

Article

From Scarcity to Abundance: Nature-Based Strategies for Small Communities Experiencing Water Scarcity in West Texas/USA

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Abstract: Water scarcity is one of the global challenges that threatens economic development and imposes constraints on societal growth. In the semi-arid expanse of West Texas, small communities are struggling with both growing populations and decreasing water resources in the regional aquifer. This study compares two nature-based methods that could solve this problem. The first approach uses ponds and wetlands to make natural processes work together to treat the wastewater that the community receives. We applied a novel Pond-in-Pond system, which offers advantages compared to conventional pond system configurations. This system unlocks strategic hydrodynamic advantages by introducing a deeper anaerobic pit surrounded by berms, which then outflows into a larger pond. The second approach consists of an alternative strategy which integrates waste stabilization ponds, a storage basin, and the reuse of wastewater for crop irrigation—a feat that not only treats water but also enriches soil fertility. Both approaches were analyzed in terms of economic potential and pollution control. The land application had a better return on investment and emphasized the importance of innovative solutions for sustainable water management in arid regions, offering economic and community benefits. The application conveys a clear message: where water is scarce, innovation can grow; where problems are big, solutions are available; and where nature's processes are understood, they can be used.

Keywords: Pond-in-Pond system; wetlands; nature-based solutions; water reuse; wastewater treatment



Citation: Silva Junior, L.C.S.d.; Costa, D.d.A.; Fedler, C.B. From Scarcity to Abundance: Nature-Based Strategies for Small Communities Experiencing Water Scarcity in West Texas/USA. *Sustainability* **2024**, *16*, 1959. <https://doi.org/10.3390/su16051959>

Academic Editor: Kaan Yetilmezsoy

Received: 16 January 2024

Revised: 22 February 2024

Accepted: 24 February 2024

Published: 27 February 2024



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1. Introduction

When considering water scarcity and growing concerns about sustainability, water resource management is crucial for achieving Sustainable Development Goal 6, which targets access to water and sanitation for all by 2030 [1]. Nevertheless, supplying an adequate quantity of water with suitable quality has proven to be a challenging task for many governments. Water scarcity occurs when the demand for water exceeds its availability [2,3]. However, the discussion on water demand remains an open topic, primarily approached in the context of real needs and water efficiency [4]. Beyond its tangible aspects, the social construction of water scarcity significantly influences how societies perceive, discuss, and respond to this challenge [5]. The discourse surrounding water scarcity encapsulates the ways in which societies conceptualize and communicate about the availability, distribution, and management of water resources [6]. This approach is not merely a reflection of objective water availability; it is intertwined with societal values, power dynamics, and cultural narratives [7]. These narratives often surpass scientific assessments, incorporating cultural, political, and economic factors [8].

For example, in India, water scarcity is not solely a result of physical shortages but is also linked to issues of governance, unequal access, and power dynamics [9]. Similarly,

in Jordan, the world's second most water-scarce country, the narrative of water scarcity is shaped by geopolitical tensions, regional conflicts, and historical water use patterns [10]. Addressing disparities in water distribution and equity across societies requires an in-depth analysis of water management practices and current allocations to identify beneficiaries, excluded groups, and marginalized communities [11], extending beyond the singular focus on water insufficiency [12]. These concepts extend to water quality [13], since access to water is limited if the available water does not meet quality standards for societal uses. In some instances, researchers have pointed out how the perception of water can be used to justify the monetization of water services [14,15]. Regardless, addressing water-related challenges should be approached with a sustainable perspective.

The increasing demand for water for human consumption, industrial, agricultural, energy, and ecological activities has been driving innovative and sustainable practices. Among the various water uses, agriculture accounts for a substantial portion of the demand, responsible for approximately 70% of global consumption, reaching 80% in South America and 90% in South Asia [16–18].

