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Efficiency of the Nam Theun 2 hydraulic structures on water aeration and methane degassing

Efficacité des structures hydrauliques de Nam Theun 2 sur l'aération de l'eau et le dégazage du méthane

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Abstract – Release of hypolimnetic water from man-made reservoirs can be a problem for downstream rivers. These effects can be significant mainly during the first years after the reservoir impoundment, especially in thermally stratified reservoirs favouring the release of anoxic methane-rich water. In tropical areas, higher temperatures decrease the oxygen solubility and enhance chemical processes responsible for the rise of reduced compounds. The Nam Theun 2 Reservoir was first filled in 2008. It experienced hypolimnetic deoxygenation and significant methane concentrations during the first 2 years. Dedicated structures to oxygenate water and degas methane were designed during the study phase. The overall aerating and degassing effects of these hydraulics structures varied from very good to moderate. Results depend on the continuous water quality improvement with time as well as on the limited range of upstream oxygen and methane concentrations tested. The hollow jet valve and the concrete tooth shaped structure were very efficient together with downstream natural turbulence in aerating/degassing compared to the staggered baffle blocks. Contrary to other structures, the efficiency of the baffle blocks structure is reduced with high discharges. The aeration weir showed a moderate efficiency in supplying oxygen to the water due to the high upstream oxygen saturations (close to 100%). However, it was very efficient for methane degassing even at low concentrations. Hydraulics structures of the Nam Theun 2 project are an efficient, reliable and low maintenance way to improve oxygen content and to degas methane.

Key words – aeration, reservoir, sub-tropical, weir, degassing, oxygen, methane

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Résumé – La délivrance d'eau provenant de l'hypolimnion des réservoirs artificiels peut être un problème pour la qualité de l'eau des rivières en aval. Ces effets peuvent être importants pendant les premières années après la mise en eau d'un réservoir et plus particulièrement dans les réservoirs stratifiés favorisant la délivrance d'une eau anoxique et riche en méthane. Dans les régions tropicales, les températures plus élevées diminuent la solubilité de l'oxygène et favorisent les processus chimiques responsables de l'augmentation des concentrations en composés réduits. Le réservoir de Nam Theun 2 a été mis en eau en 2008. Il a présenté une désoxygénation de la couche hypolimnique et des concentrations significatives de méthane au cours des 2 premières années. Des structures dédiées à l'aération et au dégazage du méthane ont été étudiées et mises en œuvre sur le site. L'efficacité globale de l'aération et du dégazage des différentes structures hydrauliques a été de très bonne à modérée. Les résultats sont évalués en tenant compte de l'amélioration continue de la qualité de l'eau et de la faible gamme de variation de concentrations d'oxygène dissous et de méthane dissous amont. La vanne à jet creux et la structure en forme de dent en béton ont été très efficaces avec la turbulence naturelle aval pour l'aération et le dégazage comparativement aux blocs de dissipation. Contrairement à d'autres structures, l'efficacité de la structure en blocs de dissipation est réduite à fort débit. Le seuil aérateur a été modérément efficace pour l'apport d'oxygène compte tenu des hautes saturations amont (près de 100 %) mais il a été très efficace pour le dégazage du méthane, même à de faibles concentrations. Les structures hydrauliques du projet Nam Theun 2 s'avèrent efficaces pour aérer et dégazer le méthane. Elles sont fiables et nécessitent une faible maintenance.

Mots clés – aération, réservoir, sub-tropical, seuil, dégazage, oxygène, méthane

1 INTRODUCTION

Release of hypolimnetic water from man-made reservoirs can alter the physical and chemical quality of downstream rivers, limit their uses and lead to a loss of biodiversity. These effects can be significant during the first years after impoundment or under strong reservoir stratification events and, are generally enhanced in tropical areas where higher temperatures decrease the oxygen solubility and enhance the chemical processes of organic matter degradation (Townsend, 1999; Abril *et al.*, 2005; Gregoire & Descloux, 2009).

Newly impounded reservoirs cause the degradation of the flooded organic matter that can lead to anoxia and high concentration of reduced and dissolved compounds. Among them, it can be found ammonium (NH_4^+), ferrous iron (Fe^{2+}), hydrogen sulfide (H_2S), carbon dioxide (CO_2) and methane (CH_4) (Galy-Lacaux *et al.*, 1997, 1999; Guérin *et al.*, 2008). Concentrations are generally higher when the water body is stratified (Abril *et al.*, 2005). Under such conditions, hypolimnetic waters are isolated from the surface waters oxygenated from photosynthesis and atmospheric gas exchange by the presence of a thermocline. Waters in hydroelectric reservoirs are generally taken from the bottom layer, *i.e.* in the hypolimnion, to maximise energy production (optimisation of the live volume). The release of bottom waters can thus affect downstream rivers throughout the year or during specific seasons, for example during the dry season when the river can be mostly influenced only by reservoir releases. As rivers are generally used for various purposes (drinking water, biodiversity, navigation and tourism, etc) and fulfill the function of self-purification, it is of high importance to preserve and guaranty their water quality.

The minimum levels of (i) dissolved oxygen (DO) to be maintained and (ii) reduced gas to be eliminated vary from site to site and with the physico-chemical characteristics of the water, the morphology of the river and the dilution effect from downstream tributaries. It also depends on the ecological requirements of the aquatic community and on the latitude (*e.g.* oxygen solubility is a function of water temperature). The downstream DO consumption by benthic community respiration or biological and chemical DO demand must also be considered. For instance, salmonids swimming is altered below 2–5 $mg.L^{-1}$ DO whereas tilapia and carps can swim at DO levels of 1–2 $mg.L^{-1}$ (Kutty, 1972; Kutty & Saunders, 1973). Tropical fishes generally have a higher tolerance of low DO. Nevertheless, DO that remains below 1 $mg.L^{-1}$ (and corresponding DO saturations equivalent to ~ 10% at 20 °C) for a few hours can affect biodiversity and generally result in large fish kills (Baylar *et al.*, 2009). Studies of the direct effects of methane on water organisms are very limited. Sackett and Brooks (1975) have shown that under experimental conditions, hydrocarbons (methane and others) did not cause harmful effects on marine phytoplankton even at high dissolved concentrations. Opposite results have been underlined with acute toxic gas effects in marine fish starting at a concentration of about 1 $mg.L^{-1}$ (Patin, 1999). But methane has the indirect detrimental effect of reducing DO content in oxic water bodies.

To maintain DO and gas concentrations compatible with aquatic life and other uses, many solutions have been tested to supply DO (namely aeration; Baylar *et al.*, 2009). Solutions range from hypolimnetic oxygen injection, reservoir clearing and selective withdrawal to the construction of dedicated hydraulic structures like weirs or baffle blocks. Creation of turbulence by hydraulic structures and subsequent aeration is a principle utilized by aeration weirs and seems to be the most efficient solution for aeration (Chanson, 1995; EPRI, 2002; Emiroglu & Baylar, 2003). DO transfer occurs when air is entrained into the flow in the form of a large number of bubbles. These bubbles greatly increase the surface area available for mass transfer (Baylar *et al.*, 2009). Very few man-made reservoirs are equipped for aeration with respect to the total number of reservoirs throughout the world. Structures built with the objective of degassing reduced gases are even more rare and the current literature data are based on the only case of the Petit Saut Reservoir in French Guiana (Gosse & Gregoire, 1997; Gosse *et al.*, 1997). Moreover, efficiency of other structures like hollow jet valves that are not specifically designed to increase DO concentration or to degas have never been assessed on site.

