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A Subsurface Horizontal Constructed Wetland Design Approach for Wastewater Treatment: Application in Ar Riyadh, Saudi Arabia

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Abstract: In this study, a decentralized new sewage water treatment system is suggested and designed in Ar Riyadh, Saudi Arabia, to safeguard the environment and reuse treated water for irrigation purposes. The system consists of a primary treatment (septic tank), a subsurface horizontal flow constructed wetland (HSSF-CW), and a storage ground tank. The research methodology employed in this study is (i) to define the wastewater characteristics, where air temperature in winter is 18.6 °C, the wastewater flow per person (q) is 150 L/d, demonstrating an inlet design discharge of 300 m^3/d, the influent pollutant concentrations for biological oxygen demand (BOD), total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and fecal coliforms (FC) are 350, 1000, 700, 50, 12 mg/L, and 10^6 CFU/100 mL, respectively; (ii) to design the septic tank based on a retention time of two days and a surfacing load rate of 1.5 m/d; (iii) the P-k-C* model was used to determine the HSSF-CW surface area based on reed beds of *Phragmites australis* (common reed) and *papyrus* plants, where the removal rate was constant at 20 °C for BOD, TP, and FC in the effluent concentrations not exceeding 20 mg/L, 3.0 mg/L, and 2000 CFU/100 mL in order to satisfy Saudi Arabia's wastewater reuse requirements; and (iv) to design the clean water tank for a hydraulic retention time of 10 h. The results demonstrate that the removing pollutants design area is 1872 m^2 divided into nine cells, each of width 8 m and length 26 m, with a hydraulic loading rate (LR) of 0.16 m/d and a hydraulic resident time (RT) of 1.1 d. The effluent pollutant concentrations for the BOD, FC, TN, and TP were 245 mg/L, 10^3 CFU/100 mL, 35, and 8.5 mg/L, respectively. The wastewater treatment system total removal efficiencies for BOD, TN, TP, and FC were estimated to be 91.8, 70, 57, and 98.5%, respectively. Design curves were developed to ease the design steps. The HSSF-CW is a green wastewater treatment technology that offers greatly decreased investment costs, and service particularly for small-scale applications up to 6000 persons.

Keywords: constructed wetlands; pollutant's removal; hydraulic loading rate; reed beds; irrigation water

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1. Introduction

The choice of wastewater treatment for both point and nonpoint source contamination has become a key priority for concerned governments all over the world. So, while choosing a suitable environmental cleanup technique, the cost of treatment is frequently used [1–4]. Constructed wetlands (CWs) are water-quality-improvement technologies that leverage natural processes involving microbial assemblages, wetland vegetation, and soils. However, there are numerous issues with the practical application of constructed wetland, such as their susceptibility to temperature and climatic changes, their substrates' ease of saturation and plugging, their vulnerability to plant species, the fact that they frequently occupy large areas, and others [5–7].

CWs can treat industrial wastewater such as wastewater from petroleum refineries, municipal, farm wastewater, stormwater, landfill leachates, textile wastewater, mining drainage, and the other contaminated wastewater [8]. In CWs, a variety of remediation techniques were applied, such as biodegradation, phytoremediation, and natural attenuation [7,9,10]. Also, CWs frequently experience physical, chemical, and biological processes such as sedimentation and filtration, precipitation, adsorption, plant assimilation and biodegradation [11–13]. Due to their ease of construction, low cost, and simple operation, CWs have shown to be a viable substitute for maintaining proper pollutant removal efficiency in wastewater treatment for small towns [14,15].

CWs are divided into free water surface (FWS) and subsurface flow (SSF) hydraulic systems. [1,16,17]. FWS and SSF CWs have a shallow water depth ranging from 0.5 to 1.0 m. Aquatic plants that are emergent, submerged, or float are the main types of vegetation that are planted in FWS flow wetlands. The SSF are divided into a vertical subsurface flow constructed wetlands (VSF-CW), horizontal subsurface flow constructed wetlands (HSSF-CW), and hybrid systems that are mostly planted with emergent aquatic plants [18]. In HSSF-CW, excavated ditches are filled with a porous medium, frequently sand, gravel, or cobbles, and the water level is slightly below the top of the porous material [19]. The most popular aquatic species utilized in HSSF-CW are *Bulrush*, *Cattail* (*Typha*), and *Phragmites* (reeds), which have root infiltrations of roughly 0.3 and 0.6 m, respectively. The choice of HSSF-CW site is influenced by the topography of the land, the soil's permeability, the necessity for bed sealing, and the climate conditions. The rate of biodegradation in the CWs often increases as the temperature rises, which has an impact on the size of the HSSF-CW [14]. The assumptions of plug flow, P-k-C* model, and uniformly distributed flow across the wetland are commonly used in HSSF-CW to calculate removal rates for BOD and TN [14]. However, due to stagnate flow zones, the large wetland rectangularity ratio, short water circulation, hydraulic loading rate, varied flow velocity, and other factors, the plug flow assumption of inlet flow in the k-C* model does not occur in some cases, and thus the model fails to present the constructed wetland treatment process. In order to satisfy the plug flow characteristics, the relaxed tanks-in-series model (P-k-C*) was recently established and adopted to stormwater CWs practices [3,5]. Wetland performance is influenced by a number of variables, including temperature, hydraulic retention time, surface loading rate, bed substrate, wetland hydrology, and microbe concentration [20,21]. Different macrophytes have been employed in planted CWs to treat municipal wastewater in a horizontal and vertical flow constructed wetlands, including *Canna*, *Cyperus papyrus*, *Phragmites australis*, *Commelina benghalensis*, *Eichhornia crassipes*, *Populus trichocarpa*, *Typha angustifolia*, *Hydrilla verticillata*, and *Salvinia natans* [22,23]. In order to treat anaerobic reactor brewery effluent at various hydraulic residence times, Alayu and Leta [24] investigated the performance of a two-stage horizontal subsurface flow constructed wetland planted with *Cyperus Alternifolius* and *Typha latifolia*. They found that increasing the hydraulic retention time from 1 to 5 days enhanced the total elimination of orthophosphate and phosphorus from 16.8 to 75.4% and 18.4 to 76.8%, respectively, while decreasing the influent mass loading rate from 5 to 0.6 and 3.8 to 0.4 $g/m^2/d$.