A forward-looking strategy to address agricultural water use efficiency is imperative for sustainable practices. Future trends underscore precision agriculture technologies [19], smart irrigation systems [20], and data-driven decision making processes in optimizing water application, minimizing waste, and maximizing crop yields [21]. Complementing these technological advancements, strategic research and development investments in water-efficient technologies [22], the promotion of drought-resistant crops [23], and the adoption of advanced irrigation practices [24] are critical components. Especially in arid regions, where rainfall and surface water resources are scarce, underground aquifers emerge as a predominant water supply alternative, particularly important for agricultural activities [25]. However, the overexploitation of these aquifers frequently exceeds their natural replenishment capacity, resulting in water level depletion and subsidence [26,27]. In the United States of America, the Ogallala Aquifer provides water for agriculture in eight states of the country [28], with important effects on the economy [29]; but the aquifer has experienced water depletion over the years, gaining attention from scientists [30,31] and demanding management actions and new solutions [32].

A promising approach to address water scarcity can involve the implementation of sustainable practices in wastewater treatment [33]. Rather than discarding the treated wastewater, the growing practice of agricultural reuse highlights the potential to effectively treat wastewater and promote a sustainable approach to the effluent by irrigating crops [34].

Waste Stabilization Ponds (WSP) are nature-based solutions that treat wastewater and are still largely used, especially in small and rural communities. This technology relies on large residence times to settle particles and to biologically degrade organic material present in the municipal wastewater with microorganisms. Several authors have investigated possible configurations of ponds in terms of area loading, volume, residence time, biokinetics, etc., [35] as well as the hydrodynamic conditions of these systems and the influence of effluent input on recirculation patterns and treatment efficiency [36]. An innovative configuration identified in the literature involves a pond with a deeper sub-basin near the inlet [37], subsequently enhanced through the incorporation of berms [38] and increased depth at the center of the pond, giving rise to the Pond-in-Pond (PIP) concept [39].

The PIP concept offers advantages such as low operational cost and higher long-term effluent quality reliability with significant organic matter reduction. The treated water can be utilized for agricultural irrigation or further treated and discharged into water bodies. Drawbacks of unplanned water reuse for irrigation include potential chemical and biological contaminations [40], and soil salinity increases due to accumulation of the salts present in the recycled water in the soil, which adversely affects plant growth [41]. Thus, it is crucial to develop appropriate engineering systems and management practices. Adequate monitoring and maintenance are also essential to ensure the efficiency of the process and the compliance with environmental standards.

There are three main land application processes [35]: slow rate, overland flow, and rapid infiltration. Slow rate involves applying effluent to vegetated soil for filtration, achieving high removal rates for organic matter, nutrients, and pathogens. However, it requires better pre-treatment, moderate soil permeability, and a large area. Overland flow systems apply effluent over plants, resulting in lower removal efficiencies. This method has a higher loading rate, requiring less area and pre-treatment. Rapid infiltration applies wastewater to a basin for percolation, working well with highly permeable soils and requiring no vegetation.

Besides appropriate engineering design, financial viability in wastewater treatment is crucial to ensure long-term operations. When comparing different solutions, it is essential to consider not only the initial installation costs but also the ongoing operational and maintenance costs over time. Nature-based treatment systems offer long-term economic benefits by reducing operational costs such as energy, personnel and chemical costs. Additionally, reusing treated water for non-potable purposes, such as crop irrigation, can generate income for the municipality [42]. When assessing financial viability, it is also important to consider the environmental and social benefits provided by alternative wastewater treatment solutions.

A gap in the literature has been identified, where few studies comprehensively address both engineering and financial feasibility aspects related to sustainability in wastewater reuse for agricultural irrigation. An interdisciplinary approach is crucial for developing effective and realistic solutions that can be applied in the real world. Integrating technical expertise with economic analyses collaborates in developing sustainable strategies that are technically efficient, environmentally sound, and economically viable, thereby generating social benefits through support for small rural families.

In this context, the aim of this study is to evaluate the engineering and financial feasibility aspects of two nature-based methods for wastewater treatment and reuse. The first method focuses on treating the wastewater in a PIP system, followed by constructed wetlands to polish the effluent for discharge. The second also uses the PIP, to reduce the organic matter, followed by a storage basin, to provide year-round water storage, and an engineered wastewater reuse system for alfalfa irrigation using the treated water that contains nutrients to enhance soil fertility. Economic potential and pollution control were evaluated for both methods.

