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Water treatment and re-use at temporary events using a mobile constructed wetland and drinking water production system

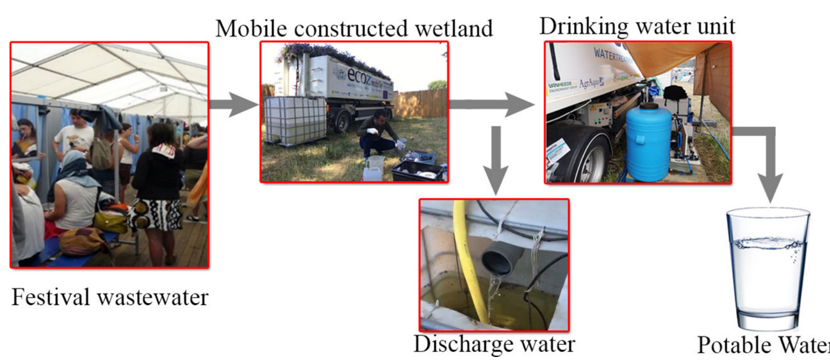
Fida Hussain Lakho [a,*], Hong Quan Le [a], Fréderic Van Kerkhove [a], Wouter Igodt [b], Veerle Depuydt [c], Joachim Desloover [d], Diederik P.L. Rousseau [a], Stijn W.H. Van Hulle [a]

[a] Laboratory for Industrial Water and Ecotechnology (LIWET), Department of Green Chemistry and Technology, Ghent University Campus Kortrijk, Graaf Karel de Goedelaan 5, B-8500 Kortrijk, Belgium
[b] Tuinen Wouter Igodt, Kastanjeboomstraat 13, B-8550 Zwevegem, Belgium
[c] Flanders Knowledge Center Water (Vlakwa), Graaf Karel de Goedelaan 34, B-8500 Kortrijk, Belgium
[d] BOSAQ, Technologiepark 82, POB 7, B-9052 Ghent, Belgium

HIGHLIGHTS

- Mobile vertical flow constructed wetland treated wastewater at different festivals.
- Removal of COD, BOD and TSS from grey water was 90%, 95%, 97% respectively.
- Removal of phosphorus and nitrogen from grey water was 76% and 25% respectively.
- MCW operated at a maximal allowable hydraulic loading rate of 1.1 $m^3 \cdot m^{-2} \cdot d^{-1}$.
- The effluent of the constructed wetland was upgraded to potable water.

GRAPHICAL ABSTRACT



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ABSTRACT

Temporary events such as music festivals are often organized in places that are not connected to a sewage network. As such, the waste (water) generated and discharged can place a heavy burden on the environment. A mobile vertical flow constructed wetland (MCW) with an area of 15 m^2 was constructed, optimized and operated for three years treating grey water (GW) as well as grey and black water (GW + BW) at different festival locations to tackle this problem. During the initial development phase, the appropriate influent type (GW and/or GW + BW) was determined and challenge tests with pre-settled diluted domestic waste water (mimicking GW) were carried out to determine the maximal allowable loading rate. The MCW was able to treat both types of water. However, for further experiments GW was selected as the discharge limits could not be met when treating GW + BW. The challenge tests demonstrated that the MCW could be operated at a maximal allowable hydraulic loading rate of 1.1 $m^3 \cdot m^{-2} \cdot d^{-1}$, corresponding to mass loading rates of 68 $gTSS \cdot m^{-2} \cdot d^{-1}$, 160 $gCOD \cdot m^{-2} \cdot d^{-1}$ and 137 $gBOD \cdot m^{-2} \cdot d^{-1}$. During treatment of GW, the MCW achieved effluent concentrations for respectively chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS) and total phosphorus (TP) of 43 $mg \cdot L^{-1}$, 16 $mg \cdot L^{-1}$, 2.7 $mg \cdot L^{-1}$ and 1.7 $mgP \cdot L^{-1}$. This corresponds to a removal of 90% (COD), 95% (BOD), 97% (TSS) and 76% (TP) respectively. Total nitrogen removal was 25% (from 45 $mgN \cdot L^{-1}$ to 34 $mgN \cdot L^{-1}$) as particularly denitrification was not complete. As a further development, the MCW was coupled to a drinking water treatment system using ultrafiltration and reverse osmosis (UF-RO) membranes to produce potable water on site. The drinking water system produced potable water that met the legislative criteria. As

* Corresponding author.
E-mail address: fidahussain.lakho@ugent.be (F.H. Lakho).

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such, a sustainable and mobile water treatment system aiming at producing potable water at temporary events was demonstrated.

1. Introduction

Music festivals and other temporary events, lasting 2 to 5 days, are frequently organized during the summer season in Belgium and many other parts of the world. In a very short period of time, these events lay a heavy burden on the environment. This includes air pollution, solid wastes from food trucks and single-use plastic products, noise pollution from transport and water pollution from discharged wastewater from sinks, showers and toilets (Van Hulle et al., 2008). For example, a British study revealed that 68% of the total waste generated at festivals goes directly into a landfill as it is mainly comprised of single-use plastics. Furthermore, festivals are associated with microplastic pollution in the form of glitter and toiletries (Johnson, 2015). Moreover, water consumption via disposable plastic bottles was reported to have a strong negative effect on the footprint of the event (Collins and Cooper, 2017).

Music festivals and other temporary events are often held in places where there is no sewer system or where the sewer system has insufficient capacity to cope with the extra load generated by such events. As such, the discharged wastewater may add considerable stress to the receiving surface water (Van Hulle et al., 2008). In response to this, environmental legislation has been introduced recently in Flanders (Flemish Government, 1995), which enforces wastewater treatment for temporary events. According to this legislation, the treated water must meet the following standards: pH between 6.5 and 9, biological oxygen demand (BOD) <25 $mg \cdot L^{-1}$ and total suspended solids (TSS) <60 $mg \cdot L^{-1}$. Furthermore, considering sustainable event management (e.g. via ISO 20121 (ISO 20121, 2012)), wastewater should not only be treated for discharge but could also be reused to mitigate the local impact of such temporary events. For reuse purposes, greywater (GW) is considered easier to treat than blackwater (BW) as the concentration of suspended solids (TSS) and the turbidity as well as the levels of organic matter, nutrients and pathogens are lower (Zraunig et al., 2019; Eriksson et al., 2002).

