Pond-In-Pond: An Alternative System for Wastewater Treatment for Reuse

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When treating municipal wastewater, there are two choices to be made that determine which treatment system will be utilized; will the effluent be discharged to a stream or will it be reused for beneficial purposes such as growing agricultural crops by land application. For land application systems, the effluent quality is less stringent, usually 2-3 times higher than that required for stream discharge. In addition, the public tends to be more supportive when it comes to the reuse of wastewater in irrigation rather than the reuse in households. A simple, low cost, low energy pond treatment system has been widely used for reuse systems. However, there is a lack of specific design guidelines for pond treatment systems, and selection of a design procedure is difficult to ascertain. This study examines various pond design approaches and recommends the use of a Pond-In-Pond (PIP) approach as the more appropriate design layout for reuse purposes, where PIP is the integration of two types of ponds—anaerobic and aerobic. The results from the Computational Fluid Dynamics (CFD) analysis of a flow-diversion mechanism in recent studies and performance data from existing PIP systems show that the PIP is a promising concept for wastewater reuse systems. The PIP system under study produced an average annual effluent BOD of approximately 40 mg/L.

Keywords: wastewater; reuse; land application; pond design; pond-in-pond; sustainability

1. Introduction

The world's freshwater resources are continuously being depleted. The increase in global population and factors associated with the changing climate have created additional stress on water availability in many parts of the world. The major consumers of fresh water in the US are thermoelectric production, agriculture (primarily irrigation), and public water supplies [1]. With irrigation near the top of the consumption list, alternatives to using freshwater for irrigation would reserve that quantity of freshwater for human consumption. As mentioned in Fedler [2], nearly 70% of the freshwater consumed worldwide is by food-production systems [3]. In the US, 42% of the total freshwater consumed is used for crop irrigation [1]. Wastewater is an easily accessible but highly underutilized resource that contains valuable nutrients required by crops that could be used to meet some of the irrigation needs. However, only a small fraction of wastewater produced is reclaimed for beneficial use with less than 6% in the US [4] and less than 3% in the global context [5]. If the recycle rate was increased to 15%, the worldwide overall freshwater available for human consumption would double [6].

The high-water consumption in agriculture has stressed water supplies and causes shortages in many parts of the world with some nations on the verge of serious long-term water crises. For agriculture-dependent countries with high rates of population growth and limited water sources, recycling could be one of the best sustainable solutions [7]. Wastewater is uniquely a resource that is increasing as other resources are decreasing. Reuse of our wastewater is a necessity in order to maintain an adaptable and, thus, sustainable future in terms of food production, reduced energy consumption, and sufficient water for human consumption [6]. The use of municipal wastewater for agricultural irrigation is often viewed as a positive means of recycling water. Potentially large volumes of water can be used, and this recycled water is a constant and reliable resource [8]. Also, the public tends to be more supportive when it comes to the reuse of water in irrigation rather than the reuse in households [9-10]. Natural ponding systems with the appropriate design could provide a viable solution to our water sustainability problem by utilizing the nutrient-rich water for crop production [2, 11-14].

Pond treatment systems can provide the desired level of treatment at a much lower cost compared to conventional mechanical systems [2, 15-18]. Several studies [19-22] have been done to evaluate the costs associated with various wastewater treatment alternatives. The results from a comparative study of capital, operating and maintenance costs of biological filters, bio-discs, stabilization ponds, and an extended-aeration-activated sludge system shows that stabilization ponds are the lowest-cost option for wastewater treatment [19]. The construction cost for stabilization ponds was 25-50% less than the cost for any other systems evaluated, and the annual operating costs were only about 5-10% of the cost required for other systems. Thus, the pond systems provide a huge savings in energy, equipment costs, and operation and maintenance costs. These ponds, however, require large land areas that limits their use to areas where low cost land is available.

Waste stabilization ponds used for treating municipal wastewater may be aerobic, anaerobic or facultative. Over the past several decades, procedures have been developed to design various types of ponds used to treat wastewater. Many of these pond designs have been in existence for decades; however, no standard design guidelines have been established for parameters such as pond depth, length-to-width ratio, retention time (both hydraulic and solids based), or reaction rate based on waste constituents. The observations and results from different pilot plants and physical models, as described in the literature, have contradictory viewpoints regarding the design of ponds. For the facultative ponds in general, performance has been largely related to depth with improved performance with deeper ponds likely due to higher retention [23-29]. Observations from other studies [30-34] conversely do not show sufficient evidence for improved pond performance with increased pond depth. In addition, there are conflicting views regarding the effects of length to width ratio [29, 33, 35-37] and the surface area loading on pond treatment [24, 28, 30-31, 33, 38-41]. The purpose of this paper is to investigate existing design criteria of facultative ponds and the appropriateness of these various designs for treatment performance required for reuse systems. In addition, use of the Pond-In-Pond (PIP) is discussed as an alternative system for wastewater treatment prior to reuse.

2. Existing knowledge on Facultative Pond Design

Several empirical and analytical models have been developed for the design of facultative ponds. Most models developed have limitations in their use due to the difficulty of determining reaction rate and other coefficients or due to the complexity of the model itself. Ideal-plug-flow model [42], complete-mix [43] and several others [30, 44-48] are the common design approaches currently in practice. However, use of one model over another is determined based on the available design parameters. The primary design approaches that have been used include the area-loading method, the regression equation approach, the first-order model approach, and the mechanistic model approach.

