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Assessment of the Efficiency of a Pilot Constructed Wetland on the Remediation of Water Quality; Case Study of Litani River, Lebanon

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Abstract

The potential use of constructed wetlands to remediate polluted rivers is promising and has recently received a great deal of interest. This study aims at evaluatingthe efficiency of a constructed wetland of the Litani River in Lebanon using two types of aquatic plants, *Phragmites australis* and *Sparganium erectum*. Comparative analysis of the mean values of water quality parameters of the inflow and outflow water of the wetland system was conducted during the period of April 2014 and July 2015. Findings show statistically significant improvement in water quality parameters. Hence, results clearly show the efficiency of the constructed wetland in the remediation of the polluted river water and the important role of the aquatic macrophytes in remediation. In conclusion, the studied wetland provides an efficient sustainable approach towards the integrated river basin management of Litani River. Further comprehensive studies to better illustrate the role of aquatic plants in the remediation process are needed.

Keywords: Constructed wetland; Litani river; *Phragmites australis*; *Sparganium erectum*; Remediation; Lebanon

Introduction

Constructed wetlands to improve water quality are valuable and appropriate technicaltools that are used alone or in combination with other water filtering and treatment systems [1-4]. Such systems enhance the naturally occurring biological, chemical and physical processes that occur in natural wetlands to optimize removal of pollutants from water. Constructed wetlands are a less energy intensive and a more environmentally sound way to manage polluted water than treatment technologies that rely on fossil fuel-generated energy and/or chemical reagents.

Constructed wetlands successfully remove contaminants as diverse as organic material, nutrients, heavy metals, synthetic chemicals, sediments, and more. Many investigators have highlighted the role of wetland-based systems in the reduction of nutrient agricultural run-off and the improvement of water quality. Nevertheless, considerable interspecific and geographical differences of plant nutrient removal efficiency along different environmental gradients do exist [5,6]. In view of the effects of burgeoning anthropogenic pressures and climate change on alteration of plant biomass, dominance patterns and community composition, assessment of nutrient sequestration efficiency of macrophytes in wetlands assumes pivotal significance [7]. In general, wetland water treatment systems have been found to reduce BOD, TSS and total nitrogen concentrations from 30 to 90 percent [1]. For total phosphorus, metals, and organic compounds removal efficiencies vary widely, typically, from 10 to 90 percent. Removal of pollutants in treatment wetlands is limited by the form and concentration of the constituents, water flow rates and residence time, the presence of oxygen, substrate type and the entire chemical makeup of the water to be treated [1]. And, while wetland systems have been successfully implemented even in harsh northern climates they are particularly well suited for the Mediterranean climate characterizing Lebanon, and thus well-suited for the remediation of our polluted rivers.

In Lebanon, the Litani River is the largest and most important water resource in Lebanon. The river is 170 km in length with 60 km of tributaries, draining over 2170 km^2 (20% of the country's area) and totally contained within its boundaries (Figure 1). The importance of

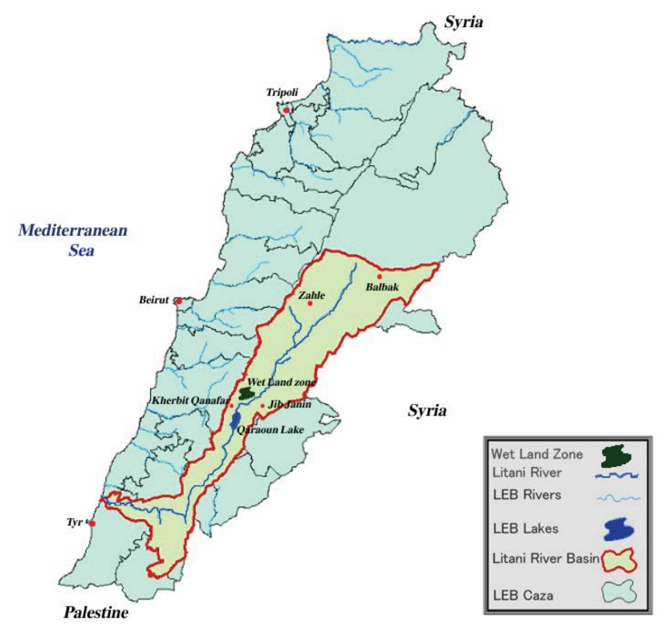

Figure 1: Litani river basin (LRBMS) [12].

