

***In situ* continuous monitoring of nitrogen with ion-selective electrodes in a constructed wetland receiving treated wastewater: an operating protocol to obtain reliable data**

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ABSTRACT

Constructed wetlands receiving treated wastewater (CWtw) are placed between wastewater treatment plants and receiving water bodies, under the perception that they increase water quality. A better understanding of the CWtw functioning is required to evaluate their real performance. To achieve this, *in situ* continuous monitoring of nitrate and ammonium concentrations with ion-selective electrodes (ISEs) can provide valuable information. However, this measurement needs precautions to be taken to produce good data quality, especially in areas with high effluent quality requirements. In order to study the functioning of a CWtw instrumented with six ISE probes, we have developed an appropriate methodology for probe management and data processing. It is based on an evaluation of performance in the laboratory and an adapted field protocol for calibration, data treatment and validation. The result is an operating protocol concerning an acceptable cleaning frequency of 2 weeks, a complementary calibration using CWtw water, a drift evaluation and the determination of limits of quantification (1 mgN/L for ammonium and 0.5 mgN/L for nitrate). An example of a 9-month validated dataset confirms that it is fundamental to include the technical limitations of the measuring equipment and set appropriate maintenance and calibration methodologies in order to ensure an accurate interpretation of data.

Key words | ammonium, electrochemical sensor, free-water surface constructed wetland, long-term monitoring, nitrate

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INTRODUCTION

The quality of surface waters with respect to eutrophication and nutrient concentrations is an objective of the Water Framework Directive which aims to achieve a good chemical and ecological status of all water bodies across the European Union by 2021. Moreover, the classification of a territory as a nutrient-sensitive area often implies more binding emission limit values for nitrogen and phosphorus for the wastewater treatment plants (WWTPs). In this context, the use of constructed wetlands receiving treated wastewater (CWtw) has recently become attractive in France under the perception that they increase water quality. Placed between the WWTP and the receiving water body, the CWtw is not included in the WWTP. Therefore, more than 500 CWtws are in operation in France; most of them

have been built in the last 5 years (Prost-Boucle & Boutin 2013). They have a multitude of configurations (meadows, ponds, ditches and ‘miscellaneous’, i.e. specific design using filling material) and intended outcomes, but no clear link between them. In these systems, the fate of conventional pollutants, such as nitrogen, depends on processes occurring in the different compartments of CWtws: free water, soil, plants. In order to monitor nitrogen concentrations along the CWtw and to assess CW performances, *in situ* and continuous measurement can be considered as a method of choice compared to a classic method needing field sampling then laboratory measurement (Olsson *et al.* 2014). Ion-selective electrodes (ISEs), electrochemical sensors based on potentiometric methods (Cammann 1979),

are more and more installed in WWTPs as they allow *in situ* and continuous measurement of ions such as nitrate and ammonium (Åmand *et al.* 2013). However, ISEs need careful precautions to be taken, and specific protocols must be deployed (installation, calibration, maintenance, data validation) to guarantee reliable data (Guigues *et al.* 2002; Thomann *et al.* 2002). In the case of sensitive areas with low outlet water concentrations for nitrogen (typically <2 mgN/L for ammonium), management of ISE probes and data processing must be considered as a challenge because the limits of the sensors may be met (Kaelin *et al.* 2008).

In this context, we propose a reliable methodology to increase the quality of data from ISE probes installed in a CWtw characterized by low ranges of nitrate (NO₃-N) and ammonium (NH₄-N) concentrations. This methodology is based on an evaluation of probe performance in the laboratory and an adapted field protocol for calibration, data treatment and validation. An example of treated and validated data shows the potential and limits of these probes for the long-term monitoring (9 months) of the nitrogen dynamic in the CWtw.