2.1. Area-Loading Rate Design Approach

The area-loading design has been in practice for decades, and most states have design criteria based on organic loading or hydraulic retention time for facultative ponds [24]. The design criteria are based on location from North to South (climatic conditions); however, there have been repeated violations of state effluent performance standards indicating the inadequacy of the design criteria. The US Environmental Protection Agency (EPA) collected the data for pond performance for four different climatic conditions --New Hampshire (NH), Mississippi (MS), Kansas (KS) and Utah (UT)--using the existing area loading rate design [49-52]. The actual loading for the ponds studied was less than the design loading except for the system at Corinne, UT, where up to seven ponds in a series were used [42]. Even with the low loadings, the effluent standards for BOD were exceeded for most ponds with higher effluent BOD concentrations during the winter months. The summary of the pond study by EPA is shown in Table 1 [42].

Table 1: Summary of Design and Performance Data from EPA Pond Studies[1]

Location	Organic loading (kg BOD/ ha. day)			Theoretical retention time (days)			Depth (m)	Area (ha)	BOD Removal (%, 1st Cell)	No. of Months Effluent BOD> 30 mg/L
	State Design Standard	Design	Actual (1974-75)	State Design Standard	Design	Actual (1974-75)				
Peterborough, NH	39.3	19.6	16.2	None	57	107	1.2	8.5	66	4
Kilmichael, MS	56.2	43	17.5	None	79	214	2	3.3	89	2
Eudora, KS	38.1	38.1	18.8	None	47	231	1.5	7.8	83	3
Corinne, UT	45.0	36.2	29.7 * 14.6†	180	180	70 88‡	1.2	3.9	59	0

*Primary cell

† Entire system

‡ Estimated from dye study

[1] Data obtained from Reed et al. [42].

Despite the limitations observed, the most adopted design process is the area-loading criteria due to its minimal required inputs [53]. One of the most notable limitations with this design approach is that neither pond dimension nor configuration is considered in the design. An average BOD loading rate has been identified for different climatic conditions based on years of experience [54]. For warm climates with average winter air temperature above 15°C, an average BOD loading rate between 45-90 kg/ha.d is recommended, and the loading rate declines with a decrease in temperature. The recommendation for average BOD loading rate for temperatures between 0 and 15 °C is between 22-45 kg/ha.d. For freezing temperatures, the BOD loading rate recommended is between 11-22 kg/ha.d. These loading rates, however, lack specific guidelines; and, considering the large range in BOD loading rate for a large temperature range, wide variation in performance is inevitable.

2.2. Regression Equations

Several regression equations [30, 47, 55] have been developed for the design of facultative ponds using the pond performance and design values determined from the performance of existing ponds. McGarry & Pescod [30] observed a statistically significant relation between BOD removal and area BOD loading in the system with a correlation coefficient of 0.995 and a 95% confidence interval of $\pm$ 32.8 kg BOD/ha.d. The equation was evaluated using the pond study by the EPA where the equation predicted higher removal than the actual performance of the ponds. Also, the equation was not found to be practically useful for loadings commonly found in the US (under 112 kg BOD/ha.d) due to its huge 95% confidence interval. With a 95% confidence interval, the equation predicts a range of removals from 42 to 108 kg BOD/ha.d for a loading rate of 90 kg BOD/ha.d. [56].

Larsen [55] proposed an empirical equation for the estimation of pond surface area using the data from a 1-year study at the Inhalation Toxicology Research Institute, NM. The equation, when evaluated using the data from the EPA pond study, underestimated the pond surface area required and was found inappropriate for the design of pond systems with huge prediction errors ranging from 190 to 248% for multiple-cell pond systems and 18 to 98% for single-cell pond systems [38].

Gloyna [47] proposed an empirical equation for pond design as illustrated by Equation 1.

$$V = (3.5 * 10^{-5}) * Q * L_a * \theta^{35-T} * f * f' \quad (1)$$

V = pond volume, m3

Q = influent flow rate, Lday-1

L_a = ultimate influent BOD or COD; mg/L

θ = temperature correction coefficient = 1.085

T = pond design temperature, °C

f = algal toxicity factor

f' = sulfide oxygen demand

The Gloyna [47] method is limited to the BOD removal efficiency of 80-90 percent [36]. The Gloyna method assumes the solar energy required for photosynthesis is above the saturation level and value of unity is assumed for both the algal toxicity factor and the sulfide oxygen demand (sulfate concentrations below 500 mg/L). It has the provisions for solar condition adjustments but does not provide any adjustments for values of algal toxicity and sulfide oxygen demand. Further, the Gloyna design is based on a 1 m (3.28 ft) depth whereas a greater pond depth is recommended for anaerobic conditions to prevail [23]. The Gloyna equation was evaluated using the reference data from the EPA study where a statistically significant relationship ($R^2 = 0.848$) was observed; however, the validity of the equation is questionable due to the considerable scatter of the data [57]. Also, the equation yielded substantially larger surface area than the actual area for ponds in the Kilmichael, Eudora, and Corinne locations; whereas, the area was less than the actual area for the Peterborough system [38]. The inconsistency observed limits the use of the Gloyna equation in the design of ponds.

