHG) are also taken into consideration in this model in order to refine the estimation of the carbon footprint of the hydropower plant for the full duration of concession period and anticipated lifespan.

The anticipated biomass decomposition under prevailing anaerobic conditions in the reservoir was expected to produce GHG such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The absolute and relative production and emission of these three GHGs depend on many biological, physical and chemical parameters such as dissolved oxygen, temperature, light penetration in the water, biomass production in the reservoir, etc. Therefore, the monitoring protocol followed a multidisciplinary approach with a large geographical coverage including the reservoir and its watershed, the Nakai Dam and its downstream section, the Power House, the Regulating Pond and water courses downstream (Xe Bangfai tributaries and Xe Bangfai River). This monitoring programme includes (i) fundamental water quality parameters such as nutrients and other major biological, physical and chemical elements, (ii) dissolved and total carbon content (total, dissolved, organic, inorganic), (iii) GHG (dissolved and fluxes) and (iv) hydrobiology: zoo and phytoplankton, macroinvertebrates and fish.

Research and development collaborations were launched (particularly for GHG and blue-green algae) with French Universities (Toulouse and Rennes) and research institutes (CNRS, IRD and EDF SEM).

Beside monitoring and research on water quality and GHG conducted by the AE Lab, NTPC's EMO developed comprehensive environmental programmes on: (i) fish biodiversity (inventories in both Xe Bangfai and Nam Theun watersheds since 1999), (ii) wildlife rescue after reservoir impoundment, (iii) Nakai elephant population monitoring and human-elephant conflict mitigation, (iv) creation of artificial wetlands above full supply level and specific work on turtles and tortoises, (v) conservation and propagation of the Indochinese Swamp Cypress (endemic tree) populations.

4.1 The metamorphosis of the Aquatic Environment Laboratory - 2009 to 2011

The AE Lab is based on the NT2 Project site to facilitate logistical challenges due to the high frequency of analysis and to ensure the quality of monitoring and analysis of physical, chemical and biological parameters of all water bodies within the NT2 Project area.

Fig. 8. Picture of the AE Lab Chemistry Unit (©NTPC, 2013).
Fig. 8. Photographie de l'Unité de Chimie du Laboratoire AE Lab (©NTPC, 2013).

The temporary premises of AE Lab were established in 2008 within an unused warehouse in Ban Oudomsouk (Nakai district), on the Nakai plateau. The permanent location of AE Lab and offices was identified at the end of 2010 and was confirmed by 2011 to be within the companies Residential Complex in Gnommalth. The layout and interior design, as well as bidding and construction supervision was done in-house. The construction works and the delivery of furniture were completed by November 2011. The 13th of December 2011, the new AE Lab was fully operational. The 250 m^2 facility is designed to accomplish, in-house, all the steps of water chemistry and biology sample processing, data management, analysis and data interpretation (Fig. 8).

From 2008 to 2013, the AE Lab was composed of a team of 12 to 15 people (10-12 Lao, 1 Thai and 2-4 French).

4.2 Presentation of the monitoring stations

A total of 36 stations are monitored within the Project area as presented in Figure 1 and Table II. 10 stations are located on the Nam Theun River and tributaries to follow the water quality of water inputs and outputs of the reservoir. 9 stations are situated in the reservoir area because of its spatial heterogeneity among the upstream, downstream and isolated zones. 3 are located downstream of the Power House and 4 along the Downstream Channel. 6 and 4 stations were respectively set up in the

Table II. Monitoring stations (name and rationale).
Tableau II. Stations de suivi (nom et description).

Name	Location	Rationale
Nam Theun and tributaries		
NTH1	Nam Theun, upstream Nam Noy confluence	Reference station, not impacted by the reservoir
NON1	Nam On, upstream reservoir	Reference stations, almost not impacted by the reservoir. To analyse the different incoming sources of carbon into the reservoir
NTH2	Nam Theun, upstream reservoir, downstream Nam Theun / Nam Noy confluence	
NXT1	Nam Xot, upstream reservoir	
NTH3	Immediate downstream of the Nakai Dam	To verify the improvement of the water quality through the riparian release / To check the possible improvement of the water quality of the Nam Theun between Nakai Dam and Theun Hinboun Headpond. Control spilling
NTH4	Nam Theun downstream Nakai Dam but upstream Nam Phao confluence	
NTH5	Nam Theun downstream Nam Phao confluence	
NTH6	Nam Theun 10 km upstream Nam Theun bridge	
NTH7	Nam Theun at Nam Theun bridge	
NPH1	Nam Phao upstream Nam Theun confluence	
Reservoir		
RES1	Immediately upstream Nakai Dam	Downstream sector, in the area of flooded primary forest, to measure the impact of organic matter decomposition on water quality
RES2	Between dam site and Ban Thalang	
RES3	Nam Malou Area	An area with low flow, the water quality is likely to deteriorate more severely than in other areas, with a particularly high risk of fish mortality
RES4	At Ban Thalang (under the bridge)	Middle of the reservoir. Narrow waterway. Transition between east and west part of reservoir
RES5	Middle of the upstream zone	Middle of the reservoir in an open area
RES6	Junction between old alignment of the Nam Theun and the Headrace Channel	To study the upper part of the reservoir and also check the water quality before entering the Headrace Channel and intake
RES7	Middle of the reservoir, in front of the water Intake	Central part of the reservoir in an open area
RES8	Upstream zone of the reservoir	Upstream part of the reservoir in an open area
RES9	Water intake	To assess the quality of the water leaving the reservoir