The creation of the Nam Theun 2 Reservoir (NT2) in the Lao PDR has led to the submersion of 489 km² of forest and agricultural soils. Descloux *et al.* (2011) have estimated the quantity of flooded carbon including above ground and below ground biomass to 5.1 MtC. It was foreseen that the major part of the DO consumption would come from the decomposition of this organic matter (mainly from the soils). In addition, other processes can increase DO consumption, such as respiration from aquatic plants and chemical oxidation (iron and other metals such as Mn in soils). The residence time of the NT2 Reservoir is about 6 months, which is relatively long, and the water body is stratified about half a year during the warm season (Chanudet *et al.*, same issue). These characteristics may affect DO concentrations and generate reduced gases and it was decided during the study phase to build dedicated structures to increase DO concentrations and to degas supersaturated gases. Moreover, for the NT2 Project, the guideline for minimal DO is fixed at 5 $mg.L^{-1}$, a target for all the re-aeration structures.

The objectives of this study were i) to determine the aeration and methane degassing efficiency of dedicated and non-dedicated structures of the NT2 project over 5 years following the first filling of the reservoir and ii) to compare the efficiency of these hydraulic structures.

2 METHODS

2.1 Study site

The NT2 Project, located in Lao PDR, was impounded in April 2008 and commissioned in April 2010. The reservoir is located on the Nakai Plateau. The turbinated water is captured at the Intake in the upper part of the reservoir, channelled through the Pressure Tunnel, the Power House, then released into the Regulating Pond equipped with a Regulating Dam (used to buffer discharge variations of the Power House) and into the 27 km long Downstream Channel (through the Aeration Weir) which joins the Xe Bangfai River about 30 km south of the Power House (Descloux *et al.*, same issue). The Regulating Dam which also receives water from the upstream Nam Kathang River also delivers a minimum flow towards the downstream Nam Kathang River, a tributary of the Xe Bangfai River. The Nakai Dam is located in the lower part of the reservoir far (around 40 km) from the water intake and delivers a riparian release to the Nam Theun River for environmental considerations. The mean annual inflow in the Nam Theun Reservoir is 238 $m^3.s^{-1}$ (Descloux *et al.*, same issue). The NT2 Reservoir is relatively shallow with an average depth of 8 m and is characterized by a large drawdown area. The reservoir surface fluctuates from 86 km² at the minimum operating level (525.5 masl) to 489 km² at the full supply level (538 masl; DTG, 2012; Descloux *et al.*, same issue). Three seasons are distinct in this sub-tropical environment; the warm-wet (WW: July to October), cool-dry (CD: November to February) and warm-dry (WD: March to June) seasons (Descloux *et al.*, same issue).

2.2 Aerating and degassing structures of the NT2 Project

2.2.1 The Nakai Dam

The concession agreement stipulates that the Nam Theun 2 Power

Fig. 1. Picture of the riparian release structure of the Nakai dam site on the Nam Theun River (hollow jet valve).

Fig. 1. Photographie du débit réservé relâché au site du barrage de Nakai sur la rivière Nam Theun (vanne à jet creux).

Company (NTPC) has to release a minimum environmental flow of 2 $m^3.s^{-1}$ into the downstream Nam Theun River. This flow is taken from the reservoir surface, 2 meters below the surface, through a multi-level off-take structure (diameter 1.54 m). The flow then goes through a hollow jet valve (section of 5 x 3.7 m) that creates turbulence oxygenating the flow (Figs. 1 and 5A) which reaches a designed stilling basin before its release into the Nam Theun River. Air is also entrained into the basin and it is the combined efficiency of the two devices (jet and basin) and the natural aeration along the 0.7 km downstream river stretch that was assessed in this study. During high floods, flow can be spilled out through flap and radial gates.

2.2.2 The Regulating Dam

The Regulating Dam has three outlets. The first structure is dedicated to the Downstream Channel water release (passing through point DCH1 in Fig. 5B). Based on the water level difference between the reservoir and the channel, around 40 MW of energy (which corresponds to approximately 315 $m^3.s^{-1}$) have to be dissipated downstream of the gates. A model was built to design adequate features with the objective of dissipating this flow energy. A decision was made to dissipate this energy with staggered baffle blocks installed in a convergent section (7 blocks 3 m high, 12 m width and 4 m long), made with high strength concrete (60 MPa), as shown in Figure 2. The high turbulence created by the energy dissipation devices is deemed to produce a good aeration of the water, for all the range of discharges.

The second outlet is through the 'restitution gate' which releases flows higher than 1 $m^3.s^{-1}$ dedicated to the Nam Kathang River (Descloux *et al.*, same issue and point NKT3 in Fig. 5B).

Fig. 2. Picture of the staggered baffle blocks installed downstream of the Regulating Dam in a convergent section in the Downstream Channel.

Fig. 2. Photographie des blocs de dissipation installés en aval du barrage de démodulation dans le chenal aval.

It is capable to release the natural upstream inflow plus 10 or 15 $m^3.s^{-1}$, depending on the power station operation and natural inflows (from the upper Nam Kathang) into the Regulating Pond. It has a capacity of 30 $m^3.s^{-1}$ at the minimum operating level. In order to provide a good aeration, a dedicated concrete tooth shaped device has been designed to split the flow jet in 2 parts, and spread it, in order to create a large area of water in contact with air (Fig. 3). The third outlet is a single canal that delivers the minimum environmental flow (below 1 $m^3.s^{-1}$) to the Nam Kathang during the dry season. The dedicated concrete tooth shaped device is not used with this configuration.

2.2.3 The Aeration Weir

A weir was built approximately 8.3 km downstream from the Regulating Dam to aerate/degas the flow and thus improve water quality in the Downstream Channel before it flows into the Xe Bangfai (Fig. 5C). It is a dedicated structure designed to provide maximum aeration at the maximum flow of 330 $m^3.s^{-1}$. The structure includes a U-shaped weir made of reinforced concrete walls. The total overflow crest length is approximately 340 m. Sub-horizontal perforated wooden devices are attached to the total overflow crest length (allow to spread the flow over 1.2 m). They divide the flow over the weir into multiple discharges to increase the water surface area as much as possible to provide maximum aeration/degassing potential. The weir height from crest to the downstream water level is greater than 1.5 m at normal flow (330 $m^3.s^{-1}$), with a water mattress depth almost equal to 3 m (Fig. 4). The structure performance was firstly tested

Fig. 3. Picture of the concrete tooth shaped structure downstream of the Regulating Dam in the Nam Kathang River.

Fig. 3. Photographie des dents en béton installées en aval du barrage de démodulation dans la rivière Nam Kathang.

Fig. 4. Picture of the aerating weir downstream of the regulating dam in the Downstream Channel.

Fig. 4. Photographie du seuil aérateur installé en aval du barrage de démodulation dans le chenal aval.

by a physical model study that focused on bubble trajectories, and allowed the designers to implement deflection walls (vertical concrete wall attached to the main structure; Fig. 4). The water flow speed in the Downstream Channel from the Regulated Dam to the Aerating Weir was calculated to approximately 1.7 $m.s^{-1}$ at 330 $m^3.s^{-1}$. The Downstream Channel is 56 m width (20 m horizontal and on each side: 2 x 3 m with a 3/1 slope and 2 x 6 m with a 2/1 slope).

Other small weirs are situated all along the Downstream Channel and are able to increase DO concentrations and degas remaining reduced gases with lower efficiencies. Nevertheless, there is no small weir between the Regulating Dam (DCH1) and the Aeration Weir (DCH2) and the Aeration Weir (DCH2) and the sampling station downstream the Aeration Weir (DCH3). The Tunnel outlet structure at the end of the Downstream Channel is also dedicated to dissipate the energy of the flow while creating high turbulences. These structures are not included in the present study as no water quality monitoring was conducted there.