2.3. First-order Models

2.3.1. Complete-mix Model

Marais & Shaw [43] developed an equation based on the complete mix model and first-order reaction rate as shown in Equation 2. The model has an upper proposed limit for the BOD concentration of 55 mg/L to avoid the anaerobic conditions and odors, which is a major limitation for its applicability in the design of facultative ponds.

$$\frac{C_n}{C_o} = \left[\frac{1}{1 + k_c t_n}\right]^n \tag{2}$$

C_n = effluent BOD5 concentration, mg/L

C_o = influent BOD5 concentration, mg/L

k_c = complete mix first-order reaction rate, days-1

t_n = hydraulic retention time in each cell, days

n = number of equal-sized pond cells in series

2.3.2. Ideal Plug-flow Model

The other approach for the design of facultative ponds is the ideal plug-flow model as shown in Equation 3. It is based on the plug-flow first-order reaction rate (k_p) that varies with the BOD loading rates.

$$\frac{C_e}{C_o} = e^{-k_p t} \tag{3}$$

C_e = effluent BOD_5 concentration, mg/L

C_o= influent BOD_5 concentration, mg/L

k_p = plug flow first-order reaction rate, $days^{-1}$

t = hydraulic retention time, days

e = base of natural logarithms = 2.7183

These methods, when evaluated using the pond performance study by the EPA, produced a wide variation in the reaction rate values and limits the use of models for the design of facultative ponds [1]. Selection of the reaction rate is often challenging in these designs, as it can have a significant effect on pond retention time [56].

2.4. Wehner-Wilhelm Equation

Wehner & Wilhelm [44] developed an equation for the design of a chemical reactor with mixed flow patterns somewhere between ideal plug flow and complete mix as shown in Equation 4.

$$\frac{C_e}{C_o} = \frac{4ae^{\frac{1}{2D}}}{(1+a)^2(e^{\frac{a}{2D}} - (1-a)^2 e^{-\frac{a}{2D}})} \tag{4}$$

C_o = influent BOD_5 concentration, mg/L

C_e = effluent BOD_5 concentration, mg/L

e = base of natural logarithms = 2.7183

a = $(1+ 4\,ktD)^2$

k = first-order reaction rate constants, days^{-1}

t = hydraulic retention time, days

D = dimensionless dispersion number = $\frac{H}{vL}$ = $\frac{Ht}{L^2}$

H = axial dispersion coefficient, area per unit time

v = fluid velocity, length per unit time

L= length of the travel path of a typical particle

Thirumurthi [46] observed a similar flow pattern in facultative ponds and recommended the use of the Wehner and Wilhelm equation for the design of facultative ponds. He further developed a chart for a product of reaction rate *(k)* and hydraulic retention time *(t)* versus the percentage of BOD remaining (kt versus % BOD remaining) for dispersion numbers *(D)* ranging from zero for an ideal plug flow unit to infinity for a completely mixed unit. The dispersion number for wastewater pond varies from 0.1 to 2, with most values being less than 1. The selection of a design value for dispersion number and reaction rate *(k)* is a trial-and-error approach and can have dramatic effects on retention time required for specific effluent quality [58]. Polprasert & Bhattarai [27] later developed an equation for selecting the dispersion number based on hydraulic retention time; however, the retention time was analyzed by tracer studies and is not a very convincing and robust approach. Again, based on experiences, the actual retention time is considered half the theoretical retention time in most designs.

2.5. Advances in Pond Design with Mechanistic Models

Facultative ponds consist of three diverse zones – aerobic, facultative, and anaerobic, with different biochemical processes and microbial populations in each zone. The facultative ponds thus exhibit high complexity and pose a huge challenge in modeling the processes within the system. Several models have been developed over the last few decades that, in general, either focus on hydrodynamics [59-60] or on biochemical processes [61]. Computational Fluid Dynamic (CFD) models [59, 62-63], the biokinetic model [48] and integrated model [64] are the commonly studied mechanistic models for the design of facultative ponds.

CFD models simulate the fluid flow more precisely and offer higher flexibility in understanding the effects of external factors such as wind, thermal stratification, baffles [65-66], and the pond inlet/outlet configurations and dead zones [67-68] within the pond. The CFD models showed that the use of baffles and inlet/outlet configurations has significant effects on pond performance and flow efficiency respectively and has, thus, allowed designers to more fully understand why Stone [69] added the flow diversions to the process.

The biokinetic model provides a different design approach over the first-order models using the Monod equation where the reaction rate depends not only on the substrate concentration but depends also on organism concentrations and organism-environment interactions. Integrated models combine 3-D hydrodynamics with a mechanistic water quality model; and, such models have been used to evaluate the effects of wind and the addition of baffles on the flow pattern and effluent qualities. The mechanistic models in general have helped provide a better understanding of the flow regime. However, these models require intensive computing power and time and lack sufficient validation due to lack of adequate field data [70].