Currently, there are different permanent decentralized wastewater treatment facilities which are installed to treat wastewater. However, there is a lack of nature-based mobile (waste)water treatment systems (MWTS). These MWTS can be used for the treatment of (waste)water to a desired quality depending mainly on the intended application at various temporary events. The water treatment steps can vary from primary treatment such as sedimentation and/or sand filtration to secondary treatment such as biofiltration, activated carbon filtration and/or membrane filtration. For example, Litaor et al. (2015) developed a mobile water treatment plant consisting of a coagulation-flocculation treatment, followed by an aerobic treatment to process wastewater from different small wineries. The system achieved a removal efficiency for TSS, chemical oxygen demand (COD) and total phosphorus (TP) of 95, 90–95 and 95% respectively with a maximum residence time of 1.6 days. The treated water could be used to irrigate the vineyards. Park et al. (2015) combined various treatment techniques such as pore control fiber filter, microfiltration, reverse osmosis with polishing steps such as activated carbon and disinfection using UV for the design and construction of a MWTS which can be used in emergency cases for the production of potable water. The system was able to treat different wastewater flows with a capacity of 1.5 $m^3 \cdot h^{-1}$, while achieving removal efficiencies for total nitrogen (TN), TP and TSS of 98, 99 and 98% of respectively. Another MWTS was constructed by installing reverse osmosis membranes that produced potable water with a capacity of 5 $m^3 \cdot d^{-1}$. This system was coupled to solar panels and wind turbines to provide potable water during emergencies (Fuso Nerini et al., 2015). Portable membrane-based water treatment devices were considered to be the most effective method to treat water for any affected area. Shamsuddin et al. (2016) suggested to use photovoltaic solar energy powered reverse osmosis system for drinking water productions and disinfection.

Compared to other technologies, constructed wetlands (CWs) are beneficial because of their low energy consumption and efficiency, especially for decentralized waste water treatment (Liu et al., 2015; Ramprasad et al., 2017; Zraunig et al., 2019). CWs are engineered systems designed to make use of the natural processes to treat wastewater (Vymazal, 2014). The vegetation plays a vital role in supporting microbial growth and to maintain the permeability in the filter (Hanssen et al., 2008). Pollutants can be effectively removed by both physical and biological processes mediated by the substrate and the biomass growing on the substrate (Wang et al., 2017; Fang et al., 2016). Different types of CWs exist. In the vertical flow (VF) CW systems, the wastewater fills periodically the wetland matrix and then drains completely by gravity, providing high levels of oxygen transfer within the substrate, which allows for good treatment performance, especially for organic matter and nitrogen (Brix and Arias, 2005).

Driven by the fact that there is a need for a sustainable and cost-effective mobile decentralized treatment system that can be deployed at different short-term events, a mobile constructed wetland (MCW) was developed. In this study, the MCW was tested in different circumstances with regard to the removal efficiency of some components such as pH, TSS and BOD, COD, nitrogen and phosphorus in order to meet the respective legislative standards mentioned above. In addition,

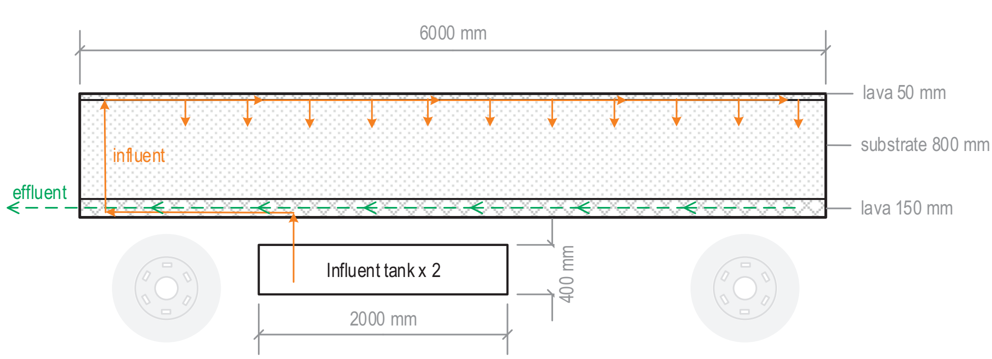

Fig. 1. The MCW layout.

the removal of metals and micropollutants was verified. In addition, a potable water production system is also demonstrated to evaluate the potential of in situ water reuse on music festivals. As such, a sustainable mobile decentralized system for water treatment and re-use will be demonstrated.

2. Materials and methods

2.1. Mobile constructed wetland configuration

The MCW is a vertical flow type CW designed as a trailer, which enables it to be deployed at different festivals. The complete system as depicted in Fig. 1 has dimensions of 6 × 2.5 × 1 m (L × W × D), corresponding to a surface area of 15 m^2. The substrate consists of three layers, i.e. two layers of lava rock (8–16 mm) at the bottom and top with heights of 50 and 150 mm respectively, and a proprietary main substrate layer of 800 mm in the middle. The MCW was designed to meet the allowable weight limit of 21 tons while on the road and 24 tons when stationary and in operation. The trailer has two connected influent tanks (120 L each) on each side. One of them is equipped with a pump (13.5 $m^3 \cdot h^{-1}$) that is controlled by a water level sensor, which triggers the pump (on/off) based on preset water levels. This ensures the typical pulsating operation of VF CWs. The operation regime of the influent pump was the same for all experimental phases. Pumping hours were logged in order to monitor the flow rates. After pumping, the wastewater is distributed on the wetland surface by a network of perforated pipes. Flowers (geraniums) were planted, mostly for aesthetic reasons but also because they have an extensive root system that supports biofilm growth. The treated water is finally collected through a drainage pipe system at the bottom and flows to a collection tank before being discharged or further treated for water reuse purposes.

2.2. Potable water system

The post-treatment system for potable water production was introduced as part of a trial for water reuse. The system is modular and consists of an ultrafiltration (UF) membrane (PVDF 4.5 m^2 Polymem UF100L-S2F), operating at ±1 bar differential pressure with a flow rate of ±150 $L \cdot h^{-1}$, along with a Reverse Osmosis (RO) membrane (Filmtec BW2521) working at around 4 bar feed pressure with flow rate of ±25 $L \cdot h^{-1}$. To protect the UF-RO system from clogging and to remove some organic (micro)pollutants, the water is first passed through a sieve (100 μm), an activated carbon filter and another sieve (25 μm). The water was remineralized after RO. Four LED-UV lamps (Aquisense, type Pearl Aqua micro 12 C) were used for disinfection.