METHODS

Site description and instrumentation

The studied CWtw is located in the city of Marguerittes (Southern France) and has been operating since summer 2013. The CWtw is similar to a free water surface CW and consists of two ponds in series, P1 and P2 (Figure 1), of 3,575 m² and 6,370 m² respectively. The pond P1 receives between 1,000 and 3,000 m³/d of treated wastewater from the 15,000 population equivalent (PE) WWTP. Then, the water flows into the pond P2 composed of five different areas before discharging into the Canabou River. The measured average hydraulic residence time (hydraulic

tracing with uranine/fluorescein; recovery rates between 69 and 90%) along the CWtw is approximately 3 days.

The CWtw has been instrumented with six ISE probes (specific sensors VARION AN/A WTW-Secomam) measuring NO₃-N and NH₄-N concentrations with a 5-min step recording. This study presents a 9-month dataset running from August 2015 to April 2016. A focus is made on probe #1, located at the outlet of the WWTP, which represents the influent of the CWtw (Figure 1). According to manufacturer instructions, the measurement ranges of NO₃-N and NH₄-N concentrations are 0.1–100 mg/L with a response time of 3 min in both surface water and wastewater. During the installation of new sensors (typically every 6–9 months), a calibration with manufacturer solutions (from 5 to 60 mgN/L) was systematically performed. It was followed by a matrix adjustment using water from the CWtw spiked with sodium nitrate and ammonium sulfate (AnalaR NORMAPUR quality) to reach NO₃-N and NH₄-N concentrations around 5 mgN/L.

Measurement of reference NO₃-N and NH₄-N concentrations

Ionic chromatography was used as reference method for the determination of NO₃-N and NH₄-N concentrations in the solutions used for laboratory tests and in the grab samples collected in the CWtw. The NF EN ISO 10304-1 (2009) and NF EN ISO 14911 (1999) standards were applied, respectively, for NO₃-N and NH₄-N measurements. Limits of quantification (LoQ) for NO₃-N and NH₄-N are 0.45 mgN/L and 0.02 mgN/L respectively, and precision was better than 6% for NO₃-N and 8% for NH₄-N.

Laboratory tests

The performance of ISE probes was evaluated in the laboratory based on the ISO 15839 (2003) standard (Rieger *et al.*

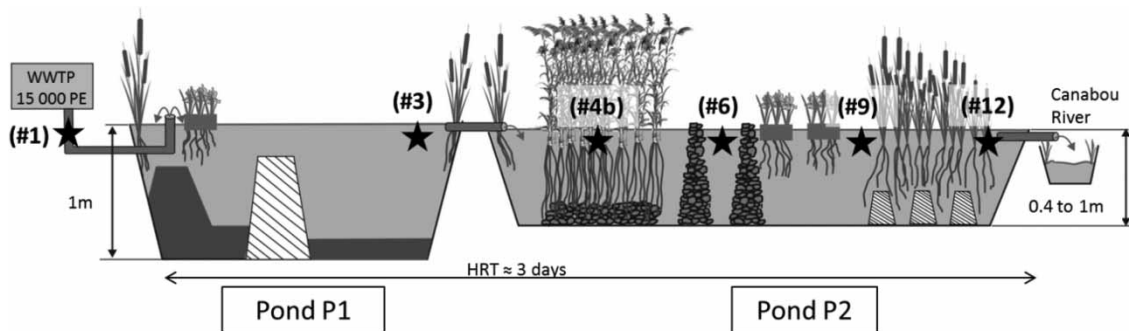


Figure 1 | Schematic representation of the CWtw constituted by two main ponds (P1 and P2) and location of the six ISE probes (#1), (#3), (#4b), (#6), (#9) and (#12) (black stars).

2002). The applied protocol needed the preparation of several solutions spiked with well-defined $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations (ammonium sulfate and sodium nitrate, AnalaR NORMAPUR quality). French bottled mineral water (Saint Antonin) was used for its composition without nitrogen ($\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations were below 0.45 mg/L and 0.02 mg/L, respectively). Because the measurement is influenced by the ionic strength and the matrix of the measuring water (Rieger *et al.* 2002), the solution used for the experimentations (S_{exp}) was prepared by diluting the mineral water three times with ultra-pure water to fit the ionic strength of the CWtw. $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations of the different solutions prepared by spiking S_{exp} were systematically controlled using the reference methods. The following key parameters have been evaluated.