3. Comparative Study of Existing Design Methods

Each design approach has its own constraints and applicabilities that make the direct comparison of the design models difficult. The selection of a reaction rate and other design parameters is the major limitation with most of the design approaches. The ponds, in general, are designed at their best to reach the theoretical hydraulic retention time; however, the actual mean retention time varies from the theoretical due to the flow dynamics within the pond. An examination of the hydraulic retention times, surface area, and the total volume requirements showed that the use of different methods gave different pond size requirements as shown in Table 2 (data extracted from USEPA [71]). The results shown in Table 2 are for the following assumed characteristics of wastewater and environmental condition:

Flow rate = Q = 3785 $m^3 d^{-1}$ (1 MGD)

Influent BOD_5, C_o = 200 mg/L

Required effluent BOD_5, C_e = 30 mg/L

Operating water temperature = 5 ^0C

Reaction Rate K_T at 20 ^0C = 0.15 d^{-1}

Table 2: Summary of Results from Various Design Methods[2]

Method	Hydraulic Retention Time, days	Depth, m	Volume, m^3	Surface area, m^2
Wehner-Wilhelm	53.9	2.45	204012	83270
Surface Area*	145.7	2.45	551547	225124
Complete mix	61.2	2.45	231533	94503
Gloyna	67.5	2.45	255334	104218
Plug flow	98.7	2.45	373646	152508

*Values based on surface loading rate of 34 kg/ha.d. At 66 kg/ha.d, the results would be close to the others but a reliable effluent BOD5 of 30 mg/L might not be as attainable.

The area-loading rate is the simplest design approach and is the most conservative of the design methods. It requires a minimum of input data thereby being the simplest approach for engineers. However, this approach leads to high investment cost for plant owners.

The regression equations serve as a handy tool for design and operation of a pond; however, the wide range of design approaches with different inputs in their model makes the use of these equations questionable and poses difficulties for engineers to select an optimal model.

In many cases, facultative ponds are arranged in a series of ponds and the flow scheme is approximated by a plug flow model. Performance of many facultative ponds has been found to be adequately described by plug flow hydraulics and first-order reaction rate [31, 46, 56, 72]. In contrast, Marais & Shaw [43] assume complete-mix hydraulics. It is based on a major limiting requirement that the primary cell will not become anaerobic [27, 36].

[2] Data extracted from USEPA [71]

The reaction rate constants and the dispersion number are the critical parameters for the pond design based on the Wehner & Wilhelm [44] model that uses both a reaction rate constant and a dispersion number in their equation. However, due to the difficulty of selecting these design parameters; use of the Wehner-Wilhelm model is not useful until after performance data from the ponds is collected.

The mechanistic models have helped design engineers better understand the flow regime and the biochemical processes within the pond; yet, such models lack sufficient field data for validation which limits the applicability of such models. Also, such models require huge computing powers and time, and may not be applicable for pond treatment systems.

Each of the design methods discussed above can provide a reasonable design if the proper parameters are selected. However, obtaining the necessary design parameters such as reaction rate constant and dispersion number for the various waste streams is not possible since the numbers do not exist and can only be obtained after a system is installed and tests are run on the performance of the system. Several internal and external factors such as reactant concentrations, pond configuration, waste constituents, and weather conditions can largely affect these parameters yet are absent in most of the models available. In the absence of proper design parameters, and the associated limitations with available design approaches, there is no proper basis for selecting the *best* procedure. The pond systems have been in existence for decades; but, the above discussion continues to show the inadequacy in the design of facultative ponds.

4. Experiences with Facultative Pond Design

4.1. Area-Loading

Most recommendations for designing ponds use an area-loading concept [42, 73-75]. The design of ponds based on area-loading approach, however, is not well justified and is highly controversial among some authors [38, 40, 75]. Several studies [24, 30, 38, 40-41, 75] have been done to determine the effectiveness of surface loading for pond design.

A decline in BOD removal was observed with increasing surface loading [41] where the surface organic loadings were applied in a range of 55 to 68 kg BOD/ha.d. A significant decrease in BOD removal was observed at loadings greater than 60 kg/ha.d. for the 1-1.5 m (3.2 - 4.9 ft) deep ponds. McGarry & Pescod [30] suggest the area loading as the most critical factor in determining the BOD removal in facultative ponds and the ponds must be designed for maximum area loading to minimize the pond surface area. These authors further suggest that the depth and retention period have little influence on pond performance.

In studying over 40 facultative ponds from climates around the world, the authors of this paper found that there was no correlation between area-loading rate and percent reduction in BOD. The regression model, however, only takes depth, retention time, temperature and area loading into consideration due to unavailability of other uniform data. Also, the model has a limitation due to its wide spatial and temporal distribution. Likewise, a study by Finney & Middlebrooks [38] found that loading rates and retention time based upon region (North to South) could not be used to determine the performance of the treatment system. In their paper, three empirical design equations and two kinetic models for facultative pond design were studied, where none of the equations yielded predictions substantiated by published pond performance data. Further, Abis &

Mara [75] found that lower loading and longer retention time led to only slightly better performance. Furthermore, in their later article Abis & Mara [40] found that the sludge accumulation rate was independent of BOD loading and retention time.

4.2. Pond Depth and Hydraulic Retention Time

A report by Oswald [23] highlights the effects of pond depth and hydraulic retention time on pond performance. The results from his study showed that the BOD removal efficiency increases with the increasing pond depth. An increase in retention time in deeper ponds helps increase the digestion of sludge and BOD removal. And no recirculation is required in deep ponds as the rising gas bubbles aid with mixing. BOD removal, methane fermentation, and coliform destruction increase with the increasing depth in ponds deeper than 2.13 m (7 ft). Ponds with depths less than 1.83 m (6 ft) lead to unnecessary algal growth and odor nuisance and vector nuisance. However, deeper ponds, in turn, have lower bottom temperatures which inhibit methane fermentation. Thus, Oswald [23] says that ponds should be designed for optimum depth but there was no mention of what constitutes optimal depth.

