Chapter

Designing River Diversion Constructed Wetland for Water Quality Improvement

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Abstract

Constructed wetlands are recognized as viable potential technology for reducing pollution load and improving quality of water and wastewater. The use of river diversion wetlands is gaining place for improving quality of river and stream water. However, the design criterion for this category of wetlands has not been fully established, and there is a need to optimize existing approach to enhance operational performance. This chapter presents a step-by-step approach for the design of a typical river diversion constructed wetland intended to remove some pollutants and improve river water quality. The approach focused mainly on water quality objective and outlined simple criteria, guidelines, and model equations for the design procedure of a new river diversion constructed wetland. The design of constructed wetlands is generally an iterative process based on empirical equations. Thus, this approach combines simple equations and procedure for estimating the amount of river water to be diverted for treatment so as to assist the designer in sizing the wetland system. The novel approach presented may be useful to wetland experts as some of the procedures presented are not popular in wetland studies. However, this may improve existing river diversion wetlands' design and development.

Keywords: design, river diversion, constructed wetland, water quality, rating curve, empirical equations

1. Introduction

There is no doubt that streams and rivers are important freshwater sources for man due to their influence on social and economic development of human societies. However, the quality of water in most streams and rivers is being threatened worldwide due to pollution connected with human activities [1]. The situation is worsened with increasing industrial pollution and use of fertilizers and other agrochemicals in agriculture, rapid urbanization, and continuing use of improper sanitation systems especially in developing countries [2]. Consequently, aquatic ecosystems that depend on water flows and seasonal changes within these water bodies are often threatened by poor water quality [3]. Water quality problems represent a major global challenge. For example, pollution of water bodies, especially nutrient loading, has worsened water quality in almost all rivers in Africa, Asia, and Latin

America. Therefore, future global water demands cannot be met unless concerted efforts are made to address water quality and wastewater management challenges.

Therefore, sustainable management of freshwater resources needs to aim at protecting or reducing pollution load of freshwater sources especially streams and rivers to avoid negative impacts on water quality and ecosystems. In this regard, constructed wetlands are recognized as potential technology for meeting water quality and other requirements of these important freshwater sources. The use of constructed wetlands for water quality improvement is increasing with new applications and technological possibilities [4, 5]. In recent times, the use of river diversion wetlands is gaining more relevance for improving quality of water in riverine systems [6–8]. The incorporation of constructed wetlands into management strategies for rivers and streams may help to reduce pollution load and enhance their absorbing capacity against impacts [9].

Despite the recognition of constructed wetlands as an effective and economical way of improving water quality, many of those in operation are underperforming. The shortcomings are partly attributed to limitation and inconsistencies of equations used in designing them [10–12]. Besides, most of the available design methods are either related to municipal wastewater treatment or stormwater quality improvement with the primary aim of peak flow retention to attenuate flood water which may lead to overestimation. For river diversion wetlands, specific design criteria have not been fully established, and further research is needed to optimize existing approach in order to enhance performance capabilities of these types of wetlands [7]. However, the design of constructed wetlands is generally based on empirical equations using zero- or first-order plug flow kinetics as basis for predicting pollutants' removal and improving water quality [13].

This chapter aimed to provide guidance on the design of a typical river diversion constructed wetland intended to improve quality of river water. The chapter provides an overview of factors to be considered for the wetland design, water quality characterization, wetland inflow estimation, computation of the wetland hydrodynamic parameters, wetland sizing, and configuration and guide on designing of conveying and inlet and outlet structures. The approach presented may be useful to wetland experts as some of the procedures adopted are not popular in wetland studies.

2. Types of constructed wetland systems

Basically, two main types of constructed wetlands exist. These are free water surface (FWS) flow and subsurface flow (SSF) systems. FWS flow wetlands operate with water surface open to the atmosphere, while for SSF, water flow is below the ground through a sand or gravel bed without direct contact with the atmosphere [14, 15]. Both are characterized by shallow basins usually less than 1 m deep. FWS wetlands require more land than SSF wetlands for the same pollution reduction but are easier and cheaper to design and build [16].

FWS flow wetlands are further sub-classified based on the dominant type of vegetation planted in them such as emergent, submerged, or floating aquatic plants. SSF wetlands which are often planted with emergent aquatic plants are best sub-classified according to their flow direction as horizontal subsurface flow (HSSF), vertical subsurface flow (VSSF), and hybrid system [17]. Another sub-division of constructed wetland types which have emerged recently is river diversion wetlands. These are mostly FWS wetlands located near or within a stream or river system. They are distinguished according to their location as off-stream and in-stream wetlands. Off-stream wetlands are constructed nearby a river or stream where only a portion of the river flow enters the wetland. On the other hand, in-stream wetlands are constructed within the river bed, and all flows of the river enter into the wetland [18]. **Figure 1** shows a typical arrangement of both types.