- The response times of the sensors to sudden increasing and decreasing changes of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations were estimated by successively immersing the probe in S_{exp} spiked with $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations of 5.0 and 80 mgN/L (i.e. 5% and 80% of the concentration range).
- The linearity between measured concentrations and theoretical concentrations was evaluated by measuring $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations in S_{exp} adjusted to 0.5, 1.0, 2.0, 5.0, 10, 25, 40, 60, 80 and 95 mgN/L. This experiment was repeated six times in intermediate precision conditions. The check of the linearity was performed by comparing the mean bias for each concentration with maximum permissible deviation (MPD) values determined on the basis of the laboratory expertise.
- Based on the NF T 90-210 (2009) standard, assumed LoQs of 0.5 and 1.0 mgN/L for $\text{NO}_3\text{-N}$, and 1.0 and 2.0 mgN/L for $\text{NH}_4\text{-N}$ have been analyzed.
- The interferences were quantified in a solution containing $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations of 5.0 mgN/L in which successive additions of chloride potassium were completed (maximum concentration for chloride: 700 mg/L; for potassium: 800 mg/L), as chloride and potassium ions represent the main interferences for $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ measurements, respectively (Winkler *et al.* 2004).

Field procedures

The maintenance frequency was set at 2 weeks. Sensors were cleaned with CWtw water and then tap water if necessary. If biofouling was observed, a soft tissue could be used. To evaluate the impact of the cleaning frequency on measurements, $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations

measured by the probes before and after the cleaning procedure were systematically recorded.

ISE probes are subject to drift over time (Winkler *et al.* 2004) and a protocol was developed to evaluate this potential drift. After the cleaning procedure, the probes were systematically immersed in a drift control solution (Sol_{DC}) for $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ measurement. The Sol_{DC} consists of filtered water ($<0.45 \mu\text{m}$) collected in the CWtw and spiked with ammonium sulfate and sodium nitrate (AnalaR NORMAPUR quality) to reach $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations of 5 mgN/L. The Sol_{DC} was stored at 4 °C in the dark. Every 2 weeks, the $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations of the Sol_{DC} were measured using reference methods to control the stability of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations, and then 1 L of Sol_{DC} was brought to the field for drift control.

Despite the initial manufacturer calibration and matrix adjustment, additional local calibration has been performed. Every 2 weeks, water was systematically sampled close to each probe just before the cleaning maintenance. The $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations given by the probes during the sampling were associated with the corresponding concentrations measured in the grab samples by reference methods in laboratory. The resulting dataset was split into two parts: 50% was used for local calibration and the other 50% was used for data validation. In order to cover a broader range of concentrations, three additional couples ($\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$) of concentrations were produced by using water from the CWtw adjusted to 10, 15 and 20 mgN/L for $\text{NO}_3\text{-N}$ and 5.0, 10 and 15 mgN/L for $\text{NH}_4\text{-N}$.

RESULTS AND DISCUSSION

ISE performance evaluation in laboratory

The response times for increasing concentration changes were evaluated to about 2 min for the two sensors. The response times for decreasing concentration changes were found to be close to 15 s (Table 1). These results are consistent with response times given by the manufacturer (<3 min). The estimated response times seem to be sufficiently low to observe the variation of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations along the CWtw. Moreover, this result confirms that an acquisition frequency of 5 min is well adapted.