Uhlmann [25] and Uhlmann et al. [26] studied the influence of BOD loading, retention time, and temperature on the first-order reaction rate (*k)* and found that *k* depends on all three factors. However, the influence of retention time and temperature was less dramatic as compared to the changes in BOD loading. A study by Ellis & Rodrigues [28] observed that BOD loading, retention time, pond depth, the ratio of solar radiation intensity to hours of sunshine, and rainfall were the most important variables to describe BOD removal efficiency in facultative ponds.

Pearson et al. [32] suggested that a significant reduction in a pond's retention time does not necessarily produce a corresponding reduction in its performance. Further, in their later article, Pearson et al. [33] showed that increasing pond depth and thus the retention time under the same surface loading did not significantly improve the effluent quality. A similar idea was presented again in the early 2000s where Pearson et al. [34] investigated the depths versus performance in a primary facultative pond, and the results showed that varying the depths from 1.25 m (4.1 ft) to 2.3 m (7.5 ft) had no effect on BOD removal rates. On the contrary, the deeper facultative ponds have a higher risk of odor nuisance due to the higher concentration of hydrogen sulfide being produced and had negative impacts on coliform removal. This was most likely because the shallower ponds were more aerobic as opposed to facultative and had deeper UV light penetration for more effective coliform removal.

McGarry & Pescod [30] present design criteria for stabilization ponds in tropical Asia where the effects of BOD loading, retention time, and pond depth on BOD removal was observed. The results showed that the area BOD loading had by far the strongest influence on BOD removal efficiency, whereas pond depth and retention period had little effect. These authors further suggest that the pond depth should not be guided by BOD removal and should rather be determined to achieve vector prevention and protection of the lower anaerobic layer.

4.3. Pond Geometry and Dispersion Ratio

Wastewater treatment ponds are designed with different length-to-width ratios, and differing opinions exist on the effects of those dimensions on the level of treatment. Several studies [27, 29, 35-37] have observed the effects of pond geometry on pond performance. Polprasert & Bhattarai [27] proposed the dispersed-flow equation for the design of ponds where the effects of dispersion number were factored into the pond design. The dispersion number was related to retention time, kinematic viscosity, and the pond shape -- length, width, and depth. Reynolds et al. [35] studied the pond performance under different baffle systems and found that a longitudinally baffled pond produced a superior effluent as compared to other baffle systems. Further, a study by Martínez et al. [29] observed that increasing the number of baffles in facultative ponds improves the hydraulic efficiency of ponds and thus increases the BOD removal efficiency where the optimal length for baffles was about 70% of the length of the pond.

Likewise, Agunwamba et al. [36] observed the effects of pond geometry on pond performance and observed that the increase in length-to-width ratio and the width-to-depth ratio of the pond had improved effects on BOD removal efficiency. This was because the increase in these ratios helped to reduce the dead zone volume in the pond, therefore allowing wastewater to stay in the pond for a longer time which leads to higher quality effluent. Also, the results of computational dynamic modeling [37] showed that BOD removal efficiency of the pond increases with the increase in the length-to-width ratio of the pond and number of baffles. The results further showed that ponds with a length-to-width ratio of 4:1 with 2 and 4 baffles at $1/3^{rd}$ and $1/5^{th}$ of pond length were the most effective design.

In contrast, Pearson et al. [33] found no significance in building long rectangular ponds or including baffles in facultative ponds to encourage plug or piston flow. Little effects were observed on the performance and effluent quality while changing the length-to-width ratios from 1:1 to 6:1 and depths from 1 m (3.28 ft) to 2 m (6.5 ft). They further state that the positioning and depths of the inlet and outlets may have a greater beneficial impact than pond shape and vertical stratification and is probably more important in design.

5. Pond-In-Pond Approach: Alternative Treatment System

Both aerobic and anaerobic ponds have their own advantages and limitations; but, if the two systems are integrated into a single pond, the symbiotic relationships of related microorganisms proceed without inhibition. The Pond-In-Pond (PIP) is a treatment technology where the two types of ponds--anaerobic and aerobic--are combined into a single pond [12, 76]. The initial concept of the PIP was first considered by Stone [69] where a small, deeper sub-basin was placed within one corner of a much larger basin. This concept was further advanced by Oswald [76] where he not only placed the deeper section within a larger outer pond, but the inner pond had berms added for confining the influent to a small section of the overall pond. The entire interior pond is submerged within the outer pond, such as the PIP system, which was called an Advanced Facultative Pond (AFP). This AFP was the first pond in series of the Advanced Integrated Wastewater Ponding System (AIWPS) developed for stream discharge of the effluent and had the influent BOD removal of 60 to 80% [77]. Fedler & Wheeler [12] later used the PIP system for treating cattle waste. The purpose of using this approach was to provide increased solid retention time and to capture as much methane as possible by covering the inner pond only without having to cover the entire pond.

