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Reliability and economic feasibility of online monitoring of constructed wetlands performance

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ABSTRACT

This study aimed at determining the reliability and feasibility of constructed wetlands (CWs) performance evaluation by online monitoring. Redox potential (E_H), turbidity and ammonium (NH_4) were continuously monitored for one year by means of online sensors in a pilot plant based on horizontal sub-surface flow constructed wetlands (HSSF CWs). Results were compared with conventional laboratory analyses. Online measures and laboratory analyses showed good agreement for NH_4 ($r = 0.84$, $p < 0.01$). A significant correlation was also found for: online turbidity vs. Total suspended solids (TSS) ($r = 0.85$, $p < 0.01$); online turbidity vs. Biochemical oxygen demand (BOD) ($r = 0.88$; $p < 0.01$) and E_H vs. BOD ($r = -0.62$; $p < 0.01$). Results suggested that in full-scale CWs, continuous monitoring of turbidity, E_H and NH_4 would help to both daily monitoring and improvement of CWs performance. A general overview about economic aspects suggested that, continuous monitoring of wastewater quality could be technically feasible and cheaper than traditional chemical-based monitoring.

Keywords: Ammonium; Constructed wetlands; Continuous online monitoring; Performance; Redox potential; Turbidity

1. Introduction

Constructed wetlands (CWs) have been proven to be a promising alternative for wastewater treatment. CWs have been set up all over the world as an alternative to conventional intensive systems especially for the sanitation of small communities. They have low investment and operation costs and produce high-quality effluents with low-energy requirements [1–3].

Wetlands are complex reactors in which physical, chemical and biological processes occur simultaneously. There is no single pathway to describe the complete range of processes involved in the removal of a given contaminant [1]. Additionally, in CWs contaminants removal efficiency depends on multiple factors (such as design and operational parameters, environmental conditions and wastewater quality) [4–7]. Therefore, CWs have been considered complex in their functioning while easy to build and operate.

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The number of research studies on the evaluation of CWs removal efficiency has dramatically increased during the last years. However, current studies are mostly based on surveying laboratory- or pilot-scale systems with a limited amount of experimental data collected on a monthly or weekly basis. Comparatively, the number of long-term studies based on assessing the long-term performance of full-scale CWs is very low [8]. Therefore, long-term assessment of CWs performances on a daily basis remains quite unexplored, though it will provide useful information for enhancing wetlands performance.

The main objective of this study was to determine the reliability and both technical and economic feasibility of online measurement for CWs performance assessment. To this aim, the performance of a pilot plant of horizontal sub-surface flow constructed wetlands (HSSF CWs) was monitored by means of both laboratory and online measures. Redox potential (E_H), turbidity and ammonium (NH_4) were continuously measured by means of online sensors during one year and compared with laboratory analyses. E_H, turbidity and NH_4 were chosen for CWs control evaluation for the following reasons: (i) E_H characterizes oxidation–reduction conditions of wetland media which are associated with contaminant removal efficiency in CWs [9]; besides E_H monitoring with online equipment in CWs is considered simple and inexpensive; (ii) turbidity in wastewater is caused primarily by suspended solids [10]; therefore, turbidity in CWs can be monitored in order to estimate TSS removal; (iii) NH_4 has an important role in degrading the environmental conditions of receiving waters [10], NH_4 removal indicate the good state of the wastewater treatment processes occurring in CWs. Also NH_4 is a key parameter for CW modelling and practice dictates that when it is removed, organic matter is consequently removed.

2. Materials and methods

2.1. Experimental plant

The experimental plant used in this study was set in operation in February 2007 and treated domestic wastewater directly pumped from a municipal sewer. It was located at the Department of Hydraulic, Maritime and Environmental Engineering of the Universitat Politècnica de Catalunya, in Barcelona, Spain. The experimental plant consisted of 3 lines, named as batch, control and anaerobic lines (Fig. 1). Further details on the pilot plant configuration and/or operation can be found at [5,11].