2. Materials and Methods

The methodology involves three key steps for effective project planning: first, define design parameters to establish project specifications; next, estimate costs for a realistic financial overview; finally, perform a financial analysis to evaluate economic viability. The project incorporates sustainability considerations across social, environmental, and economic dimensions to ensure a comprehensive and responsible design.

2.1. Study Area

The northwest part of Texas is a vast region characterized by a flat and elevated landscape that stretches for hundreds of kilometers. Rainfall is generally limited and irregular, making water management an important aspect for agriculture and daily life. The state of Texas, in general, exhibits a significant variation in precipitation, with annual average precipitation (Figure 1) ranging from 61 inches in the coastal region, gradually decreasing to 18 inches in the northwest region, and 9 inches in the extreme west.

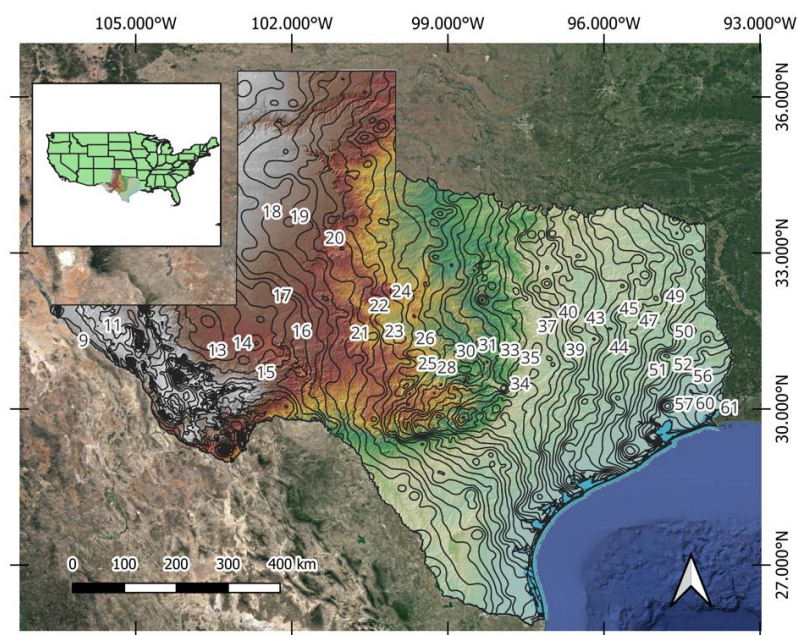


Figure 1. Annual average precipitation isolines, in inches per year, from 1981 to 2010. Public data obtained from the Natural Resources Conservation Service (NRCS).

Agriculture in the northwest region plays a significant role in the regional economy, with farms dedicated to the production of cotton, livestock, and grains. The population is generally dispersed, with smaller towns and rural communities distributed across the territory. Prominent cities in the region include Lubbock, Amarillo, and Abilene. The area is also known for the Ogallala Aquifer (Figure 2), an underground source of freshwater. However, overexploitation and the growing demand for water pose challenges to the sustainability of the aquifer. Figure 2 highlights water extraction wells in the region, obtained from The Texas Water Development Board (TWDB), Drillers Report (SDR) Database, with records of approximately 117,000 wells in the Texas portion of the Ogallala Aquifer.