The PIP system provides more efficient conversion of the waste, including high-strength waste, to end products through a system that requires essentially no energy input, except for the pumping of the waste into the system if gravity flow is not possible [12]. The basic premise of the PIP is to provide a protective zone for the anaerobic organisms to perform without interruption, especially from the annual pond mixing caused by temperature stratifications that naturally occur. Because of the wind mixing potential, a greater depth is suggested. In contrast to depths of between 1.5 m (4.9 ft) and 2 m (6.5 ft) with a maximum of 3 m (10 ft) [53] recommended in most studies, a minimum depth of 4.6 m (15 ft) for the inner pond of the PIP to facilitate the breakdown of waste organics and a minimum depth of 3 m (10 ft) for the outer pond is recommended [12]. These depths are based on the experience of a system in operation for over 15 years. Also, the simulation results using mechanistic models (CFD) for pond design provided convincing reasons for increased depth and the addition of flow diversions in the process [60, 62]. Figure 1 shows the sludge deposition zones that occurs within a typical pond as compared to the protected zone in the PIP, which shows how the anaerobic zone is protected from naturally occurring mixing.

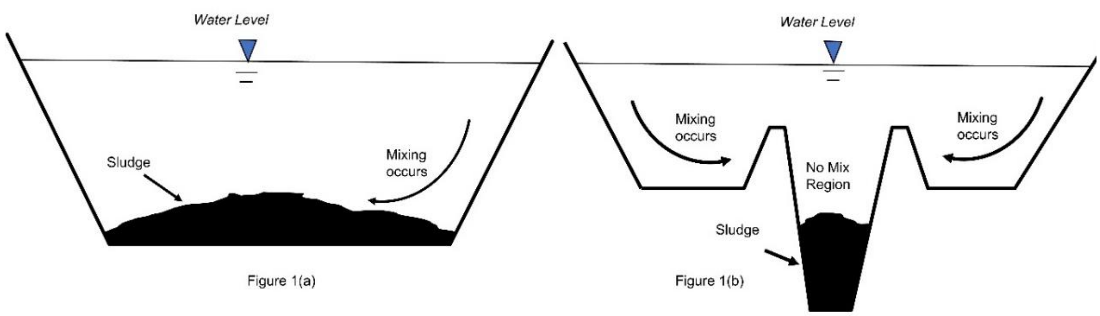

Figure 1: Mixing regime of the typical wastewater pond [1(a)] compared to the Pond-In-Pond (PIP) [1(b)]

Even though the PIP concept was introduced decades ago, it did not receive much attention. The authors of this paper suggest that the early concept of using deeper sections and berms within a pond adds the functionality similar to having baffles in the pond. Such a sub-basin or a pond within a pond induces a flow diversion which was found to be beneficial from the CFD analysis on baffled ponds [37, 60, 62]. In addition, the deeper section of the inner pond allows for a much higher solid retention time so that long-chain carbon compounds can degrade more completely.

5.1. Additional Benefits of the PIP

The PIP system not only serves as an alternative system for treatment of wastewater for reuse; but, adopting such a system provides several economic benefits. One of the major benefits of using PIP is a reduction in the land area requirement, which has been a major limitation in most multiple pond systems. The concept of using a deeper pond inside another pond eliminates the installation of two separate units and significantly reduces the land area requirements by approximately 40-60% which reduces capital costs. This number was obtained through a comparative analysis of area requirements for different pond systems -aerobic, anaerobic and facultative-for the same level of treatment.

Further, PIP systems require a minimal operation and maintenance cost as compared to other treatment systems [78]. The PIP system does not require an external source of energy nor any mechanical systems. This eliminates the cost for energy [12]. Its ease of operation eliminates the need for technical experts to operate the system. Further, these systems have been in continuous operation without sludge removal for 20+ years [77], thereby reducing the cost for sludge handling and removal.

In addition to reduced capital, operation and maintenance costs, PIP systems have the potential to generate revenue. Several studies [12, 79] have been performed to evaluate the energy and nutrient recovery potential using such systems. A system in Texas, where PIP has been used to treat cattle waste is expected to provide over $ 5 US million of revenue per annum from all the cattle feedlots located in Texas [12].

5.2. Case Study: PIP for Wastewater Treatment

5.2.1. Study Area

A PIP system in Southwest Texas established in 2004 was designed for treating municipal wastewater for a population of 10,000 with an average annual influent BOD of about 280 mg/L. The system consists of two PIP units, each with a surface area of approximately 24000 sq. m. (6 acres), 3:1 side slope, and retention time of 22 days. The depth of the inner pond is 4.6 m (15 ft) and the outer pond is 3 m (10 ft) deep. The raw wastewater from the city is passed through a splitter to divide the flow into the two ponds in parallel. The PIP effluent is collected and passed into a secondary pond. The effluent is sampled at the edge of the secondary pond near the outlet pipe, and the effluent is stored in a storage basin for reuse on a land application site. The secondary pond has a retention time of only about 3 days and does not add significantly to the treatment of the effluent from the PIP.

5.2.2. Pond Performance

The PIP system has already been in operation for more than 15 years, and the performance data for the last 10 years of operation shows that the PIP system is performing within its design limits of an effluent BOD less than 60 mg/L. The performance data consists of monthly minimum, maximum, and average effluent BOD from January 2010 until June 2019. The monthly averages reported by the city were the arithmetic averages of all samples collected every 2 weeks. As a first-step analysis, the data were analyzed as obtained and the results showed that the average annual effluent BOD was below the required limits of 60 mg/L for all years except 2015, in which the effluent BOD was 69 mg/L. Likewise, the monthly average effluent BOD was below the standards except for the month of April with effluent BOD of 66 mg/L.