Potential benefits of river diversion wetlands include merits relating to river water quality improvement, flood attenuation, increasing connectivity between rivers and floodplains, and creation of mixed habitat of flora and fauna communities [8, 19]. The systems are also cost-effective due to their simple designs and construction when compared to conventional treatment systems. Major drawbacks of these types of wetland systems relate to emissions of greenhouse gases and losses of biodiversity which may result from continued pollution loading [20]. Unlike the in-stream wetlands, a major advantage of the off-stream river diversion wetlands is that they can be used to mitigate non-point source pollution from agricultural lands before reaching the river channel. However, off-stream wetlands may require storage and flow control structures to regulate flow and a large space for layout of the wetlands which may result in high initial costs for land easements. Additionally, only part of the river flow volume can be treated at a time. On the other hand, space availability may not be a big issue for in-stream wetlands as they are constructed within the river bed, and as such the whole river flow volume can be subjected to treatment. However, it may be difficult to regulate flow especially during river peak flows and consequently retention time which is an important aspect of wetland for effective pollutant removal.

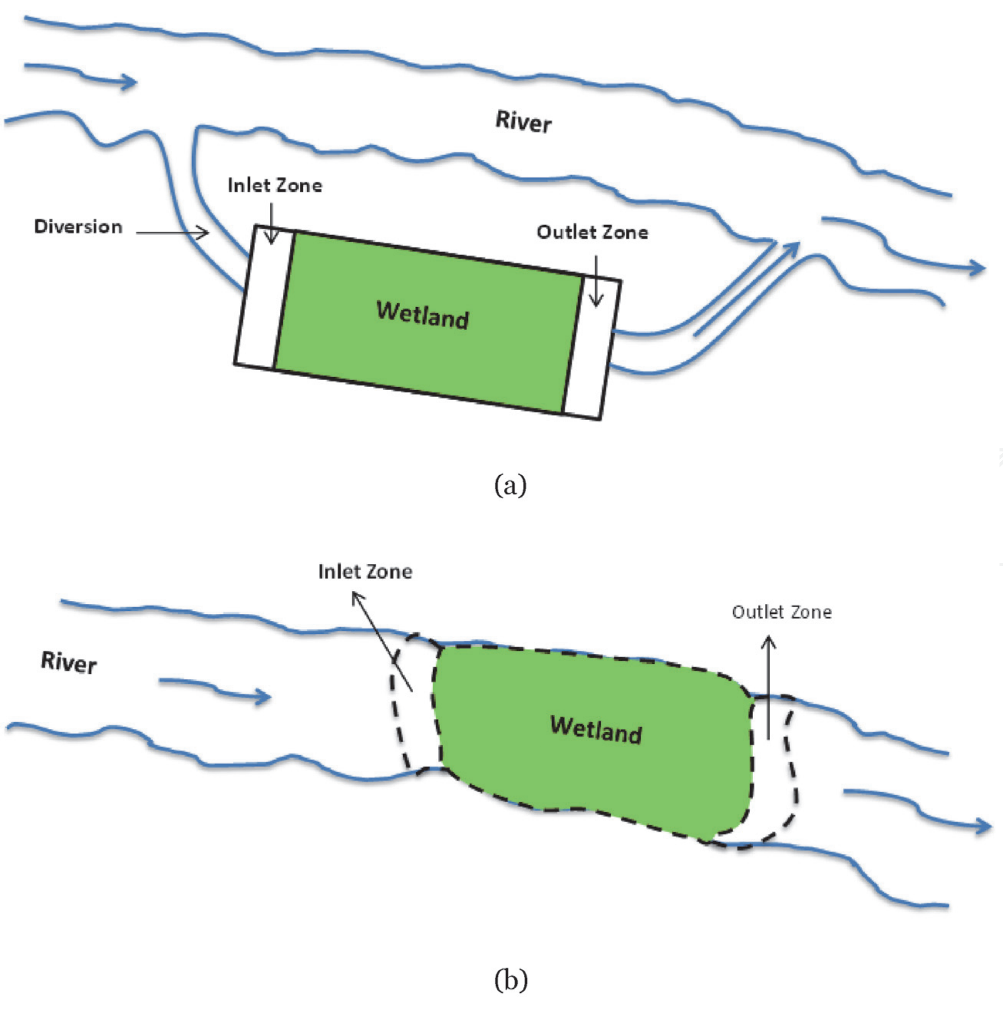

Figure 1.
Arrangement of off-stream and in-stream river diversion wetlands. (a) Off-stream river diversion wetland and (b) in-stream river diversion wetland.

