Research Article

Joint influence of hydraulic load and hydraulic retention time on oilfields wastewater contaminant removal dynamics in free water surface flow constructed wetland

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Abstract

Constructed wetlands have been proposed to address the frequency and magnitude of oil and gas-related environmental contamination. The effect of co-variation of hydraulic load and hydraulic retention time on the dynamics of contaminant removal efficiency of heterogeneous plant species was assessed using ordinary least squares regression. The results showed that hydraulic load (HL), hydraulic retention time (HRT) and plant species jointly explain 87%, 79%, 83%, 85% and 66% of the total variance in removal efficiency of conductivity, TDS, BOD, COD, and total coliform bacteria, respectively. The models also explain 86%, 80% and 81% of the variations in removal efficiency of oil and grease, total phosphorus, and nitrate. More than 90% of the explained variance of total coliform removal efficiency is jointly attributable to hydraulic load and retention time. Hydraulic load of 1000 L and retention time of 72 h (1000 L 72 h) recorded optimum removal efficiency for TDS and conductivity. Optimum removal efficiency for BOD, COD and total coliform bacteria were achieved at HL and HRT of 1000 L 72 h, 1000 L 48 h and 1250 L 24 h, respectively. *Alternanthera philoxeroides* recorded the highest removal efficiency for oil and grease, conductivity and TDS, whereas *Ruellia simplex* recorded the highest removal efficiency for COD. *Typha latifolia* had the highest removal efficiency for total phosphorus and nitrate. Plant species suppressed the relationship between HL and HRT (1250 L 48 h, 1500 L 72 h, 1750 L 48 h and 2000 L 48 h) and removal efficiency for conductivity. Similarly, plant species suppressed the relationship between 1000 L 48 h and 1750 48 h and removal efficiency for TDS. These relationships underscore the complex dynamics between optimal contaminant removal efficiency and required hydraulic load, hydraulic retention time and plant species.

Keywords *Alternanthera philoxeroides* · *Ruellia simplex* · *Typha latifolia* · Regression · Contaminants · Multivariate statistics

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1 Introduction

Natural wetlands have areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support prevalence of vegetation typically adapted for life in saturated soil conditions [18]. The ecosystem services of natural wetlands have been extensively utilized to treat different kinds of wastewater including domestic, agriculture and industrial [7, 31]. Over the past three decades, wetlands have been constructed to mimic the structure, function and utility of natural wetlands. Constructed wetlands have universal application; they have been constructed for domestic wastewater treatment in small community applications, and are also applied at several mining and industrial sites, as well as for stormwater and urban catchment management, riverine rehabilitation and protection, groundwater recharge and development of urban nature reserves and ecological sites across the globe [7].

Constructed wetlands exhibit some level of flexibility in the nature and scope of plant type, media, hydraulic load and retention time for treating wastewater. Shallow hydrologic environment in treatment wetlands create unique biogeochemical conditions which are necessary for improving water quality of which microorganisms play a key role. Each species of microbes contribute toward treatment of wastewater from different sources having varying pollutant loads [5, 8]. Contaminants are generally removed either aerobically or anaerobically by complex oxidation/methanation processes with the help of diverse microorganisms in the system. Aerobic microbial degradation occurs at the air–water interface of the wetland and usually takes a shorter time, while anaerobic microbial degradation may occur at the water–sediment region of the wetland and this take a longer time [6]. Microbial degradation and plant absorption are major mechanisms that act to eliminate and transform nutrients and pollutant loads in constructed wetlands [13].

Several authors have shown that constructed wetland can be applied as an add-on and/or standalone treatment technology for oilfields wastewater. For instance, Stefanakis et al. [23] used large-scale free surface constructed wetland to treat oilfields produced water in southeastern Arabian Peninsula Nimr. Tate [26] also used a pilot scale constructed wetland to treat oilfields produced water. In addition, Ji et al. [12] and Tatoulis et al. [27] have also shown that heavy oil-produced water can be purified using FWSFCW. Murray-Gulde et al. [20] used FWSFCW to enhance the quality of oilfields wastewater to meet irrigation purposes.

Hydrology is a very important feature in wastewater treatment by natural and constructed wetlands because it determines the timing and extent of flooding or soil saturation. In particular, the formation, persistence, size, and function of wetlands are controlled by hydrologic processes and it is considered as the driving force in wetland formation [24]. Hydrological factors are critical as they control the functions and potential optimization of wetland systems in relation to their treatment efficiency [7, 28, 34]. Carter [4] indicates that although wetland hydrology is very important, it can sometimes be the most difficult factor to determine in the field because it can be highly variable. Considering appropriate hydrological variables is important to ensure that contaminants have optimum contact time with established microbial community residing in the rhizosphere, sediment and water column of the constructed wetlands to ensure efficient treatment. Key hydrological variables that affect contaminant removal include hydraulic loading (HL) and hydraulic retention/residence time (HRT) [34].

Previous studies have investigated the importance of the roles of the primary components of the constructed wetland system regarding three fundamental attributes (a) media: soil, gravel, gold slimes, power station and coal ash and combinations thereof; (b) plant species: grass, rushes, reeds and tall grasses; (c) wastewater type: screened primary domestic sewage, effluents from anaerobic and oxidation ponds, biofilter and activated sludge systems, industrial cooling water, petrochemical and septic tank effluent (see [7, 31, 33]). Substantial work has been on the independent effects of hydraulic retention time on treatment efficiency of constructed wetland (see [7, 31]). However, hitherto, studies on the combined effect of hydraulic load and hydraulic retention time are lacking in the extant literature. Guo et al. [9] point out that although knowing the joint effect of HRT and HL could lead to optimizing the system design and eventually increase resource utilization and improve the performance of free water surface flow constructed wetland, little attention has been devoted to this topic of concern. It is against this background that the study seeks to assess the removal dynamics of contaminants with respect to hydraulic retention time and loads and the combined effect of these key hydrological variables on the removal efficiency of a surface flow constructed wetland. This is necessary for effective constructed wetland management and effluent water quality improvement.