For each sensor, two LoQs have been verified depending on the MPD values (high value: 60%; intermediate value: 30%; Table 1) which are chosen by the laboratory based on its own expertise. Given that $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations measured along the CWtw are generally low and

Table 1 | Results of the performance evaluation for the ISE probe obtained in laboratory. LoQs were analyzed with MPD values of 30% and 60%

		NO ₃ -N sensor	NH ₄ -N sensor
Response time (s)	to increasing concentrations	130	125
	to decreasing concentrations	14	13
LoQ (mgN/L)	with 30% MPD value	0.5	1.0
	with 60% MPD value	1.0	2.0
Interference ratio	Chloride	negligible	–
	Potassium	–	1:25

less than 2 mgN/L, the lowest LoQ is chosen, i.e. 0.5 mgN/L for NO₃-N and 1.0 mgN/L for NH₄-N, to allow the quantification of a maximum of data. In return, we assume a lower quality of data close to the LoQ concentrations.

According to the manufacturer, chloride and potassium may be considered as the main interfering ions for NO₃-N and NH₄-N measurement, respectively. During the interference tests, the NO₃-N concentrations remain more or less constant with increasing chloride concentrations (Table 1). This suggests that the chloride interferences on NO₃-N measurement may be considered as negligible despite chloride concentration variations observed along the CWtw (160–230 mg/L; data not shown). The NH₄-N concentrations linearly increase with increasing potassium concentrations. The interference is evaluated to be 1 mgN/L NH₄-N for a potassium concentration increase of 25 mg/L (Table 1). The potassium concentrations measured along the CWtw varied from 15 to 25 mg/L (data not shown). This suggests that NH₄-N concentrations are potentially interfered by ±0.2 mgN/L in the case of the studied CWtw and may be neglected. For both sensors, the estimated interferences are lower than those announced by the manufacturer (3% for chloride and 10% for potassium) and are consistent with the cross-sensitivities values given by Winkler *et al.* (2004) with 1:300 for chloride and between 1:15 and 1:30 for potassium.

The verification of the linearity in the range of 0.5–100 mgN/L was performed by comparing, for each concentration, the mean bias ($n = 6$) with MPD values defined by the laboratory (Table 2). For NO₃-N concentrations higher than 2.5 mgN/L and NH₄-N concentrations higher than 5 mgN/L, the mean biases were less than 20%. For lowest concentrations the mean biases increased and ranged between 25% and 65% (Table 2). Increase of bias for low concentrations is consistent with electrochemical theory that suggests non-Nernstian response (i.e. nonlinear response) for low concentrations around a few mgN/L (e.g. Winkler *et al.* 2004). However, taking into account MPD

values of 60% for concentrations lower than $5 \times \text{LoQ}$ concentrations and 20% for higher concentrations, these results suggest that the linearity of the sensors may be verified from 0.5 to 100 mg/L for NO₃-N and from 1 to 100 mg/L for NH₄-N. The estimated bias may be also used to compare concentrations measured by two different probes.

The repeatability, calculated as the standard deviation of the measurements of each concentration level, was generally better than 10% for both sensors and for the whole concentration range (Table 2). This low value may be used to evaluate significance of NO₃-N and NH₄-N concentration variations measured by a given probe.

Cleaning frequency

No strong difference (generally <20%) is observed between NO₃-N and NH₄-N concentrations measured before and after the cleaning procedure (Figure 2), except for one probe for which stronger deviations are observed for the NO₃-N sensor. Moreover, no difference has been observed between summer (maximum potential of biofouling development) and winter. Therefore, these results suggest that the biofouling impact may be considered as negligible for an exposure time of 2 weeks without any maintenance in this CWtw.

Evolution of the drift over time and correction

This part is focused on the probe #1 installed at the entry of the CWtw. The drift control procedure started 5 months after the installation of the probe and covered the last 4 months of the sensor life. The NO₃-N concentrations measured in the drift control solutions stayed rather constant during the last 4 months (Figure 3(a)). Therefore, no correction is considered for the NO₃-N signal.