No information was obtained from the city that could explain the possible reasons for exceedance in effluent BOD. Thus, as a second-step analysis, the entire data was considered with the effluent BOD for every sample being reported. Numerous of the effluent BOD readings in 2015 was reported as greater than 240 mg/L which appeared to be suspicious. These readings when compared to the same months of other years and subsequent months in the year 2015, showed a significant deviation (great than 2 standard deviations from the mean). Due to a lack of specific information to simply discard the data as false, a similar analysis was performed by excluding the entire data for 2015 to determine the effects of those data on the overall monthly averages. The results did not show any spikes for the month of April and the effluent BOD was below 60 mg/L. The annual and monthly averages are shown in Figure 2(a)[3] and Figure 2(b) respectively where the error bars represent one standard error about the mean in either directions.

Further, variability in overall annual and monthly average effluent BOD was analyzed. The results from a box and whisker diagram[4] showed higher variability using data for all years as compared to data with year 2015 excluded from the dataset, and this is shown in Figure 3(a) and Figure 3(b). With all years considered, the 75th percentile of overall annual and monthly average effluent BOD was below 50 mg/L with few effluent observations beyond the desired value of 60 mg/L.With data from the year 2015 excluded from the analysis, the annual and monthly average effluent BOD was below 60 mg/L with 75th percentile of observation below 45 mg/L and a mean of approximately 40 mg/L.

[3] The red color dashed horizontal line in Figure 2 and Figure 3 represents the required effluent BOD limits (60 mg/L) for reuse.

[4] The central rectangle represents the interquartile range (IQR) with segment inside the rectangle representing the median. The whiskers above and below the box show the location of the maximum and minimum. And, any data points 1.5*IQR or more above the third quartile or 1.5*IQR or more below the first quartile are considered as outliers.

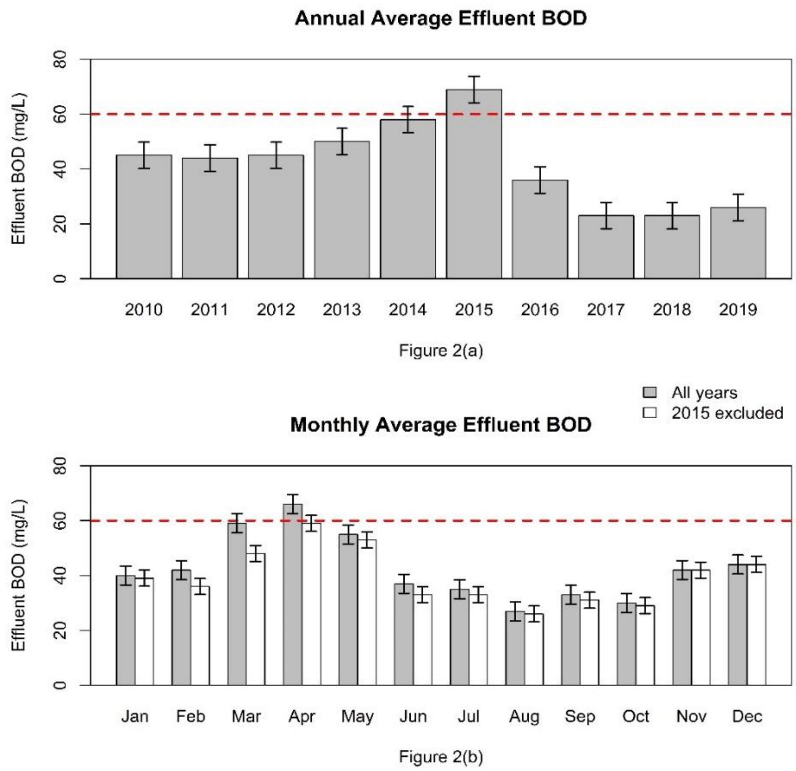

Figure 2: Annual [2(a)] and monthly [2(b)] average effluent BOD

Lastly, the monthly variability in effluent BOD was observed for both cases as discussed above. The results from both the analysis with year 2015 [(Figure 3(c)] and without year 2015 [(Figure 3(d)] showed similar variability but with lower deviations when 2015 was excluded. The months of March[5], April and May have the largest variability followed by November and December. One possible explanation for the variability in months April and May could be the increase in algal growth following the increase in surface water temperature of the pond [80-83]. In addition, there could be a turn-over of the dead algal biomass that has settled to the bottom of the outer pond because a similar situation, on a lesser scale, occurs in November and December.

[5] Reduced variability with year 2015 excluded as some values are recognized as outliers represented by hollow circles in the plot.