2.3. System setup and sampling strategy

2.3.1. Initial testing at different music festivals

The MCW was monitored during the summer festival periods of 2017 and 2018 at 4 festivals in Belgium: Boomtown in Ghent, Dranouter festival in Heuvelland, Paradise City in Perk and Ieperfest festival in Ieper (Table 1). One month prior to the festivals, the MCW was started-up with presettled domestic wastewater to allow the microorganisms in the substrate and on the plant roots to develop. Fertilizers were added for faster plant growth as the visual aspect was considered important.

The aim of these first experiments was to compare the treatment efficiency of grey water (GW) and grey water combined with black water (GW or GW + BW). To this end, GW (from showers and food trucks) or combined GW and BW (from toilets) was pumped from a 1 m^3 settling tank to the influent container of the MCW, and from there to the wetland. Once every day, influent and effluent samples were collected during the morning peak flow from 9 am to 11 am.

2.3.2. Challenge tests to determine the optimal loading rate time of the MCW

The main goal of the challenge tests was to establish the optimal hydraulic loading rate (HLR). The MCW was therefore installed at the municipal wastewater treatment plant of Aquafin in Harelbeke (116,000 PE) described elsewhere (Chys et al., 2017). Due to the fact that the challenge tests were performed during wintertime, the wastewater was diluted by rainwater and had similar characteristics as GW. Influent for the wetland was collected from a buffer tank installed after coarse screening and the sand trap of the full-scale installation to avoid clogging. The HLR was systematically increased, i.e. 4, 8, 12 and 16 m^3/day. For each HLR, two grab samples of the influent and effluent were taken once the system had adapted itself to the new conditions (assumed to be the case after the retention time of three empty bed volumes).

2.3.3. Performance testing of the MCW under optimal conditions

The performance of the MCW treating GW was further assessed during the summer festivals period of 2019 at Dranouter and Paradise City. In total 92 m^3 and 11 m^3 of wastewater from the showers was treated in 3 days and 4 days, respectively. As for the initial tests, a prior start-up period of one month was foreseen. The effluent of the MCW was further treated in the drinking water system. Samples were collected once every day from the influent tank of the MCW, the effluent tank of the MCW and at the effluent of the drinking water system.

2.4. Sample analysis

The main parameters considered in this work were chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), total kjeldahl nitrogen (TKN), nitrite (NO_2^--N) and nitrate (NO_3^--N), total phosphorus (TP), orthophosphate (PO_4^{3-}), surfactants (anionic, cationic and non-ionic), metals (As, Cd, Co, Cu, Hg, Ni, Pb, Zn and Cr) and pharmaceutical residues (Diclofenac, Carbamazepine, Metoprolol, Sulfamethoxazole, Trimethoprim, Clarithromycin, Propranolol, Hydrochlorthiazide, Solatol). For the drinking water, the parameters that were analyzed are electrical conductivity (EC) and the same nitrogen compounds as for the wastewater. Different analytical methods were used in different laboratories due to the collaboration of various project partners. For quality assurance purposes, several samples have been analyzed by different partners and deviations between the results were minimal.

For the challenge tests, temperature, pH, dissolved oxygen and conductivity were measured with Hach Lange Field Case HQ30d and the turbidity was measured with the HI 98703 turbidity meter (HANNA instruments). TSS were determined according to Standard Methods (APHA et al., 2012) and the biological oxygen demand (BOD) measurement was carried out according to the protocol "5-Day BOD Test" of standard method 5210B (APHA, 1992). The measurement of COD, TN, TP, NH_4^+-N, NO_2^--N and NO_3^--N were done with spectrophotometric test kits (Hach, USA) following Standard Methods (APHA-AWWA-WEF, 2012).

For initial and performance tests, COD was measured by standard method ISO 15705:2002 (closed tube digestion, Hach) and BOD was measured according to ISO 5815-1 (dilution method). Nitrite, nitrate and phosphate were measured following standard method ISO 15923-1. TSS were measured according to ISO 11923 and EN 872. TKN was analyzed by ISO 5663 and EN 25663. TP was measured according to ISO 11885. Surfactants were measured by a colorimetric method (Macherey-Nagel) according to DIN 38 409-H23-1 and APHA 5540 (APHA, 1992).

Micropollutants were determined in an external laboratory by using ultra-high performance liquid chromatography-quadrupole time-of-flight mass spectrometry (UHPLC/Q-TOF-MS). Metals were analyzed by the inductively coupled plasma optical emission spectrophotometer (ICP-OES, Agilent 7000 series ICP OES, USA) analyzed after filtration

Table 1
Treated wastewater at four festivals from 2017 to 2018.

Type of wastewater	Festival	Days of operation	Source	Treated water ($m^3 \cdot d^{-1}$)
GW	Boomtown 2017	5	Dishwashing, shower	2.43
	Dranouter 2018	2		20.50
	Paradise City 2018	3		3.67
BW + GW	Dranouter 2017	5	Toilet, dishwashing, shower	2.59
	Ieperfest 2017	4		9.29
	Ieperfest 2018	1		4.00

GW = greywater, BW = blackwater.

according to standard methods set by international organizations (ISO 11885, 2007). The stock solution and standard solutions of different concentrations 100 μg/L, 75 μg/L, 50 μg/L, 25 μg/L, 10 μg/L, 5 μg/L and 1 μg/L were prepared according to standard method 200.8 (USEPA) from ICP multi-element standard solution XIII and diluted with demi water.