From a practical standpoint, different contaminants require different HRT for their removal, and it is pertinent to investigate how co-variation in HRT and HL jointly affect the removal of contaminants in the wastewater. A clear understanding of removal dynamics and the joint effect of the two variables can pave the way for customized design of treatment systems units. For developing countries in tropical regions, constructed wetlands could be an appropriate, low-cost, promising sanitation technology to improve water quality discharge when used in conjunction with conventional treatment systems to provide further polishing or tertiary treatment to cope with the numerous challenges of conventional wastewater management [2, 24]. This study is significant in four ways. It provides an overview of how the three plant species namely *Alternanthera philoxeroides*, *Ruellia simplex* and *Typha latifolia*-based constructed wetland system perform relative to their design objectives. It identifies factors affecting the performance (removal efficiency) of alternative configurations and operational approaches (HRT and HL combinations). It assesses opportunities for improving the relative performance (removal efficiency) of the different treatment approaches, and also provides general recommendations for the future implementation of the technology in Ghana.

2 Materials and methods

The study was carried out at Shama junction (5.0252° N, 1.6651° W) in the Shama District, about 23 km east of Takoradi, the capital city of Western Region of Ghana. The study site falls within the tropical climatic zone and experiences bimodal rainfall pattern. The mean annual rainfall is 138 cm with minimum and maximum rainfall of 100 cm and 170 cm, respectively. Relatively mild temperatures are experienced in the study site ranging between 22 °C and 28 °C.

The constructed wetland project was sited within the immediate environs of an oilfield wastewater management facility. Approximately 5 m by 5 m size of flat land was used for the project. The site was cleared of preexisting vegetation and the dimensions marked on the ground to create shallow basins to hold water. The length to width ratio of the shallow wetland basins was designed to be 5 m by 1 m. The ground was excavated to a depth of about 0.60 m to enable the root to extend. Surface flow into the basin was prevented by raising the borders to about 0.48 m above ground level. Major pipe lines were laid from entry of wastewater to exit in the wetland system. The four wetland cells were lined with waterproof membrane to prevent wastewater seepage. The lined cells were filled with excavated soils to about 0.40 m. This was to serve as a soil layer to support the roots of the wetland vegetation and also acts as substrate/media in the wetland. The basins were gently sloped (~1°) so that water could move through and exit the wetland via natural streams [32].

Three local wetland plant species, very young, tender and healthy looking, were grown on the harrowed soil. The macrophytes were planted from January to April, and the experimental treatment was conducted between May and September, 2017. The three plant species are *Typha latifolia,* in cell 1, *Ruellia simplex* in cell 2, *Alternanthera philoxeroides* in cell 3 and "no plant" in cell 4 (control). The macrophytes were planted diagonally at an interval of 20 cm in each wetland plant (see [9]). Eighty plants were diagonally planted per wetland cell. This was to ensure more than 50 % coverage in the wetland cell [13]. Wetland cells were immediately flooded with fresh water to about 0.25 m to aid growing of the newly transplanted plants. The newly constructed wetland was maintained with daily watering in the morning and evening to maintain the water level in the wetland and occasional pruning for a period of fourteen (14) weeks to ensure proper acclimatization [32]. The pruned leaves provided litter which served as submerged surfaces that provided physical substrate for the periphytic-attached growth of organisms responsible for most of the biological treatment. The system was roofed with transparent roofing sheet to prevent precipitation before wastewater treatment started.

2.1 Estimation of hydraulic load, hydraulic retention time

First-order kinetics was used to model the removal efficiency/desired effluent quality in the constructed wetland because conditions in constructed wetlands are diminutive of natural conditions of a natural wetland [10]. It is noteworthy that wetland systems are also living ecosystems within which life and death cycles of the biota produce residuals which can be measured as BOD, TSS, nitrogen, phosphorus, and total coliform. As a result, regardless of the size of the wetland or the characteristics of the influent, there will always be a residual background concentration of these materials in wetland systems [5]. Constructed wetlands are miniature of natural conditions especially of a natural wetland so knowledge of the functioning is not as advanced as to provide detailed predictive models, since they depend on biological characteristics such as interspecific competition and tolerance to a residual liquid of changing characteristics [10]. Therefore the designs of constructed wetlands are largely based on rule of thumb and past engineering experience in sizing [32], which are informed by empirical data rather than analytical deductions. However, hydraulic load and retention time were estimated based on the volume of wastewater stored and treated in the treatment facility where the project was undertaken.

$$a = \mathrm{Aw}/\mathrm{Ap}$$

where Aw = area of projected wetland, Ap = area of storage pond, Qw = volume of wastewater expected in the projected wetland, Qp = volume of effluent in the treatment plant

$$\beta = \mathrm{Qw}/\mathrm{Qp}$$

$$a = \beta$$

$$\mathrm{Aw}/\mathrm{Ap} = \mathrm{Qw}/\mathrm{Qp}$$

$$50\ \mathrm{m}^2/191.23\ \mathrm{m}^2 = \mathrm{Qw}/30\ \mathrm{m}^3$$

$$\mathrm{Qw} = \left(50\ \mathrm{m}^2 \times 30\ \mathrm{m}^3\right)/191.25\ \mathrm{m}^3$$

$$\mathrm{Qw} = 7.8431\ \mathrm{m}^3/\mathrm{day;approximately}\ 8\ \mathrm{m}^3(8000\ \mathrm{L})/\mathrm{day}$$

Since the total wetland area was divided into four cells, about 2.0 m^3 wastewater was to be dispensed into each wetland cell. HRT is the ratio of the volume of water within the wetland to the rate of flow through the wetland. It can be used to evaluate the time required for a hydrologic input to pass through the wetland. Hydraulic retention time was estimated using first-order kinetics based on influent and effluent BOD concentration.

Mean influent BOD =3768.75 mg/L; Effluent discharge limit for BOD = *200.00 mg/L*

$$\mathrm{Ce}/\mathrm{Ci} = e^{-K_T}t \quad \text{but} \quad t = \mathrm{In}(\mathrm{Ce}/\mathrm{Ci})/-K_T$$

where: Average temperature of wetland (T) = 29 °C; Influent BOD concentration (Ci) = 3768.75 mg/L; Desired effluent BOD concentration (Ce) = 200 mg/L; K_T = 0.678(θ)^T-20; θ at 20 °C = 1.06; K_T at 29 °C = 1.1455; t = In (200/3768.75)/–1.1455; t = 2.5672; The retention time is approximately 3 days (72 h).