Note that this configuration was adopted in order to study the clogging processes in relation with different primary treatments and operational conditions, which fall outside the scope of this paper [11]. For the purposes of this study, only the control line will be considered.

Pretreatment consisted of coarse screening. After pretreatment, the wastewater was conveyed to a plastic tank of 1.2 m^3 with a retention time of 12 h. The effluent of this storage tank was diverted to the 3 treatment lines. The control line used in this study consisted of two conventional settlers as primary treatment followed by HSSF CWs permanently saturated and intermittently fed. There were two small wetlands in parallel (0.65 m^2 each) connected to a big wetland in series (1.65 m^2). Big and small wetlands consisted of plastic containers 1.5 m long, 1.1 m wide and 0.50 m high, and 0.95 m long, 0.70 m wide and 0.45 m high, respectively. The uniform gravel layer (D_{60} = 7.3 mm, 40% initial porosity) was 0.3 m deep and the water level was kept 0.05 m below the gravel surface to give a water depth of 0.25 m. In April 2007, wetlands were planted with developed rhizomes of common reed (*Phragmites australis*) and by July 2007, the plants were well established and covered the entire surface of the wetlands. Each of the two conventional settlers was fed six times a day. Wastewater retention time in these settlers was 2 h. Small wetlands in parallel were fed six times a day and received a total flow of 42 $L\,d^{-1}$, while the big wetland in series received the combined effluent of the two small wetlands (84 $L\,d^{-1}$). Note that the particular configuration of this system was adopted to study the clogging phenomena in wetlands [11]. Wetlands were operated at a nominal hydraulic loading rate (HLR) of 28.5 mm/d. Wetlands were designed to have altogether a maximum organic loading rate of approximately 6 $g\,m^{-2}\,d^{-1}$, as suggested by [12,13].

2.2. Continuous online monitoring

E_H, turbidity and NH_4 were measured by means of online equipment. An E_H probe (Digimed TH-404) was placed at the outlet of the big wetland (Fig. 1) to measure E_H every 10 s. A turbidimeter (nephelometric method) (Digimed TB-44 M) and NH_4 online sampler (Digimed AI-NH3) were used to measure a sample per day (at approximately 9 AM) of the effluent of the conventional settler and the effluent of the plant (big wetland effluent) (Fig. 1). At each sampling spot (Fig. 1), a peristaltic pump conveyed the water to the online measuring equipment by means of a pipe about 8 m long. Data from online sensors were