2.3 Physico-chemical measurements

The physico-chemical water quality characteristics have been monitored in the NT2 system (hydroelectric reservoir and downstream rivers) since the first filling of the reservoir in April 2008. The results emphasize that the impoundment of the reservoir induced a substantial modification of the water quality in the whole aquatic system which is partially controlled by the hydrodynamics in the reservoir. During the WD and WW seasons, the reservoir water column is thermally stratified with a warm oxic epilimnion and a cooler anoxic hypolimnion (Chanudet *et al.*, same issue).

DO and methane (CH_4) concentrations in water were measured weekly, fortnightly or monthly between April 2008 and April 2013 at each monitoring station (Descloux *et al.*, same issue). The analytical methods, with the associated limits of detection and uncertainties (2% for DO saturation and 5% for CH_4) are summarized in Deshmukh *et al.* (2014) and Chanudet *et al.* (same issue). In the reservoir, between three and six samples were taken (peristaltic pump or sampling bottle) at each sampling point according to water column and oxycline depths. In the rivers, only surface water was collected.

All the upstream/downstream measurements were done between 11 am and 2 pm within 2 hours (excepted for REG1/NKT3 where the measurements were done within 24 hours due to field constraints; this does not affect the quality of the analysis as the transfer time is greater than the lag time between the two measurements). The upstream measurement has always been done before the downstream measurement. The oxygen values for 100% saturation at 20 °C, 25 °C and 30 °C are respectively 9.07, 8.24 and 7.54 $mg.L^{-1}$.

2.4 Data analysis

2.4.1 The Nakai Dam

For aeration and degassing analysis at the dam site, upstream concentrations were calculated from measurements at RES1 (situated in the reservoir around 700 m upstream of the dam) and downstream concentrations were measured about 700 m from the release at the NTH3 station (Fig. 5A; Descloux *et al.*, same issue). At RES1, the thickness and the depth of the water layer used for calculation of the upstream concentration depend on the discharge and restitution

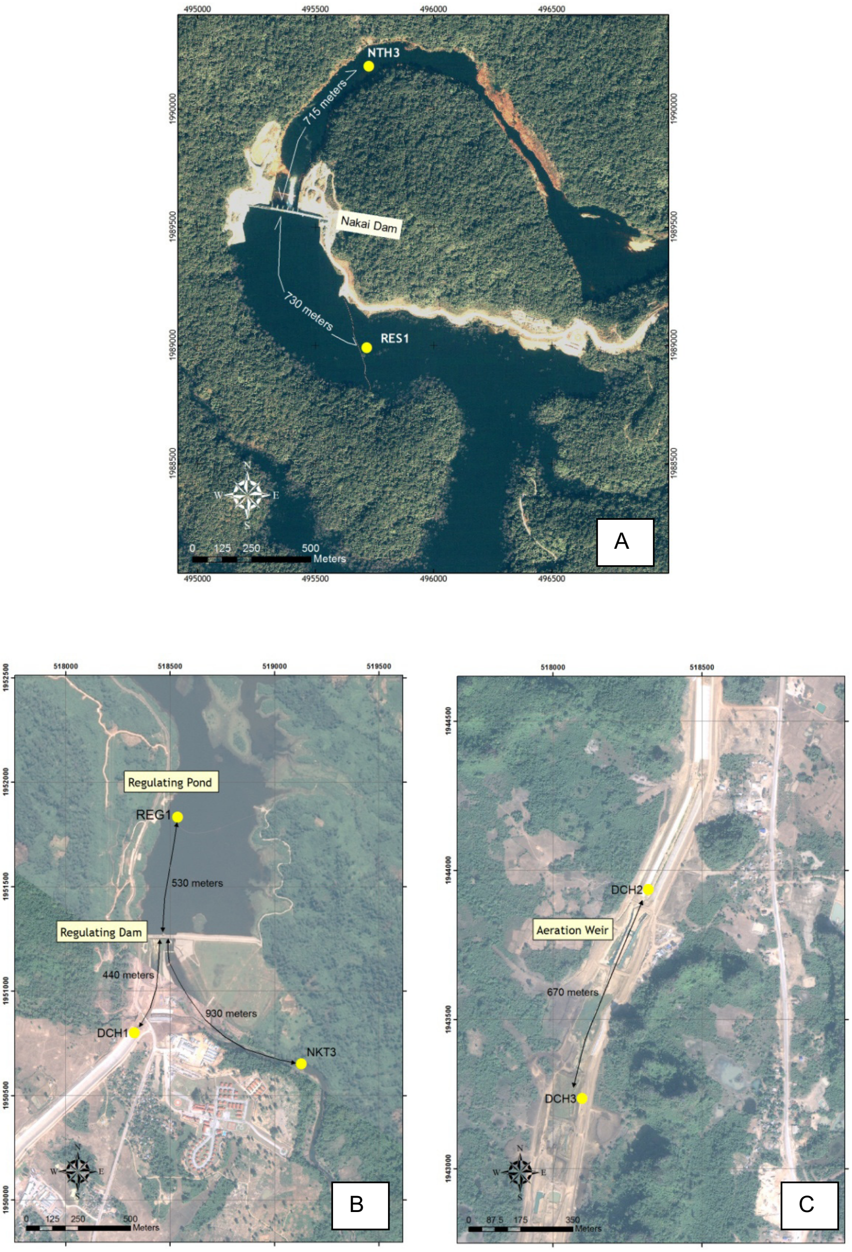

Fig. 5. Localisation of the sampling stations and length between stations and structures at A) the Nakai Dam, B) the Regulating Pond and C) the Aerating Weir (© NTPC).

Fig. 5. Localisation des stations d'échantillonnage et distances entre les structures et les stations au A) barrage de Nakai, B) bassin de démodulation et C) seuil aérateur (© NTPC).

structure (riparian release, flap gates or radial gates). For low discharges (*e.g.* the riparian release; Q ≈ 2 $m^3.s^{-1}$), velocity measurements and simulations (Fabre *et al.*, 2010) show that only the uppermost 3 meters are withdrawn through the multi-level off-take structure used for the riparian release. Most of the measurements (70% for DO and 93% for CH_4) were carried out with such a low discharge. The depth and thickness of the water layer to consider for higher discharges entering the multi-level off-take structure are more delicate to estimate. In this paper, only the flow passing through the intake surface structure and the hollow jet valve used for the riparian release are considered. DO measurements at RES1 (vertical resolution: surface level (0.2 m), then every 0.5 m in the uppermost 5 m and every 1 m downwards) were directly integrated over the uppermost 3 meters to get an average DO value while CH_4 measurements were linearly interpolated to calculate the CH_4 concentration in the uppermost 3 meters (based on CH_4 measurements made at the surface and 1 m above the oxycline usually found between 5 and 10 m; Chanudet *et al.*, same issue).