Rana and Maiti [25] found that treating municipal wastewater with CW planted with Colocasia esculenta and *T. latifolia* could reduce several significant parameters, including chemical oxygen demand (COD) by 71%, total Kjeldahl nitrogen by 64–72%, and some heavy metals. Using *Typha aungstifolia* and Acorus calamus in CW, Bhagwat et al. [26] treated landfill leachates in a different study. Using biochar with lab-scale CW, Sudarsan and Srihari [27] were able to remove color, chromium, and biochemical contaminants with 60 to 70% removal efficiency. According to Paruch et al. [28], HSSF-CW may remove up to 90% of the phosphate from home wastewater. The CW gravel bed alone has the capacity to reduce wastewater's phosphate concentration by 20–30% [29]. In 2000, Manios et al. [30] investigated how temperature and precipitation affect reed bed performance. Local weather data for temperature and rainfall in England were connected with data on ammonia-nitrogen (NH_3-N) removal, total suspended solids (TSS), and 5-day biochemical oxygen demand (BOD) from 16 distinct reed beds. The methods of linear regression and curvilinear regression were employed to determine the presence of any correlation. Three steps were involved in the data analysis. First, a linear equation was created from the equation used to construct the beds in order to compare the monthly average ambient temperature and the BOD removal values. Data from every reed bed were used to evaluate the altered equation, However, the association was weak. Second, curvilinear regression was used to compare the monthly average temperature and rainfall data with the percent removal of BOD, TSS, and NH_3–N. There was no discernible link with this method. In the end, performance data with daily rainfall for two of the reed beds were examined using curvilinear regression. They concluded that this method was unable to demonstrate any connection between rainfall or temperature and the effectiveness of the beds.

In Saudi Arabia, wastewater treatment is a strategic key to be an alternative water source to ease the country's water shortages in agricultural and industrial practices. Rainfall, which is not a stable source of water, ranges from 50 mm/year in the greatest parts of the country to 500 mm/year in the southwest. The major obstacles in the wastewater treatment sector were a deficiency of encouragement and low quality of wastewater treatment. Water use in 2018 was over 70% greater than it was in 2007, at around 3360 million m^3. Similarly, total municipal wastewater has gradually increased and is projected to reach 5.090 km^3 between 2025 and 2050. Between 2007 and 2018, treated water increased by approximately 200%, and between 2025 and 2050, it is predicted to increase by 4% yearly [18,30,31]. Water is precious and important in the Arabian Peninsula, and Saudi Arabia has changed its land use dramatically in recent decades. Rapid economic expansion, unprecedented levels of population increase, and urbanization have all contributed to these changes [11,31,32]. According to Haipeng et al. [33], shallow groundwater in wetlands is highly susceptible to pollution by long-term residential sewage treatment. This study offered the following recommendations for the creation and management of artificial wetlands: To lessen the risk to groundwater, an anti-seepage layer should be built, and management should be improved. Many of the Saudi Arabia natural ecosystems have been severely affected and degraded as a result of these changes, creating a challenge to use of natural resources in a sustainable manner. There is currently no quantifiable baseline against which future change can be measured and there is no general information available about Saudi Arabia's wetland resources, trends, or biodiversity. Due to the low population density in the rural areas of Ar Riyadh, Saudi Arabia, the cost of conventional wastewater treatment was prohibitive. As a result, it was necessary to develop a green technology and low-cost decentralized new sewage water treatment system in order to protect the environment and use the treated water for irrigation.

The aim of the present study is to propose, design, develop, and construct a wastewater treatment system in small-scale population arid regions up to 6000 persons. The system includes a septic tank, an intake well, a HSSF-CW, water control device, and ground-water tank so that wastewater can be reused for irrigation and the environment is protected from polluted wastewater in the in rural parts of Ar Riyadh (arid region), Saudi Arabia. To achieve these goals, (1) the site parameters were researched, and water quality characterization was determined in order to comply with Saudi Arabia's wastewater reuse rules, (2) the primary treatment unit (septic tank) was developed, and (3) the SHCW and ground tank was designed. The system is designed using the following input data: (i) to serve 2000 persons, wastewater flow per person (q) is 150 L/d, demonstrating inlet design discharge of 300 m^3/d, air temperature in winter is 18.6 °C, the influent pollutant concentration for biological oxygen demand (BOD), total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP) and fecal coliforms (FC) are 350, 1000, 700, 50, 12 mg/L, and 10^6 CFU/100 mL, respectively; (ii) the septic tank is designed for a retaining time of 2 days and a surfacing load rate equal to 1.5 m/d, effluent after primary sedimentation tank the BOD concentration is 245 mg/L; (iii) in order to meet Saudi Arabia's wastewater reuse criteria, the P-k-C* model was utilized to calculate the wetland surface area based on background pollutant concentration, removal rate constant at 20 °C for BOD, TP, and FC, effluent concentrations not exceeding 20 mg/L, 3.0 mg/L, and 2000 CFU/100 mL, respectively; (iv) and the clean water is kept in a storage ground tank with a hydraulic retention duration of 10 h.

2. Materials and Methods

2.1. Description of the Study Area

The Ar Riyadh region is the capital of Saudi Arabia; it is situated in the geographic center of the nation (Figure 1). Approximately 404,240 km^2, or 19.5% of the Kingdom's total area, is made up of the Riyadh region. Approximately one-third of the Kingdom of Saudi Arabia's land area is represented by this region, which comes in second place after the Eastern Province. It is the most populated city in the Kingdom, with 8.5 million people living there. A number of reverse osmosis facilities with a combined daily capacity of roughly 192,000 m^3 provide fresh water to the city [34,35]. Ar Riyadh is an arid region; the climate data are obtained from the Ar Riyadh station, a latitude of 24.71° N, a longitude of 46.7° E, and an altitude of 612 m. Figure 2 shows the average monthly temperature and details on the location of Ar Riyadh's rainfall from 1991 to 2018. The average minimum and maximum temperatures are 18.6 and 32.7 °C, respectively (Figure 2a); in addition, the relative humidity is 30% and wind speed of 42 Km/d, and annual rainfall of 98.2 mm (Figure 2b).