Table II. Continued.
Tableau II. Suite.

Name	Location	Rationale
Civil works and Downstream Channel		
PWH	Turbine in the Power Station	To assess the quality of the water leaving the reservoir
TRC1	Tailrace	To assess the quality of the water leaving the Power Station, just after the turbines
REG1	Regulating Pond, close to the Logbooms	To assess the quality of the water leaving the Regulating Pond
DCH1	Downstream the Regulating Dam	To assess the aeration efficiency of the Regulating Dam
DCH2	Upstream the Aeration Weir	To assess the efficiency of the Aeration Weir
DCH3	Downstream the Aeration Weir	
DCH4	Upstream the confluence between Downstream Channel and Xe Bangfai	To assess the quality of the water leaving the Downstream Channel
Nam Kathang & Nam Gnom		
NKT1	Nam Kathang Noy upstream Tailrace	To assess the water quality before the impact of the Tailrace and the Regulating Pond
NKT2	Nam Kathang Gnai upstream Regulating Pond	To assess the water quality before the impact of Regulating Pond
NKT3	Nam Kathang downstream the Regulating Pond	To assess the impact of the Regulating Pond on water quality
NKT4	Nam Kathang in Ban That	To assess the water quality a few km downstream of the Regulating Pond and before the impact of Gnommalath
NKT5	Nam Gnom upstream bridge National Rd 12	To assess the water quality downstream the confluence with the Nam Kathang
NGM1	Nam Gnom Upstream of the Downstream Channel Siphon	To assess the water quality before the confluence with the Nam Kathang
Xe Bangfai River		
XBF1	Upstream confluence Nam Kathang	Reference station, not impacted by the development of NT2
XBF2	Mahaxai, downstream confluence with Nam Gnom and the Downstream Channel	To assess the effect of the release of water from the Downstream Channel in the Xe Bangfai
XBF3	Sector located downstream from the confluence with the Nam Gnom.	
XBF4	Road 13 Bridge	To assess the water quality of the lower Xe Bangfai upstream of the confluence with the Mekong River

Table III. Bio-physico-chemical parameters monitored.
Tableau III. Paramètres bio-physico-chimique suivis.

Number	Groups	Parameters
1	**In situ**	Temperature, pH, dissolved oxygen, turbidity, conductivity, transparency
2	**Carbon budget**	Dissolved CH_4, dissolved CO_2, total organic carbon, total carbon, total inorganic carbon (calculation / measurements / alkalinity)
3	**Other major parameters**	BOD, COD, TSS, total N, total P, Fe II, Fe III, total dissolved iron, silica
4	**HPLC**	Potassium, sodium, calcium, magnesium, ammonia, phosphate, sulfate, chloride, nitrite, nitrate, fluoride
5	**N_2O**	Dissolved N_2O
6	**Gas fluxes**	Bubbling CH_4, CO_2, N_2O, diffusive CH_4, CO_2, N_2O
7	**Chlorophyll *a***	Chlorophyll *a*
8	**Phyto and zooplankton**	Number of individuals and species identification, biomass, visual observation (bloom, hydrophytes, macrophytes…)
9	**Benthic invertebrates**	Number and identification of individuals per family (per genus or species whenever possible)
10	**Fish**	Number, identification (species), size, weight, sex, maturity of specimens per net. Stomach content, flesh samples for mercury analysis

Nam Kathang/Nam Gnom and Xe Bangfai watershed to monitor the potential effects of the Project on these rivers.

4.3 Physico-chemical parameters and biological populations

Of the 10 groups of parameters measured within the monitoring programme framework, 7 are physico-chemical parameters (Tab. III). The design of the monitoring programme included all major elements such as carbon, nitrogen, dissolved gases and some metals such as mercury. Biological parameters are divided into 3 groups: phyto and zooplankton, benthic macroinvertebrates and fish. Biological compartments are monitored to assess the biodiversity and the stability of the habitats within the NT2 Project area. The monitoring of fish and macroinvertebrates began at the onset of the monitoring programme (2006), whereas phyto and zooplankton monitoring began by March 2009.

All sampling procedures and analysis follow standard protocols (ISO) or referenced scientific methods (NTPC, 2012).