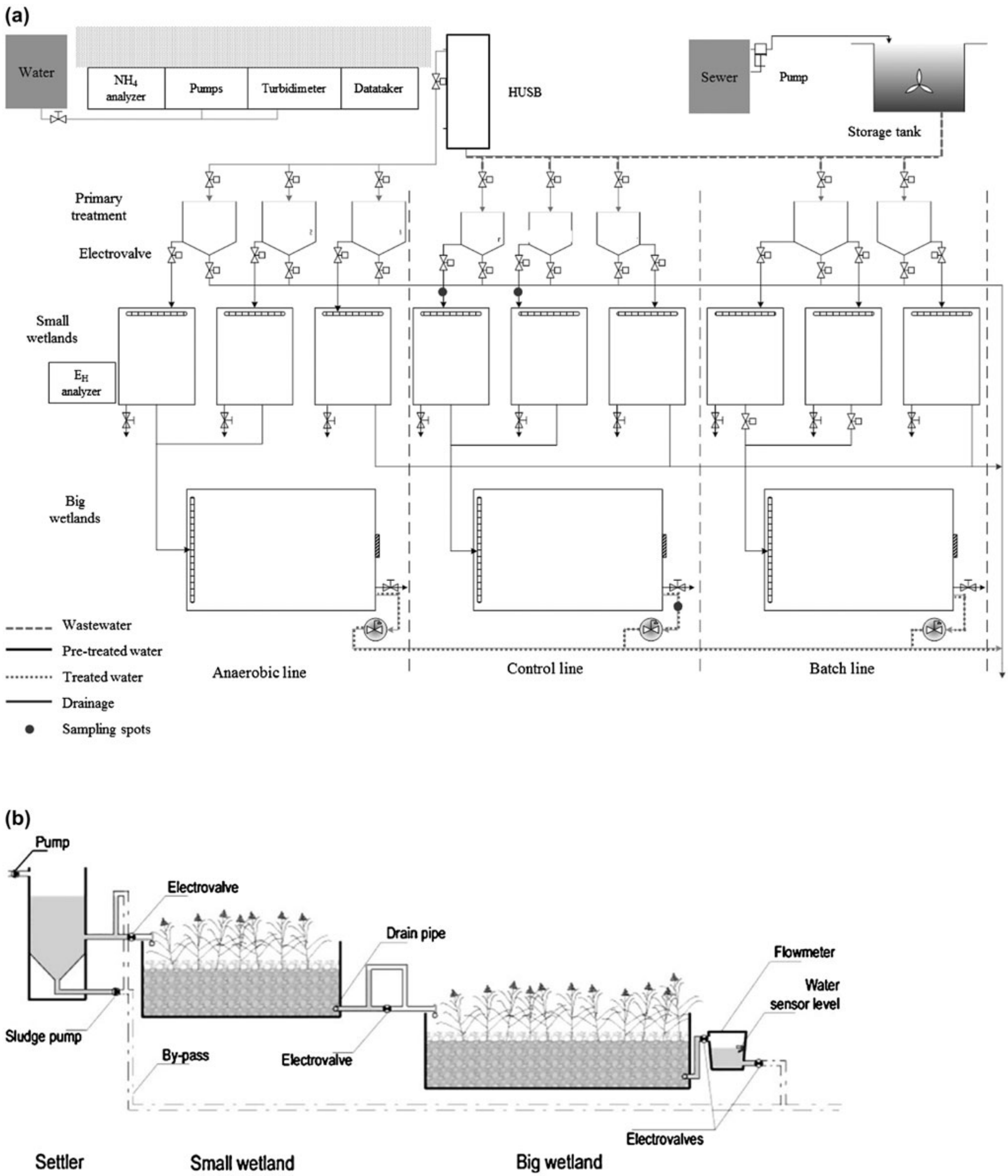

Fig. 1. Schematic diagram of the experimental plant (a) and side view of the control line (b). Modified from [5,11].

collected and stored automatically in a data logger DT50. Stored data could be downloaded via Wi-Fi Internet connection. All electrical devices of the plant (pumps, electrovalves, etc.) were controlled by an OMRON ZEN® programmable relay, programmed with ZEN Support 4.0® Software. Data were collected from

July 2008 to July 2009. Technical characteristics of the online equipment are described in Table 1.

2.3. Laboratory analyses and statistics

In order to assess the reliability of data continuously collected by online equipment, grab samples from the pilot plant were taken on weekly basis and analysed at the laboratory for NH_4, BOD_5 and total suspended solids (TSS) For the NH_4, BOD_5 and TSS analyses were carried out according to Standard Methods [14]. Furthermore, all grab samples were taken at approximately 9 AM (number of data: 46 per parameter). Sampling points are showed in Fig. 2.

Pearson correlation coefficient was calculated by using Minitab 16 software. For the calculation of correlation coefficient, weekly average was considered for online and laboratory measures. Differences were considered significant when $p < 0.05$.

3. Results and discussion

3.1. Turbidity

Table 2 shows monthly average of turbidity in settler and wetland effluents obtained by means of online equipment. A high standard deviation was observed especially in the settler effluent because of the variability of real wastewater quality. Daily values ranged from 10 to 68 NTU for primary treatment effluent. Average monthly turbidity of wetland effluent was low and fairly constant, fluctuating from 0.1 to 4 UNT.