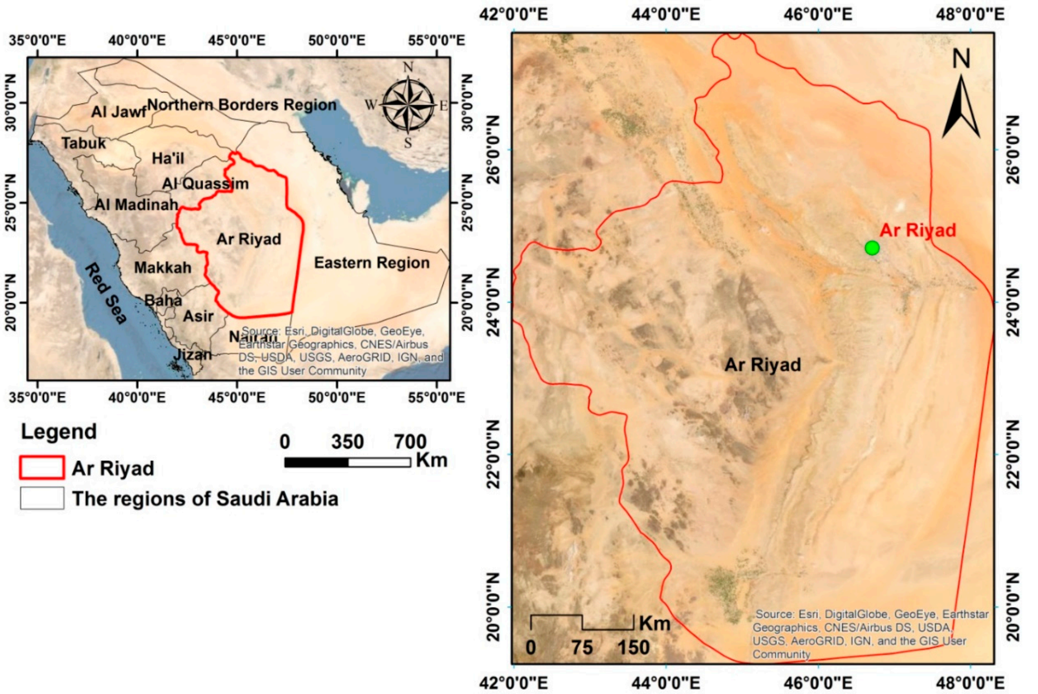
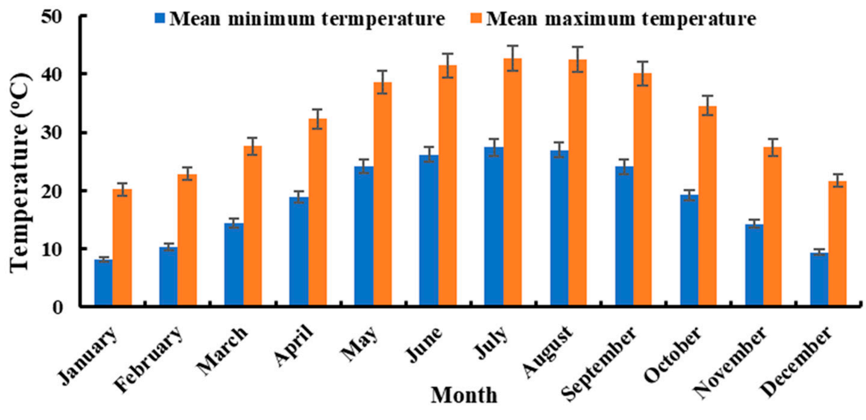


Figure 1. Map of the research area: Saudi Arabia's—Ar Riyadh.

2.2. Wastewater Treatment System Description

The suggested wastewater treatment system consists of a primary treatment septic tank, an inflow well, a HSSF-CW, a water control device, and a ground-based tank for storing treated wastewater. The typical household size in the study region's villages is five persons, and there are on average 2000 people living there. About 40 dwellings are served by the village's area, indicating a design discharge Q of 300 m^3/d. In addition, the TSS, COD, BOD, TN, TP, and FC influent pollutant concentration for the raw wastewater are 1000, 700, 350, 50, and 12 mg/L and 10^6 CFU/100 mL, respectively. A septic tank receives raw sewage, settles the particles (sludge), and then allows the remaining liquid to seep into the surrounding soil via a soakaway. Scum on the tank's surface is also kept from escaping. The sludge and scum are digested by microorganisms in the tank's anaerobic atmosphere. The system is divided into three stages: tank supply, tank itself and soak field. Septic tanks can retain sewage (greywater from washing machines and domestic garbage, and blackwater from latrines), but not rainwater. Microbial action reduces the volume of sludge, but it still needs to be emptied on a regular basis. Septic tanks are used to treat wastewater in part. Secondary treatment is provided by the soak field in the form of subsurface infiltration. The retention volume of treated wastewater and the sludge storage volume make up the septic tank's volume. One to three days is the range of the retention time (RT). Consequently, select a long retention duration of three days (operating costs) to lower cleaning frequency. On the other hand, select a short retention period (one day) to minimize tank size and initial cost. Larger tanks allow sewage to decompose for longer periods of time, reducing the pressure on the drainage system. Because of the higher turbulence in smaller tanks (under 6 m^3), longer retention durations are required (2 or 3 days). For tanks receiving solely water cycle (WC) waste, the rate of sludge and scum accumulation is about 25 L per person per year, and for tanks receiving both WC waste and sludge, the rate is about 40 L/person/year. Sludge takes up 2/3 of storage space, whereas scum takes up 1/3 [36]. In warm weather, the sludge digestion factor is equal to one. Table 1 lists the intended septic tank design data and Figure 3 illustrates the septic tanks' cross-section elevation view.