3. Design consideration for river diversion constructed wetland

The design of a constructed river diversion wetland is an iterative process involving site-specific data. Prior to design and construction, site conditions must be evaluated to assess the appropriateness of the site for the proposed constructed wetland system [4]. Thus, the following are recommended as part of the design process:

- Investigation of site characteristics
- Water quality characterization
- Wetland design inflow estimation

3.1 Investigation of site characteristics

Site condition is a very important factor in the design of a constructed river diversion wetland. This is particularly necessary when a suitable site or land is not readily available as the situation often limits possible options the designer may utilize. Thus, site investigation enables the designer to have an idea of the site characteristics including size of area or land available for the design. However, where there is sufficient suitable site or land, it gives the designer the latitude and flexibility of several design options. Therefore, identifying the required area available for optimal layout of the wetland is vital for effective reduction of pollutants.

Site characteristics to be evaluated when designing and possibly constructing a river diversion wetland include:

- Proximity of the site to the river system (the site should be situated close to the source of water to be treated for easy diversion or within the river channel depending on the type (in-stream or off-stream))
- Climate (climate can affect type and size of the space required for the wetland; climatic factors that are important include rainfall, evaporation, evapotranspiration, insolation, and wind velocity)
- Topography of the land (topographic conditions such as natural depressions and slopes are important consideration; the gradient of the land should preferably have a gentle slope so that water can easily flow by gravity)
- Groundwater condition (assess groundwater levels within the site in different seasons to guide against possible contamination)
- Soil and environmental condition of the site (the site should contain soils that can be sufficiently compacted to minimize seepage to groundwater, or necessary measures should be put in place to minimize groundwater contamination)
- Distance of the site from residential buildings to avoid creating an environment that is not conducive for inhabitants

After due consideration of the above conditions, a suitable location can be selected for siting the wetland system, and the designer can then take cognizance of the space available for the system design.

3.2 Water quality characterization

Characterization of pollutant concentration of the river water to be treated is essential for sizing of a constructed river diversion wetland and in creating a clear understanding of whether the wetland can effectively treat the water or not. Thus, the constituents of the river water and their respective concentrations need to be known before beginning the design process of the constructed river diversion wetland. However, water quality is highly variable especially in rivers due to fluctuations and variability of discharge and contaminant concentration from pollution sources [21]. Thus, a clear definition of water quality is essential, and it may be necessary to take into account previous distribution of the contaminants' concentrations in the water over time [4]. According to [22], characterization of the river water quality can be done based on available data which provides information on temporal and spatial distribution of parameters of interest and their level of concentrations in the water to be treated. Water quality parameters that are characterized in most situations include biochemical oxygen demand (BOD), nitrogen, phosphorus, suspended solids, and coliform bacteria [23]. These are pollutants that originate mostly from organic sources and are considered of most interest in treatment wetland design [24]. Others include metals, phenols, pesticides, and surfactants which may also be treated. However, these parameters require specific applications as opposed to organic pollutants [18].

BOD reflects the degree of organic matter pollution, and it is a measure of the amount oxygen removed by aerobic microorganisms for their metabolic requirement during decomposition of organic materials. Nitrogen and phosphorus are considered as primary drivers of nutrient pollution, and they occur in organic and inorganic forms. Nitrogen in water is usually measured as total nitrogen, ammonium ion, nitrate, nitrite, and total Kjeldahl nitrogen (sum of organic nitrogen and ammonium ion) or as a combination of these parameters to estimate organic or inorganic nitrogen concentrations [25]. Phosphorus in water is usually measured as total phosphorus which is the sum of organic and inorganic forms of phosphorus and includes orthophosphate (PO_4^{3-}), polyphosphates, and organic phosphates [1]. For microbial contamination, indicator organisms are used to detect the presence of pathogens (disease causing organisms). Microorganisms mostly considered are those of fecal origin, and coliform bacteria are most often used to indicate the presence of fecal pollution [26]. Suspended solids are constituents that remain in solid state in water and often occur as part of sediments carried in the water. Measurement of suspended solids is essential as sediments are responsible for contaminant transport in water. Metals can exist as dissolved, colloidal, or suspended forms in water, and their toxicity depends on the degree of oxidation of the metal ion together with the forms in which it occurs [1]. Metals mostly considered with high priority in water pollution are arsenic (As), cadmium (Cd), copper (Cu), chromium (Cr), lead (Pb), mercury (Hg), nickel (Ni), and zinc (Zn) [23]. Nevertheless, selection of any pollutant or combination of pollutants for water quality improvement will depend on the objectives for which the wetland is designed. Based on the river water quality characterization, appropriate equations can be used to determine the required area and organic loading rates of the wetland system.