3. Results & discussion

3.1. Initial testing: Greywater (GW) vs. combined greywater and blackwater (GW + BW)

At the initial testing phase, GW and BW were introduced to the MCW at different festivals in order to evaluate the performance of the system and to select an appropriate type of wastewater. Table 2 summarizes the influent and effluent characteristics as well as the removal efficiencies of the MCW. Note that for each type of wastewater, data were averaged over all festivals. For example, data presented on GW were averaged from Boomtown (2017), Dranouter (2018) and Paradise City (2018). The GW + BW is characterized by much higher concentrations of TSS, COD, BOD and TP but quite similar nitrogen concentrations compared to GW. As a result, the organic loading rate (OLR) to the MCW with GW + BW is up to 20 times higher. Nevertheless, the system has similar removal efficiencies for TSS and COD. For TSS 86% removal is obtained despite the high differences in loading rate (42 and 285 $gTSS \cdot m^{-2} \cdot d^{-1}$ for GW and GW + BW respectively). Furthermore, the system has a removal rate of 227 $gCOD \cdot m^{-2} \cdot d^{-1}$ at a loading rate of 254 $gCOD \cdot m^{-2} \cdot d^{-1}$ with GW, corresponding to 89% removal, while the removal rate for GW + BW was up to 1570 $gCOD \cdot m^{-2} \cdot d^{-1}$ at a loading rate of 2151 $gCOD \cdot m^{-2} \cdot d^{-1}$ corresponding to 73% removal. Without intensification methods (recycling, aeration, …), lower loading rates are typically recommended for cold climates, i.e. OLR up to 30 $gCOD \cdot m^{-2} \cdot d^{-1}$ and HLR 0.05–0.10 $m^3 \cdot m^{-2} \cdot d^{-1}$. In warmer climates (or in summer periods as is the case here), these values can be increased up to 80 $gCOD \cdot m^{-2} \cdot d^{-1}$ and 0.15 $m^3 \cdot m^{-2} \cdot d^{-1}$ (Dotro et al., 2017). Compared to other studies (e.g. Papaevangelou et al., 2016), the removal rates obtained in this study are much higher, probably because the operation had a temporary nature. This demonstrates the capability of constructed wetlands to cope with extreme peak loads during a short period of time. Martí et al. (2018) treated domestic wastewater with higher loadings through VF CW at various temperature ranges and found that the minimum COD effluent concentration of 18 $mg \cdot L^{-1}$ (corresponding to an influent value of 495 $mg \cdot L^{-1}$) was obtained at the high temperature (19.5 °C). Further, it was established that by increasing the organic loading, the COD effluent concentrations were significantly higher for lower temperatures. This means the system does not need to be oversized in order to account for variations in the organic load during the summer season (Boutin and Prost-Boucle, 2015).

With regard to nitrogen removal, the system performed much better in removal of TKN from GW with a removal rate of 22 $gTKN \cdot m^{-2} \cdot d^{-1}$ (corresponding to 84% removal), compared to only 6 $gTKN \cdot m^{-2} \cdot d^{-1}$ in GW + BW (corresponding to 37% removal). Nitrogen removal was low for GW + BW due to the limitation of oxygen transfer in the filter bed while the system was overloaded with high COD and nitrogen.

Overall, the results demonstrate that due to the highly oxidizing conditions in the filter bed, VF wetlands with intermittent loading are extremely efficient for removal of organic carbon (BOD or COD) and easily degrade aerobically (Dotro et al., 2017). For treating GW, similar results were observed by Stefanakis and Tsihrintzis (2012) during long term (three years) evaluation of synthetic wastewater (mimicking concentrated municipal wastewater) intermittently loaded onto a small scale vertical flow constructed wetlands. BOD and COD effluent concentrations of 20 $mg \cdot L^{-1}$ and 49 $mg \cdot L^{-1}$ respectively were obtained at the influent concentration of 476 $mg \cdot L^{-1}$ and 960 $mg \cdot L^{-1}$. As such a removal of 96% BOD and 94% COD was achieved. Furthermore, 91%, 93% and 70% removal of TKN, ammonium and TP respectively was obtained with a corresponding effluent concentration of 10 $mgN \cdot L^{-1}$, 8 $mgN \cdot L^{-1}$ and 3 $mgP \cdot L^{-1}$ (Gikas and Tsihrintzis, 2012).

Nevertheless, despite having high removal rate for TSS, COD and BOD, all the effluent concentrations from treating BW + GW were above the legislative standards. In view of meeting these standards, achieving nutrient removal and reusing water, it was concluded that the MCW is expected to have good removal efficiency with GW and would be able to reach the discharge limits. High performance operation for short time is expected under high load conditions typical for festivals. Therefore it was decided to focus on GW treatment. During this initial testing phase, the MCW was operated with different loading rates at different festivals. Therefore, it was necessary to investigate the optimal or suitable loading rate for efficient operation by challenge tests.

3.2. Challenge test to determine optimal loading rate for treating greywater

Since the optimal HLR and OLR are the main factors in the operation of vertical CWs, four different HLR (and as a consequence four different OLRs) were examined. The influent was wastewater from a combined sewer system (GW, BW and rainwater). Because of the fact that the experiments were performed in winter time, the dilution from rainwater made the influent very similar to GW that originates from music festivals. The results with regard to average influent and effluent characteristics as well as the removal efficiencies are shown in Table 3.

Although higher removal efficiencies were observed for almost all the parameters at lower HLR (Table 3), good removal of BOD and TSS for all HLR was obtained. Moreover, the lower COD and BOD removal at the highest HLR (1.1 $m^3 \cdot m^{-2} \cdot d^{-1}$) was also due to the low influent concentration. The BOD and TSS concentrations met the discharge limits as BOD was <25 $mg \cdot L^{-1}$ and TSS was <60 $mg \cdot L^{-1}$ during the experiments. In literature it has been recommended that the maximum HLR should not exceed 0.08 $m^3 \cdot m^{-2} \cdot d^{-1}$ and the interval between loadings should be ≥6 h or between 3 and 6 h (Dotro et al., 2017). Nevertheless, higher removal efficiencies were obtained with the MCW probably because the system was fully optimized and plants were mature enough.

Due to the low temperatures (the experiments were performed in winter at temperatures between 5 and 10 °C), no nitrification and as such no nitrogen removal occurred. Also little to no P removal occurred. Studies suggested that constructed wetlands show better performance at a temperature higher than 15 °C (Masi and Martinuzzi, 2007), as such better N and P removal is expected during the actual operation of the MCW when treating music festival wastewater.

Table 2
Influent and effluent characteristics as well as the removal efficiencies of the MCW at the initial development phase treating either GW or GW + BW. The characteristics of each type of wastewater are average values from all the festivals.