2.4.2 The Regulating Dam and the Aeration Weir

The aeration and degassing efficiencies of the Regulating Dam (into the Downstream Channel and in the Nam Kathang River; Fig. 5B) were analysed considering several discharges classes. Releases in the Nam Kathang using the 'restitution gate' were divided into two discharges classes: 1-5 $m^3.s^{-1}$ (26%, 2.3 $m^3.s^{-1}$ in average) and > 5 $m^3.s^{-1}$ (29%, 17.0 $m^3.s^{-1}$ in average). The remaining measurements (45%), done for discharge < 1 $m^3.s^{-1}$, were not considered as water was not released through the restitution gate: the dedicated concrete tooth shaped device is not used with this configuration. For the two discharge classes, the flow is withdrawn through a sector gate opening from 9 to 11 m below the surface. For the two classes, upstream concentrations were calculated by integrating the whole water column at REG1: measurements show that the physico-chemical parameters (DO or temperature for instance) are almost constant over the water column (Chanudet *et al.*, same issue). For instance, since the commissioning, the difference between surface and depth-averaged DO saturation did not exceed 3% in average. This homogeneity precluded any attempt to trace upstream water with physico-chemical parameters such as conductivity for instance to assess the exact water thickness to consider. Therefore, the choice of the water layer does not affect significantly the results and it justifies the use of a unique upstream concentration calculation method whatever the discharge. Downstream concentrations were measured at the surface at the NKT3 station (Fig. 5B; Descloux *et al.*, same issue).

Releases in the Downstream Channel were also divided into three discharge classes: 0-100 $m^3.s^{-1}$ (24%, 38.9 $m^3.s^{-1}$ in average for DO analysis), >100-200 $m^3.s^{-1}$ (16%, 147.1 $m^3.s^{-1}$ in average) and > 200 $m^3.s^{-1}$ (59%, 280.3 $m^3.s^{-1}$ in average). For these three classes, upstream concentrations were calculated by integrating the whole water column at REG1, considering the vertical homogeneity of the water, the low water depth close to the gates (13 m), the height of the gates (more than 4.50 m) and the depth of the sill of the gates (2 m above the bottom of the reservoir). The downstream concentrations were measured at the surface of the DCH1 station (Fig. 5B; Descloux *et al.*, same issue). The same discharge classes were used to assess the efficiency of the Aeration Weir. The upstream and downstream surface concentrations were measured just before and after the Aeration Weir at DCH2 and DCH3 respectively (Fig. 5C; Descloux *et al.*, same issue).

2.4.3 Data treatment

The overall change in oxygen concentration over time in a water body as the body travels through a hydraulic structure can be expressed as (Baylar *et al.*, 2009):

$$V\frac{dC}{dt} = k_L A(C_s - C) \qquad \text{(Eq. 1)}$$

where:
k_L: bulk liquid film coefficient (m.s^{-1});
C_s: the saturation concentration of DO in water at prevailing ambient conditions (mg.L^{-1});
C: the actual concentration of DO in the water at time t (mg.L^{-1});
A: the air–water contact area (m^2);
V: the volume of water associated with A (m^3).

The predictive relations assume that C_s is a constant determined by the water–atmosphere partitioning. If that assumption is made, C_s is constant with respect to time, and the DO transfer efficiency (aeration efficiency), E may be defined as Gulliver *et al.* (1998):

$$E = \frac{C_d - C_u}{C_s - C_u} \qquad \text{(Eq. 2)}$$

where u and d stand for upstream and downstream location, respectively.

The oxygen transfer efficiency (E) is commonly used to assess the theoretical or experimental aeration efficiency of hydraulic structures such as weir for instance. If E=1, the full transfer up to the saturation has occurred and on the contrary, if E=0, no transfer has occurred. E depends on many geometric parameters, water quality and temperature and a high number of equations have been proposed in the literature to take into these effects following the first proposal by Gameson *et al.* (1958).

By simplification, to extract from the graphical results the influence of temperature, and to visualize directly the capability of the water to dissolve oxygen, an analysis was conducted using saturation rate data (instead of concentration). This following equation is preferred over Equation 2:

$$E' = \frac{Sat_d - Sat_u}{100 - Sat_u} \qquad \text{(Eq. 3)}$$

or

$$Sat_d - Sat_u = E'(100 - Sat_u) \qquad \text{(Eq. 4)}$$

where Sat_u and Sat_d indicate upstream and downstream oxygen saturation rate.

The use of E' instead of E can however be misleading in case of water temperature variation between upstream and downstream measurements (a decrease in the downstream saturation can be due to an increase of the water temperature). In doing so, upstream and downstream water temperatures were recorded during each DO measurements. It appears that for each structure, the differences between upstream and downstream measurements were negligible (see Chapter 3), for instance water temperature differences between RES1 (uppermost 3 m) and NTH3, induced an average difference of 0.9% of saturation.

In the present study, the aeration efficiencies are measured in real conditions. The relevancy of a direct calculation of $E^{'}$ from single upstream-downstream couples may be jeopardized by measurement uncertainty or errors and natural physical (tributary or groundwater inputs) or bio-chemical processes (such as photosynthesis by phytoplankton and phytobenthos or DO consumption by biological respiration and chemical oxydation) that may occur between upstream and downstream measurements points (these effects can be enhanced with higher distance and time delay between the two points). A global value of $E^{'}$ was directly estimated from Equation 4 for each hydraulic device by plotting $Sat_d - Sat_u$ as a function of $100 - Sat_u$.

CH_4 degassing efficiency (*e*) has been defined as the ratio between the CH_4 loss and the upstream concentration (Abril *et al.*, 2005):

$$e = \frac{[CH4]_u - [CH4]_d}{[CH4]_u}. \qquad \text{(Eq. 5)}$$

This equation is acceptable for concentrations of methane greater than the atmospheric saturation concentration corresponding to 0.003 µmol.L^{-1} at 25 °C.

Slopes and intercepts of the regression lines were tested using an ANCOVA and pair wise-comparisons to analyse the differences among regression equations for each class of each structure. The overall significance level is 0.05. The R software was used (R Development Core Team, 2009).

3 RESULTS

3.1 The Nakai Dam

Aeration evolved with time and upstream DO saturation at the reservoir site (Fig. 6). In 2008 and 2009, the upstream DO saturation level was low, ranging from 5.5% to 67.2% (23.0% in average, except during the 2009 WD season ~55%) and the average aeration gain was about 60%. From the WD 2010 season, the upstream saturation level increased (71.4% in average between March 2010 and March 2013) and the aeration gain (downstream – upstream saturation) decreased. Above an upstream saturation of 80%, the capacity of the device to increase the DO saturation level was low but allowed the downstream river to reach the optimum of 100%. The CD seasons always showed a minimum upstream saturation level (Chanudet *et al.*, same issue) and concomitant higher aeration. The overall efficiency of the hollow jet valve and the downstream stretch of the river was high with $E^{'} = 0.91$ close to the optimum of 1 (Fig. 7).

The seasonal evolution of CH_4 concentrations at RES1 and NTH3 can be found in Deshmukh *et al.* (submitted). Upstream concentration ranged from 0.03 to 65.9 µmol.L^{-1} while downstream concentration ranged from 0.07 to 27.8 µmol.L^{-1}. The overall efficiency of