3.3 Wetland design inflow estimation

The amount of water flow per unit time that passes through a wetland system is one of the important parameters required in the design of a constructed river diversion wetland. Flow rate of water is an important hydrological parameter required to facilitate sizing of a constructed wetland [4]. Even though flow into a wetland can be continuous or intermittent, it however passes through the system at low velocities. There are different approaches employed to determine the quantity of inflow (volumetric inflow rate) into a wetland, depending on the wetland type, treatment objectives, and incoming water to be treated.

For wastewater treatment wetlands, inflow is mostly based on wastewater concentration and generation rates [27]. Mass loading charts with reference to the required level of pollutant removal are mostly used in the United States, while in Europe estimation is based on wastewater generation volume and pollutant concentration [27, 28]. For stormwater constructed wetlands, a range of hydrologic methods are applied to estimate design flows. Typical approaches include the use of routing in response to a storm event like the average recurrence interval (ARI) flow criterion, level-pool routing, and estimation of peak runoff flow rate using curve number (CN) model and rational method [29–31]. The ARI is applied in Australia and level-pool in Malaysia, and the CN is mostly used in the United States. While all these methods are mainly applied to stormwater treatment wetlands, they are however used with reference to specific available data and scenarios in these countries [29]. Moreover, not all wetlands are designed for treatment of maximum expected peak flows; otherwise the vegetation are likely to be damaged due to high flows, and the wetland system would need to be extremely large or the outflow water quality requirement considerably relaxed. Furthermore, the CN model has been examined to be inaccurate due to inherent limitation associated with inconsistency of the fixed ratio (λ) between initial abstraction (I_a) and soil maximum potential retention (S) in the model [32–34]. The rational method was found to be more suitable only for estimating runoff for relatively small catchment that is preferably less than 50 ha [31]. Besides, paucity of site-specific data especially in Africa can make the use of these methods difficult and inaccurate.

For river diversion wetlands, a specific method for estimating design inflow has not been fully established [7]. However, more recently, [8] evaluated the performance of a river diversion wetland for improving quality of river water using relations that can be used to estimate design inflow for a similar wetland system. These relations are presented below.

$$\alpha = \frac{A_w}{A_{rw}} \tag{1}$$

$$\omega = \frac{Q_{w-i}}{Q_{rd}} \tag{2}$$

where α = wetland/river catchment area ratio; ω = wetland/river flow diversion ratio; A_{rw} = river catchment area (ha, m^2); Q_{rd} = average flow volume /discharge in river (m^3, m^3 per unit time); Q_{w-i} = inflow rate (m^3/d); A_w = proposed area of wetland (m^2) based on available space.

Application of the above equations requires estimation of average flow volume of a river. However, flow rates vary over time because of normal variability in precipitation patterns, and a key factor governing hydrological regime of rivers is their discharge variability [35]. Therefore, to determine river flow or discharge regimes, historical flow data are required, including possible seasonality trend of the flows, pattern of past flows (low, moderate, and high flows), and stream gauge information close to the wetland site location [4, 36]. Flow data are important to facilitate understanding of fluctuations in the amount of flowing water in the river and to support development of a rating curve for the river where it is not available. The rating curve has been an important tool widely used for routing purposes in hydrology to estimate discharge in natural rivers [37]. It is a graphical representation that gives relationship between flow regimes and stage heights or water levels of a river at a given site and over a period of time [35, 38]. However, very few rivers have absolutely stable flow characteristics, and thus the rating curve may require revision over time and under unsteady conditions. A comprehensive review of the various equations developed by several authors for correcting unsteady to steady flow condition was presented by [38].

3.3.1 Using the rating curve for estimation of river flow regime

Another crucial aspect of wetland design is the estimation of average river flow regimes. The river flow regimes are required to:

- Guide in determining the amount of water per unit time that can be diverted into the wetland system without compromising the flow needed for survival of the river ecosystem.

- Aid the design and estimation of inflow regime(s) for which the wetland system will be operated since the goal of the wetland is to improve quality of river water.