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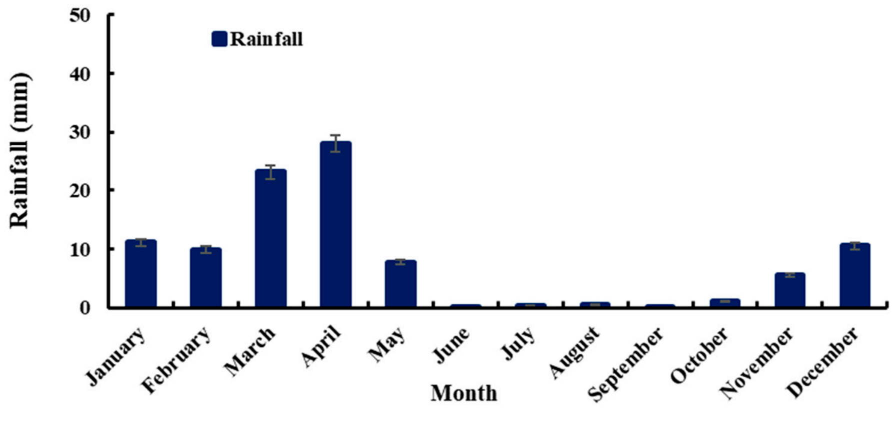


(*b*)

Figure 2. (**a**) Mean maximum and minimum temperatures, and (**b**) Rainfalls for Ar Riyadh climate station for the period from 1991 to 2021 [34].

Table 1. Septic tank design criteria, dimensions, and the influent and effluent pollutants concentrations.

Parameter	Design Values	Design Criteria [36]
Inlet raw water discharge (Q) (m^3/d)	300	-
Hydraulic residence time (RT) (day)	2	2–4
Sedimentation volume (VT) (m^3) = Q × HRT	600	
Tank sedimentation water depth (d) (m)	3	5–8
Tank surface area (SA) = VT/d (m^2)	200	
Number of tanks	2	
Dimensions of sedimentation tank:		
Length (L) m,	10 m	
Width (B) m,	10 m	
Water depth (d) m	3.0 m	
Length to width ratio	1:1	
Tank sludge zone dimensions:		
Rate of sludge and scum accumulation (L/year/capita)	40	
Emptying the tank every two years in a warm climate (day)	2	
Sludge volume, (m^3)	160	
Number of tanks	2	
Length (L) m,	10	
Width (B) m,	10	
Sludge depth (m)	0.8	
Inlet raw wastewater BOD (mg/L)	350	
Predictable effluent after primary sedimentation for BOD (mg/L)	245	Removal efficiency = 30%
Inlet raw wastewater COD (Mg/L)	700	
Expected effluent after primary treatment for COD (mg/L)	490	Removal efficiency = 30%
Inlet raw wastewater TN (mg/L)	50	
Predictable effluent after primary sedimentation for TN (mg/L)	35	Removal efficiency = 30%
Inlet raw wastewater TP (mg/L)	12	
Predictable effluent after primary sedimentation for TP (mg/L)	8.4	Removal efficiency = 30%
Inlet raw wastewater TSS (mg/L)	1000	
Predictable effluent after primary sedimentation for TSS (mg/L)	400	Removal efficiency = 60%
Inlet raw wastewater FC CFU/100 mL	10^6	
Predictable effluent after primary sedimentation for FC CFU/100 mL	10^5	Removal efficiency = 10%

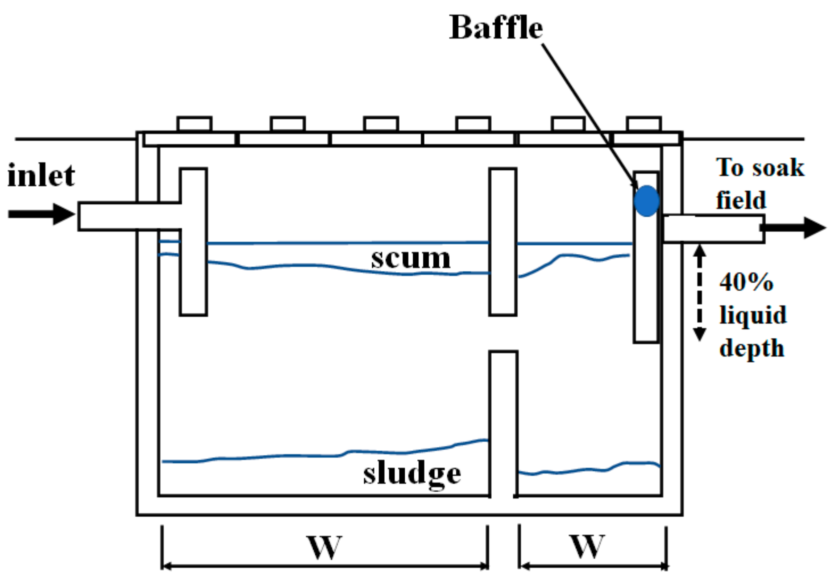


Figure 3. Septic tank cross-section elevation.

2.3. Design Procedure of the HSSF-CW

The existing design (output flow from the septic tank) will address the pollutant wastewater characteristics of BOD, COD, TN, TP, TSS, and FC with concentrations of 300, 490, 35, 8.4, 400 mg/L, and 105 CFU/100 mL, respectively. In a healthy wetland system, the effluent concentration needs to be lower than the limits considered acceptable by [37–39]. The permissible effluent levels are 20 mg/L, 3 mg/L, and 2000 CFU/100 mL for BOD, TP, and FC, respectively. The primary issue in the HSSF-CW is the clogging of the media because of the ongoing reduction in the media cross-section; as a result, the flow might be described as mixed flow. The first order P-k-C* model or relaxed tanks in a series created by [14] was used to determine the surface area of the BOD, TP, and FC as a result:

$$\frac{C_{in} - C^*}{C_{out} - C^*} = \left(1 + \frac{K_T}{LR}\right)^{-N} \tag{1}$$

where C_{in} is the pollutant input concentration of BOD and TP in mg/L, and FC in CFU/100 mL; C* is the background pollutant concentration; C_{out} is the pollutant output concentration for BOD and TP in mg/L, and FC in CFU/100 mL; N is the number of mixing cells of equal size; K_T is the response rate constant in (m/d); and LR is the hydraulic loading rate in (m/d) given as

$$LR = \frac{Q}{A} \tag{2}$$

$$RT = \frac{V}{Q} = \frac{Ayn}{Q} = \frac{yn}{LR} \tag{3}$$

where Q is the design flow rate (m^3/d); A is the surface area of CW (m^2); V is the CW volume (m^3); y is the flow depth (m); and n is the fractional porosity. The K_T has a particular value to adapt to the climatic conditions in the dry and semiarid regions [40].