2.2 Experimental treatment

Effluent from the conventional oily wastewater treatment plant was received in intermediate bulk containers (IBC) tanks with the help of a forklift. Triplicate samples were picked from the entry point of the wetland to determine the influent characteristics and gently released to the wetland cells using the batch feeding mode. The batch feeding mode was preferred because of its effectiveness in creating aerobic and anaerobic conditions efficient for contaminant removal in free surface flow constructed wetlands (see [35]). According to Mitsch and Gosselink [19], the pulsation of the water regime over time is important for promoting wetland biological productivity. Specified hydraulic loads, i.e. 1000 L, 1250 L, 1500 L, 1750 L and 2000 L, were received in IBC tanks connected through pipes, positioned anteriorly to the wetland cells. A specified hydraulic load was released through the connected pipes into the wetland cells through the pipes at a constant flow rate of 0.0001 m^3/s within a maximum period of 3 days. The effluent was then discharged through the outlet positioned posteriorly to the wetland cell. Triplicate samples from the wetland cells were taken at a retention time of 24 h, 48 h and 72 h for analysis to determine the effluent characteristics. The hydraulic load varied from 1000 L to 2000 L with an interval of 250 L. For each hydraulic load influent characteristics were determined and effluent characteristics were also measured at the three hydraulic retention times (24, 48 and 72 h). Treatment for each load was repeated four times, and measurements were taken for a period of 5 months. Parameters measured include total dissolved solids (TDS), electrical conductivity, biochemical oxygen demand (BOD), chemical oxygen demand (COD), oil and grease (O and G), total coliform bacteria, total phosphorus (TP) and nitrate (NO_3). These parameters were selected based on priority to the waste management facility and their quantities in the oily wastewater.

EC was determined using a calibrated standard cell electrode connected to a standard meter at a constant temperature based on APHA 2510, while TDS was measured gravimetrically based on APHA 2540C. BOD in this study was measured using respirometric method based on method APHA 10099, COD was determined using reactor digestion method based on APHA 8000 while oil and grease was measured using hexane extractable gravimetric method based on APHA 5520B. Determination of TP was by acid persulfate digestion method based on APHA 8190, nitrate by cadmium reduction method based on APHA 8039 and total coliform by plate count method based on (ISO-4833-2, 2013).

2.3 Data analysis

The study employed ordinary least squares regression model to assess the combined effect of hydraulic load and hydraulic retention time on the removal efficiency of oilfields wastewater contaminants. Hydraulic load and hydraulic retention time were combined to generate the independent variable called hydraulic characteristics with fifteen (15) groupings. The regression model was first run without plant type in model 1 and with plant type in model 2 to understand how plant type influences the linear relationship between hydraulic characteristics (explanatory variable) and pollutant removal (outcome variable).

3 Results and discussion

Particle size analysis showed that the soil (substrate/media) used in the constructed wetland consists of 22.03% clay, 15.21% silt and 62.74% sand indicating a sandy clay loam texture. The removal efficiency of eight parameters namely biochemical oxygen demand, chemical oxygen demand, total dissolved solids, total coliform bacteria, conductivity, oil and grease, total phosphorus and nitrate monitored are reported in this section and summarized in the Supplementary Table 1 (S1). An important reason for monitoring the performance of constructed wetlands is to collect data that can be used to develop process performance and control strategies. The specific parameters that need to be monitored will depend on the design objectives, local conditions, and regulatory requirements. In addition to meeting regulatory reporting requirements, monitoring data should be used to assess process stability and performance, spotting trends before they become problems [33]. Generally, the removal efficiency of the parameters was better in the planted wetlands than the unplanted control. This finding resonates with Wood and Steffen [33], who indicate that it is generally accepted that better wastewater treatment is achieved in vegetated rather than unvegetated beds, and largely interpreted it to be a result of an oxygenated rhizosphere, although the amount of oxygen provided to aerobic microorganisms is not well defined. The joint effect of hydraulic load, hydraulic retention time and plant species on removal efficiency of EC and TDS are shown in Table 1 (Fig. 1).

Figure 2 shows coefficient plots and confidence intervals for the removal efficiency for conductivity and TDS. When the role of plant species was taken into account, the models for conductivity and TDS explained about 87% ($R^2 = 0.867$) and 79% ($R^2 = 0.787$) of the total variation in the decrease of EC and TDS. The confidence intervals for the coefficients became smaller when plant type was controlled for in model 2, indicating that plant type served as mediator in the relationship between removal efficiency and the hydraulic characteristics (HL and HRT). This means that a decrease in electrical