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the Litani River lies on its indispensable usage for supporting urban development and the agricultural and industrial sectors. However, the river is suffering at present from the ever increasing demands for water, widespread exposure to pollution from untreated sewage, industrial wastewater effluents, uncontrolled solid waste dumping and agricultural run-off. Moreover, most of the wastewater treatment plants along the river are currently not functional or marginally operating, thus diverting untreated sewage directly to the river course increasing the hydrologic loading of the various contaminants. And, numerous studies have primarily detected hypertrophic levels of phosphorus and nitrogen, elevated levels of suspended solids, heavy metals, BOD and fecal pathogens [8-11].

While efforts to construct additional wastewater treatment plants along the river are ongoing, governmental funds to complete construction and sustain the operation of the existing plants is still lacking due to major technical and economic constraints. As such, and in an attempt to address the deteriorating water quality, the Litani River Management Support Program (LRBMS–USAID funded project) with the Litani River Authority (LRA) designed and constructed a wetland system between 2012 and 2013. The wetland is situated directly adjacent tothe Litani River at the Kherbit Kanafar irrigated lands. An inlet structure permits the diversion of water from the river into the wetland, while a concrete outlet structure re-conducts water back to the river through a riparian wetland channel containing *Phragmites australis* and *Sparganium erectum* meant to mimic historical aquatic features in this reach of the Litani River. As such, the main objective of this study is to assess the wetland performance during the first two years of its construction to determine the treatment efficiency and the improvement in the quality of the river's water.

Materials and Methods

Constructed wetland system

The constructed wetland under study is a Free Water Surface (FWS) wetland constructed in 2013 at a publicly owned site (southeast of the Litani River Authority agricultural extension center in Kherbit Kanafar in the southern plains of the Bekaa Valley). It lies along the Litani River, just upstream of Qaraoun Lake and was designed to provide improved water quality downstream to Lake and the Canal 900 irrigation conveyor. The constructed wetland is approximately 2.5 ha in size and receives 30 L/s of water flow during the dry season and 60 L/s during the rest of the year. These rates represent between 20 to 100% of the water flow during the dry season and approximately 1 to 2% of the flow for the wet season. The system consists of an oval-shaped basin containing alternating deep ponds (2-3 m of depth) and shallow zones (30-50 cm of depth) for a ratio of 70%/30% of deep ponds/shallow zones (Figure 2). The shallow zones were planted with two native vegetation species (*Phragmites australis* and *Sparganium erectum*) that are common in the region. The deep zones serve to promote mixing and uniform flow, while the shallow zones promote the growth of the emergent wetland vegetation that provides a biologically and chemically diverse environment for pollutants removal.

Constructed wetland operation

The constructed wetland includes a pumping station next to the river to provide the inflow and an adjustable weir outflow structure needed to maintain consistent water levels and to convey wetland effluents to a discharge channel that leads back to the river. The wetland system was projected to remove between 30 to over 90% of the pollution load, depending on the type of pollutant and the time of year. Rates of nitrogen removal are known to be lower in wintertime due to the effect of low temperatures on microbial activity which is the dominant removal mechanism [12].

Water quality assessment

Water samples were collected monthly during the period of April 2014 through June 2015 from both the constructed wetland's inflow and outflow. Salinitywas determined by tracer pocket tester (LaMotte/ code 1749), ammonia (NH_3), nitrates (NO_3^-), phosphates (PO_4^{-3}) by colorimetry (La Motte, Model SMART2, USA), and BOD_5 by BOD System 6–FTC 90–r Refrigerated incubator (VELP- Scientifica, Spain) at the lab of the Training and Extension Center of the Litani River Authority in Kherbit Kanafar (Bekaa region). Statistical analyses of the results were conducted by paired t-test using PASW (SPSS) software version 18 (SPSS Inc., Chicago, IL).