Influent type →		GW (Boomtown, Paradise city and Dranouter) No. of samples = 5						GW + BW (Ieperfest) No. of samples = 5					
Parameter →		TSS	COD	BOD	TP	TKN	TN	TSS	COD	BOD	TP	TKN	TN
Influent ($mg \cdot L^{-1}$)	Mean	76	395	150	3.3	40	40	603	3920	2733	23	28	28
	Std	13	131	26	1.6	16	16	253	1287	1004	13	7.7	7.7
	Max	90	470	180	5.5	55	56	900	5060	1280	6.1	18	18
	Min	59	200	120	1.8	18	18	223	1850	3530	36	37	37
Effluent ($mg \cdot L^{-1}$)	Mean	10	42	35	7.9	6	20.5	83	1058	683	17	18	76
	Std	10	8	4.2	3.7	2	11.1	24	686	630	6	13	99
	Max	21	51	24	12	8.6	29.1	105	1980	1540	24	38	233
	Min	3	35	09	5	5	8.1	42	350	200	11	3	3
Hydraulic loading rate ($m^3 \cdot m^{-2} \cdot d^{-1}$)	Mean	0.64						0.55					
Loading rate ($g \cdot m^{-2} \cdot d^{-1}$)	Mean	49	254	97	2	26	26	331	2151	1499	13	16	16
Removal rate ($g \cdot m^{-2} \cdot d^{-1}$)		42	227	46		22	13	285	1570	1125	3	6	
% Removal	Mean	86%	89%	76.7%		84%	49%	86%	73%	75%	25%	37%	

GW = Greywater, GW + BW = Greywater and blackwater, Std = Standard deviation, Min = Minimum, Max = Maximum.

The obtained results can be compared to other studies treating similar waste water. Ghosh and Gopal (2010) carried out a study regarding the performance of a CW at different HLRs (ranging between 0.06 $m^3 \cdot m^{-2} \cdot d^{-1}$ and 0.24 $m^3 \cdot m^{-2} \cdot d^{-1}$). A COD removal between 16% and 46% was observed, while the BOD was removed for 84%–89%. In the experiments with the MCW presented in Table 3, similar BOD removal but higher COD removal was observed for all hydraulic loading rates (98–97% for BOD and 91–87% for COD). In contrast, ammonium and nitrate were almost completely removed (Ghosh and Gopal, 2010) with efficiencies of 100% for ammonium and 97% for nitrate at the highest residence time. Atalla et al. (2020) also examined the performance of a VFCW treating domestic wastewater with different influent concentrations different HLRs (0.2, 0.28 and 0.16 $m^3 \cdot m^{-2} \cdot d^{-1}$). At higher HLR (0.2 and 0.28 $m^3 \cdot m^{-2} \cdot d^{-1}$), the removal of COD (68%) and TSS (44 to 47%) was somewhat lower as compared to experiments presented in Table 3. High BOD removal (85%) was observed at the lowest HLR (0.16 $m^3 \cdot m^{-2} \cdot d^{-1}$) which is more or less equal to obtained results in the current study (Table 3). Millot et al. (2016) tested a VFCW at different HLRs (0.06, 0.09 and 0.12 $m^3 \cdot m^{-2} \cdot d^{-1}$). The COD removal efficiencies were reported between 30% and 65%. Furthermore, the removal decreased with increasing HLR (similar to the study presented here). The lower removal compared to the MCW were attributed to the lower area of the VFCW as well as its depth. Indeed, the area of the MCW applied in this study was 7 times higher than the area of the VCFW in the study of Millot et al. (2016). Also, the influent composition was different. This might explain the higher removal at higher HLRs obtained with the MCW. The treatment performance of vertical subsurface flow (VSSF) wetland systems under varying HLRs was investigated by Weerakoon et al. (2016). The highest removal of BOD (±95%) was obtained for both planted and unplanted systems at a HLR of 0.025 $m^3 \cdot m^{-2} \cdot d^{-1}$. The HLR was inversely proportional to BOD and TSS removal due to insufficient contact time between wastewater and the VSSF (Weerakoon et al., 2016). The results obtained with the MCW in this study also demonstrate an inverse relation between removal and HLR. Raphael et al. (2019) investigated the performance of a VFCW treating GW at a HLR of 0.058 $m^3 \cdot m^{-2} \cdot d^{-1}$. The mean removal efficiencies for BOD, COD, TN, TP and TSS were 35%, 57%, 92%, 65% and 60% respectively which is less as compared to the results presented in Table 3.

The results presented in Table 3 can be considered thus to be good as compared to literature. In terms of effluent quality, it was expected that the MCW would work with a HLR of 1.1 $m^3 \cdot m^{-2} \cdot d^{-1}$. This HLR is much higher than values found in literature discussed above (0.06–0.24 $m^3 \cdot m^{-2} \cdot d^{-1}$).

3.3. Performance testing under optimal conditions

During the festival period of 2019, at the Paradise City and Dranouter festivals, in total 11 m^3 and 92 m^3 (originating from more than 200 showers) of wastewater was treated. The MCW was operated for 4 days at the Paradise City festival and for 3 days at the Dranouter festival. The drinking water system was coupled to the MCW at the Dranouter festival to test the potential of water reuse.

Table 3
Results of challenge tests for determining the optimal loading of the MCW ($n = 2$).

Hydraulic loading rate($m^3 \cdot m^{-2} \cdot d^{-1}$)		TSS			COD			BOD		
		Concentration ($mg \cdot L^{-1}$)	Load ($g \cdot m^{-2} \cdot d^{-1}$)	Removal (%)	Concentration ($mg \cdot L^{-1}$)	Load ($g \cdot m^{-2} \cdot d^{-1}$)	Removal (%)	Concentration ($mg \cdot L^{-1}$)	Load ($g \cdot m^{-2} \cdot d^{-1}$)	Removal (%)
	inf	108	29	90%	444	118	91	289	77	98%
0.3	eff	11			41			4.8		
	inf	127	68	99%	139	74	80	173	92	96%
0.5	eff	1.2			27			8		
	inf	41	33	96%	201	160	87	171	137	97%
0.8	eff	1			26			4.8		
	inf	37	39	87%	77	82	43	57	61	79%
1.1	eff	4.8			44			12		

n = No. of samples, inf = Influent, eff = Effluent.