Concerning the NH₄-N sensor, a drift is observed after 30 days of monitoring (Figure 3(a)). Assuming a linear drift-over time, we estimate that NH₄-N concentrations increased by 0.1 mgN/L every day. However, an offset

Table 2 | Mean relative bias ($n = 6$) and repeatability (calculated as standard deviation, $n = 6$) for each tested concentration. The MPD values were defined by the laboratory at 60% for concentrations less than $5 \times \text{LoQ}$ and at 20% for higher concentrations

Concentration (mgN/L)	NO₃-N sensor		NH₄-N sensor	
	LoQ to $5 \times \text{LoQ}$ 0.5–2.5	$>5 \times \text{LoQ}$ 2.5–100	LoQ to $5 \times \text{LoQ}$ 1.0–5.0	$>5 \times \text{LoQ}$ 5.0–100
Relative mean bias	25%–46%	–2% to 20%	32%–64%	–3% to 20%
MPD values	60%	20%	60%	20%
Repeatability	7%–12%	2%–7%	4%–7%	3%

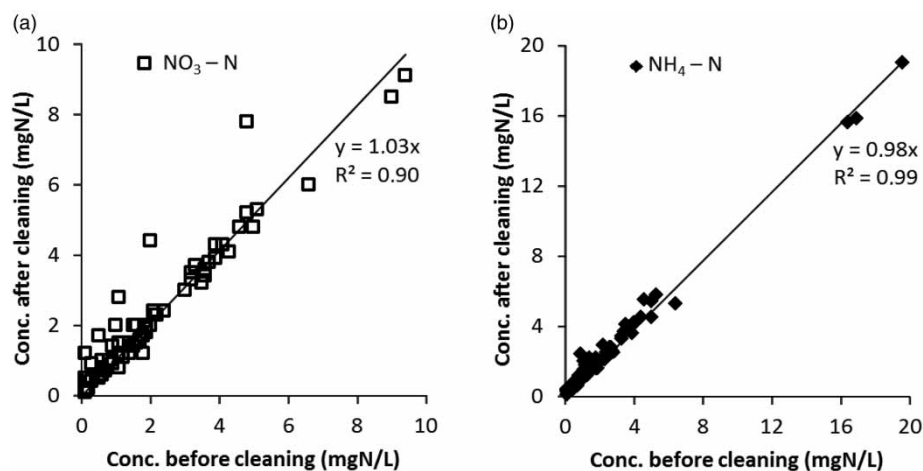
daily correction of 0.1 mgN/L applied on the raw signal leads to negative values which suggests that the drift experimentally determined is overestimated. Another way to estimate the drift is possible thanks to the grab samples with concentrations below 0.10 mgN/L, assuming that their corresponding probe concentrations should remain steady over time and form a baseline. Despite the low number of grab sample concentrations ($n = 4$), this baseline seems to increase linearly with time (Figure 3(b)). The slope of the relationship, i.e. 0.03 mgN/L/d, was used to estimate a more appropriate drift. The raw NH₄-N signal was corrected by subtracting 0.03 mgN/L/day from November 2015.

Local calibration and data validation

After the drift correction, local calibration is completed using (i) 50% of available couples of probe–grab sample points and (ii) the three additional couples of adjusted concentration points (Figure 4(a) and 4(b)). Each slope of linear regression is used to correct the data measured by the probe. For the studied probe #1, a correction by a factor 1.24 is applied on NO₃-N concentrations (Figure 4(a)). The local

calibration of NH₄-N concentrations is more complex as all NH₄-N concentrations measured into grab samples are always below 1 mgN/L (i.e. below the LoQ determined for the NH₄-N sensor). In consequence, only the three additional couples of adjusted concentration (5, 10 and 15 mgN/L) points are used to build the calibration curve (Figure 4(b)). For the probe #1, a correction factor of 0.60 is applied to the NH₄-N signal already corrected from the drift.