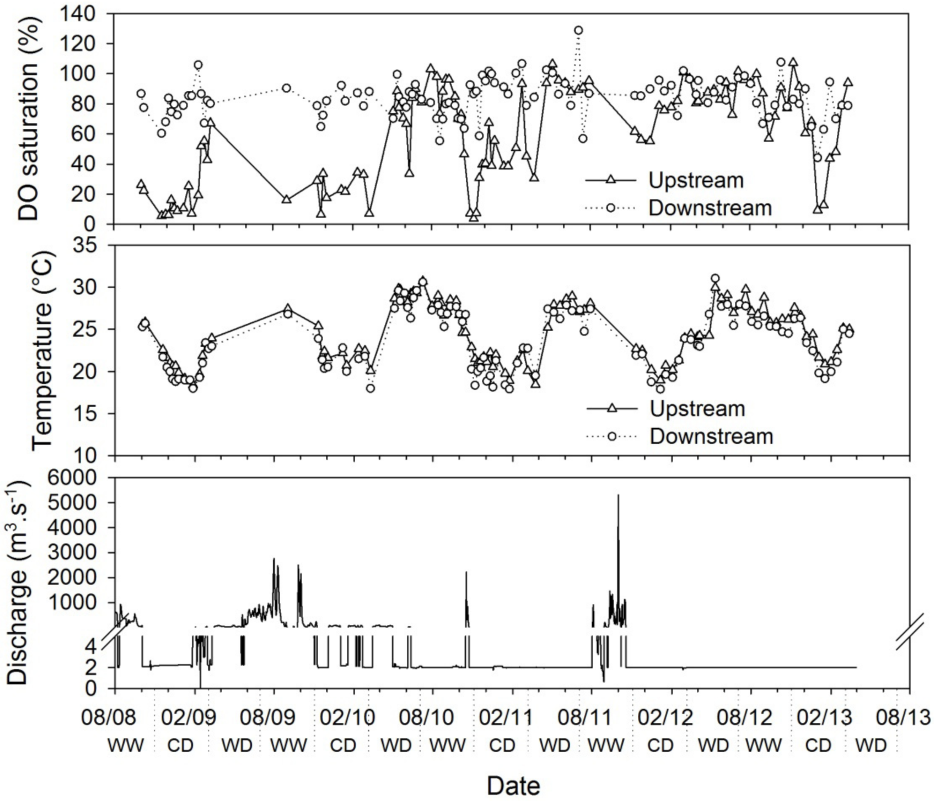

Fig. 6. Evolution of the upstream (RES1) and downstream (NTH3) oxygen saturation (%), temperature (°C) and discharges ($m^3.s^{-1}$; from Descloux *et al.*, same issue) with time between 2008 and 2013 at the Nakai Dam site.

Fig. 6. Évolution de la saturation en oxygen (%), de la température (°C) et du débit ($m^3.s^{-1}$ après Descloux *et al.*, même numéro) aux stations amont (RES1) et aval (NTH3) avec le temps entre 2008 and 2013 au site du barrage de Nakai.

degassing by the hollow jet valve and the downstream stretch was very good and close to 100% even at very low concentrations (e = 0.97; Fig. 8).

3.2 Regulating Dam

3.2.1 From the Regulating Dam to the Downstream Channel

The mean upstream DO saturation level at REG1 increased from 2009 (46.9% in average) to 2012 (65.3%; Fig. 9). Contrary to RES1 (Fig. 6), the maximum upstream DO concentration was observed during the CD seasons. This phenomenon is due to the hydrodynamic characteristics of the reservoir. At RES1, mixing of the water column decreased DO concentration in the subsurface layer due to mixing with DO-depleted bottom water, while mixing at the power station intake improved DO concentration in the downstream

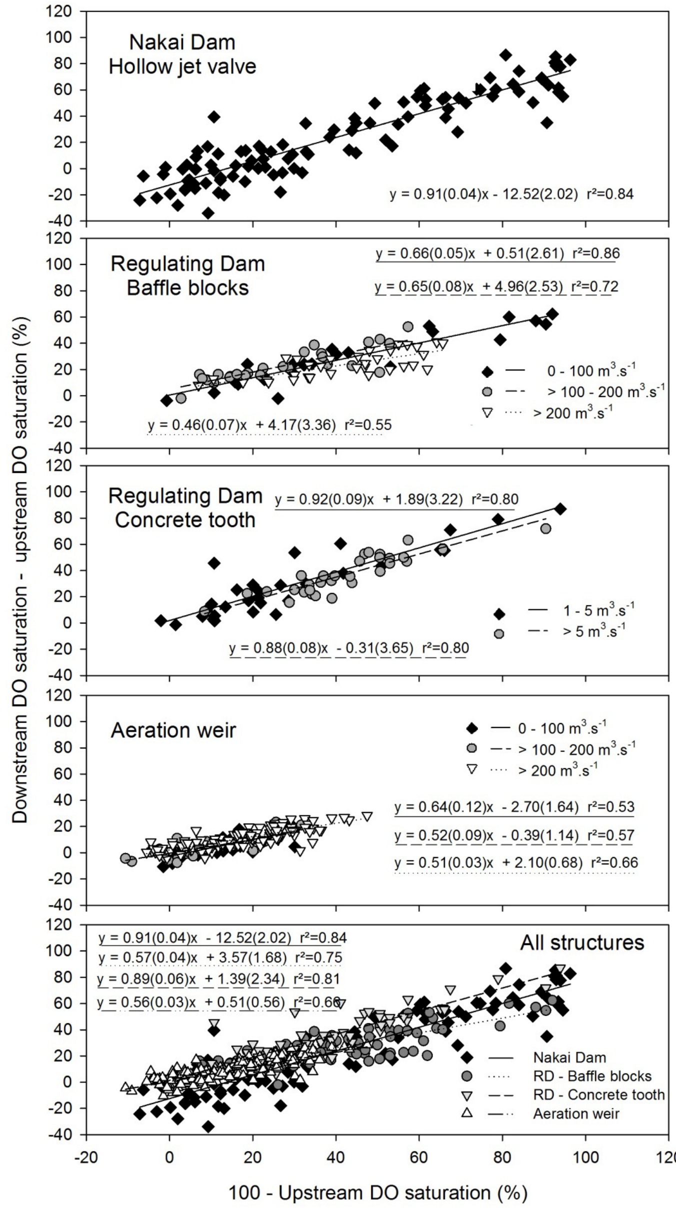

Fig. 7. Relationships between upstream oxygen saturation (%) and downstream – upstream oxygen saturation (%) for the 4 structures and among the four hydraulic structures. The regressions are represented by the solid lines.

Fig. 7. Relations entre la saturation amont en oxygène (%) et la saturation en oxygène aval – amont (%) aux quatre structures et entre les quatre structures hydrauliques. Les régressions sont représentées par les lignes.