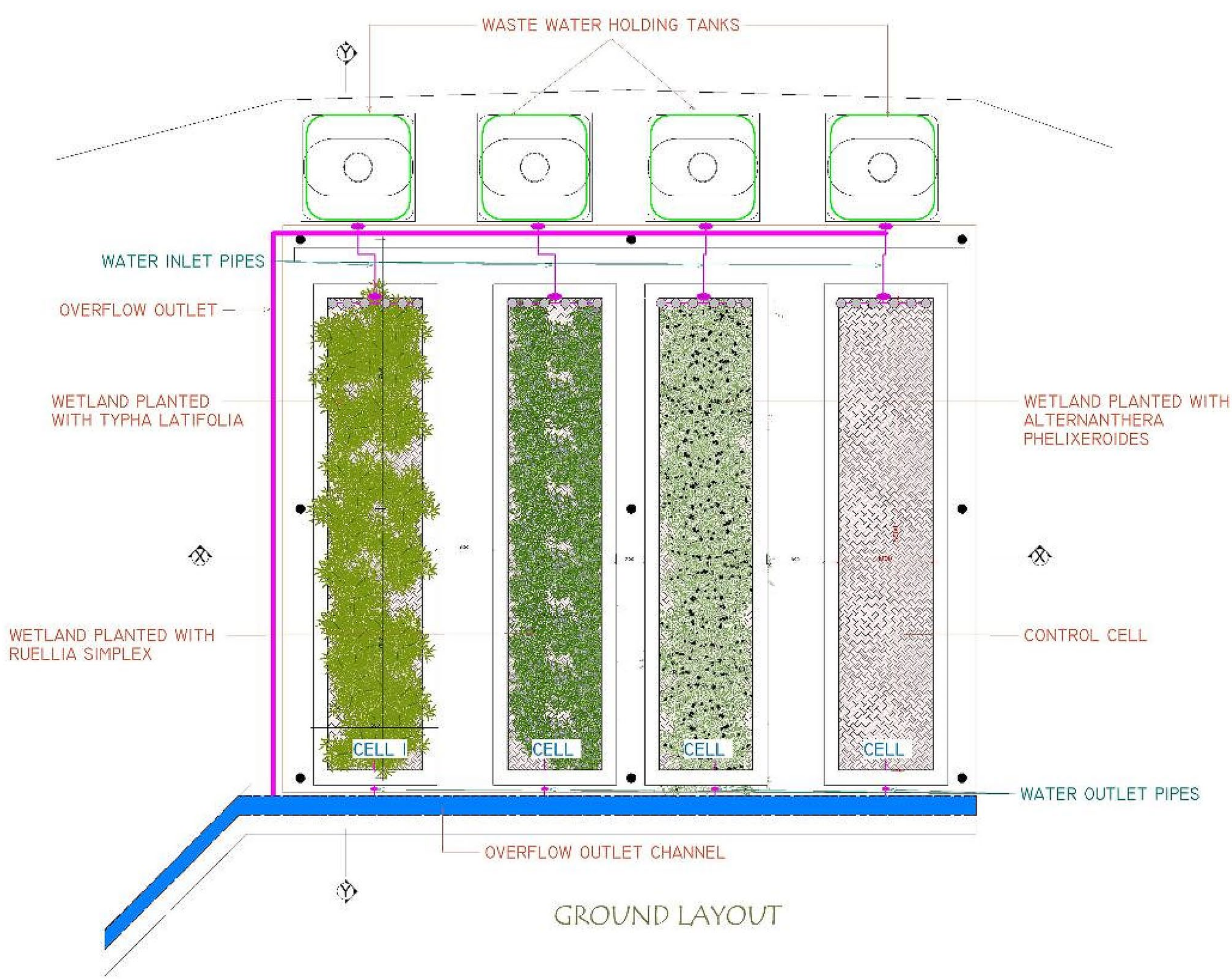

Fig. 1 Schematic diagram of free water surface flow constructed wetland

Table 1 Ordinary least squares regression model showing the combined effect of hydraulic load, retention time and plant species on the removal efficiency for conductivity and TDS

Hydraulic load and retention time (ref: 1000 L 24 h)	Conductivity				TDS			
	Model 1: $R^2 = 0.435$		Model 2: $R^2 = 0.867$		Model 1: $R^2 = 0.448$		Model 2: $R^2 = 0.787$	
	Coefficient	*P* value	Coefficient	*P* value	Coefficient	*P* value	Coefficient	*P* value
1000 L 48 h	−22.417	**0.000**	−22.417	**0.000**	7.000	0.055	7.000	**0.002**
1000 L 72 h	13.333	**0.011**	13.333	**0.000**	21.750	**0.000**	21.750	**0.000**
1250 L 24 h	−19.167	**0.000**	−19.167	**0.000**	11.500	**0.002**	11.500	**0.000**
1250 L 48 h	−5.917	0.253	−5.917	**0.020**	14.250	**0.000**	14.250	**0.000**
1250 L 72 h	2.083	0.687	2.083	0.410	−0.083	0.982	−0.083	0.971
1500 L 24 h	−11.167	**0.032**	−11.167	**0.000**	4.000	0.271	4.000	0.080
1500 L 48 h	3.083	0.551	3.083	0.223	19.250	**0.000**	19.250	**0.000**
1500 L 72 h	6.833	0.187	6.833	**0.007**	14.917	**0.000**	14.917	**0.000**
1750 L 24 h	−12.417	**0.017**	−12.417	**0.000**	3.000	0.408	3.000	0.188
1750 L 48 h	5.333	0.303	5.333	**0.036**	6.000	0.099	6.000	**0.009**
1750 L 72 h	−15.167	**0.004**	−15.167	**0.000**	19.750	**0.000**	19.750	**0.000**
2000 L 24 h	−18.917	**0.000**	−18.917	**0.000**	−0.750	0.836	−0.750	0.741
2000 L 48 h	−7.167	0.167	−7.167	**0.005**	8.000	**0.028**	8.000	**0.001**
2000 L 72 h	−14.917	**0.004**	−14.917	**0.000**	−0.750	0.836	−0.750	0.741
Treatment and control setup (ref: typha)								
Ruellia			0.467	0.721			−5.956	**0.000**
Alternanthera			5.244	**0.000**			2.378	**0.044**
Control			−22.067	**0.000**			−14.867	**0.000**
Constant	49.417	**0.000**	53.506	**0.000**	30.000	**0.000**	34.611	**0.000**