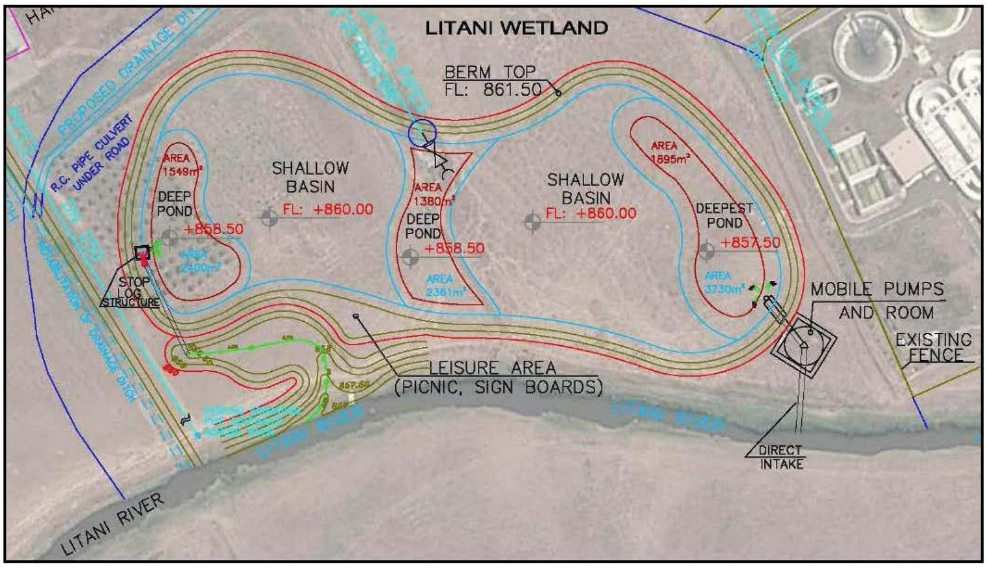


Figure 2: Overview of Litani river constructed wetland (LRBMS, [12]).

Results and Discussion

Comparative influent and effluent water quality summary

Table 1 shows the comparative mean values, standard deviation (SD) and percent decrease of the tested water quality parameters, in both the inflow and outflow water of the constructed wetland. Parameters such as temperature and pH remained approximately constant through the wetland system, while salinity-related parameters (salinity, EC and TDS) and sulfates showed a slight decrease in levels. All these quality parameters that were determined in both the inflow and outflow water are within the acceptable ranges for fresh water [13,14]. Additionally, nitrogen species reductions ranged from approximately 33% for nitrites to 93% for ammonia. Orthophosphate was further reduced by approximately 83%. Moreover, levels of dissolved oxygen increased approximately by 25%, while BOD levels were reduced by approximately 66%. And, with the exception to SO_4^{2-}, the t-test analysis revealed that these changes were significant at $p<0.05$.

Nitrogen

Figure 3a presents a time series plot of ammonia during the study period. The figure shows a strong seasonal trend in ammonia in the wetland inflow, with the highest inflow concentrations occurring in spring and summer. Ammonia in water is mostly due to the river basin wastewater discharged from the numerous dairy farms in addition to both treated and untreated sewage. Outflow concentrations remained relatively constant throughout the study, demonstrating ammonia concentration reductions ranging from approximately 80% to as high as 99%. In spite of the considerable uncertainty in the magnitude and rates of nitrogen cycling under the influences of many factors such as temperature, DO level, pH and other conditions of the constructed wetland, the likely removal mechanisms include plant uptake, nitrification and possible release of volatile ammonia gas to the atmospheres. And, as this data represent the first two growth seasons for the wetland, rates of plant uptake of ammonia are expected to be higher than that in a mature wetland. As the wetland matures and reaches equilibrium of annual growth and senescence of vegetation, the rate of ammonia removal would become less. Still, despite the high observed decrease in ammonia concentration, NH_3 levels in wetland outflow were generally above (mean of 0.95 mg NH_3-N/L) the water quality criteria of 0.05-0.35 mg NH_3-N/L for short-term exposures and 0.01-0.02 mg NH_3-N/L for long-term exposures that are recommended to protect sensitive aquatic animals [15-20]. More comprehensive investigations are necessary to better understand the dynamics of the nitrogen cycle in the constructed wetland understudy.

