

# Atmospheric nitrogen deposition in a subtropical hydroelectric reservoir (Nam Theun II case study, Lao PDR)

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## Abstract

This study presents an estimation of the atmospheric inorganic nitrogen deposition into the NT2 hydroelectric reservoir, in the subtropical region of the Lao PDR, based on a two-year monitoring (June 2010 to July 2012) including gas concentrations and precipitation. Dry deposition fluxes are calculated from monthly mean surface measurements of NH<sub>3</sub>, HNO<sub>3</sub> and NO<sub>2</sub> concentrations (passive samplers) together with simulated deposition velocities. Wet deposition fluxes are calculated from NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> concentrations determined in single event rain samples (automated rain sampler). Annual rainfall depth was 2502 mm and 3162 mm in 2010 and 2011, respectively. The average nitrogen deposition flux is estimated at 1.26 kg N ha<sup>-1</sup> yr<sup>-1</sup> from dry processes and 5.01 kg N ha<sup>-1</sup> yr<sup>-1</sup> from wet ones, i.e., an average annual total nitrogen flux of 6.3 kg N ha<sup>-1</sup> yr<sup>-1</sup> deposited into the NT2 reservoir with 80% from wet deposition.

**Key words:** Dry and wet Depositions, Nitrogen, water surface, Lao.

## Introduction

Atmospheric deposition is an important source of nitrogen (N), and it has been shown that excessive fluxes of N from the atmosphere have resulted in eutrophication of terrestrial and aquatic ecosystems (Liu et al., 2010). Atmospheric N can reach coastal waters directly by wet deposition (precipitation) and dry deposition of both aerosol particles and gases. It can also enter the coastal waters by indirect pathways through deposition first to the land surface and then subsequent runoff. A large fraction of the atmospheric nitrogen input is in the form of inorganic nitrogen, mainly ammonium (NH<sub>4</sub><sup>+</sup>) and nitrate (NO<sub>3</sub><sup>-</sup>) (Ayars and Gao, 2007).

Nam Theun 2 is a hydroelectric reservoir located in Lao PDR, impounded in 2008, which has been monitored since then. As in every newly impounded reservoir, degradation of the flooded organic matter lead to partial deoxygenating of the water column and high concentration of reduced and dissolved compounds. Monitoring includes inputs and outputs survey of dissolved and particulate carbon and nitrogen (N), as well as greenhouse gas (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O) concentrations.

This paper presents the first estimation of the atmospheric inorganic nitrogen deposition into the Nam Theun 2 reservoir. The gaseous N concentrations (NH<sub>3</sub>, HNO<sub>3</sub> and NO<sub>2</sub>) and inorganic N concentrations in rain samples (NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup>) were measured on a forested site surrounding the reservoir for a two-year period (Jun/July 2010-July 2012). Dry deposition fluxes were estimated using the inferential method, which is a combination of gaseous concentration measurements and modeling of deposition velocities according to the resistance analogy (Zhang et al., 2003). Wet deposition fluxes were estimated from NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> concentrations in single event rain samples.

## Materials and methods

### *Sampling site and field measurements*

The Nam Theun 2 (NT2) hydroelectric reservoir (17°59'49" N, 104°57'08" E) was built on the Nam Theun River, in the subtropical region of the Lao PDR, and is operated by the Nam Theun 2 Power Company (NTPC). The flooded area was mainly covered by dense, medium, light and degraded forests (81%), whereas agricultural lands accounted for 11%, with the rest made up of riparian forest, swamps, water and road. The study site is under a subtropical monsoon climate, with a wet season from May to October, a dry season from November to April. This site has been comprehensively described in Deshmukh et al. (2014). The surrounding landscape is generally the same as the flooded area with different percentage coverage. The sampling site was located in a degraded forest, about half a kilometre from the NT2 reservoir shoreline. Ambient air gas

concentrations were performed for a two-year period (July 2010 to July 2012), when precipitation chemistry where done for the two wet seasons of 2010 and 2011 (June 2010 to December 2011).

### *Wet deposition*

Precipitation events were collected at the sampling station using an automatic precipitation collector, which have been designed for the IDAF (IGAC-DEBITS-Africa) network (Galy-Lacaux et al., 2009).

The automatic instrument is designed to collect only wet deposition. It collects precipitation with a high degree of cleanliness in a single-use polyethylene bag, avoiding aerosol deposit before the onset of rain. A precipitation detector automatically controls the aperture of the cover, which hermetically closes the polyethylene bag. The surface of rain collection is 225 cm<sup>2</sup>. After each precipitation event, 50 cm<sup>3</sup> of the collected precipitation is sampled in 50 ml Greiner tubes. For this study, all samples were stored in a deep freeze environment from collection to analysis. All samples were brought to the Laboratory of Aerology (LA) in Toulouse, France, for Ionic Chromatography analysis. More details about analytical procedures are described in Galy-Lacaux et al. (2009).