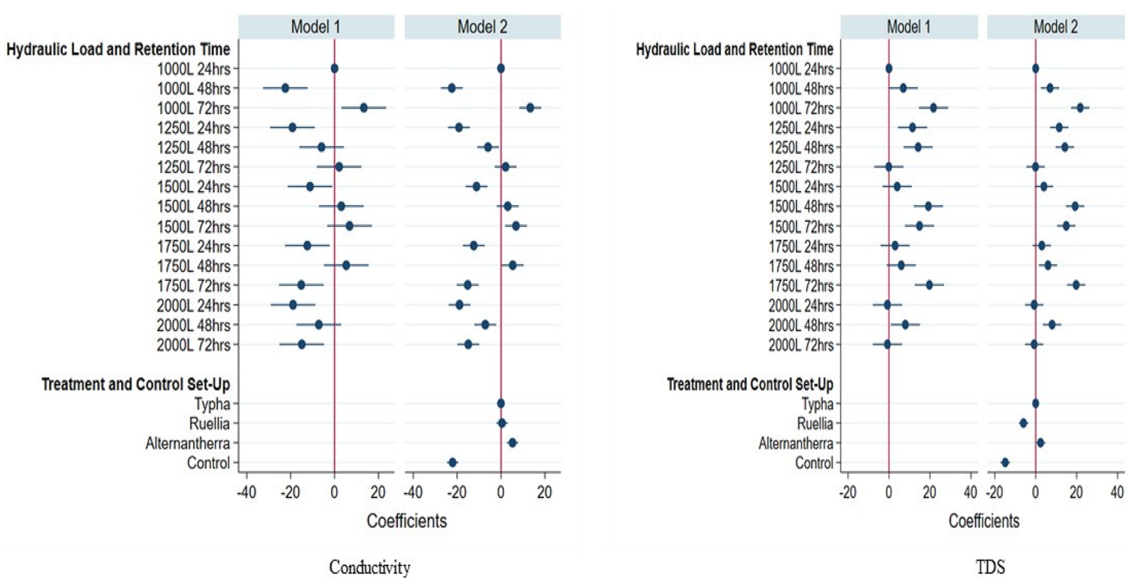

Fig. 2 Graphical representation of the coefficient plots and confidence intervals for the removal efficiency of conductivity and TDS

conductivity (EC) and TDS in constructed wetlands depends on hydrology and also dominant plant type [16, 34]. HL and HRT such as 1250 L 48 h, 1500 L72 h, 1750 L 48 h and 2000 L 48 h which were not statistically significant in model 1 became significant in model 2. Similarly, 1000 L 48 h and 1750 48 h subgroups that were not statistically significant in TDS model 1 became significant in model 2, indicating that plant type was suppressing the relationship between removal efficiency and the hydraulic variables. Hydraulic load of 1000 L and retention time of 72 h (1000 L 72 h) recorded the highest reduction for TDS and conductivity. La Mora-Orozco et al. [16] observed a decrease in electrical conductivity from 12% to 23% and 15% to 65% for TDS, respectively, when HRT was increased from 5 to 10 days showing wetland treatment for these parameters may require a longer retention time. However, studies on wetlands usually present a challenge with regard to comparing data sets on treatment efficiency because of differences that might exist in design configuration, wastewater characteristics, plant type, substrate and environmental conditions [24]. Wetland cell planted with *Alternanthera philoxeroides* recorded the highest reduction efficiency for the two parameters, probably because the plant is found to thrive in saline environment due to the presence of salt glands and bladders responsible for selective ion exclusion and accumulation.

The regression models for the removal efficiency of BOD, COD and total coliform bacteria explain 84% ($R^2=0.838$), 85% ($R^2=0.852$) and 66% ($R^2=0.664$) of the total variations in removal efficiency of the treatment wetlands. The estimations in model 2 had smaller confidence intervals compared to model 1 for BOD and COD but generally the same (Table 2) for total coliform bacteria in the two models (see Fig. 3).

This indicates that removal efficiency of BOD and COD is likely to be predominantly influenced by plant type as compared to total coliform bacteria. Hydraulic loads and retention times such as 1250 L 48 h, 1500 L 72 h and 2000 L 48 h which were not statistically significant in BOD and COD model 1 became significant in model 2. This indicates that plant species suppressed the relationship between the removal efficiency and the hydraulic characteristics. It was also observed that HL and HRTs such as 1250 L 48 h and 1500 L 24 h that were not statistically significant in the total coliform bacteria model 1 became significant in model 2; still pointing to the fact that plant species suppressed the relationship between the removal efficiency and the hydraulic characteristics. Saeed and Sun [22] indicate that the effect of hydraulic load and retention time is influenced by temperature and plant species. Wood and Steffen [33] also point out that the permeability limitations of media, particularly soils, will ultimately be the deciding factor on the hydraulic loading that the wetland system can accommodate where pollutant adsorption is the desired treatment mechanism. Highest removal efficiency

Table 2 Ordinary least squares regression model showing the cumulative effect of hydraulic load, retention time and plant species on the removal efficiency for BOD, COD, and total coliform bacteria

Hydraulic load and retention time (ref: 1000 L 24 h)	BOD				COD				Total Coliform Bacteria			
	Model 1: $R^2=0.316$		Model 2: $R^2=0.834$		Model 1: $R^2=0.562$		Model 2: $R^2=0.852$		Model 1: $R^2=0.604$		Model 2: $R^2=0.664$	
	Coef.	*P* value	Coef.	*P* value	Coef.	*P* value	Coef.	*P* value	Coef.	*P* value	Coef.	*P* value
1000 L 48 h	−10.750	**0.004**	−10.750	**0.000**	14.250	**0.000**	14.250	**0.000**	−16.500	**0.000**	−16.500	**0.000**
1000 L 72 h	14.250	**0.000**	14.250	**0.000**	12.000	**0.000**	12.000	**0.000**	−4.500	0.163	−4.500	0.133
1250 L 24 h	4.500	0.227	4.500	**0.015**	−5.000	0.090	−5.000	**0.004**	14.250	**0.000**	14.250	**0.000**
1250 L 48 h	2.500	0.501	2.500	0.172	−1.500	0.610	−1.500	0.384	−6.000	0.063	−6.000	**0.046**
1250 L 72 h	3.250	0.382	3.250	0.076	11.250	**0.000**	11.250	**0.000**	−2.500	0.437	−2.500	0.403
1500 L 24 h	−0.250	0.946	−0.250	0.891	2.750	0.350	2.750	0.112	−6.000	0.063	−6.000	**0.046**
1500 L 48 h	−0.500	0.893	−0.500	0.784	−11.750	**0.000**	−11.750	**0.000**	−7.750	**0.017**	−7.750	**0.010**
1500 L 72 h	5.000	0.179	5.000	**0.007**	14.000	**0.000**	14.000	**0.000**	−16.000	**0.000**	−16.000	**0.000**
1750 L 24 h	−2.500	0.501	−2.500	0.172	−3.250	0.269	−3.250	0.061	−10.750	**0.001**	−10.750	**0.000**
1750 L 48 h	−0.500	0.893	−0.500	0.784	11.750	**0.000**	11.750	**0.000**	0.750	0.815	0.750	0.802
1750 L 72 h	10.250	**0.006**	10.250	**0.000**	5.250	0.075	5.250	**0.003**	−28.500	**0.000**	−28.500	**0.000**
2000 L 24 h	−3.750	0.313	−3.750	**0.041**	−4.000	0.175	−4.000	**0.021**	−14.250	**0.000**	−14.250	**0.000**
2000 L 48 h	9.250	**0.014**	9.250	**0.000**	7.750	**0.009**	7.750	**0.000**	−10.500	**0.001**	−10.500	**0.001**
2000 L 72 h	2.750	0.459	2.750	0.133	8.500	**0.004**	8.500	**0.000**	−8.250	**0.011**	−8.250	**0.006**
Treatment and control setup (ref: typha)												
Ruellia			−6.667	**0.000**			−6.867	**0.000**			0.200	0.897
Alternanthera			2.400	**0.012**			0.133	0.881			0.067	0.966
Control			−17.200	**0.000**			−13.400	**0.000**			−6.667	**0.000**
Constant	40.000	**0.000**	45.367	**0.000**	30.500	**0.000**	35.533	**0.000**	56.500	**0.000**	58.100	**0.000**