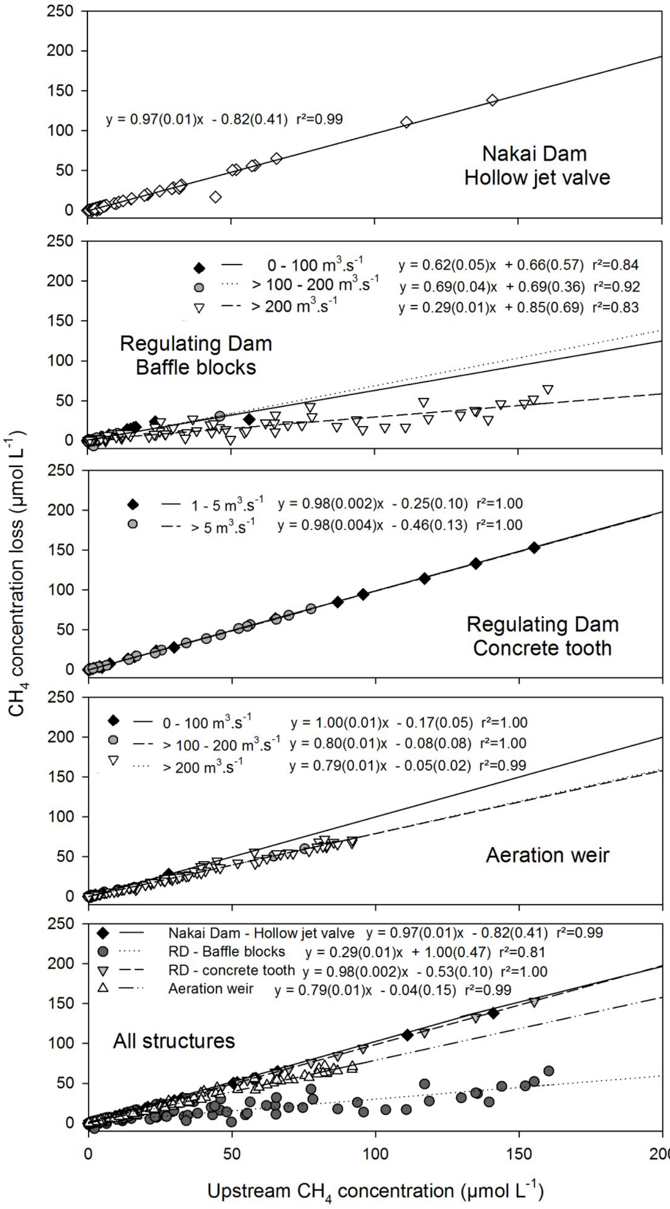

Fig. 8. Relationships between upstream methane concentrations (µmol.L^{-1}) and methane loss (downstream – upstream methane concentrations (µmol.L^{-1}) for the 4 structures and among the four hydraulic structures. The regression are represented by the solid lines.

Fig. 8. Relations entre la concentration amont en méthane (µmol.L^{-1}) et la concentration en méthane aval – amont (µmol.L^{-1}) aux quatre structures et entre les quatre structures hydrauliques. Les régressions sont représentées par les lignes.

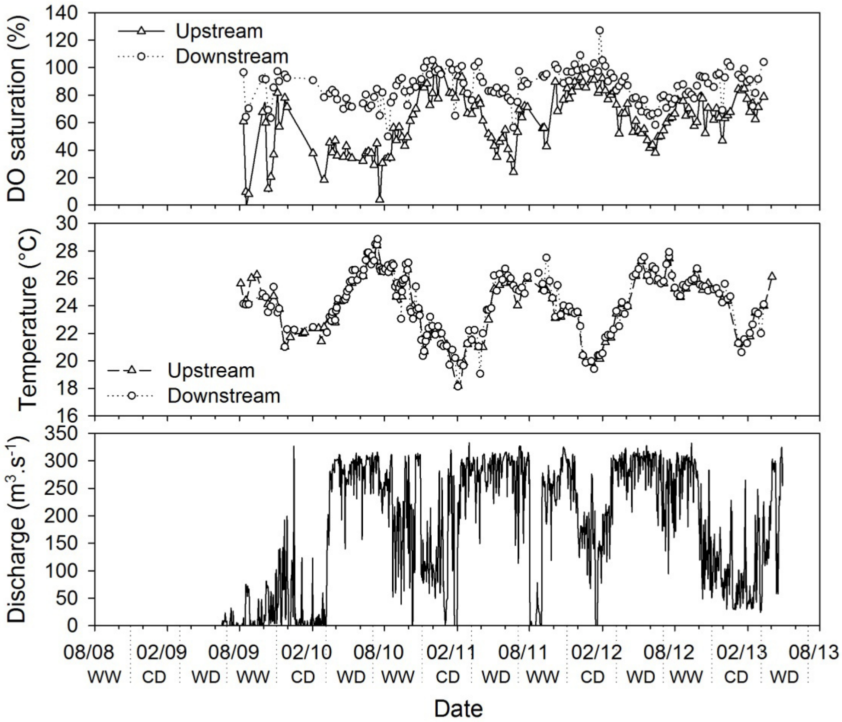

Fig. 9. Evolution of the upstream (REG1) and downstream (DCH1) oxygen saturation (%), temperature (°C) and discharges ($m^3.s^{-1}$; from Descloux *et al.*, same issue) with time between 2008 and 2013 at the Downstream channel site.

Fig. 9. Évolution de la saturation en oxygen (%), de la température (°C) et du débit ($m^3.s^{-1}$ après Descloux *et al.*, même numéro) aux stations amont (REG1) et aval (DCH1) avec le temps entre 2008 and 2013 au site du Chenal aval.

stations. The DO gain slightly decreased with increasing upstream oxygen concentrations. It fluctuated between -3.8 and 62.33% in 2009-2010 (mean: 33.1%) and between -2.3% and 43.2% in 2012-2013 (mean: 19.1%) depending on upstream saturation. The overall aeration efficiency was better at low ($E' = 0.66 \pm 0.05$ at 0-100 $m^3.s^{-1}$) and moderate flows ($E' = 0.65 \pm 0.08$ at 100-200 $m^3.s^{-1}$) than higher flow ($E' = 0.46 \pm 0.07$ at > 200 $m^3.s^{-1}$ value obtained with a lower correlation coefficient; Fig. 7).

CH_4 concentrations decreased after a peak corresponding to the beginning of the operation phase. In the Regulating Dam (REG1), CH_4 depth-averaged concentrations ranged from 0.01 to 160.3 $\mu mol.L^{-1}$ with a seasonal pattern: maximum during the WD seasons and minimum during the CD seasons (Deshmukh *et al.*, submitted). At DCH1, concentrations ranged from 0.03 to 113.0 $\mu mol.L^{-1}$. The CH_4 loss remained low [0-25 $\mu mol.L^{-1}$] and the maximum loss was observed for high upstream

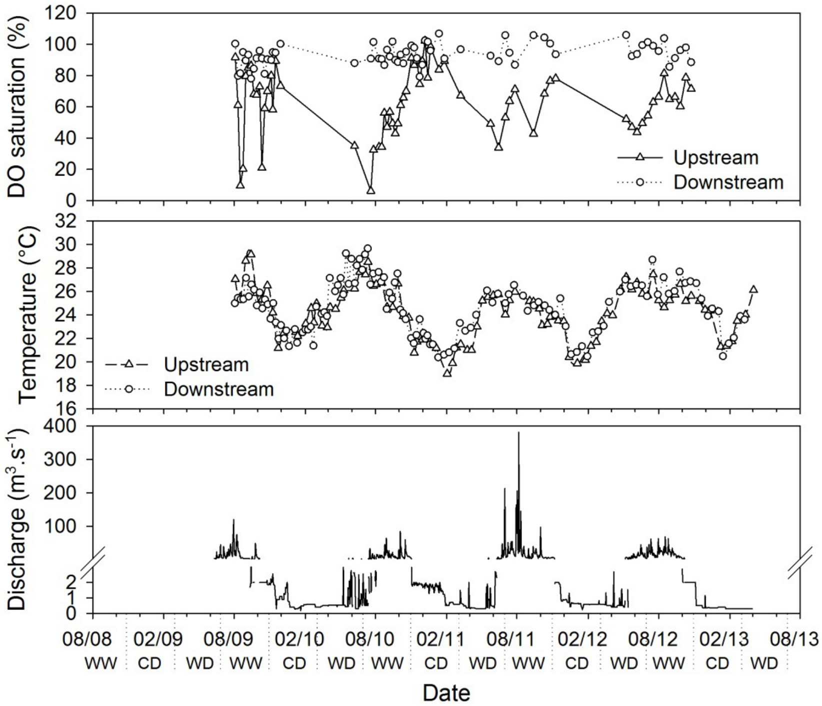

Fig. 10. Evolution of the upstream (REG1) and downstream (NKT3) oxygen saturation (%), temperature (°C) and discharges ($m^3.s^{-1}$; from Descloux *et al.*, same issue) with time between 2008 and 2013 at the Nam Kathang site.