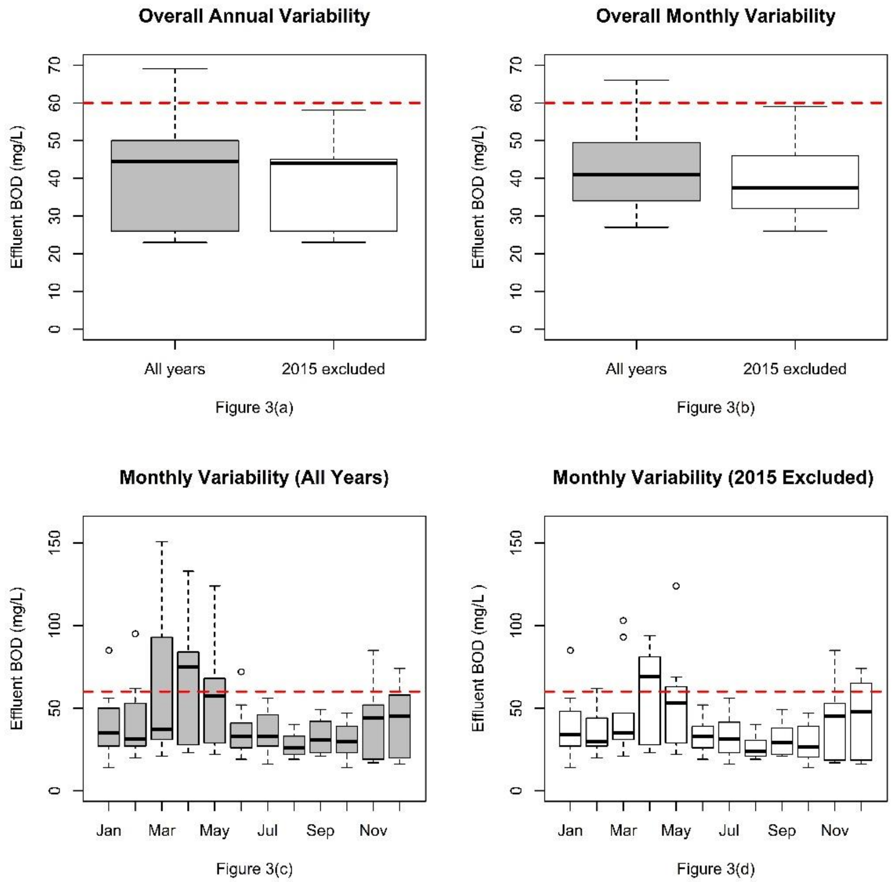

Figure 3: Variability in average effluent BOD [3 (a) & 3(b) - Overall annual and monthly variability, 3(c) & 3(d) - Monthly variability with all years' data and with year 2015 excluded]

6. Discussion

Design parameters for ponds are limited primarily to the area-loading criteria. That is, at best, a rule-of-thumb design process with numerous contradictions. The basic area-loading design concepts of facultative ponds have been created using basic performance data, but there are no functional design parameters or kinetic data considered for producing an optimal design. The practice of using the organic loading rates and retention times based upon a regional determinant (North to South) has often been reported as not meeting the effluent standards. Therefore, this should not be used to determine the performance of the treatment system. The regression equations established using the pond dimensions are adequate for preliminary design; however, serious considerations on flow dynamics and environmental conditions are required for the use of such design approaches on a larger scale since extrapolation is not recommended. Design approaches based on first-order kinetic rates and dispersion numbers would, ideally, serve as the best design approach; yet, the use of such models is often limited due to difficulty in obtaining needed design parameters, which occur after performance data from the installed ponds are collected. The recent advances in pond design with the application of computational fluid dynamics models and integrated models have helped design engineers better understand the flow dynamics and the effects of pond configuration on treatment performance. However, the applicability of such mechanistic models is questioned due to the lack of model validation and the huge computing power requirements.

Lastly, there exist strong contradictory viewpoints regarding pond dimensions and pond performance. Researchers have opposing claims of hydraulic loading and its relationship to depth. Similarly, some researchers claim pond dimensions such as length-to-width ratio and depth have no effect on pond performance; whereas, others say that the ratio and depth are major design factors. This clearly illustrates that existing knowledge on the design of ponds is inadequate and that more research is required to develop an effective pond design procedure. In addition, when combining this system with a land application system for recycling the effluent, very limited attention has been provided to develop a more optimal designed "system."

The PIP system studied produced the average annual effluent BOD of approximately 40 mg/L which clearly shows that PIP systems can be used for reuse systems. The PIP concept includes flow diversion within the pond while increasing solid retention time. This improves performance. Furthermore, the configuration of the PIP helps reduce the land area required as compared to conventional pond systems for the same level of treatment. This is, therefore, a lower-cost treatment system. The authors of this paper suggest use of the Pond-in-Pond approach for the treatment of municipal wastewater prior to its reuse. The authors firmly believe that this system given proper research and a more in-depth study on pond configuration could be a more appropriate treatment system in the future.

7. Conclusions

Currently, there is no design approach that adequately predicts output performance of facultative ponds. In addition, there is no agreement on the pond configuration required for optimal performance. The best next-step is to take a totally different approach in the configuration of the pond by using the Pond-in-Pond (PIP). The PIP is a treatment technology in which two types of ponds--anaerobic and aerobic--are combined into a single pond. The PIP consists of a deeper inner section entirely submerged within the outer pond and is a simple, low-cost and low-energy system.

The performance data from an existing PIP system and the results presented on the CFD analysis on baffled ponds indicate that the PIP configuration can be a potentially viable system for wastewater treatment where effluent reuse is utilized. Average annual BOD levels in the effluent are below 40 mg/L, which is more than sufficient for land application and crop production. Such systems have applicability especially in small and rural communities due to their low capital and operation costs. The PIP with water reuse is also believed to offer a sustainable solution to the water shortage issues found in many parts of the world where most of the available freshwater is consumed for crop production.

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Author Agreement/Declaration

All authors have seen and approved the final version of the manuscript being submitted. They warrant that the article is the authors' original work, hasn't received prior publication, and isn't under consideration for publication elsewhere.

Declaration of Interest

There are no conflicts. There's no financial/personal interest or belief that could affect the research's objectivity.

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