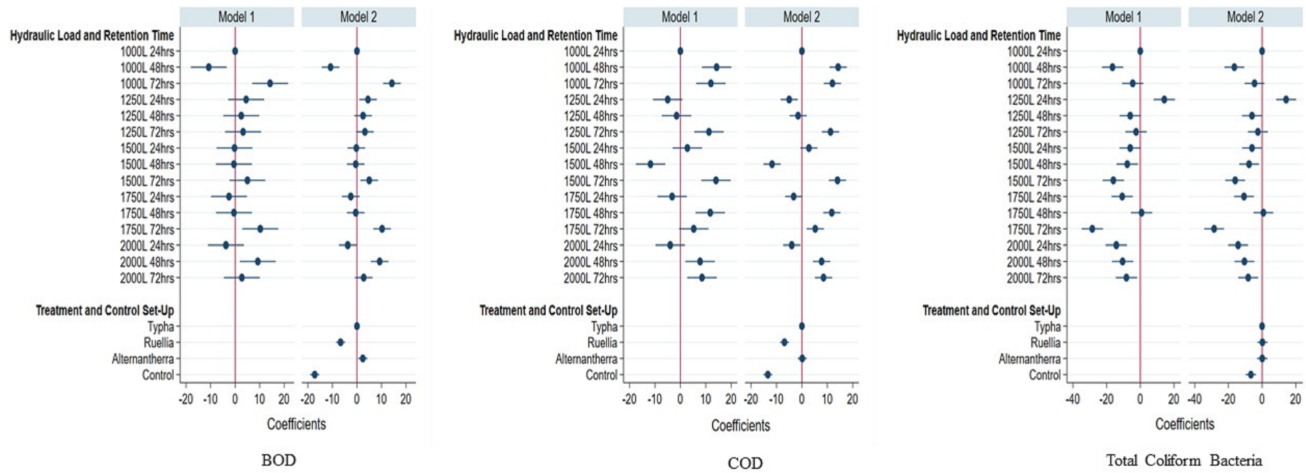

Fig. 3 Graphical representation of coefficient plots and confidence intervals of the linear regression model for BOD, COD and total coliform bacteria

for BOD, COD and total coliform bacteria were achieved at HL and HRT of 1000 L 72 h, 1000 L 48 h and 1250 L 24 h, respectively. This observation could be attributed to the fact that if the concentration of BOD and suspended solids is too high, oxygen transported to the plant roots may be wasted in treating sludge that accumulates around the roots, as opposed to treating the organic matter in the fluid bulk. This situation assists recycling in balancing the loading to the inlet area [16]. Similarly, Lee et al. [17] reported that the removal of organics takes a shorter time than nitrogen removal. Regarding wetland vegetation, *Alternanthera philoxeroides* and *Ruellia simplex* recorded higher removal efficiency for BOD compared to the reference plant, *Typha latifolia*. Removal of BOD and COD was highest in the *Alternanthera philoxeroides* vegetated wetland. This may be attributable to its unique morphological features such as extensive roots and stem that support excellent filtration and bacterial growth [1]. Biofilms located on plant surfaces offer pathways for plants to break down organics [21].

Ruellia simplex recorded the highest removal efficiency for COD. The finding agrees with the observation made by Gearheart et al. [6] that COD effluent concentration even with a tenfold hydraulic loading is associated with the type of aquatic plants in the wetland. However, the total coliform bacteria model showed no statistically significant difference in terms of removal efficiency between *Alternanthera philoxeroides* and *Ruellia simplex* compared to the base plant (*Typha latifolia*). Removal of pathogenic organisms including coliform bacteria is influenced by factors such as water composition, presence of vegetation and filter media such as sand; oxygen, sunlight and pH levels; and seasonal temperature changes as well as patterns of water flow and retention time. However, plants type may support removal mechanisms such as filtration, adsorption, and secretion of biocides. Plant type with unique attribute toward the latter processes may record an increase in removal efficiency of coliform bacteria [3].

The water level in systems and the duration of flooding can be important factors in the selection and maintenance of wetland vegetation. *Typha latifolia* grows well in submerged soils and may dominate in standing water of over 150 mm [33].

The coefficients from the regression models for oil and grease, total phosphorus and nitrate are reported in Table 3. Figure 3 presents the coefficients plots and confidence intervals of the relationship between oil and grease, total phosphorus and nitrate, on the one hand, and the hydraulic characteristics and plant species, on the other hand. The regression models for oil and grease, total phosphorus and nitrate indicate that HL and HRT explain 86% ($R^2 = 0.857$), 80% ($R^2 = 0.803$) and 81% ($R^2 = 0.807$) of the total variations in removal efficiency of the constructed wetlands. The estimations in model 2 had smaller confidence intervals compared to model 1 for all parameters (see Fig. 3).