The other part of available couples of probe–grab sample points is used for data validation. Relative errors are calculated as the difference in the concentrations measured by the probe and measured in the grab sample and divided by the concentration measured in the grab sample. For NO₃-N concentrations between LoQ and $5 \times \text{LoQ}$ (i.e. 0.5–2.5 mgN/L), the relative errors are negative and close to –30% (Table 3). For NO₃-N concentrations higher than $5 \times \text{LoQ}$ (i.e. 2.5 mg/L), the relative errors slightly decrease and vary from –2% to 20% (Table 3). These results suggest that measurement by the ISE probe is of good quality for NO₃-N monitoring in the CWtw. For NH₄-N, data for validation is not available as the whole dataset has been used for the local calibration. To remedy this situation, additional samples could be prepared using

**Figure 2** | NO₃-N (a) and NH₄-N (b) concentrations measured just before and after cleaning procedure by the six probes installed on the CWtw.

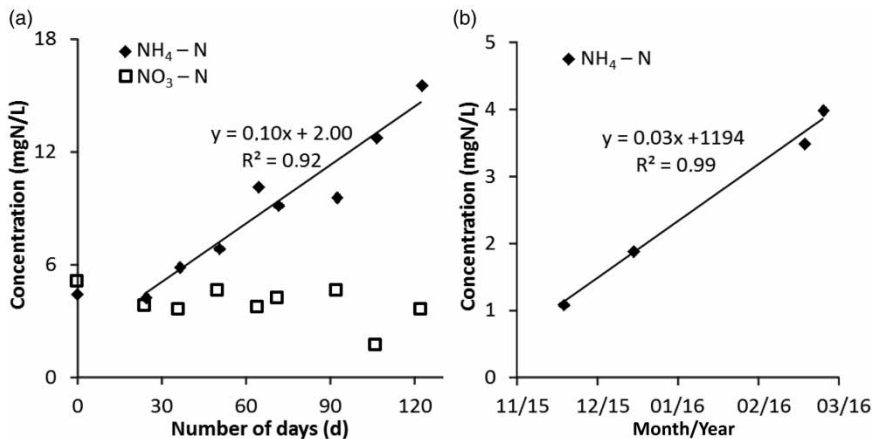


Figure 3 | (a) Evolution of the $\text{NO}_3\text{-N}$ (open squares) and $\text{NH}_4\text{-N}$ (black diamonds) concentrations measured by the probe (#1) in the Sol_{bc} during the last 4 months of the sensor life. (b) Evaluation of the $\text{NH}_4\text{-N}$ drift based on the increase over time of the $\text{NH}_4\text{-N}$ concentrations measured by the probe for the period where concentrations measured in the grab samples were low (<0.10 mgN/L).

CWtw water spiked with $\text{NH}_4\text{-N}$ to cover the concentration range measured by the probe (until 40 mgN/L). Half of these samples could be used for local calibration and the other half could be used for validation. Moreover, for the next dataset produced by new sensors, cross-validation will be considered, to improve the local calibration and validation procedure.

Example of data processing

Figure 5 shows the raw $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations measured by the probe (#1) and the corrected concentrations. Drift correction has only been performed for $\text{NH}_4\text{-N}$ signal, while local calibration correction has been applied for $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ signals. During the 9-month studied period, the $\text{NO}_3\text{-N}$ concentrations monitored at the entry of the CWtw are clearly variable and ranged between the

LoQ value (0.5 mgN/L) and ~ 13 mgN/L (Figure 5(a)). Only a few values are below the LoQ ($<10\%$ of data). Daily variations are observed with maximum concentrations generally measured around midnight (Figure 5(a)). The amplitude of these variations are far greater than the measurement repeatability evaluated in the laboratory ($<10\%$), confirming the significance of the $\text{NO}_3\text{-N}$ daily peaks. Only *in situ* and continuous measurement allows the observation of $\text{NO}_3\text{-N}$ concentration dynamic at this temporal scale over a long period.