To calculate wet N deposition to NT2 reservoir, we have compiled the monthly or annual volume weighed mean (VWM) concentrations of nitrate and ammonium from the precipitation collected at the sampling site. Annual rainfall depth was 2502 mm and 3162 mm in 2010 and 2011, respectively.

### *Dry deposition estimate*

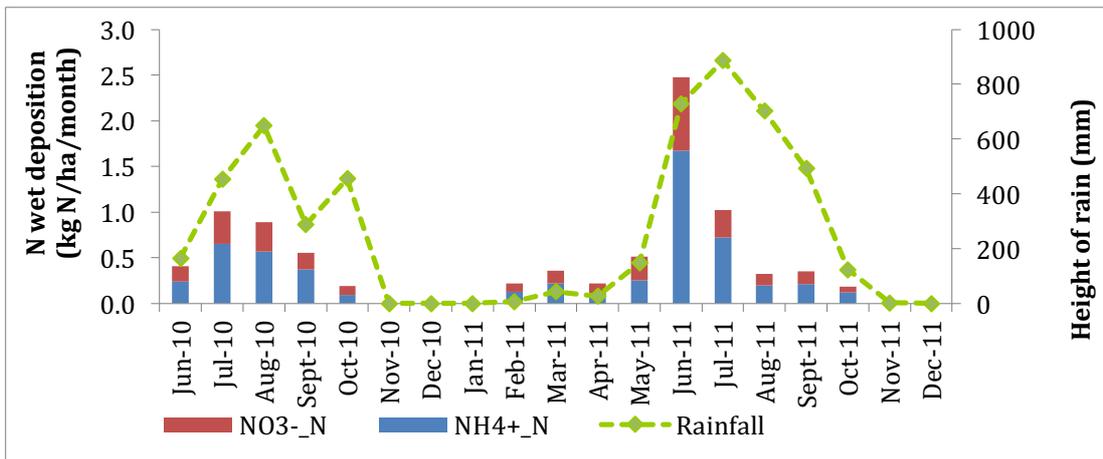
The inferential method, which combines measured air concentrations together with modelled exchange rates, was used here to estimate the dry deposition fluxes of the different gaseous species. Atmospheric concentrations of NO<sub>2</sub>, HNO<sub>3</sub> and NH<sub>3</sub> were measured with IDAF passive samplers on a monthly basis at the sampling site. The samplers were exposed in pairs at about 10 m above the ground. The sampling procedure and chemical analysis of samples, as well as the validation method according to international standards, have been widely detailed in Adon et al. (2010).

The dry deposition velocities ( $V_d$ ) were calculated using the big-leaf dry deposition model of Zhang et al. (2003) that has been used in our previous study for IDAF sites (Adon et al., 2013). Meteorological data from the four field campaigns (May 2009, March 2010, March 2011 and June 2011) performed over the NT2 reservoir surface (Deshmukh et al., 2014) were used to calculate  $V_d$  values over water surface.