It is observed from Fig. 4 that the removal efficiency of nitrates depends immensely on plant species. Five HL and HRT (1000 L 72 h, 1250 L 24 h, 1250 L 72 h, 1750 L 72 h and 2000 L 48 h) which were not statistically significant in the oil and grease model 1 became significant when plant type was controlled for in the model 2, suggesting that the relationship between oil and grease removal efficiency and hydraulic variables is suppressed in the absence of plant. HL and HRT of 1250 L 72 h which was not statistically significant in the total phosphorus model 1 became significant in model 2. Five HL and HRT (1000 L 72 h, 1250 L 72 h, 2000 L 24 h and 2000 L

Table 3 Ordinary least squares regression model showing the combined effect of hydraulic load, retention time and plant species on the removal efficiency for oil and grease, total phosphorus and nitrate

Hydraulic load and retention time (ref: 1000 L 24 h)	Oil and Grease				Total Phosphorus				Nitrate			
	Model 1: $R^2=0.511$		Model 2: $R^2=0.857$		Model 1: $R^2=0.556$		Model 2: $R^2=0.803$		Model 1: $R^2=0.379$		Model 2: $R^2=0.807$	
	Coef.	*P* value	Coef.	*P* value	Coef.	*P* value	Coef.	*P* value	Coef.	*P* value	Coef.	*P* value
1000 L 48 h	0.500	0.874	0.500	0.771	−7.083	**0.010**	−7.083	**0.000**	9.250	**0.001**	9.250	**0.000**
1000 L 72 h	−3.500	0.267	−3.500	**0.043**	14.167	**0.000**	14.167	**0.000**	5.250	0.062	5.250	**0.001**
1250 L 24 h	5.750	0.069	5.750	**0.001**	2.667	0.326	2.667	0.145	1.250	0.655	1.250	0.427
1250 L 48 h	−21.750	**0.000**	−21.750	**0.000**	3.417	0.209	3.417	0.062	−1.250	0.655	−1.250	0.427
1250 L 72 h	−4.250	0.178	−4.250	**0.014**	−4.583	0.093	−4.583	**0.013**	−3.500	0.211	−3.500	**0.027**
1500 L 24 h	−13.250	**0.000**	−13.250	**0.000**	−15.083	**0.000**	−15.083	**0.000**	13.750	**0.000**	13.750	**0.000**
1500 L 48 h	−17.500	**0.000**	−17.500	**0.000**	−1.333	0.623	−1.333	0.465	12.500	**0.000**	12.500	**0.000**
1500 L 72 h	−3.000	0.341	−3.000	0.082	−7.833	**0.004**	−7.833	**0.000**	8.000	**0.005**	8.000	**0.000**
1750 L 24 h	−10.000	**0.002**	−10.000	**0.000**	3.167	0.244	3.167	0.084	9.500	**0.001**	9.500	**0.000**
1750 L 48 h	−16.500	**0.000**	−16.500	**0.000**	−8.833	**0.001**	−8.833	**0.000**	−0.750	0.788	−0.750	0.633
1750 L 72 h	−5.750	0.069	−5.750	**0.001**	2.917	0.283	2.917	0.111	1.000	0.720	1.000	0.525
2000 L 24 h	−10.750	**0.001**	−10.750	**0.000**	3.167	0.244	3.167	0.084	4.500	0.109	4.500	**0.005**
2000 L 48 h	−3.500	0.267	−3.500	**0.043**	3.417	0.209	3.417	0.062	5.000	0.075	5.000	**0.002**
2000 L 72 h	0.250	0.937	0.250	0.884	7.667	**0.005**	7.667	**0.000**	0.750	0.788	0.750	0.633
Treatment and control setup (ref: typha)												
Ruellia			−5.156	**0.000**			−3.467	**0.000**			−3.200	**0.000**
Alternanthera			2.778	**0.002**			−3.200	**0.001**			−5.533	**0.000**
Control			−13.489	**0.000**			−12.711	**0.000**			−14.600	**0.000**
Constant	57.250	**0.000**	61.217	**0.000**	39.833	**0.000**	44.678	**0.000**	31.750	**0.000**	37.583	**0.000**

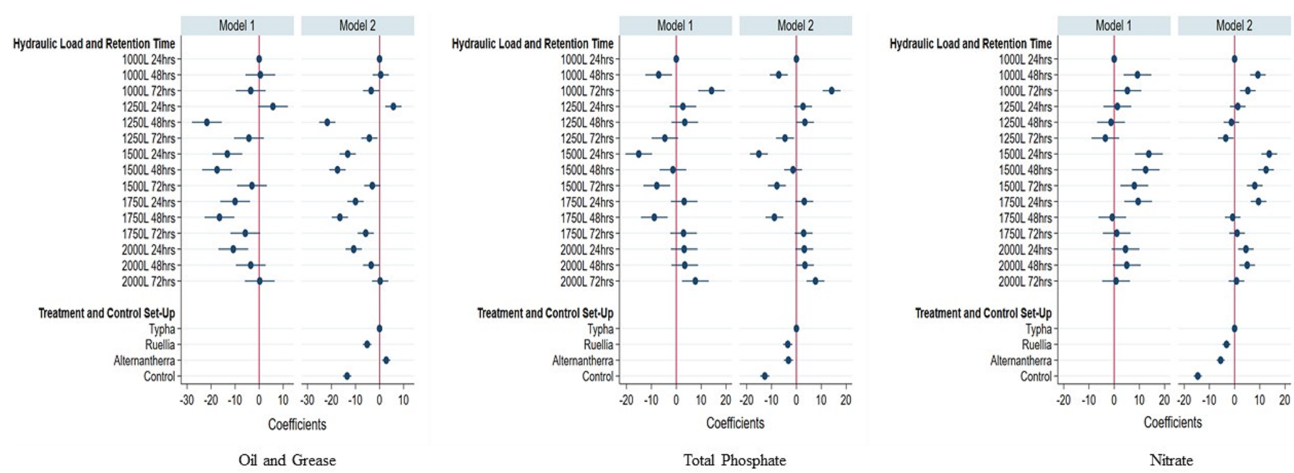

Fig. 4 Graphical representation of coefficient plots and confidence intervals of the linear regression model for oil and grease, total phosphorus and nitrate

48 h) that were not statistically significant in the nitrate model 1 became significant when plant type was introduced in the model 2, suggesting suppression of the effect of hydraulic characteristics on removal efficiency of nitrate. The joint hydraulic load and retention times that recorded the highest removal efficiency for oil and grease, total phosphorus and nitrate were 1250 L 24 h, 1000 L 72 h and 1500 L 24 h, respectively.