Contrary to $\text{NO}_3\text{-N}$, data treatment has strongly modified the $\text{NH}_4\text{-N}$ concentrations (Figure 5(b)) and corrected $\text{NH}_4\text{-N}$ concentrations are approximately two-fold lower than the raw concentrations. Several $\text{NH}_4\text{-N}$ peaks are observed with maximum $\text{NH}_4\text{-N}$ concentrations reaching 15 mgN/L. These peaks are not easily observable with traditional monitoring (i.e. weekly sampling and

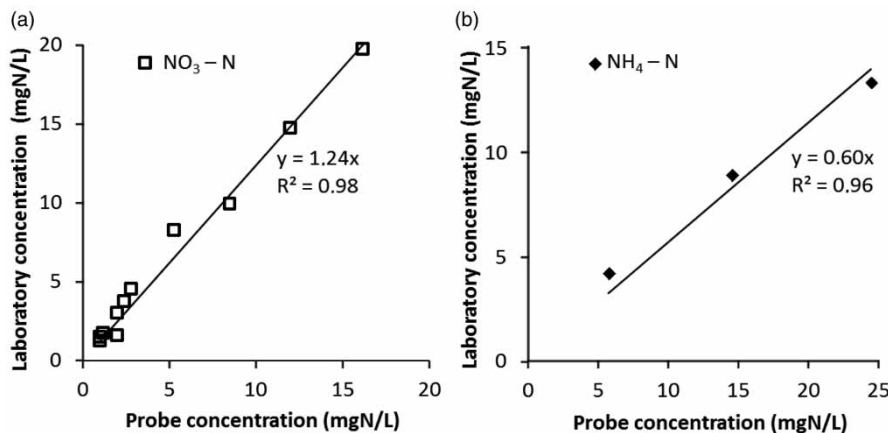


Figure 4 | $\text{NO}_3\text{-N}$ (a) and $\text{NH}_4\text{-N}$ (b) local calibrations performed for the probe #1.

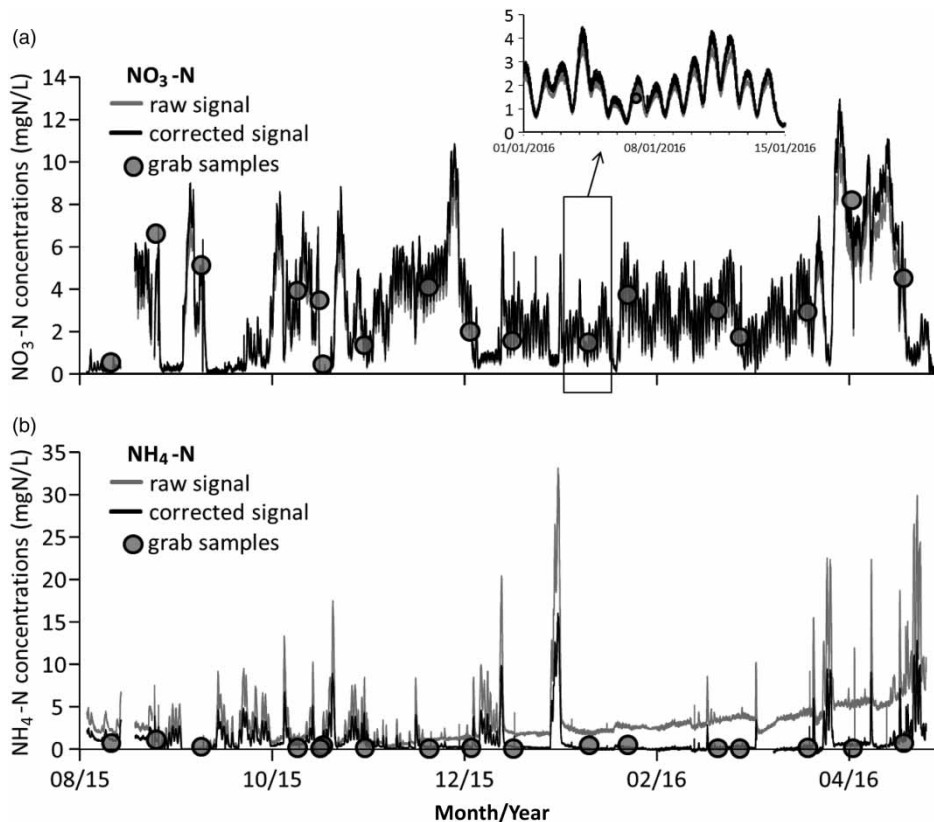
Table 3 | Sample set used for validation of $\text{NO}_3\text{-N}$ measurement: raw probe concentrations, corrected probe concentrations (from local calibration) and reference laboratory concentrations, relative errors between corrected and reference concentrations