The BOD, TP, and FC background pollutant concentrations are assumed to be 1 mg/L, 0.119 mg/L, and 4 CFU/100 mL, respectively, according to similar study carried out by [40]. Additionally, K_T values for BOD, TP, and FC assumed to be 0.662, 0.16, and 1.492 m/d, respectively [40].

2.4. Pollutants Removal Efficiency

The following is the HSSF-CW treatment performance (η):

$$\eta = \frac{C_{in} - C_{out}}{C_{in}} \tag{4}$$

where C_{in} is the concentration of pollutants in the inlet flow and C_{out} is the concentration of pollutants in the outflow flow.

Sizing a New HSSF-CW

Table 2 summarizes the model input data as the effluent pollutant's concentrations are in the range of allowable Saudi Arabia regulations for treated wastewater [38,40]. The methodology to design a new HSSF-CW is as follows:

1. Define the wastewater characteristics such as air temperature in the winter season is 18.6 °C and in the summer season is 32.7 °C, the wastewater flow per person (q) is 150 L/d, demonstrating an inlet design discharge of 300 m^3/d, the influent pollutants concentration for biological oxygen demand (BOD), total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and fecal coliforms (FC) are 350, 1000, 700, 50, 12 mg/L, and 10^6 CFU/100 mL, respectively.
2. Design the septic tank based on a retention time of two days and a surfacing load rate of 1.5 m/d,
3. Design the HSSF-CW utilizing common reed (*Phragmites australis*) and *papyrus* plant beds and gravel with a size range of 40 to 80 mm is used in the entrance zone,

16 to 32 mm in the treatment zone, and 40 to 80 mm in the outflow zone to prevent HSSF-CW clogging. In addition, an anti-seepage layer PVC membrane lining was constructed to prevent wastewater seepage and safeguard the groundwater aquifer.

4. Using an Excel spreadsheet to solve Equation (1) yields the surface area of the HSSF-CW for BOD, TP, and FC in.
5. Using Equation (2), calculate LR for BOD, TP, and FC as well as the related hydraulic residence time (RT), assuming that the porosity n = 0.3 and y = 0.6 m for the water depth.
6. Determine L and W for a length to width (L/W) ratio of 2.5, and then divide the length into cells with a width of 8.0 m to determine the number of cells.

Table 2. Model input data for HSSF-CW sizing.

Parameter	Value
Population	2000 Capita
Unit wastewater flow	0.15 m^3/capita/d
Design discharge	300 m^3/d
Design average winter air temperature	18.6 °C
Design average summer air temperature	32.7 °C
Design influent (BOD) after septic tank	245 mg/L
Water density ρ = 1000 kg/m^3	1000 kg/m^3
Number of tanks (N)	3
C* for the BOD,	1 mg/L
C* for TP,	0.119 mg/L
C* for FC	4 CFU/100 mL
K_T for BOD	0.662 m/d
K_T for TP	0.16 m/d
K_T for FC	1.492 m/d
Design influent Fecal coliforms (FC)	10^5 CFU/100 mL
Influent total Nitrogen (TN) after sedimentation Septic tank	35 mg/L
Inlet total Phosphorus (TP) post Septic tanks	7.0 mg/L
Influent (TSS) after Septic tanks	400 mg/L
Water depth (y)	0.6 m
Porosity medium for gravelly sand (φ)	0.3
Effluent (BOD)	20 mg/L
Effluent FC	2000 CFU/100 mL
Effluent (TP)	3 mg/L

C*, background concentrations; and K_T, the reaction rate constant.

3. Results and Discussion

3.1. Design of Primary Treatment (Septic Tank) and the New HSSF-CW

The design volume of the Septic tank was 93.75 m^3. Figure 4 depicts the septic tank's dimensions, and Table 1 provides a summary of the pollutant concentrations at the input and exit.

Based on the model input data used to size the HSSF-CW (Table 2), the area of 1824 m^2 is obtained for three tanks using Equation (1). Equation (1) for three tanks yields an area of 1824 m^2. Equation (2) also shows that LR = 0.16 m/d and RT = 1.1 d. With a cell width (wi) of 8 m, L/W = 2.5, W = 26 m, and n = L/wi = 9 cells, the actual area is 1872 m^2 in this case. The output of the model is summarized in Table 3, and as a result, the removal efficiencies of BOD, TN, TP, and FC are 91.8, 70, 57, and 98.5%, respectively. To make the design process easier, design curves based on the population equivalent are created. The design curves for HSSF-CW are shown in Figure 4 as A: Population and HSSF-CW area relationship and B: Population, Cell Length and Cell Number relationship. Therefore, Tables 2 and 3's depiction of the relationship between the population and BOD, TP, and FC area for influent and effluent concentrations shows a linear equation for BOD as

$$y = 0.912x - 0.1923 \tag{5}$$

where y is the area of BOD in m^2 and x is the equivalent population. R^2 is the determination factor for Equation (5) equal to 1. In addition, for the HSSF-CW TP removal area,

$$y = 0.9469x + 0.1538 \quad (6)$$

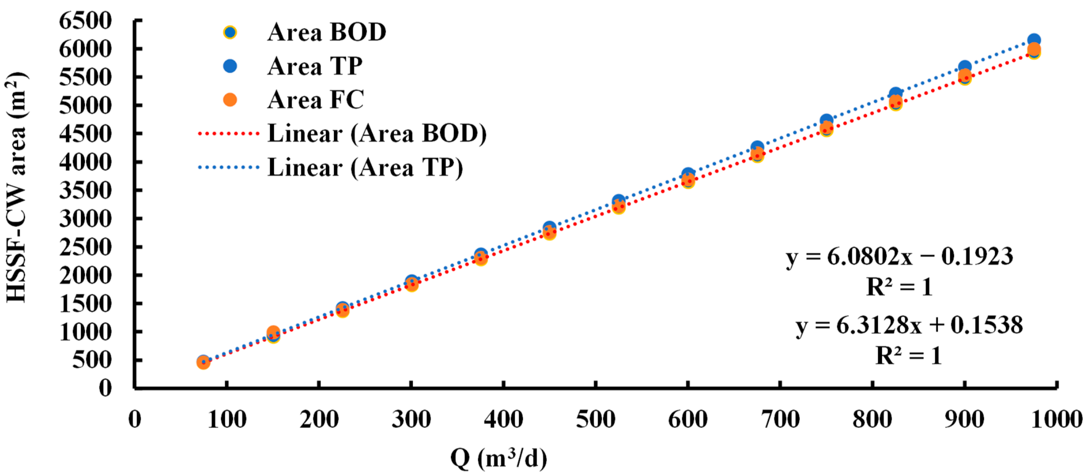
where y is the area of TP in m^2 and x is the equivalent population. R^2 is the determination factor for Equation (6) equal to 1. Figure 4b shows population equivalent, length of cell, and number of cell relationships, indicating population equivalent and length of cell power function as