Figures 3b and 3c show the time series plots of nitrite and nitrate during the study period. These data show a similar seasonal pattern in inflow concentration of ammonia, with peaks in the spring/summer periods. With the exception of the last data point from July 2015, nitrite and nitrate outflow concentrations were relatively consistent and exhibiting greater removal in warmer summer months. This is expected given the strong temperature dependence of microbial denitrification which converts NO_2^-/ NO_3^- to NO_x and N_2 gases [1]. Given that large reductions in NH_3 were observed in the wetland, particularly in spring and summer months, it is expected that some of the NH_3 reduction was due to nitrification of NH_3 to NO_2^-/NO_3^-, meaning that the nitrification/denitrification processes that are common in constructed wetlands are most likely responsible for a reduction in NO_2^-/NO_3^- levels (~33% and ~62%, respectively) as presented in Table 1 [1]. In fact the mean total inorganic nitrogen (TIN, calculated as the sum of NH_3, NO_2^- and NO_3^-) reduction in the wetland was 84.6% (24.9 to 3.8 mg N/L)during the warm months (May–September) and 62.3% (6.7 to 2.5 mg N/L) during the cooler months (December–April).Furthermore, the levels of NO_2^- (0.83 ± 1.42 mg/L and 0.56 ± 1.43 mg/L) and NO_3^- (5.33 ± 3.78 mg/L and 2.00 ± 1.38 mg/L) were found to be lower than the guideline levels for protecting sensitive aquatic animals during short-term exposures [15].

Orthophosphate

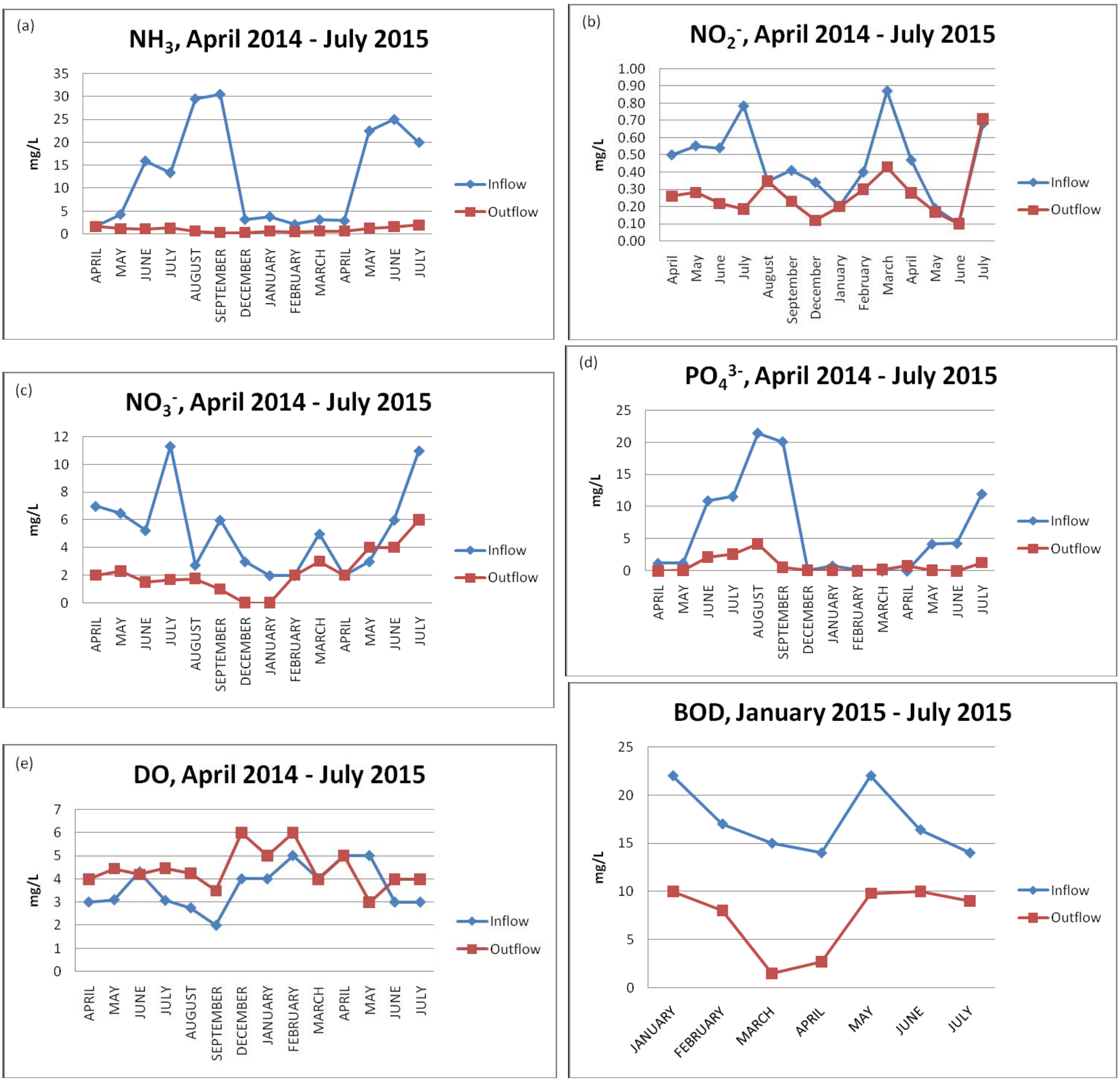
Figure 3d shows a time series plot of the orthophosphate levels. Similar to nitrogen, a clear seasonal trend is evident in wetland inflow, with dramatically higher orthophosphate levels in the inflow from the Litani River in the summer months. However, similar to NH_3, a fairly consistent outflow concentrations was observed at generally below 1.0 mg PO_4^{3-}–P/L except during the highest inflow conditions. While both inflow and outflow levels were far above the limit set by USEPA (0.1 mg/L) to prevent eutrophic conditions and algal growth, the average reduction over the course of the study was approximately 83%. The removal mechanism for orthophosphate is likely a combination of plant uptake as the wetland plants grew as well as sorption or other storage in wetland sediments [1]. As the wetland matures and plant growth and senescence reaches an equilibrium and phosphorus sorption sites in the new soil structure saturates, we expect this level of orthophosphate removal to decrease.