## **Results and discussion**

### *Wet deposition of N species*

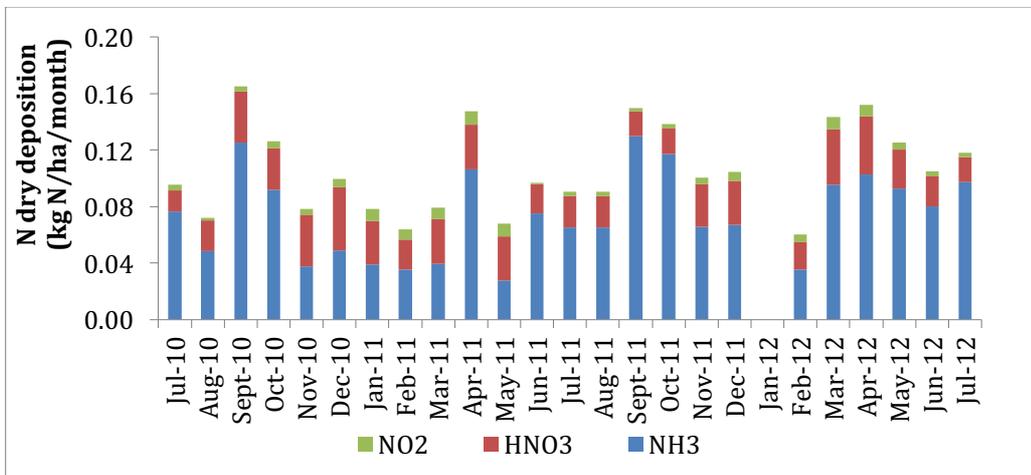
Annual VWM concentration of NO<sub>3</sub><sup>-</sup> measured in 2011 is 0.06 mg N L<sup>-1</sup>, and higher for NH<sub>4</sub><sup>+</sup> with 0.10 mg N L<sup>-1</sup>. Even if the year 2010 is not completely sampled and excludes the first rainy month of May, annual VWM measured concentrations of NO<sub>3</sub><sup>-</sup> and NH<sub>4</sub><sup>+</sup> with 0.05 mg N L<sup>-1</sup> and 0.09 mg N L<sup>-1</sup> respectively, are comparable to 2011. Monthly wet deposition fluxes at the NT2 site are presented on Figure 1 for the period from June 2010 to December 2011. The monthly wet deposition fluxes for rainy months ranged from 0.09 to 1.67 kg N ha<sup>-1</sup> month<sup>-1</sup> for NH<sub>4</sub><sup>+</sup>-N and from 0.06 to 0.81 kg N ha<sup>-1</sup> month<sup>-1</sup> for NO<sub>3</sub><sup>-</sup>-N. The highest fluxes for both NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N occurred in the wet months of June, July and August. On a seasonal basis, wet deposition flux is equal to 2.67 kg N ha<sup>-1</sup> for NH<sub>4</sub><sup>+</sup>-N and 1.54 kg N ha<sup>-1</sup> for NO<sub>3</sub><sup>-</sup>-N in the wet season with a total of 4.21 kg N ha<sup>-1</sup>. In the dry season (November to April), which represents only 2.5 to 3.5 % of the total annual rainfall during the period 2010-2011, wet deposition fluxes is estimated to be 0.46 kg N ha<sup>-1</sup> for NH<sub>4</sub><sup>+</sup>-N and 0.34 kg N ha<sup>-1</sup> for NO<sub>3</sub><sup>-</sup>-N representing a total of 0.8 kg N ha<sup>-1</sup>. Wet deposition fluxes of NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N in the wet season are respectively 6 and 4.5 times higher than in the dry season. At the annual scale, wet deposition fluxes of NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N equal to 3.13 and 1.88 kg N ha<sup>-1</sup> yr<sup>-1</sup>, respectively, or a total N wet deposition of 5.01 kg N ha<sup>-1</sup> yr<sup>-1</sup>. Total annual nitrogen wet deposition occurred at 62.5% in the reduced form (NH<sub>4</sub><sup>+</sup>) and 37.5% in the nitrate form.



**Fig.1: Monthly nitrogen wet deposition fluxes of NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N and precipitation (Height of rain, mm) to NT2 reservoir from Jun. 2010 to Dec. 2011.**

*Dry deposition of N species*

Monthly mean concentrations of NO<sub>2</sub>, HNO<sub>3</sub> and NH<sub>3</sub> were 0.13-1.03, 0.17-0.44 and 0.33-1.67 μg N m<sup>-3</sup>, respectively, at the NT2 reservoir site during the study period (2010-2012). For the dry deposition velocities over water surface, the modelling period covered March and May-June, to represent typical dry and wet season conditions. As a first approximation for HNO<sub>3</sub> and NH<sub>3</sub>, the mean V<sub>d</sub> calculated for the two March campaigns is representative for the dry season, and the mean V<sub>d</sub> calculated from the May and June campaigns for the wet season. Thus, the seasonal V<sub>d</sub> of HNO<sub>3</sub> and NH<sub>3</sub> are respectively 0.44 and 0.42 cm s<sup>-1</sup> for the dry season, and 0.32 and 0.30 cm s<sup>-1</sup> for the wet season. For NO<sub>2</sub>, the mean V<sub>d</sub> to the water surface is constant with a value of 0.035 cm s<sup>-1</sup> in the dry and wet seasons. Monthly dry deposition fluxes of NO<sub>2</sub>, HNO<sub>3</sub> and NH<sub>3</sub> to NT2 reservoir were estimated from the combined monthly concentrations and seasonal dry deposition velocities of gases. The monthly dry deposition fluxes ranged from 0.03 to 0.13 kg N ha<sup>-1</sup> month<sup>-1</sup> for NH<sub>3</sub>, from 0.01 to 0.04 kg N ha<sup>-1</sup> month<sup>-1</sup> for HNO<sub>3</sub> and from 0.001 to 0.010 kg N ha<sup>-1</sup> month<sup>-1</sup> for NO<sub>2</sub> (Fig.2).