$$y = 0.2373x^{0.6404} \quad (7)$$

where y is the length in m and x is the equivalent population. R^2 is the determination factor for Equation (7) equal to 0.9948. In addition, for a cell width wi = 8.0 m, population equivalent and number of cells indicating also, a power function as

$$y = 3.3055x^{0.3555} \quad (8)$$

where y is the number of cells (n) and x is the equivalent population. R^2 is the determination factor for Equation (8) equal to 0.9771.



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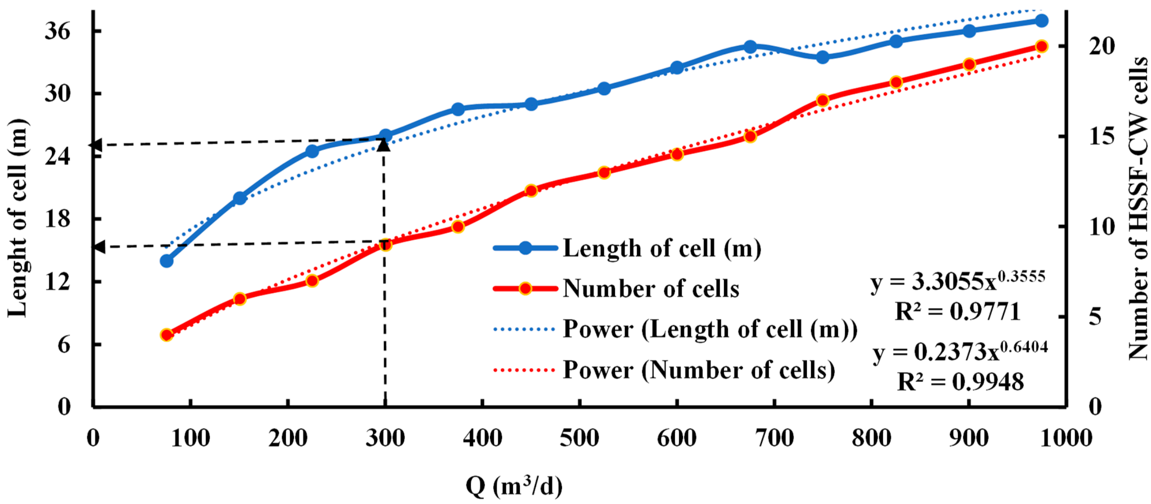


(**b**)

Figure 4. Design curves for HSSF-CW, (**a**) population and HSSF-CW area relationship, and (**b**) population, length of cell, and number of cells relationship.

Table 3. HSSF-CW model output show dimensions, RT, LR and the expected effluent pollutants removal efficiency.

Parameter	Value
Design residence time (RT) is for BOD	1.1 d
Design area (A)	1824 m^2
Design hydraulic load (LR)	0.16 m/d
Subsurface wetland length (L) = area (A)/width (W)	60.42 m
Length to width actual ratio (L: W)	2.5
Subsurface wetland total width (W) = area (A)/length (L)	26 m
L	72 m
Width of cell (wi)	8 m
Number of cells (n) = L/wi	9
Actual area	1872 m^2
BOD removal efficiency	92%
TN removal efficiency	70%
TP removal efficiency	57%
FC removal efficiency	98.5%

3.2. Methodology Validation with Existing Data

The area of some HSSF-CW in India and Egypt was computed using the available database in terms of temperature, discharge, influent, and effluent BOD and FC. The SHCW area computed was a good match for the existing field wetland area [19,40,41], as shown in Table 4. The removal performance of the CWs is influenced by various factors such as the kind and design of CWs, aeration, substrate medium, vegetation, hydraulic parameters, and contaminant properties. It was discovered that the best hydraulic loading and retention rates for removing agricultural pollutants from wetlands were 10–30 cm/d and 6–8 days, respectively [42]. The understudied nature of the contaminants in agricultural wastewater, omitting nutrients and sediment, and the treatment of these pollutants using various nature-based methods, including wetlands, suggests that more research on this topic is necessary. Although wetlands are excellent at treating agricultural wastewater (removal > 90%), many questions remain after reading this article and additional research is needed to test the constructed wetland hybrid systems that have higher nitrogen treatment efficiency [43]. Moreover, a CW setup with a 15% dose of Lantana weed biochar (BC) demonstrated the highest removal of PO_4^{-3} (79.06%), NH_4-N (78.79%), SO_4^{-2} (67.93%), and NO_3-N (77.42%) from wastewater, according to Parihar et al. [44].

Table 4. Wetlands with horizontal subsurface flow that are present and expected in semi-arid areas.

System Name	Temperature (°C)	Reed Beds	Discharge (m^3/d)	Pollutant's Concentrations		Wetland Surface Area Existing A (m^2)
				Influent (mg/L)	Effluent (mg/L)	
Current HSSF-CW	18.6–32.7	*Phragmites australis* and *Papyrus*	300	BOD = 245 TP = 7 FC = 105 (CFU/100 mL)	BOD = 20 TP = 3 FC = 1500 (CFU/100 mL)	1874
Agaa wastewater treatment, Delta of Egypt [19]	18	*Phragmites australis* and *Papyrus*	1500	BOD = 250	BOD = 60	1840
Lake Manzala reciprocating wetland system, Egypt [39]	14.1–27.8	Unplanted	250	BOD = 25 FC = 3342 (CFU/100 mL)	BOD = 4 FC = 153 (CFU/100 mL)	324
Campus of Indira Gandhi National Tribal University (IGNTU), Amarkantak, MP, India [3]	18.2–31.6	*T. latifolia*	6	BOD = 375	BOD = 147	35