3.3.1. Wastewater treatment performance

The average influent and effluent characteristics, as well as the overall performance of the MCW to remove common parameters, is shown in Table 4. An efficient removal of COD, BOD, TN and TSS was obtained, with an effluent concentration in the range of 40 $mg\cdot L^{-1}$, 16 $mg\cdot L^{-1}$, 34 $mg\cdot L^{-1}$ and 6.7 $mg\cdot L^{-1}$, respectively. As such, the system successfully reduced TSS, BOD and COD by >90%. The TN was reduced by 25% at Dranouter festival, as mainly nitrification occurred resulting in nitrate in the effluent. TP removal was 50.8% while in the challenge test no TP removal was observed. This was due to usage of fertilizer for the plants and the P from the fertilizer was washed out. The MCW performed very good and the discharge limits could be met. Similar results were reported in the literature for COD, BOD and TSS while treating grey water with integrated HF CW in a vertical set-up with four cascading stages (Zraunig et al., 2019).

Among concerned metals, the best removal efficiencies were for Cd, Cr, Pb, Zn and As (Table 4). The same performance was observed at both music festivals. The negative values for metals like Co and Ni were found, which might be due to leaching from the substrate and also due to variation of the influent during earlier operations.

Because the MCW was treating water coming from a shower installation, the MCW was also tested for the removal of anionic and cationic detergents (non-ionic detergent concentration was too low to be detected (<0.2 mgL^{-1})). The average influent and effluent concentrations with standard deviation are shown in Table 4. Especially for the Dranouter festival (2019), the anionic and non-ionic detergents removal was very good (>90%).

In total the wastewater was analyzed for 9 micropollutants as described in Section 2.4. However, for most micropollutants the results were below the detection limit except for 3 micropollutants as shown in Table 4. This can probably be explained by the fact that certain micropollutants are applied on the skin (such as diclofenac) as well as some (unwanted) urination in the shower (resulting in antibiotics such as trimethoprim (used for e.g. bladder infections)). Furthermore, little to no removal was observed in the MCW.

It can be concluded that the MCW worked very well to remove all the contaminants including metals and micropollutants and all the effluent concentrations were below the legislative values (Flemish Government, 1995).

3.4. Results comparison

There were three phases in this study, i.e. initial testing, challenge tests and performance test as elaborated above. The results of different loading rates in all those phases with respect to their removal rates are summarized below.

3.4.1. COD loading

The COD removal rates against different applied COD loadings for all the experiments are shown in Fig. 2(a) which confirms that the system was operated far beyond the recommended loading rates (i.e. 30 $gCOD\cdot m^{-2}\cdot d^{-1}$ in winter and 80 $gCOD\cdot m^{-2}\cdot d^{-1}$ in summer periods). Indeed, compared to literature, high COD removal rates were observed. Gunes (2007) treated domestic wastewater with a VFCW at a loading rate of 103 $gCOD\cdot m^{-2}\cdot d^{-1}$ and obtained removal rate of 94 $gCOD\cdot m^{-2}\cdot d^{-1}$ (92% removal). Carvalho et al. (2018) carried out a study for 6 months treating domestic wastewater in which an average COD loading of COD of 38 $gCOD\cdot m^{-2}\cdot d^{-1}$ was applied to a VFCW. A removal of 95% corresponding a removal rate of 36 $gCOD\cdot m^{-2}\cdot d^{-1}$ was found. Furthermore, Wang et al. (2017) reduced an influent COD concentration of 142 $mg\cdot L^{-1}$ to an effluent value of 32 $mg\cdot L^{-1}$, corresponding to a removal rate of loading of 28 $gCOD\cdot m^{-2}\cdot d^{-1}$ and 93% removal. Boutin and Prost-Boucle (2015) observed a removal efficiencies of 56% and 70% for higher organic loads of 300 $gCOD\cdot m^{-2}\cdot d^{-1}$ and 75 gCOD·m-2·d^{-1} respectively. Overloads could be handled up to any short-term pollutant discharges lasting less than three months (in summer seasons). In another study carried out by Stefanakis and Tsihrintzis (2012), VFCW systems were capable of treating high organic loads up to 200 $gCOD\cdot m^{-2}\cdot d^{-1}$, with a removal of 140–195 $gCOD\cdot m^{-2}\cdot d^{-1}$. A lower effluent concentrations could be observed for higher loadings during spring and summer months (higher temperatures). In another study, four pilot scale VFCW were used to treat raw domestic wastewater at different COD loadings and a maximum removal efficiency of >90% was obtained at a loading rate of 30 $gCOD\cdot m^{-2}\cdot d^{-1}$ to 50 $gCOD\cdot m^{-2}\cdot d^{-1}$. Furthermore, the maximum COD loading applied to the system was 200 $gCOD\cdot m^{-2}\cdot d^{-1}$ for which 150 $gCOD\cdot m^{-2}\cdot d^{-1}$ removal was obtained (Millot et al., 2016).

Fig. 2(a) also demonstrates that the COD removal increased linearly with the loading rate, except at the highest loading rate of 2151 $gCOD\cdot m^{-2}\cdot d^{-1}$ with an observed removal rate of 1570 $gCOD\cdot m^{-2}\cdot d^{-1}$. As a VFCW system in principle cannot reach high enough oxygen transfer rates to cope with such a high organic load (Kadlec and Wallace, 2008), this result points to anoxic/anaerobic processes or more likely a temporary storage in the wetland bed.

3.4.2. BOD loading

The BOD loading rates for all the experiments are shown in Fig. 2(b). The system was operated above BOD loading rates reported in literature. Brix and Arias (2005) and Prochaska et al. (2007) applied BOD loading rates in the range of 10–40 $gBOD\cdot m^{-2}\cdot d^{-1}$ and 20–40 $gBOD\cdot m^{-2}\cdot d^{-1}$ respectively. VFCW systems maintain stability of treatment efficiency throughout the monitoring period and achieve removal rates of 4.3 to 5.5 $gBOD\cdot m^{-2}\cdot d^{-1}$ for applied BOD load of 5.1 to 7.9 $gBOD\cdot m^{-2}\cdot d^{-1}$ respectively at relatively short hydraulic residence times of 3 and 4 days (Ghosh and Gopal, 2010). Weerakoon et al. (2016) assessed the performance of a VFCW for planted and unplanted system by applying various loads. It was revealed that the 8.3 $gBOD\cdot m^{-2}\cdot d^{-1}$ and 7.4 $gBOD\cdot m^{-2}\cdot d^{-1}$ was obtained for planted and unplanted system respectively at an applied loading of 9.8 $gBOD\cdot m^{-2}\cdot d^{-1}$. In addition, macrophyte *T. angustifolia* were capable of removing higher loads of BOD, COD and TSS. Papaevangelou et al. (2016) found optimal performance while using cattail as a substrate in a VFCW and obtained 57 $gBOD\cdot m^{-2}\cdot d^{-1}$ removal at a loading of 70 $gBOD\cdot m^{-2}\cdot d^{-1}$. Vegetation and temperature (>15 °C) played an effective role in lowering effluent values despite the high loading rates.