Dissolved oxygen and biochemical oxygen demand

Figures 3e and 3f show time series plots of DO and BOD, respectively. The data do not show clearly evident seasonal trends, but the wetland system increased DO (average of ~25%) and reduced BOD

Parameter	Number of Samples	Inflow	Outflow	Decrease (%)	*p* Value
T°*C*	24	21.58 ± 2.87	21.67 ± 2.86	-0.41	0.647
Salinity mg/L	24	387.79 ± 93.95	360.46 ± 72.03	7.04	0.014
NH_3 mg/L	24	14.14 ± 13.61	0.94 ± 0.74	93.30	0.000
EC µS/cm	24	785.25 ± 167.47	712.17 ± 144.58	9.30	0.000
DO mg/L	24	3.49 ± 0.96	4.37 ± 0.88	-25.28	0.001
NO_3^- mg/L	24	5.33 ± 3.78	2.00 ± 1.38	62.47	0.000
NO_2^- mg/L	24	0.83 ± 1.42	0.56 ± 1.43	33.17	0.014
pH	24	7.56 ± 0.27	7.65 ± 0.27	-1.10	0.176
PO_4^{3-} mg/L	24	9.02 ± 10.73	1.55 ± 1.80	82.82	0.001
SO_4^{2-} mg/L	24	46.29 ± 20.28	38.67 ± 12.93	16.46	0.056
TDS mg/L	24	550.38 ± 119.96	497.25 ± 98.01	9.65	0.000
BOD mg/L	6	28.50 ± 25.94	9.66 ±8.77	66.08	0.049

Table 1: Mean values of water quality parameters and variation percentages of the inflow and outflow of the constructed wetland of the Litani river.



Figures 3: (a-f) Monthly evolution of water quality parameters in the inflow and outflow of the constructed wetland of Litani river.

(average of ~66%). The mechanism for these was likely passive aeration due to the cascading inflow piping and wind mixing action on the open water deep zones. Growth of oxygen producing algae and submerged vegetation could also have contributed to these results.

Water quality improvement efficiency summary

To further the highlight the efficient performance of the constructed wetland, a comparative analysis between the projected and experimental levels of improvement obtained was conducted (Table 2). It is to be noted that the expected values were calculated based on the available data from similar constructed wetlands for river water treatment and the personal experience of the designer [12]. Strikingly higher removal efficiencies of nutrients are noted in the experimental levels. Similarly, higher improvement levels were also achieved with DO increase and BOD reduction. These analytical results further confirm the efficiency of the constructed wetland and the improvement of water quality.