A significant correlation was found between online turbidity values and TSS ($r = 0.85$, $p < 0.01$) and between online turbidity measures and biochemical oxygen demand (BOD) ($r = 0.88$; $p < 0.01$) (Fig. 2). Turbidity in wastewater is caused primarily by suspended solids, although soluble organic compounds can also contribute [10]. In Europe Council Directive 91/271/EEC [15], set the maximum legal limits for TSS and BOD_5 effluent concentration at 35

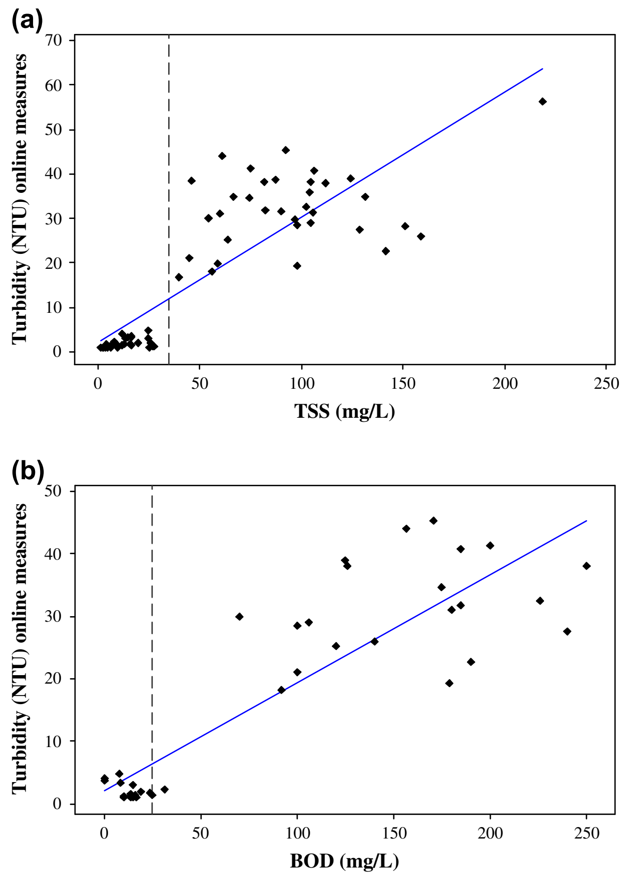

Fig. 2. Correlation between values measured by online equipment and analytics of turbidity vs. TSS (a) and turbidity vs. BOD (b). Weekly average was considered for online and laboratory analysis. Reference lines are shown for maximum legal limits of effluent concentration, according to Europe Council Directive 91/271/EEC (35 and 25 mg/L for TSS and BOD, respectively).

and 25 mg/L, respectively. Fig. 2(a) and (b) showed that when turbidity was higher than 5–10 NTU, TSS and BOD_5 were above the legal limits. Results of this study suggested that turbidity values measured with online sensors was a reliable and easy-to-operate method to assess the legislation compliance in terms

Table 1
General characteristics of E_H probe (Digimed TH-404), turbidimeter (Digimed TB-44 M) and NH_4 probe (Digimed AI-NH3)

	Digimed TH-404	Digimed TB-44 M	Digimed AI-NH3
Parameter	E_H	Turbidity	NH_4
Range	±1999.9 mV	0–1,000 NTU	0–100 ppm
Resolution	0.1–1 mV	0.001 NTU	0.1 ppm
Relative accuracy	0.01%	3%	0.5%
Temperature	−20–120°C	–	0–45°C

Table 2
Monthly average of turbidity, E_H and NH_4 concentration of primary treatment and wetland effluents obtained by means of online equipment