Despite the higher loadings, it can be seen from Fig. 2(b) that the overall BOD removal at different loading rates was very good, except for the highest BOD loading rate of 1499 $gBOD\cdot m^{-2}\cdot d^{-1}$ corresponding to an observed BOD removal rate of 1125 $gBOD\cdot m^{-2}\cdot d^{-1}$. The BOD removal occurred preferentially in the upper region (top 20 cm of the VF bed), due to higher availability of oxygen and presence of microbial biomass. In general, VF wetlands are considerably more effective in degradation of organic matter (including BOD) as the load-and-rest operating protocol for these wetlands allows the introduction of oxygen directly into the wetland bed (Kadlec and Wallace, 2008).

3.4.3. TSS loading

In Fig. 2(c) TSS loading rate and removal rate obtained from all experiments are summarized. Again, values obtained for the MCW are higher than the results mentioned in literature. Bohórquez et al. (2017) assessed the treatment of domestic wastewater through eight pilot-scale VFCW. A removal rate of 9 $gTSS\cdot m^{-2}\cdot d^{-1}$ was obtained, corresponding to a reduction of 85%. Atalla et al. (2020) demonstrates a higher TSS removal of 19 $gTSS\cdot m^{-2}\cdot d^{-1}$ at a loading rate of 44 $gTSS\cdot m^{-2}\cdot d^{-1}$ mainly due to presence of earthworms in VFCW. These worms contributed to the size reduction of the organic and inorganic solid particles in the wastewater.

As such it is demonstrated that VFCWs are highly effective in TSS removal, provided they are managed in a way to avoid bed clogging problems, typically accomplished through a load and rest operation regime (Kadlec and Wallace, 2008).

Table 4
Average influent and effluent characteristics during the performance tests at Paradise city and Dranouter. The means were calculated as average of different data points.

Festival	Paradise City (4 days) HLR = 0.24 ($m^3 \cdot m^{-2} \cdot d^{-1}$) No. of samples = 3					Dranouter (3 days) HLR = 2.0 ($m^3 \cdot m^{-2} \cdot d^{-1}$) No. of samples = 4				
	Influent		Effluent		Removal %	Influent		Effluent		Removal %
Parameters	Mean	Std	Mean	std		Mean	std	mean	std	
pH	7.2	0.06	6.9	0.3		6.5	0.4	6.6	0.02	
Turbidity (NTU)	90.5	30.8	2.1	78.5	98	118.7	15.9	2.5	1.5	97.9
EC ($\mu S \cdot cm^{-1}$)	904.8	138.3	1082	112		1122.7	29.8	1513.3	526.5	
DO ($mg \cdot L^{-1}$)	3.8	0.9	5.9	2		3.63	2.9	4.9	0.4	
TSS ($mg \cdot L^{-1}$)	82.7	32.8	2.7	2.9	97	136.7	32	6.7	3.5	95
UV-VIS (254 nm)	0.05	0.04	0.01	0.01	71	0.14	0.09	0.03	0.02	81
COD ($mg \cdot L^{-1}$)	440	254.2	43.3	11.5	90	417	70.9	40	2.1	90
BOD ($mg \cdot L^{-1}$)	320		35		89	355	21.2	16.3	6.6	95
TKN ($mg \cdot L^{-1}$)	55	10.5	8.75	3.2	84	45	4.5	18.3	7	59
TN ($mg \cdot L^{-1}$)	55.4	28.3	45.06	11.4	18.6	45	5.5	34	13.4	24
NH_4^+-N ($mg \cdot L^{-1}$)	7.4	3.7	2	1.4	73	20	25.8	5.5	3.15	72
NO_2^--N ($mg \cdot L^{-1}$)	0.4	0.5	4.5	3.9		0.02	0	4.7	2.6	
NO_3^--N ($mg \cdot L^{-1}$)	0.2	0.6	33.3	16.7	28	0.2	0	12.5	6.7	18
TP ($mg \cdot L^{-1}$)	7.1	2.1	1.7	0.1	76	4.3	0.5	2.1	0.2	50.8
PO_4^--P ($mg \cdot L^{-1}$)	5.9	1.8	1.5	0.1	75	3.1	0.6	1.7	0.2	45.7
Metals										
As ($\mu g \cdot L^{-1}$)	0.8	0.3	0.15	0.2	81.9	0.17	0.05	0.1	0.2	41
Cd ($\mu g \cdot L^{-1}$)	0.05	0.05	0.025	0.1	50	0.07	0.05	0	0.1	100
Co ($\mu g \cdot L^{-1}$)	0.1	0	0.32	0.09		0.23	0.11	0.7	0.3	
Cu ($\mu g \cdot L^{-1}$)	37.15	22.5	10.7	2.4	71	29.4	14.6	17.4	4.3	40.8
Hg ($\mu g \cdot L^{-1}$)		1.03		0.5	56.9		0.7		0.5	47.3
Ni ($\mu g \cdot L^{-1}$)	1.55	0.64	4.7	1.6		2.8	0.5	6.77	2.4	
Pb ($\mu g \cdot L^{-1}$)	12.7	2.9		2.8	103.7		2.3		2.1	64.5
Zn ($\mu g \cdot L^{-1}$)	30.35	24.7	18.45	11.2	39.2	116.9	54.9	49.6	19.9	57.6
Cr ($\mu g \cdot L^{-1}$)	0.65	1.17	0.78	1.07		0.96	1.1	0.03	0.2	96.8
Detergents										
Anionic detergent ($mg \cdot L^{-1}$)	16.5	8.5	0.3	0.1	98.4	25.3	7.5	0.2	0	99
Non-ionic detergent ($mg \cdot L^{-1}$)	3.7	1.4	0.3	0	91.7	5.8	0.7	1.9	1	66.3
Micropollutants[a]										
Diclofenac ($\mu g \cdot L^{-1}$)	NA	NA	NA	NA	NA	0.03		0.079		
Carbamazepine ($\mu g \cdot L^{-1}$)	NA	NA	NA	NA	NA	<0.010		0.013		
Trimethoprim ($\mu g \cdot L^{-1}$)	NA	NA	NA	NA	NA	0.19		0.095		50

HLR = Hydraulic loading rate, std. = Standard deviation.
[a] Analyzed compounds that were under detection limit were not included in this table.