The highest removal efficiency for BOD and total phosphorus were recorded at 1000 L and 72 h. These parameters are typically removed through processes such as sedimentation, filtration, aerobic/anaerobic microbial degradation, adsorption-precipitation reactions and plant uptake. These processes are affected by retention time and consequently the nutrients and solid removal efficiencies in the wetlands [3, 15]. Sedimentation, filtration, aerobic microbial degradation and nitrification occur in the aerobic (air–water interface) zone of the wetland and they occur faster than other removal processes such as denitrification and anaerobic microbial degradation that occur in the anaerobic (water–sediment interface) zone of the wetland [6]. The removal of phosphorus and nitrogen ordinarily require a longer retention time [22]. However, the observed higher removal at a lower hydraulic load (1000 L) and longer retention time (3 days) may be attributed to the fact that newly constructed free water surface flow treatment wetlands are able to adsorb, absorb and undergo precipitation reaction with the mineral ions in the substrate until the soil is saturated [15]. Phosphorus has been found to interact strongly with wetland soil and biota to provide short-term removal and long-term storage [15]. The results show higher nitrate removal at a shorter hydraulic retention time (1 day) and lower hydraulic load (1000 L). This could be attributed to the fact that lower hydraulic load facilitate efficient metabolism by microbial community and increases rate of filtration and sedimentation of contaminants [11]. The removal of nitrate might have occurred through nitrification and denitrification in the oxic and anoxic zone of the water column of the wetland, respectively [6, 31].

Toet et al. [29], found higher nitrogen removal at HRT of 19.2 h and lower removal efficiency at HRT of 7.2 h which is attributed to incomplete denitrification. The results observed in this study are consistent with findings by Tchobanoglous [28], Lee et al. [17], Saeed and Sun [22] and Velvizhi [30] who found higher removal efficiencies at increased retention time and reduced hydraulic load. Higher removal efficiency of coliform bacteria and oil and grease were recorded at 1250 L and 24 h. This could be due to the fact that removal process for pathogens in constructed wetland may depend much on environmental conditions, water chemistry and exposure to UV radiation, rather than pollutants loads and retention time [16]. *Alternanthera philoxeroides* recorded the highest removal efficiency for oil and grease among the three plant types and the control probably because of its unique morphological features such as growth habit of forming a mat and extensive root system enable it to harbor large community of microorganisms that mediate in removal of organic pollutants [1]. The removal efficiency of total phosphorus and nitrate was highest in wetland cell planted with *Typha latifolia*. This observation may be attributable to the fact that nutrients accumulation by plants in constructed wetland has been associated with biomass. Ammonia and nitrate are the two important forms of nitrogen that are generally used for assimilation by plants; however when ammonium is plentiful, wetland plants prefer ammonium over nitrate as a nitrogen source for biomass growth [25, 31]. Most plants are capable of absorbing any form of soluble nitrogen, especially if acclimatize to its environment. Vymazal [31] indicates that as the rate of biomass and nutrient accumulation diminishes, Typha spp. are able to translocate nutrients and photo-assimilate from leaves to rhizome. This might have contributed to the higher removal of nitrate in *Typha latifolia*. Brix [3], Kadlec [14] and Wu et al. [34] all indicate that although hydraulic retention time plays important role in specific pollutant removal, their effects may depend on plant species dominant in the wetland system. La Mora-Orozco et al. [16] has also reiterated that hydraulic retention time alone is not the determining factor for removal of total phosphorus; other factors such as plant type, hydraulic loads, and soil minerals also play a role. Similarly, increase in coliform, nitrogen and phosphorus removal with increased HRT, sometimes up to 15 days, have been reported by Toet et al. [29].

Several important issues emerge from this study. Despite the plant species being perceived to be a primary treatment mechanism, their contribution is generally average, whereas the configuration and optimal operating stretagies of the wetland, in terms of hydraulic characteristics, is of significantly greater importance. The primary performance (removal efficiency) limitation is flow control through the system. Low permeability of the bed media tends to encourage surface flow rather than filtration through the bed for systems internationally designed for subsurface flow. Also, surface flow systems, as in this study, demonstrate significant short-circuiting. These factors minimize available residence times and contact opportunity for optimal treatment. Management techniques must be developed to ensure optimal treatment; and these should allow for operational changes to be made in response to changes in the wastewater characteristics, effluent quality, climatic conditions, and effluent discharge requirements [33].

4 Conclusion

Based on this study, it is obvious that co-variation of hydraulic characteristics (load and retention time) explains more of the dynamics of contaminant removal efficiency of this constructed wetland system. Parameters (biochemical oxygen demand, chemical oxygen demand, total dissolved solids, nitrate-nitrogen) that are removed by processes that occur in the aerobic zone occur faster, Plant species explained less of the variability in removal efficiency for all parameters except nitrate and BOD. The results of this study underscore the complex interplay of hydraulic characteristics and plant species heterogeneity in influencing the removal efficiency of contaminants in the constructed wetland. Plant species either mediated or suppressed the relationship between contaminant removal and the hydraulic characteristics. By and large, removal efficiency appeared to be highly dependent on hydraulic characteristics (hydraulic loading and retention/residence time) and influent concentration for certain parameters. For parameters such as conductivity, TDS, BOD, total phosphorus and nitrate, removal rates at greater loadings may require greater hydraulic retention time to increase the contact time between wastewater and biofilms in the water column, rhizosphere and sediment. Given that removal efficiency for most parameters, attributable to the plant species alone, was not excellent, there is room for improvement in the design of this free water surface constructed wetland. Surface flow systems, whether open bed or channel configuration, may be improved by provision of alternate shallow and deep water areas, and intermediate berms to assist flow and velocity buffering. Multiple species planting in defined areas through which the wastewater must flow assists contact opportunities for treatment by physical filtration, adsorption and absorption and biological treatment by attached microorganisms. In conclusion, constructed wetlands can provide a viable and effective complement for polishing oil fields wastewater treatment. A primary consideration is the need to control the hydraulics and increase land area to optimize retention times and contact opportunities for effective treatment.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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