	Turbidity (NTU)		E_H (mV)	NH_4 (mg/L)	
	Settler effluent	Wetland effluent	Wetland effluent	Settler effluent	Wetland effluent
Number of data	226	292	3,110,400	132	254
July 2008	34.67 ± 12.60	1.64 ± 1.08	−156.47 ± 62.05	37.50 ± 19.95	1.02 ± 0.63
August 2008	28.69 ± 13.90	1.68 ± 0.39	−120.60 ± 82.07	13.74 ± 9.03	0.13 ± 0.10
September 2008	25.62 ± 14.39	2.63 ± 0.43	9.35 ± 100.67	–	0.21 ± 0.04
October 2008	36.36 ± 10.25	1.41 ± 0.40	−69.39 ± 100.82	37.91 ± 16.90	0.38 ± 0.18
November 2008	34.06 ± 18.06	1.20 ± 0.22	126.05 ± 102.78	44.54 ± 15.65	0.29 ± 0.20
December 2008	32.11 ± 11.61	3.58 ± 0.60	42.66 ± 95.26	43.85 ± 13.24	13.38 ± 5.03
January 2009	38.12 ± 7.14	3.26 ± 1.06	−8.63 ± 110.58	34.79 ± 10.55	15.70 ± 5.60
February 2009	24.40 ± 8.26	1.85 ± 0.70	−132.27 ± 21.49	43.17 ± 13.47	27.21 ± 6.55
March 2009	32.60 ± 13.88	1.51 ± 0.80	−100.10 ± 108.90	34.97 ± 1.38	27.70 ± 6.14
April 2009	26.77 ± 11.03	1.21 ± 0.38	135.67 ± 151.28	29.03 ± 11.16	0.74 ± 0.71
May 2009	33.83 ± 12.13	1.45 ± 0.91	160.47 ± 115.92	–	0.50 ± 0.40
June 2009	40.56 ± 12.38	1.63 ± 1.21	109.78 ± 64.85	–	0.56 ± 0.18
July 2009	–	1.40 ± 0.20	–	36.60 ± 10.07	0.52 ± 0.23

of TSS and BOD_5 in CWs (Fig. 2(a) and (b), respectively).

3.2. Redox potential

E_H is key parameter associated with contaminant removal efficiency in CWs [1,9]. In this study, daily E_H effluent values fluctuated from −202 to +320 mV. Table 2 shows monthly average of E_H. A negative correlation was found between effluent E_H (measured with online sensors) and effluent BOD_5 ($r = -0.62$; $p < 0.01$) (Fig. 3). Previous studies recommended continuous measurement of redox potential in SSF CW effluents because it is closely related to oxygen supply and contaminants removal efficiency [16,17]. Moreover, [17] observed that low values of E_H were associated with high concentrations of organic pollutants measured as BOD_5 and COD. E_H monitoring with online equipment in CWs is considered simple and inexpensive. Results suggested that when effluent E_H was lower than −100 mV, BOD effluent concentration could be higher than the legal threshold (25 mg_{BOD}/L) (Fig. 3). Consequently, E_H online measures could be used in full-scale CWs plants in order to qualitatively estimate if legal limits are respected. When E_H values lower than −100 mV are recorded, more actions could be taken in order to find out if any operational problem is occurring.

3.3. Ammonium

Monthly average concentrations of NH_4 at the effluent of both the settler and wetland are shown in Table 2. A high standard deviation was observed especially in the settler effluent because of the variability of real wastewater quality. A significant correlation was found ($r = 0.84$; $p < 0.01$) between NH_4 concentration measured by online equipment and the results obtained from laboratory analyses (Fig. 4). The difference between online and lab results could be related to the differences on the method used. It is worth noticing that laboratory analyses could be even less reliable than online measurements because of the lower working range used for the standard method (0.1–1 ppm) which involves sample dilution. According to that, NH_4 could be monitored by continuous online equipment, rather than using laboratory analyses, in order to obtain daily information about wetlands performance.

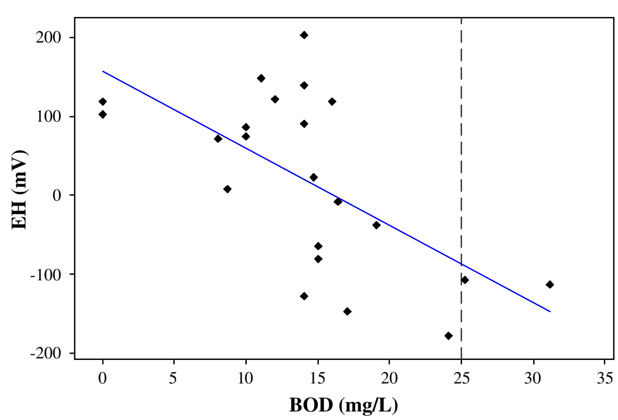

Fig. 3. Correlation between values measured by online equipment of E_H and analytics of BOD. Weekly average was considered for online and laboratory analysis. Reference line is shown for maximum legal limit of 25 mg/L for BOD effluent concentration, according to Europe Council Directive 91/271/EEC.