3.5. Potable water production

The mobile potable water production unit was installed treating the effluent of the MCW. The aim was to produce potable water by removing all harmful components (e.g. metals and organic micropollutants). Nitrogen components were the main focus due to (i) the insufficient nitrogen removal in the MCW (about 25%), (ii) the fact that nitrite and ammonium are considered as toxic and (iii) because nitrite and ammonium are small molecules that can be used as probe components for RO performance assessment. Table 5 shows that the water that is produced meets the standards for potable water as N removal proved to be quite satisfying. A mixed bed ion exchange cartridge after RO was installed which reduced the nitrite from 4.8 $mg \cdot L^{-1}$ to below 0.03 $mg \cdot L^{-1}$, nitrate from 12.5 $mg \cdot L^{-1}$ to below 2.0 $mg \cdot L^{-1}$ and ammonium from 3.8 $mg \cdot L^{-1}$ to below 0.2 $mg \cdot L^{-1}$.

4. Conclusions

The MCW was tested to treat discharge water from different (music) festivals in Belgium. The treatment unit is suitable to treat GW since the discharge limits are met, even though the system had high efficiency treating GW + BW. In terms of removal efficiency, the MCW was capable to operate with the hydraulic loading rate up to 1.1 $m^3 \cdot m^{-2} \cdot d^{-1}$ without showing any deterioration of the effluent quality. During the performance test after optimization good removal of COD, BOD, TSS, TN and TP were observed as 90%, 95%, 97%, 24.7% and 76% respectively. With the potable water treatment system good removal of nitrogen components was obtained and potable water was produced that met all the legislative standards. This study demonstrates the potential of mobile water treatment and potable water reuse at temporary events and festivals.

CRediT authorship contribution statement

Fida Hussain Lakho: Conceptualization, Investigation, Methodology, Writing - original draft.**Hong Quan Le:**Data curation, Writing - review & editing.**Fréderic Van Kerkhove:**Investigation.**Wouter Igodt:**Investigation, Methodology.**Veerle Depuydt:**Project administration, Conceptualization, Methodology, Funding acquisition.**Joachim Desloover:**Investigation.**Diederik P.L. Rousseau:**Writing - review & editing.**Stijn W.H. Van Hulle:**Project administration, Conceptualization, Supervision, Methodology, Writing - review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

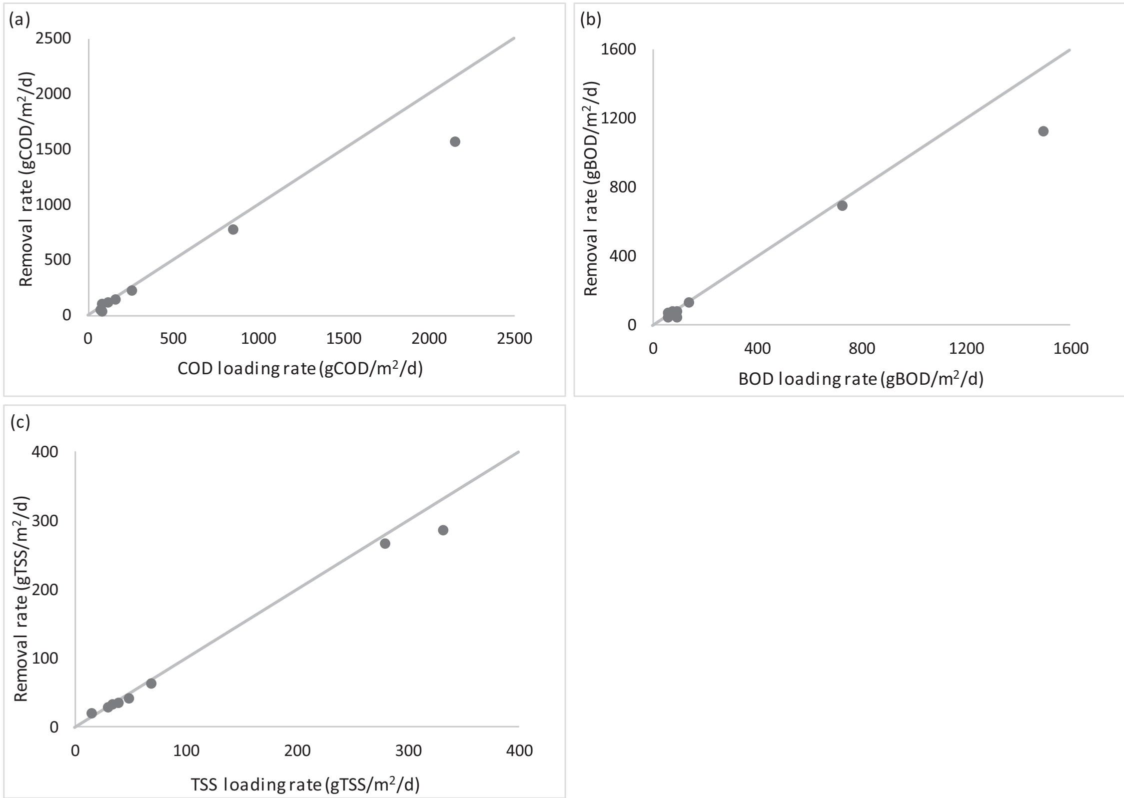

Fig. 2. Summary of overall obtained data (a) COD loading rate versus removal rate, (b) BOD loading rate versus removal rate, (c) TSS loading rate versus removal rate

Table 5
Drinking water production at Dranouter 2019.

Parameters	Effluent MCW ($n = 4$)		Drinking water ($n = 3$)		Standard limit
	Mean	std	Mean	std	
EC (μS/cm)	1513.3	526.5	56.1	42.1	2500
NH_4^+-N (mg·L^{-1})	5.5	3.15	<0.2	0.2	
NO_2^--N (mg·L^{-1})	4.7	2.6	<0.03	0.5	0.5
NO_3^--N (mg·L^{-1})	12.5	6.7	<2.0	4.1	50

n = No. of samples, std. = Standard deviation.

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