Therefore, obtaining or developing appropriate rating curve may be necessary to facilitate characterization of flow regimes of the river. Based on the rating curve, the river flows can be classified into low, moderate, and high flows. **Figure 2** shows a typical river rating curve with flows classified into three regimes as indicated. For example, based on the rating curve (**Figure 2**), three flow regimes (0.29 m^3/s, 1.97 m^3/s, and 3.96 m^3/s) (marked with dotted red lines) were selected corresponding to low, moderate, and high flows of the river, respectively. The classification of the flow regimes into low, moderate, and high flows was based on their computed flow velocities as presented in **Table 1**.

For flood or peak flow control wetlands, high flows are often considered for the design, while for water quality improvement, moderate to low flows are mostly the target. Where high flow is to be used for design of river diversion wetland intended for water quality improvement, it may be necessary to include a retention basin in the design to slow down flow energy and allow for gradual release into the system.

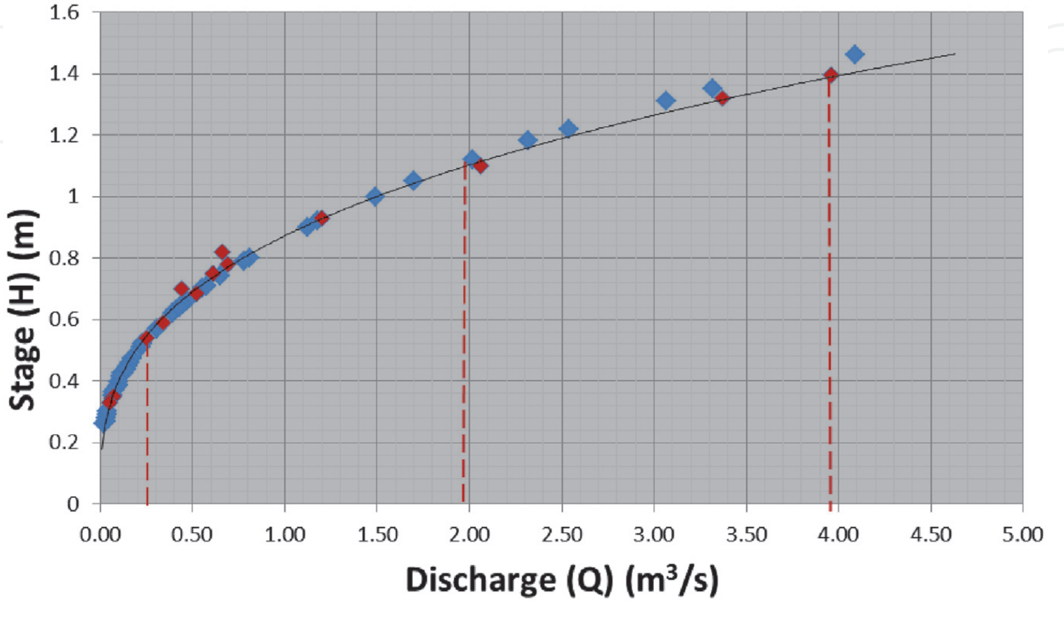

Figure 2.
Typical river rating curve with flows classified into three regimes.

Flow regimes (m^3/s)	Mean cross-sectional area of river gauging section (m^2)	Velocity (m/s)	Velocity* groups (m/s)	Classification
0.29	3.34	0.09	<0.10	Low flow
1.97	3.34	0.59	0.10–0.60	Moderate flow
3.96	3.34	1.19	≥0.70	High flow

**Values of velocity groups adapted from [39].*

Table 1.
Classification of the flow regimes.

Since the river diversion wetland under discussion is intended to be designed for water quality improvement, only a portion of the river flow regimes is required to be diverted into the wetland system per unit time. Thus, to determine the quantity of the design inflow rate of the wetland, Eq. (3) derived from Eqs. (1) and (2) can be used together with the average river flow regime(s).

$$Q_{w-i} = \frac{A_w Q_{rd}}{A_{rc}} \tag{3}$$

where all parameters remain the same as previously defined in Eqs. (1) and (2).

The wetland can be designed to operate with the three river flow regimes (low, moderate, and high) to take into account seasonal flow variability or a single flow regime depending on the objective and availability of space within the site.