**Fig. 2: Monthly N dry deposition fluxes of NO<sub>2</sub>, HNO<sub>3</sub> and NH<sub>3</sub> to NT2 reservoir over the study period (Jul. 2010 - Jul. 2012).**

On a seasonal basis, the total fluxes of NO<sub>2</sub>, HNO<sub>3</sub>, and NH<sub>3</sub> were 0.02, 0.14 and 0.51 kg N ha<sup>-1</sup> in the wet season, and 0.04, 0.19 and 0.36 kg N ha<sup>-1</sup> in the dry season, respectively. On an annual basis, the total dry deposition fluxes estimated were 0.06 kg N ha<sup>-1</sup> yr<sup>-1</sup> for NO<sub>2</sub>, 0.34 kg N ha<sup>-1</sup> yr<sup>-1</sup> for HNO<sub>3</sub> and 0.86 kg N ha<sup>-1</sup> yr<sup>-1</sup> for NH<sub>3</sub>. Total N (NO<sub>2</sub> + HNO<sub>3</sub> + NH<sub>3</sub>) dry deposition fluxes show almost no seasonal variation with 0.67 kg N ha<sup>-1</sup> deposited in the wet season, 0.59 kg N ha<sup>-1</sup> in the dry season for an annual total N dry deposition of 1.26 kg N ha<sup>-1</sup> yr<sup>-1</sup> over the study period. The contribution of NH<sub>3</sub> and HNO<sub>3</sub> to the total N dry flux was 68% and 27%, respectively.

### Total N deposition fluxes to NT2 reservoir

Total N deposition appeared to be highest in the wet season (May through October), with a wet season flux of 4.88 kg N ha<sup>-1</sup>, or about 78% of the total deposition. The dry season flux of total N deposition was estimated to be 1.39 kg N ha<sup>-1</sup> (Table 1).

**Table 1: Mean seasonal and annual atmospheric N deposition fluxes at the NT2 reservoir site (2010-2012)**

flux (kg N ha <sup>-1</sup> )	Wet N deposition (NH <sub>4</sub> <sup>+</sup> , NO <sub>3</sub> <sup>-</sup> )	Dry N deposition (NH <sub>3</sub> , HNO <sub>3</sub> , NO <sub>2</sub> )	Total N deposition
Wet season	4.21	0.67	4.88
Dry season	0.80	0.59	1.39
Annual	5.01	1.26	6.27

On an annual basis, the total N deposition flux directly to the NT2 reservoir surface was 6.27 kg N ha<sup>-1</sup> yr<sup>-1</sup> over the study period. Wet deposition is the dominant removal process, accounting for 80% of the total annual N flux. The reduced (NH<sub>4</sub><sup>+</sup>, NH<sub>3</sub>) and oxidized (NO<sub>3</sub><sup>-</sup>, HNO<sub>3</sub>, NO<sub>2</sub>) forms of the total N deposition flux were calculated to be 3.99 kg N ha<sup>-1</sup> yr<sup>-1</sup> and 2.28 kg N ha<sup>-1</sup> yr<sup>-1</sup>, respectively. The annual total deposition flux in 2011, a complete measurement year, was estimated to be 6.87 kg N ha<sup>-1</sup> yr<sup>-1</sup>, with a contribution of wet deposition of 82% of the total flux. With a surface area of 490 km<sup>2</sup> for NT2 hydroelectric reservoir, the total direct atmospheric N deposition to the reservoir was estimated to be 33.7 × 10<sup>7</sup> g N yr<sup>-1</sup> in 2011 or an average 30.7 × 10<sup>7</sup> g N yr<sup>-1</sup> over the study period (June 2010- July 2012).

### Conclusion

This study provides an estimation of the atmospheric inorganic nitrogen deposition into the NT2 hydroelectric reservoir from June 2010 to July 2012. The total (dry + wet) annual nitrogen deposition flux is estimated to be 6.27 kg N ha<sup>-1</sup> yr<sup>-1</sup> onto the reservoir surface. Wet deposition was the major source of the atmospheric nitrogen input to the NT2 reservoir, contributing to 80% of the total atmospheric deposition. More than 84% of the annual wet N deposition (5.01 kg N ha<sup>-1</sup> yr<sup>-1</sup>) occurred during the wet season (May through October), along with 90-98% of the recorded annual rainfall. The dissolved organic nitrogen and particulate nitrogen were not been taken into account in this budget. Therefore, our estimates of atmospheric N deposition should be regarded as a lower limit of the nitrogen deposited from the atmosphere.

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