3.3. Vegetation and Type of Substrate

The results show that the effluent pollutants concentrations for the BOD, FC, TN, and TP were 245 mg/L, 10^3 CFU/100 mL, 35, and 8.5 mg/L, respectively. In addition, the total removal efficiencies for BOD, TN, TP, and FC were 91.8%, 70%, 57%, and 98.5%, respectively. In the subsurface flow wetland, primary sedimentation plays a significant role in reducing TSS to prevent the wetland body from becoming blocked. Figure 5c shows the reed bed details for the proposed HSSF-CW. Therefore, the body of HSSF-CW, which is crucial to the treatment process, is built using substrates [45]. According to [46,47], CWs simultaneously exhibit the impacts of substrates (physical filtration and interception, adsorption, and ion exchanges), plants, and microorganisms on the remediation of pollution. The various elements in CWs, including pH, salinity, dissolved oxygen, hydroperiod, and plant development, are influenced by the types and arrangements of substrates. The roles of substrates in CWs are primarily focused on the aspects of (i) filtration and interception for larger particles and contaminants, (ii) adsorption for various contaminants, (iii) electron donor function for metabolism and denitrification, (iv) carrier function for microorganisms, and (v) physical support for wetland plants. These activities determine how quickly pollutants are removed in the CWs and are intricately related. Vegetation in the CWs is the factory of treatment; cattails and bulrushes are the most prevalent emergent plant species found in surface flow wetlands. Although reeds are the most frequent plant species found in sub-surface flow wetlands, other species like cattails, bulrushes, reed canary grass (Pharis arundinacea), and managrass (Glyceria maxima) have also been used [22,23]. According to Fernando et al.'s [48] study, the elimination efficiency of BOD, COD, total coliforms, fecal coliforms, ammonia nitrogen and phosphates was at 80.69%, 69.87%, 98.08%, 95.61%, 69.69% and 50.0% for *Cyperus papyrus* elimination and 75.39%, 64.78%, 96.02%, 93.74%, 70.70% and 49.38% for *Phragmites australis*, respectively. While *Phragmites australis* was more effective at removing suspended particles, *Cyperus papyrus* was marginally more effective at removing these parameters. Due to its high elimination efficiency, these findings suggest that *Cyperus papyrus* may be a macrophyte species that is best suited for wetlands that are constructed on a vast scale. Because of the likely predominance of anaerobic conditions in some system areas, the system failed to remove nitrates.

3.4. HSSF-CW Cost Estimation

The HSSF-CW treatment system is depicted in Figure 5 in the following ways: (a) section elevation; (b) plan view; and (c) reed bed details. The principal sedimentation tank's (septic tank) measurements are 4 m long, 4 m wide, and 3 m deep, which corresponds to a cost of USD 9000 dollars. Phragmites australis (common reed) and papyrus plants are found in the HSSF-CW reed bed, which is seen in Figure 5c. The water depth is 0.6 m, and the root density is 25 rods per square m. The reed bed media consists of 40–80 mm gravel in the inlet zone extends to a length of 4.0 m, 16–32 mm gravel in zone 2 extends to a length of 6.0 m, treatment zone (zone 2) includes 8–12 mm gravel of 12 m length, and outlet zone contains 40–80 mm gravel extends to 4.0 m length. The gravel media are laid on a plain concrete surface of 10 cm thickness to prevent seepage and the cells are divided by a brick wall of thickness of 0.25 m and 0.75 m in height. From the wetland's inlet to its exit, a slope of 1° was maintained to sustain a gravity flow. The total cost of cell construction and the inlet distribution channel of width 2.0 m and outlet distribution channel width of 4.0 m (for solar disinfection) including excavation, brick wall, and plain concrete are USD 38,000. Control valves and PVC pipes of USD 1000. In addition, the cost of transplanting the reeds into cells is 7000$. The treated wastewater is stored in an underground tank. It is designed based on a 10 h retention time and a HSSF-CW designed discharge of 300 m^3/d indicating a storage volume of 125 m^3. Therefore, the tank dimensions are 3 m water depth and 6.5 m × 6.5 m area. The mark cost of the reinforced concrete underground tank is USD 18,000. Therefore, the total cost of the construction of the HSSF-CW is USD 63,000, or 33.65 USD/m^2. On the other hand, the cost per capita is USD 31.5. Operation and maintenance (O&M) as an important issue to achieve high efficiency of the WC pollutants removal and to protect the shallow groundwater from pollution on the long run due to water leakage from wetlands [36,43]. Good and regular operation and maintenance of the wetland treatment unit helps to achieve the required design removal efficiency of pollutants. Therefore, Kadlec and Wallace [16] offer thorough explanations and checklists for each of the aforementioned topics. The wetland treatment unit needs to be properly operated and maintained in order to remove pollutants at the required design removal efficiency. In order to achieve this, it is necessary to check the inlet and outlet works, pumps, syphons, grids, remove collected solids and CW cells for leaks and overflow in addition to checking them daily for poor drainage and ponding. Additionally, there must be some weekly checks for the shift flow to another CW cell (dry–wet cycle), flow measuring equipment, water quality tests and analysis, performance monitoring, and disposal of accumulated solid waste and/or harvested vegetation. Finally, the monthly inspections include fixing CW levees, levelling sloped areas between CW cells, checking retaining walls for stability or movement/settlement, inspecting the integrity of roads, repairing local gullies and erosion, controlling rodents, and checking the function of rainwater runoff drainage works.