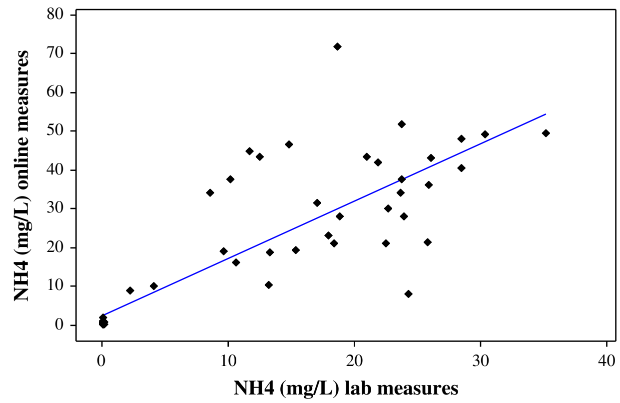

Fig. 4. Correlation between values measured by online equipment and analytics of NH_4. Weekly average was considered for online and laboratory analysis. Reference line is shown for maximum legal limit of 25 mg/L for BOD effluent concentration, according to Europe Council Directive 91/271/EEC.

4. Economic aspects

Economic aspects were considered in order to have an overall comparison between costs associated with online monitoring and laboratory measures. For a CWs plant, costs for periodical monitoring are the expenses associated with laboratory tests. In Barcelona (Spain), the price of routinely laboratory analyses are about 8, 6, 7, 27 and 12 euro for NH_4, turbidity, E_H, BOD and TSS, respectively. Furthermore, expenses associated with online monitoring equipment in this study were 880, 1,200 and 4,400 euro for Digimed TH-404, Digimed TB-44 M and Digimed AI-NH3, respectively. Moreover, costs of pumps (100 euros), programmable relay (around 100 euros) and data logger DT50 (1,800 euros) must be also considered. Taking into account, a minimum life span of five

Table 3
Costs associated with equipment, personnel, maintenance and electricity for online measurement of E_H, turbidity and NH_4 per sample. A measurement of E_H every 10 s and a daily measurement of turbidity and NH_4 were considered

Parameters	Equipment (€/sample)	Personnel costs for maintenance (€/sample)	Electricity (€/sample)	Total online measurement (€/sample)	Laboratory analysis (€/sample)
E_H	<0.01	<0.01	<0.01	<0.03	7
Turbidity	1	<2	<0.1	<3	6
NH_4	2	<2	<0.2	<4	8

years for online equipment, a daily measurement of turbidity and NH_4, and a measurement of E_H every 10 s, a maximum cost of about two euro per sample was obtained (Table 3). Other costs to be considered are electricity and man-power costs for maintenance, associated with weekly or monthly equipment cleaning. Considering these additional costs, a maximum cost of about four euro per sample can be reached (Table 3). This general overview about economic aspects suggested that also from an economic point of view monitoring of wastewater quality is feasible.

5. Conclusions

Turbidity values measured with on-line sensors is a reliable and easy-to-operate method to assess the legislation compliance in terms of TSS and BOD_5 in CWs. Results suggested that when turbidity was higher than 5–10 NTU, TSS and BOD_5 were above the legal limits.

Effluent E_H lower than -100 mV could be associated with BOD effluent concentrations above the legal threshold ($25\,mg_{BOD}\,L^{-1}$). Consequently, E_H online measures could be used in full-scale CWs plants in order to qualitatively estimate if BOD effluent concentration respects legal limits.

Ammonia measured with online sensors and regular laboratory analyses are in good agreement. Therefore, ammonia could be monitored by using continuous online equipment, rather than using laboratory analyses, in order to obtain daily information about wetlands performance.

The cost associated with the online measurement of the water quality parameters considered in this study is that of two times lower than conventional laboratory-based analyses.

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