4. Computing hydrodynamic parameters of the wetland

4.1 Wetland design equations

The design of constructed wetlands is generally based on empirical equations using zero- or first-order plug flow kinetics as basis for predicting pollutant removal and improving water quality [13]. With zero-order kinetics, the reaction rate does not change with concentration but varies with temperature [4], while first-order kinetics simply implies that the rate of removal of a particular pollutant is directly proportional to the remaining concentration of the pollutant at any point within the wetland [40]. Plug flow means that every portion of flow entering into the wetland takes almost the same amount of time to pass through it which is rarely the case [41]. The kinetic equations also considered FWS wetlands as attached growth biological reactors similar to those found in conventional wastewater treatment systems [23]. Generally, two types of equations are popular that use two different approaches in the design of FWS wetlands based on "rule-of-thumb" (no account for the many complex reactions that occur in a constructed wetland). There is the volume-based or zero-order kinetic equation which uses hydraulic retention time to optimize pollutant removal [42, 43]. The second is the area-based or first-order kinetic equation where the entire wetland area is used to provide the desired pollutant treatment [44]. The key difference between the two equations is in the use of kinetic rate constants. Volume-based equation assumes horizontal or linear kinetics and uses volumetric and temperature-dependent rate constant, with calculations being based on available volume of the wetland and average water temperature. The area-based equation assumes vertical or areal kinetics and uses rate constants which are independent of temperature but related to the wetland surface area. The volume-based equation was developed by [43], and the equations are presented below:

$$\frac{C_e}{C_i} = e^{-K_T t} \tag{4}$$

$$K_T = K_R \theta_R^{(T_w - T_R)} \tag{5}$$

where C_e = outflow pollutant concentration (mg/l); C_i = inflow pollutant concentration (mg/l); t = nominal hydraulic residence or retention time (d); K_T = reaction rate constant for BOD at T_w (/d); K_R = rate constant at T_R (/day); θ_R = temperature coefficient for rate constant; T_R = reference temperature (°C); T_w = ambient or water temperature (°C).

The area-based model equation was developed by [44], and the equations are presented below:

$$\frac{C_e - C^*}{C_i - C^*} = e^{-\frac{K_l}{h_l}} \tag{6}$$

$$h_l = \frac{Q_{w-i}}{A_w} \tag{7}$$

where C^* = background pollutant concentration (mg/l); K_l = reaction rate constant for phosphorus and fecal coliform (m/d); h_l = hydraulic loading rate (m/d); Q_{w-i} = inflow rate (m^3/d); A_w = proposed area of wetland (m^2) based on available space and other parameters as defined in Eq. (1).

The volume-based model was developed based on those parameters that are removed primarily by biological processes such as biochemical oxygen demand (BOD), ammonia (NH_4), and nitrate (NO_3). The areal equation considered more parameters and in addition includes total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), and fecal coliform (FC). According to [45], while the [43] method provides a relatively conservative area estimate, [44] approach may require considerable land space, depending on the pollutant concentration limit. Furthermore, the [45] model appears to be less sensitive to different climatic conditions as temperature changes are only considered significant for nitrogen removal [46]. However, temperature plays an important role in constructed wetland systems as it enhances higher biological activity and productivity which may lead to better performance of the systems [47, 48]. For this reason, the use of these models may lead to wide variations in performance due to effect of changes in climatic conditions. Additionally, many authors have developed more complex models like the Monod-type and mechanistic compartmental models [49, 50]. However, the [43, 44] models appear to be more straightforward and can be applied with ease by wetland designers [13]. Data limitation on operational performance of constructed wetlands prevented the development of equations which can clearly describe the kinetics of known wetland processes [23]. Thus, optimal design of constructed wetland systems has not yet been determined. However, in order to take advantage of [43, 44] models and ease complexity of computation, [24] presented a simplified approach for the design and sizing of FWS constructed wetlands using the two equations. The approach was based on performance criteria for the removal of four water quality parameters that included BOD, nitrogen, phosphorus, and coliform bacteria. According to [24], rates of BOD and nitrogen removal are principally temperature dependent and therefore utilized equations proposed by [43] model for removal of these parameters. On the other hand, the reduction of phosphorus and coliform bacteria was assumed to be governed by physical processes which are less temperature-dependent, and thus [44] equations were used. In addition, [24, 51] proposed the following relationships for nominal hydraulic retention time and removal of total nitrogen (TN), respectively.

$$t = \frac{V_{w-n}}{Q_{w-i}} = \frac{A_w y_w \varnothing}{Q_{w-i}} = \frac{y_w \varnothing}{h_l} \quad (8)$$

$$\frac{C_e}{C_i} = e^{-K_{TN}t} + e^{K_{TD}t} - e^{K_{TN}t}e^{K_{TD}t} \quad (9)$$

where V_{w-n} = wetland nominal volume (m^3); y_w = theoretical or nominal depth of wetland water flow (m); ∅ = porosity (percent, expressed as decimal fraction); K_{TD} = reaction rate constant for denitrification (/d); K_{TN} = reaction rate constant for nitrification (/d) and other parameters as defined in Eqs. (1), (3), and (4).