Parameter	Experimental Level (%)	Expected Level (%)
NH_3	93.30	59.00
NO_3^-	62.47	51.00
PO_4^{3-}	82.82	35.00
BOD	66.08	35.50

Table 2: Experimental and expected levels of Litani river's wetland performance.

Still, as flow rates in the Litani River near the wetland were not measured during the study and detailed wetland inflow and outflow measurements were not taken, we cannot calculate mass-based removal performance of the system. However, the wetland inflow pump station

	Dry Season (May-Oct)		Wet Season (Nov-Apr)	
Parameter	Approximate Mass Removed (kg/d)	% of Litani River Mass Removed	Approximate Mass Removed (kg/d)	% of Litani River Mass Removed
PO_4^{3-}	26	1.7%	2	0.2%
TIN	53	1.8%	16	0.2%
NH_3	42	1.9%	12	0.2%
NO_3-	10	1.4%	4	0.1%

Table 3: Mass removal of select contaminants in the Litani river wetland.

was operated at approximately 2,500 m^3 per day during the course of the study. Likewise, the seasonal flow patterns in the Litani River can be estimated from monthly flow data [12]. Using these data we estimated the seasonal mass of various contaminants removed by wetland and the overall reduction in the contaminant load the River (Table 3).

It is important to note that due to seasonally warm temperatures (dry season), evapotranspiration in the wetland can cause a significant reduction (50% or more) in the water volume. This would cause an even greater mass of contaminants to be removed by the wetland than estimated in Table 3. As expected, due to a combination of higher removal rates in the dry season and lower contaminant concentrations in the Litani river during the wet season (potentially due to increased dilution from higher flows in the river), mass removals in the dry season are higher than in the wet season. The percentage of contaminants removed by the wetland appear small (e.g. <2% in dry season and ~0.2% in wet season), however the wetland system at 2.5 ha represents less than 0.0012% of the Litani river drainage area.

Conclusion

The substantial reduction in the levels of inorganic nitrogen species and PO_4^{3-} clearly demonstrate that the constructed wetland achieved high efficiencies of nutrients removal, BOD reduction, and DO enrichment resulting in improved river water quality. In addition, with the exception of NH_3, the mean values of these quality parameters are below the recommended levels for fresh surface water and aquatic life. Thus, the constructed wetland has contributed to reducing the level of pollution in the river. Such improvement in water quality can be at least partially attributed to the utilization of the planted macrophytes which have been shown by numerous studies to be highly efficient in the uptake of nutrients during their growth period, and to have a positive correlation between biomass production and nutrient uptake [20-24]. And, wetlands containing such types of plants remove larger quantities of nitrate than unplanted wetlands [25-28]. Contrary to terrestrial plants, a vast majority of aquatic plants are also shown to have a substantial ammonium preference which is consistent with the highest drop in the ammonia level (93.30%) in this study [2]. Additional nitrogen removal was likely due to the microbial-mediate nitrification/denitrification cycle in the wetland.

Hence, this study has illustrated that the constructed wetland of Litani River has a high removal capacity of nutrients and leads to DO enrichment and BOD reduction. This can shift the levels of pollution from high to light and can concurrently help in the restoration of the water quality and ecologic viability. As such, the use of constructed wetlands has promising potential and should be considered as a sustainable and cost effective-technology tool in the integrated management of this important water body. And, as a small-scale constructed wetland may not have a significant impact on water quality of large water body such as Qaraoun Lake, expansion of wetlands is preferable. Numerous small-scale implementations or large-scale constructed wetlandcould indeed have a meaningful and lasting impact, not only on improved water quality and aquatic ecosystem habitat, but also on the livelihood of surrounding community and socioeconomic development of marginalized communities of this region of the country. Additionally, such sustainable approaches remain of utmost importance in a country where water resources governance is burdened by socio-economic challenges and political commitment.

Moreover, further studies are needed to illustrate the role of the aquatic macrophytes (*Phragmites australis* and *Sparganium erectum)* in enhancing the treatment efficiency and its impact on other processes of the wetlands ecosystem. Finally, the possibility of optimizing different wetland services in one multipurpose wetland for water quality improvement, biodiversity and biomass production would also be interesting to explore.

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