4.4 Measurement frequencies

The measurement frequencies of each group defined in Table III are presented in Table IV. Unless otherwise stated in the table, all sampling stations defined in Table II are measured. In-situ measurements and samplings are performed on a weekly, monthly or seasonal basis according to the targeted parameters. A key focus on the understanding of processes occurring in reservoir and on the monitoring of water releases from the Power House, led to conduct sampling campaigns on a weekly and fortnightly basis. The chemical and GHG monitoring began with a frequency of 75 samples points per month in January 2009 and stabilized at 150 samples per month at the end of the 2009. It resulted in approximately 10000 data values per month that are entered into a database (analytical results and metadata).

Biological monitoring follows a monthly, bi-annual or a quarterly frequency in line with the main seasons prevailing in the region. Phytoplankton and zooplankton are monitored on a monthly basis in association with chlorophyll *a* determination. Aquatic invertebrates and fish are respectively monitored on a bi-annual and a quarterly basis.

5 CONCLUSION

This is the first long term environmental monitoring programme in a sub-tropical region (from 2008 to 2017) focusing on complex issues related to a hydropower project, such as water quality, greenhouse gas emissions and aquatic ecology. A similar monitoring programme in the reservoir of the Petit Saut Project in French Guiana, provided valuable lessons on the design and the implementation of the comprehensive environmental monitoring programme for the NT2 Project, making the startup of the monitoring more efficient and effective.

This monitoring programme contributes to a profound understanding of consequences of the reservoir impoundment on the aquatic ecosystem and will lead to a number of unique studies and publications of scientific interest.

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Table IV. Frequencies and locations of measurements per type of analysis (Tab. III).
Tableau IV. Fréquences et stations de mesures par type d'analyse (Tab. III).

Group of stations		Frequencies			
		Weekly	Fortnightly	Monthly	Biannual
Nam Theun River and tributaries	NTH3	-	1, 2	1, 2, 3, 4, 5	-
	NTH4	-	1, 2	1, 2, 3, 4, 5	-
	NTH5	-	1, 2	1, 2, 3, 4, 5	-
	NTH6	-	-	-	9, 10
	NTH7	-	1, 2	1, 2, 3, 4, 5	-
	NPH1	-	1, 2	1, 2, 3, 4, 5	-
	NTX1	-	1, 2	1, 2, 3, 4, 5	-
	NTH2	-	1, 2	1, 2, 3, 4, 5	-
	NON1	-	1, 2	1, 2, 3, 4, 5	-
	NTH1	-	-	-	9, 10
Reservoir *	RES1 (6)	-	1, 2	1, 2, 3, 4, 5, 7, 8	-
	RES2 (3)	-	1, 2	1, 2, 3, 4, 5	-
	RES3 (6)	-	1, 2	1, 2, 3, 4, 5, 6, 7, 8	-
	RES4 (6)	-	1, 2	1, 2, 3, 4, 5, 7, 8	9, 10
	RES5 (6)	-	1, 2	1, 2, 3, 4, 5	-
	RES6 (3)	-	1, 2	1, 2, 3, 4, 5, 6, 7, 8	-
	RES7 (6)	-	1, 2	1, 2, 3, 4, 5	-
	RES8 (3)	-	1, 2	1, 2, 3, 4, 5, 6, 7, 8	-
	RES9 (6)	-	1, 2	1, 2, 3, 4, 5	-
Civil works	PWH	1, 2, 3, 4, 5	-	-	-
	TRC1	1, 2, 3, 4, 5	-	-	-
	REG1	1, 2, 3, 4, 5	6	-	-
	DCH1	1, 2, 3, 4, 5	-	-	-
	DCH2	1, 2, 3, 4, 5	-	-	-
	DCH3	1, 2, 3, 4, 5	-	-	-
	DCH4	1, 2, 3, 4, 5	-	-	-
Nam Kathang & Nam Gnom	NKT1	-	1, 2	1, 2, 3, 4, 5	-
	NKT2	-	1, 2	1, 2, 3, 4, 5	-
	NKT3	-	1, 2	1, 2, 3, 4, 5	-
	NKT4	-	1, 2	1, 2, 3, 4, 5	-
	NKT5	-	1, 2	1, 2, 3, 4, 5	9, 10
	NGM1	-	1, 2	1, 2, 3, 4, 5	10
Xe Bangfai	XBF1	-	1, 2, 3, 4, 5	-	9, 10
	XBF2	-	1, 2, 3, 4, 5	-	9, 10
	XBF3	-	1, 2, 3, 4, 5	-	-
	XBF4	-	1, 2, 3, 4, 5	-	-

* The number in brackets indicates the number of depths sampled per profile. The sampling was organised to have at least one measurement per week (group 1) on the reservoir to avoid missing any particular event.

Bêche who reviewed and improved this version of the manuscript as a native English speaker.

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