The authors recommended that the above equations can be used together with those presented by [43, 44] to determine the hydrodynamic and size parameters of a new FWS flow constructed wetland, depending on the target pollutant or combination of pollutants (BOD, nitrogen, phosphorus, and coliform bacteria) required to be removed from the wastewater. As indicated by [52], the approach presented by [24] is useful in the design of a new FWS constructed wetland and for performance evaluation of existing ones.

4.2 Using a combination of equations for river diversion wetlands

The use of a combination of wetland design equations proposed by [24, 51] was found to be useful for determination of river diversion wetlands' hydrodynamic parameters. These parameters include nominal hydraulic retention time and hydraulic loading rate.

4.2.1 Hydraulic retention time (HRT)

Determination of nominal hydraulic retention time is important for design guide and estimating possible pollutant removal ability of the wetland system. Thus, the nominal HRT for a river diversion wetland can be estimated based on the kinetic equations governing the removal of basic water quality parameters (BOD, nitrogen,

Parameter	Empirical equations	Equation no.	Source
BOD (mg/l)	$\frac{C_e}{C_i} = e^{-K_T t}$	(1)	[41]
	$K_T = 0.678\ (1.06)^{T_w - 20}$	(11)	[12]
TN (mg/l)	$\frac{C_e}{C_i} = e^{-K_{TN}t} + e^{K_{TD}t} - e^{K_{TN}t}e^{K_{TD}t}$	(9)	[12]
	$K_{TN} = 0.2187(1.048)^{T_w - 20}$	(12)	
	$K_{TD} = (1.048)^{T_w - 20}$	(13)	
TP (mg/l)	$\frac{C_e}{C_i} = e^{\frac{K_l}{h_l}}$	(10)	[22]
	$t = \frac{y\varnothing}{h_l}$	(14)	[13]
FC (CFU/100 ml)	$\frac{C_e}{C_i} = e^{\frac{K_l}{h_l}}$	(10)	[22]
	$t = \frac{y\varnothing}{h_l}$	(14)	[13]

Note: K_l = reaction rate constant for TP = 0.0273 m/d and FC = 0.3 m/d); ∅ = porosity or space available for water flow through vegetation (0.65–0.75); T_w = water or ambient temperature.

Table 2.
Parameters and equations for computing design HRT.

phosphorus, and coliform bacteria), often used for sizing of constructed wetlands. **Table 2** shows the parameters and kinetic equation used for determining the nominal HRT.

4.2.2 Hydraulic loading rate (HLR)

The HLR of the wetlands system can be computed using Eq. (7) by [44]. The determination of the HLR is essential to guide in the design and can assist to avoid overloading the system. Thus, the design may confirm the organic loading rate is within the wetland limit; an equation developed by [51] can be used to compare the K_T value with the loading rate. The equation is presented as:

$$K_T \leq \frac{-10\ \text{In}\left(C_e/C_i\right)}{C_i y_w \varnothing} \tag{10}$$

where all parameters remain the same as defined in Eqs. (1), (2), and (4).

5. Wetland sizing and configuration

Sizing is an important component of wetland design and vital for pollutant removal processes to take place. Most of the design recommendations provided certain approaches to wetland sizing to maximize removal of pollutants. For wastewater treatment wetlands, population equivalent (PE) is mostly employed for the determination of design wetland area. The required surface area is usually expressed as unit area per population equivalent (m^2/PE). For example, 5–10 m^2/PE was recommended for FWS, while for SSF it ranges between 2 and 5 m^2/PE depending on the type (HSSF, VSF, and hybrids) [27]. For stormwater wetlands, the typical approach is to consider relative percentage of the contributing catchment area or connected impervious area, and 1–5% of the contributing watershed was recommended as actual sizing criterion [4]. For full-scale river diversion wetlands, a minimum of 2–7% of the total catchment area was recommended as wetland area [20]. However, such sizing criteria pose challenges of overestimation and do not account for any performance consideration [53]. Therefore, such prescribed wetland sizing criteria may be unrealistic due to space limitation and cost. Nevertheless, an approach derived based on empirical determination of actual area required for pollutant removal with reference to hydraulic loading rate as presented by [24] appears to be more realistic for estimating actual area of river diversion wetlands intended for water quality improvement. Thus, the actual area required for such a wetland system can be determined using Eq. (16) which was derived from Eq. (8) by [24].

$$A_{wc} = \frac{Q_{w-i}\, t}{y_w \varnothing} \tag{11}$$

where A_{wc} = actual area of the wetland (m^2) and other parameters as defined in Eq. (8).