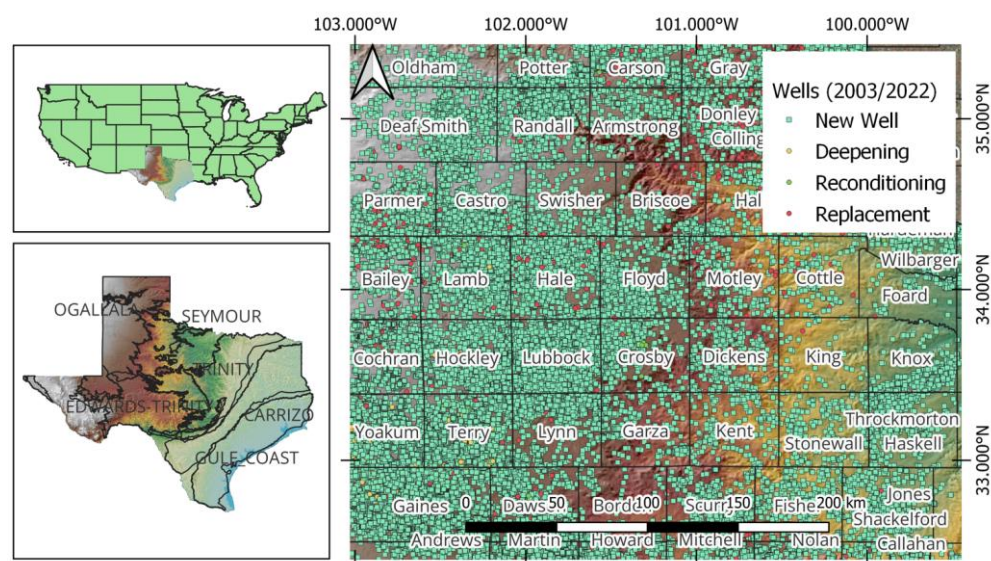


Figure 2. Location map highlighting northwest Texas, cities, and water abstraction wells relying on the Ogallala aquifer.

2.2. Population Estimative

Based on census data from 2020, the West Texas region, limited to counties with a population ranging from 1000 and 100,000 inhabitants, presented an average population of 7791 for the reference year. The region has been experiencing an annual population growth rate of 4.1% [43]. Projecting over 20 years, the average population will reach 17,108 inhabitants.

According to Texas Water Development Board [44], water consumption in Texas averages 86 gallons (325 L) per capita per day. Considering an 80% return rate, the daily production of wastewater for the average population would be 0.53 MGD (23.2 L/s) and would reach 1.18 MGD (51.7 L/s) in year 20.

2.3. Nature-Based Solutions for Wastewater Treatment

The nature-based solutions used for municipal wastewater treatment explored were the Pond-in-Pond systems, free water surface constructed wetlands (FWS-CW) for stream discharge, and land application systems for effluent reuse. Pond systems provide extensive suspended solids and Biochemical Oxygen Demand (BOD) removal and are primarily used as the main treatment unit for small municipalities. BOD and total suspended solids are the only effluent limitation parameters for stabilization ponds, according to Texas Commission on Environmental Quality (TCEQ) standards [45]. Moreover, BOD is the only recommended parameter, according to the United States Environmental Protection Agency (EPA) [46], for land application.

Although ponds are largely used as the main treatment unit, it can be challenging to achieve year-round consistent BOD removal in ponds. Therefore, an additional unit is usually added downstream to improve wastewater treatment. The most suited nature-based solution for a wastewater treatment unit to polish pond's effluents is constructed wetlands.

Pond and wetland operations are simple and are based on physical processes. In the anaerobic pit of the PIP, solids settling is the predominant process, whereas in the outer pond, the wind-driven aeration promotes oxygen transfer, and, therefore, the oxidation of organic matter. In wetlands, the adsorption of contaminants in macrophytes is the major process.

2.4. Pond and Constructed Wetland Designs

The PIP designed for both solutions has a design similar to the system studied by Adhikari and Fedler [39], also located in Colorado City, a small city in West Texas. The geometrical configuration for the PIP was a squared pit, with a 1:1 Length-to-Width Ratio (LWR) and 6 m depth. The outer pond was designed with a 3:1 LWR and 3 m depth, and the walls had a 3:1 slope factor. The drawings were presented in previous publications [35,38], and a picture of this PIP system was presented by Silva Junior and Fedler [36].