	Raw conc. (mgN/L)	Corrected conc. (mgN/L)	Reference conc. (mgN/L)	Relative error
$<5 \times \text{LoQ}$	0.8	1.0	1.4	-27%
	1.2	1.5	2.0	-26%
$>5 \times \text{LoQ}$	3.3	4.1	4.1	-1%
	3.8	4.7	3.9	20%
	4.8	6.0	5.1	16%
	5.2	6.5	6.6	-2%

analysis in laboratory). Unfortunately, the validation of $\text{NH}_4\text{-N}$ data is less effective than for $\text{NO}_3\text{-N}$ due to very low concentrations in the grab samples. About 50% of data are below the LoQ (i.e. 1 mgN/L).

The performance evaluation of sensors in laboratory coupled with the quality procedure on the field help to improve the quality of data exploitation. The knowledge of the probe limitations (e.g. LoQ, response time, repeatability) avoids misinterpretations of temporal $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ recordings. For example, we recommend to not consider concentrations less than 0.5 mgN/L for $\text{NO}_3\text{-N}$ and

less than 1 mgN/L for $\text{NH}_4\text{-N}$. In the case of nitrogen flux estimation along the CWtw, the values less than the LoQ may be replaced by $\text{LoQ}/2$ values. Furthermore, an apparent $\text{NH}_4\text{-N}$ increase can be the result of the signal drift and not the degradation of water quality entering into the CWtw (for example the global increase observed since November 2015 on the raw signal, Figure 5(b)). Differences in $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations measured by a probe at different times or by several probes in different locations may be now discussed with regard to the evaluated bias, relative errors and repeatability.

**Figure 5** | Raw signals (black lines) recorded by the probe #1 for $\text{NO}_3\text{-N}$ (a) and $\text{NH}_4\text{-N}$ (b) during August 2015 to March 2016 and signals after correction procedures. The black circles represent the grab samples and the dashed lines represent the LoQ estimated for the probe.

CONCLUSIONS

The methodology implemented for the monitoring of low $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations in a CWtw has allowed an efficiency correction of produced data. This methodology is firstly based on an evaluation in the laboratory of the sensor performances (mainly LoQs and repeatability of the measurements). Specific procedures have been implemented to correct data. The evaluation of the potential impact of the biofouling shows that a 2-week maintenance frequency is sufficient. The monitoring of signal drift shows no drift for the $\text{NO}_3\text{-N}$ signal whereas $\text{NH}_4\text{-N}$ signal drift can be corrected using grab samples. Despite initial calibration and matrix adjustment, a local calibration with grab samples is necessary. Observing these procedures for data correction, a good agreement exists between corrected probe concentrations and reference concentrations measured in the laboratory. The consolidated data made possible a reliable quantification of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations along the CWtw and a better interpretation of the temporal recordings of low concentrations, taking into account the technical limitations of the probes (mainly LoQ and repeatability). The presented methodology still needs to be improved by (i) the production of $\text{NH}_4\text{-N}$ concentrated samples for validation, (ii) the use of cross-validation, or (iii) data comparison of two probes installed at the same location.

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