For ease of operational control (flow control and water level adjustment) and increased removal efficiency, multiple wetland units often referred to as cells may be used where possible than a single unit wetland. This is particularly more applicable to design of off-stream river diversion wetland. Multiple cells have the advantages of providing greater flexibility in design and operation and enhancing the performance of the system by decreasing the potential for short-circuiting.

Wetland cell size depends primarily on water quality treatment needs and cost considerations.

The actual area of the wetland is then computed using Eq. (16). Based on the computed values, the actual area of the wetland is thus selected as the maximum of areas obtained for each of the target pollutants (BOD, nitrogen, phosphorus, and coliform bacteria).

Wetland system configuration is an important element in the design of river diversion constructed wetland technology. After determining an appropriate wetland size, it is necessary to define the system configuration or layout by choosing an appropriate aspect ratio. Aspect ratio represents length (L) to width (W) ratio (L/W) of the wetland. It was suggested that choosing a good aspect ratio can assist to minimize short-circuiting and maximize flow distribution within the wetland system for biological activities [54]. Aspect ratio of as low as 1:1 was recommended for SSF [55], while length to width ratio of between 3:1 and 5:1 was recommended for FWS from an optimal point of view by [23]. However, based on findings by [56], 10:1 was recommended for FWS for good hydraulic efficiency. For water quality improvement, a river diversion wetland should be designed to operate with the most efficient aspect ratio.

Wetland bed slopes are also critical to maintain a uniform water depth throughout the wetland system and facilitate drainage. In order to minimize short-circuiting, a uniform bed slope from inlet to outlet is recommended. Thus, the bed slope for SSF should be 2% or less, while that for FWS should be 0.5% or less [14]. A river diversion wetland can also be designed to operate with similar bed slope as recommended for FWS since they are related in mode of operation.

6. Water conveying system: inlet and outlet structures of the wetland

This aspect of the wetland design focused on selecting or designing a water conveying system, inlet and outlet control structures that can facilitate flow and distribute inflow and drain outflow water from the wetland effectively. Depending on the type of river diversion wetland, flow diversion structure may be designed to consist of either a pipe or channel system and should function to provide a controlled flow of water to the wetland. However, it is necessary to be explicit about flow capacity at the time of design so that appropriate sizing of flow diversion structure can be made. Generally, the design flow conveyance structure is based on hydraulic; therefore the reader is referred to hydraulic books for detailed information.

In order to ensure that the inflow water is uniformly distributed across the entire wetland area, multiple entry openings or gates should be considered rather than single to deliver the range of design flow regimes required. Flow control structures should be used to control inflow rate and maintain water levels. Control valves or weirs or a combination can be used depending on the type of inlet structured selected. Since the wetland system is for water quality improvement, high incoming water velocities should be discouraged. Therefore, energy dissipation system may be required for the incoming water to provide protection for the wetland inlet. The inlet openings should be designed large enough to avoid obstruction. Inlet zones should provide access for sampling and flow monitoring.

Wetland outlet design is essential in avoiding possible dead zones and controlling water level and for monitoring flow and water quality. Depending on the size of the wetland, a combination of outlets (primary and secondary) or multiple outlets consisting of hydraulic control structures can be considered to collect and discharge treated water for the range of design flow regimes and maintain required water storage level. The purpose of the primary outlets is for water quality control, while the secondary is to act as a spillway and control flows in excess of the maximum design flow regime. Different types of control structures are available that can be used to control water level within the wetland. These may include number of individual pipes that fit together in a combination to obtain the desired water level, drop structures, or weirs. The design requirements of drop control structures and weirs can be found in hydraulic books. The outlet or water level control structure should be able to completely dewater the wetland when needed and allow for changes to be made easily.

7. Conclusion

The management and restoration of water bodies like rivers should go beyond protection through the use of regulations. It should also make the most of opportunities that arise from using ecosystem properties to enhance self-purification capacity of rivers for water quality improvement. A key consideration is the use of constructed river diversion wetlands.

This chapter provided guidance on the design of a river diversion constructed wetland aimed at improving quality of river water. The use of a combination of empirical equations was presented to guide in the estimation of the actual wetland area rather than relying on an assumed rate. The design approach using these equations may present a promising method for the design of river diversion wetlands. Furthermore, this novel approach may be useful to wetland experts as some of the procedures adopted are not popular in wetland studies. This may provide opportunity for wetland designers to document approaches that have been found promising and come up with suitable design criteria for constructed river diversion wetlands.

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Conflict of interest

None declared.

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