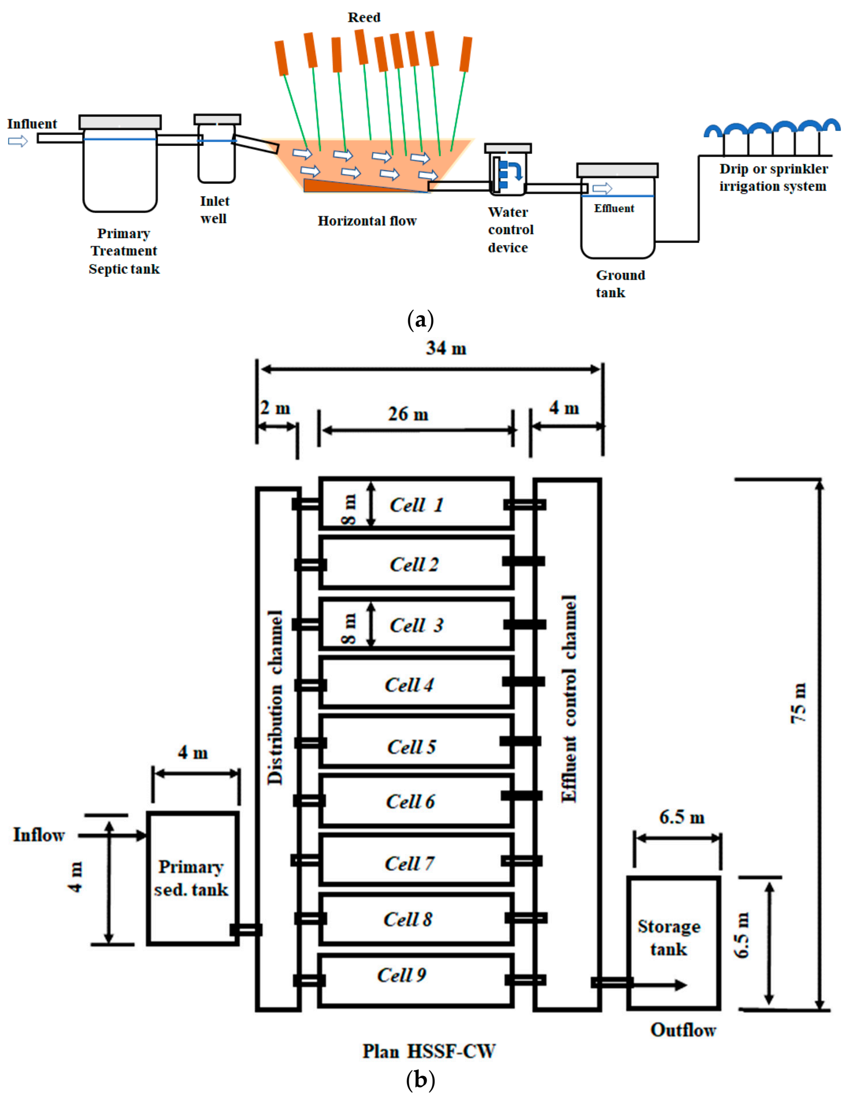
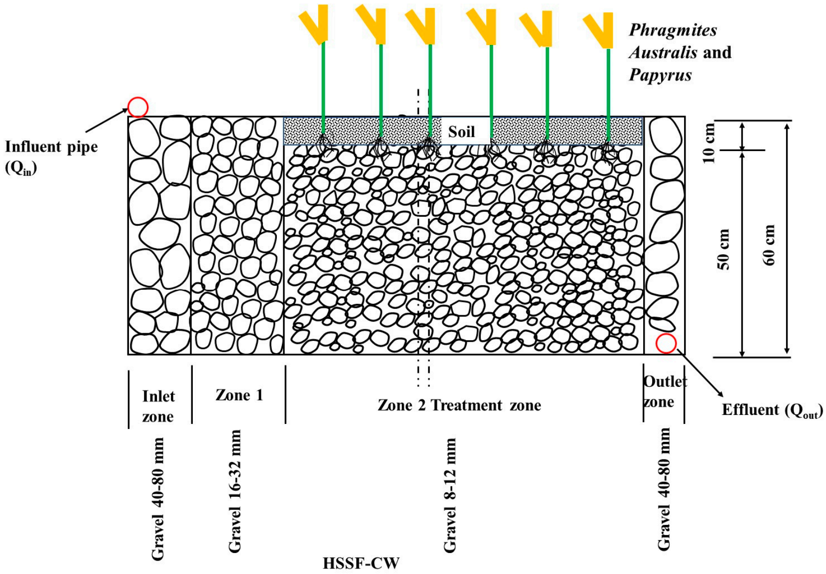


Figure 5. *Cont.*



(**c**)

Figure 5. HSSF-CW treatment system, (**a**) section elevation, (**b**) plan view, and (**c**) HSSF-CW reed bed details.

According to [14], the frequency time-schedule of various O&M activities is to check inlet and outlet works every 1 to 2 days, as well as pumps and siphons, clean grids, remove collected solids, CW cells for poor drainage or ponding, CW cells for leaks and overflow, and shift flow to other CW cell (dry–wet cycle). The works that need weekly maintenance are shift flow to other CW cell (dry–wet cycle), flow measuring devices, water quality sampling and analyses, performance monitoring, and dispose of accumulated solid wastes and/or harvested vegetation. In addition, works need monthly maintenance such as check/repair CW levees, repair erosion of sloping areas between CW cells, check retaining walls for stability or movement/settlement, check access road integrity and repair local erosion/gullies, check and control mosquito breeding and rodents and check function of rainwater runoff drainage works.

4. Conclusions

For the rural areas of Ar Riyadh, Saudi Arabia, a new eco-friendly decentralized wastewater treatment system with a capacity to service 2000 people and a discharge of 300 m^3/d was proposed and designed. The primary treatment unit (septic tank), inflow well, subsurface horizontal flow constructed wetland (HSSF-CW), water control device, and storage water ground tank make up the wastewater treatment system. BOD, FC, TN, and TP concentrations of influence pollutants are 350 mg/L, 10^6 CFU/100 mL, 50 mg/L, and 12 mg/L, respectively while entering the primary sedimentation unit. In the summer and winter, the average air temperature was 32.7 °C and 18.6 °C, respectively. The hydraulic design theory was used to size the HSSF-CW, and reed beds of *Phragmites australis* (common reed) and *papyrus* plants were used in the first order P-k-C* model. To make the design process easier, design curves were developed. This study demonstrates that the removal efficiencies for BOD, TN, TP, and FC were estimated to be 91.8, 70, 57, and 98.5%, respectively. The proposed wastewater treatment system may be a convenient, decentralized, low-cost, and energy-efficient way to treat urban wastewater sources, especially for small-scale applications involving up to 6000 people. It is advised to conduct small-scale pilot trials for the suggested wastewater treatment system before implementation to confirm its efficacy.

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