Fig. 10. Évolution de la saturation en oxygen (%), de la température (°C) et du débit ($m^3.s^{-1}$ après Descloux *et al.*, même numéro) aux stations amont REG1) et aval (NKT3) avec le temps entre 2008 and 2013 au site de la Nam Kathang.

concentrations. Low and medium flows were significantly more efficient in degassing (*e* = 0.62 and 0.69 respectively; Fig. 8) compared to higher flows (*e* = 0.29; P<0.001).

3.2.2 From the Regulating Dam to the Nam Kathang River

Upstream DO saturation levels are presented in the previous section (Fig. 10). Downstream, intra-annual variations were observed with maximum DO saturation level during the CD seasons and minimum saturation level during the WD seasons (saturation gain at 16.6% in the CD seasons and 46.5% during the WD seasons in average). Aeration efficiency did not differ among the two flow classes (P>0.05). The efficiency was high, ranging from 0.88 to 0.92 (Fig. 7).

The upstream CH_4 pattern is described in the previous section. For the common upstream-downstream data set, maximum upstream concentrations appeared in the WD season of 2010 (155.3 µmol.L^{-1}). Downstream,

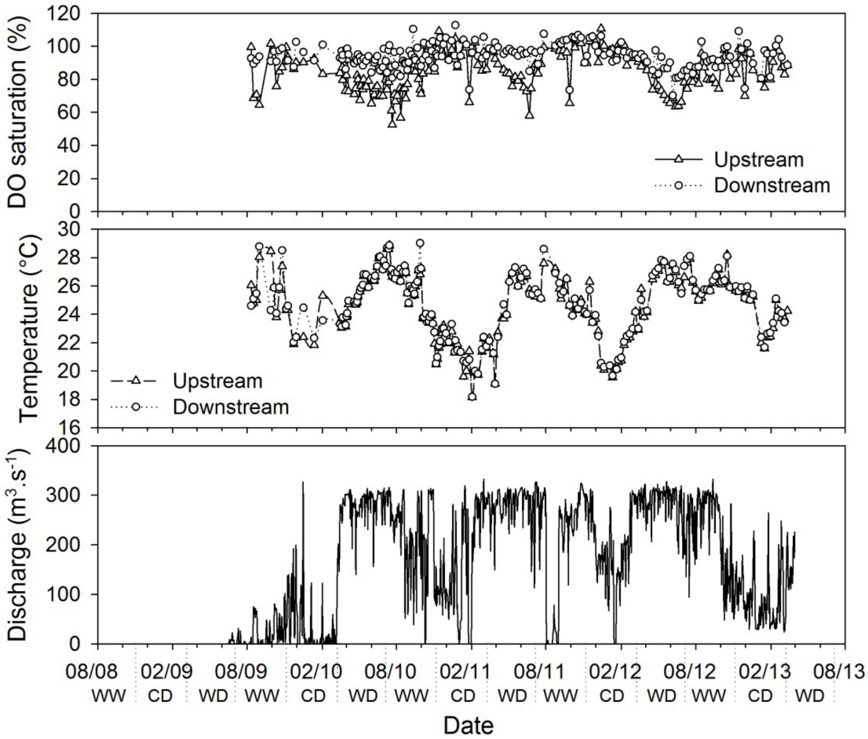

Fig. 11. Evolution of the upstream (DCH2) and downstream (DCH3) oxygen saturation (%), temperature (°C) and discharges ($m^3.s^{-1}$; from Descloux *et al.*, same issue) with time between 2008 and 2013 at the Downstream channel site.

Fig. 11. Évolution de la saturation en oxygen (%), de la température (°C) et du débit ($m^3.s^{-1}$; après Descloux *et al.*, même numéro) aux stations amont (DCH2) et aval (DCH3) avec le temps entre 2008 and 2013 au site du Chenal aval.

from 2011, methane is almost absent from the water body during the WW (2.6 µmol.L^{-1}) and CD (0.7 µmol.L^{-1}) seasons in average (Deshmukh *et al.*, submitted). The degassing efficiency was very high (e = 0.98; Fig. 8) with no significant differences among the two flow classes.

3.3 Aeration Weir

DO saturation levels and CH_4 concentrations in the water at the weir site were highly influenced by the upstream structures. Upstream of the weir at DCH2, DO saturation levels were always above 52.5% (85.2 in average from 2009 to 2013) even at the beginning of the operation phase (Fig. 11), underlying the good water quality leaving the NT2 Reservoir (Chanudet *et al.*, same issue) and the downstream aeration efficiency of the baffle blocks at the Regulating Dam and the small aeration weirs. There was no DO evolution from year to year: there was a seasonal pattern with a maximum seasonal saturation level (93.3% in average) during the CD season and a minimum saturation level (78.4%) during the WD seasons. The WW season presented intermediate DO saturation levels (83.7%). The mean DO apparent gain was therefore low (2.3% in average) during the CD season and at 13.3%during the WD season. The corresponding overall aeration efficiency seems moderate with a higher effect found at low flow (E' = 0.64±0.12; Fig. 7) than medium and high flows (E' = 0.52±0.09 and 0.51±0.03 respectively; P<0.05).

The upstream CH_4 concentrations also depended on the Regulating Dam releases and degassing efficiency. They followed the same inter and intra-annual patterns as at REG1-DCH1 (Deshmukh *et al.*, submitted). The mean upstream CH_4 concentrations at this site decreased since the beginning of the operation phase from 31.74 μmol.L^{-1} in 2010 to 7.16 μmol.L^{-1} in 2012 in average. The upstream CH_4 concentrations were still high during the WD seasons but the CH_4 loss was close to 100%. Since 2011, during the WW and CD seasons, there was almost no more CH_4 upstream the Aeration Weir (0.62 μmol.L^{-1} and 1.89 μmol.L^{-1} for instance during the 2012 WW and CD seasons). The overall degassing efficiency was very high and significantly higher at low flow (e =1.00±0.01, Fig. 8) compared to medium and high flows (e = 0.80±0.01 and 0.79±0.01 respectively; P<0.001). The weir resulted in degassing of almost all of the remaining dissolved CH_4 in the Downstream Channel water.

3.4 Comparison of the structures

The data showed that all the devices and the short downstream flow stretches tested in this study were able to oxygenate waters. The hollow jet valve of the Nam Theun riparian release and the concrete tooth shaped device of the Nam Kathang release had an aeration efficiency significantly higher (E' = 0.91±0.04 and 0.89±0.06 respectively; Fig. 7) than the staggered baffle blocks of the Downstream Channel (E' = 0.57±0.04; P<0.001) and the downstream Aeration Weir (E' = 0.56±0.03; P<0.001). The downstream Aeration Weir that has been designed to aerate the water seems the less efficient structure, but the uncertainty is high as upstream measurements are close saturation. Efficiencies of the staggered baffle blocks and downstream Aeration Weir were not significantly different (P>0.05).

The hollow jet valve of the riparian release and the concrete tooth shaped device of the Nam Kathang release were able to degas CH_4 efficiently (e = 0.97±0.01 and 0.98±0.002 respectively, Fig. 8). Their efficiencies were significantly higher than the Aeration Weir that remained quite efficient (e = 0.79±0.01; P<0.001; Fig. 7) and than the staggered baffle blocks of the Downstream Channel which had a low efficiency at high flow (e = 0.29±0.01; P<0.001). It has to be noted that the Aeration Weir was very efficient at low flow (e = 1±0.01, Fig. 8).

4 DISCUSSION

The aeration and methane degassing efficiencies depend on the type of hydraulic structures through which the flow passes but also on other parameters like the magnitude of the discharge, the water temperature, the length of time of the air-water exchange (Chanson, 1995; EPRI, 2002; Emiroglu & Baylar, 2006). Moreover, to obtain an unbiased estimate of the intrinsic efficiency of the devices, an assessment of the contribution of flow stretches between the devices and the downstream measurement points should have been made and it would have been better to test the structure under the entire range of upstream conditions (0 to 100% of upstream DO saturations and low to very high CH_4 saturations); which has not been possible to test for the Aeration Weir for instance. Upstream DO saturations were too close to the saturation at this site preventing any measurement at low DO saturation conditions and thus, it may have artificially underestimate the intrinsic efficiency potential of the structure (see also Chapter 2.3 on uncertainties and calculations).

Our study demonstrates that, for the range of upstream DO and methane concentrations tested, aeration efficiency is very high with the hydraulic systems using the hollow jet valve and the concrete tooth, substantial with the downstream weir and moderately efficient using the baffle blocks especially at high discharges. Deswal (2009) found in a laboratory experiment that DO aeration efficiency of a hollow jet valve increases with the increase in jet velocity and that this device is competitive with other types of aeration systems. At NT2, the hollow jet after passing through the atmosphere plunges into a water pool where substantial amount of air is entrained, leading to a high air-water interfacial area. At NT2, water flow was constant and the overall good aeration efficiency was confirmed on site.

The three devices that were tested under contrasting water flows generally presented a better aeration efficiencies at low flows. This result is consistent with previous studies (Chanson, 1995; Richard *et al*., 2005) that demonstrated that low flows had higher waterfall, facilitating the flow to plunge into the water body. At low discharges, breakup of the jet is observed as drop height increases. High flows decrease the total height of the Aeration Weir and thus both the duration of the air-water exchange and the depth of air bubbles driven into the water. The efficiency of a weir was found to be maximum at a tailwater depth of approximate 0.6 times the drop height, indicating that a trade-off exists between bubble residence time, pressure, and turbulence levels (Avery & Novak, 1978). High flows may also decrease the turbulences created by the structure (baffle blocks or concrete tooth) by decreasing the difference of water level between the upstream and the downstream of the structure. At the Nam Kathang site, contrary to the other devices, the maximum flow recorded during the measurements remained low (41 $m^3.s^{-1}$) thus limiting the effect on downstream water level. The weir remained moderately efficient for oxygenation but is less sensitive to the water discharge due to its optimized conception. The aerating weir located downstream of the Petit Saut Reservoir (French Guiana) had an overall aerating efficiency close to 0.90 for turbinated discharge up to 200 $m^3.s^{-1}$ (Gosse & Gregoire, 1997; Richard *et al*., 2005). The high level of efficiency at high discharge is coming from the design of the weir made of hexagonal metallic structures with two consecutive falls. Other studies from Hauser & Proctor (1993), reported an efficiency of the aerating single fall weirs of South Holston and Chatuge around 0.60 and 0.68 respectively and Baylar & Bagatur (2000) reported an efficiency of approximately 0.70 for low-head overflow weirs. All of these aeration efficiency studies are in accordance with the results of our study.

Our hypothesis suggesting that baffle blocks are able to highly aerate the water body was based on the study of Kaya & Emiroglu (2010), that have reported that storm water systems, channels and canals commonly use baffle blocks or baffled chutes for energy dissipation. They indicated a close relationship between energy dissipation and oxygen transfer efficiency and have shown an effective oxygen transfer. Johnson (1975), also previously predicted that flow into a highly baffled basin might produce higher aeration than a conventional hydraulic jump basin. This is not supported by the results of the monitoring, with the baffle block structure being only moderately efficient. Contrary to the hollow jet valve, the baffle blocks (and the concrete tooth) were not designed to have a plunging flow increasing the air-water exchange, which could partially explain the results. The overall efficiency of the baffle blocks can be compared to aeration efficiency of natural stepped cascades. Toombes & Chanson (2000) reviewed the efficiency of stepped cascades mainly located in the USA and Emiroglu & Baylar (2006) measured aeration efficiency of stepped chutes in an experiment. They found aeration efficiencies close to our study ranging from 0.50 to 1.00 depending of the flow and the height of the steps. The higher the step is, the better the efficiency is. Overall stepped cascades were very efficient because of the strong turbulence mixing and associated air entrainment and residence time. They also found that aeration efficiency was better at low flow (nappe flow regime).

The hollow jet valve, the concrete tooth structure and the Aerating Weir demonstrated a very good efficiency in degassing CH_4. The baffle blocks structure is moderately efficient in oxygenating and degassing at low and intermediate flow discharge and is not efficient at high flow discharge. Nevertheless, flow discharge seems to have less effect on CH_4 degassing efficiency than for aeration for other structures. For instance the CH_4 degassing efficiency of the concrete tooth structure is equivalent whatever the flow discharge.

Dissolved CH_4 concentrations remained high at DCH2 (upstream of the Aeration Weir) and the Aeration Weir contributed to the elimination of almost all of the remaining CH_4 from the water body. The weir installed in March 1995 in the Petit Saut Reservoir, had a good degassing efficiency similar to the NT2 Aeration Weir, with close to 80% of the dissolved CH_4 eliminated from the turbined water (Richard *et al.*, 2005; Gregoire & Descloux, 2009).

Except for the baffle blocks structure at high flow discharge, all the hydraulic structures of the NT2 Project are able to aerate/degas the water body with a good efficiency. These structures have the advantages to be reliable while requiring low maintenance. The hollow jet valve and the concrete tooth structure are very efficient in aerating/degassing waters but they can be used only for low flows contrary to other structures that can be used under a wide range of flow discharge.

Thanks to the hydraulic structures, no anoxia/low DO saturations were observed since the beginning of the monitoring into the downstream rivers (Chanudet *et al.*, same issue). The specific design and level of the water intakes also contribute to improve the water quality of the downstream releases. For instance the Nam Theun River mainly received water from the sub-surface of the reservoir whereas the Downstream Channel and Nam Kathang River receive mixed water from the NT2 Reservoir through the Regulating Pond (Chanudet *et al.*, same issue).

5 CONCLUSION

The NT2 Reservoir was first impounded in 2008. The reservoir experienced hypolimnetic deoxygenation and periods of anoxia below the thermocline during the first 2 years that were anticipated with dedicated aerating civil work structures. The study assessed for the first time the efficiency, on site, of several dedicated and non-dedicated structures on aeration and CH_4 degassing. Moreover, the time series allows for a quantification of the evolution of these effects with time, taking into account that some civil works were tested for a limited range of upstream DO and methane concentrations. With the improvement of the water quality (increase in DO saturation and decrease of CH_4 contents), the overall aerating and degassing effects of the hydraulics structure ranged from very good to moderate. The hollow jet valve and the concrete tooth shaped structure were more efficient in aerating/degassing compared to the staggered baffle blocks. At the Aeration Weir the DO gain is limited by the high upstream saturation but this device is very efficient for methane degassing, even at low concentrations. While the DO content could have been good in the Downstream Channel without the Aeration Weir, it was obviously useful to eliminate the remaining methane in water. The water quality of the downstream rivers of the NT2 Project has always been good since the impoundment of the reservoir thanks to the particulate design of the Intake, the overall water quality of the reservoir and the aeration of the hydraulic structures examined in this study.

These hydraulics structures are an efficient, reliable and low maintenance way to improve DO and to degas CH_4 at reservoir releases. However the efficiency of a structure is always a tradeoff between the energy production loss due to the head reduction and the downstream water quality requirements.

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