Adhikari and Fedler [39] assumed the incoming influent had 200 mg/L of BOD concentration. The Pond-in-Pond was designed according to Adhikari and Fedler [39] with an anaerobic pit and an outer pond. The anaerobic pit, responsible for settling most of the suspended solids, was designed with a 2-day Hydraulic Retention Time (HRT). Additionally, based on these authors, it was estimated that this pit would remove 45% of the organic matter, in the form of BOD. The outer pond was designed using an iterative model to estimate the necessary time to simulate the biodegradation of BOD to reach below 40 mg/L, using a first-order decay model ($C = C_{in} \times e^{-kt}$). Based on empirical results, these authors analyzed the PIP's performance over the years, and accounting for seasonal variations, such as wind conditions, a biokinetic coefficient was estimated. When adjusted for the lowest regional temperature, 5 °C, this coefficient was 0.069 d⁻¹.

Although an effluent with 40 mg/L of BOD is below the recommended BOD concentration of 100 mg/L by EPA [46], it is not yet suitable for discharge, according to TCEQ standards, which recommend 30 mg/L of BOD [45]. Therefore, for stream discharge, an additional treatment unit would be required. The wetland design was designed according to Reed et al.'s (1995) [47] procedure to dimension FWS-CW. This wetland was designed

with a 3:1 LWR and 0.67 m depth. The assumptions were an influent BOD of 40 mg/L, as previously calculated for the PIP, a desired effluent of 20 mg/L for discharge, a media porosity of 0.65, an initial influent temperature of 5 °C, and a biokinetic coefficient of 0.68 day⁻¹. Lastly, the design was checked for ice formation, summer condition, and hydraulics.

2.5. Land Application Design

The land application system used the final projection of inflow and was designed for 1.25 MGD (54.8 L/s). It assumed a salts concentration of 500 mg/L, electrical conductivity with a 10% decrease in production of 3.4 mmhos/cm [48], and climatic data for the city of Lubbock; the evapotranspiration calculation was based on the Penman–Monteith model, proposed by the FAO [49] and used in studies [50–52] around the world, and the crop evaluated was Alfalfa.

Although the TCEQ [46] requires its standard model for the design of land application, it is very conservative and does not account for storage in the vadose zone. This method promotes larger land areas and storage volumes, which increases the capital costs. On the other hand, the Texas Tech University (TTU) method, introduced by Fedler and Borrelli [39], was presented as an alternative water balance approach. It was later improved by Fedler [35] to include nitrogen and salt.

$$SM_i = SM_{i-1} + P_i + I_i - ET_i - L_i \pm S_i$$

where SM_i represents the soil moisture in month i ; SM_{i-1} is soil moisture in the previous month, $i - 1$; P_i is the precipitation in month i ; I_i is the irrigation provided to the crop in month i ; ET_i is the calculated evapotranspiration for month i ; L_i is the amount of leaching to the groundwater for month i ; and S_i represents the water going in and out of the storage unit. All units are expressed length of water per time, e.g., m/month.

As described by Fedler [35], this method offers a lesser storage requirement, decreasing the construction costs; yet it requires the largest land area, promoting more land to grow crops. Moreover, this method offers the advantage of considering nitrogen uptake, therefore, reducing groundwater contamination risks, and it accounts for salts balance, which can severely impact the crop yield. This is also a sustainable method because it uses the vadose zone to store water, reducing pond requirements and water losses to evaporation.

The crop selection was based on the regional perspective to achieve a crop that is usually grown in the area and yields a competitive selling price to maximize the revenue income to the land application system. Based on local observations, alfalfa crops are significantly grown in the region, can reach up to 4 cycles per year in the area, and have a high selling price, when compared to other crops.

Nitrogen was also simulated to prevent groundwater contamination by nitrate, which is the soluble fraction of nitrogen. The model assumes effluent nitrogen concentration from the pond system of 30 mg/L of N as total nitrogen, 400 lb/ac (44.8 g/m²) of nitrogen uptake by alfalfa [49], the effluent flowrate applied for irrigation, and the land area for each phase.

Additionally, the salts balance was considered to prevent soil salinity from excessively deteriorating crop efficiency. The salts modeling was carried out by calculating the leaching rate according to FAO [49] standards and assuming 500 mg/L of total salts concentration in the effluent.

2.6. Financial Estimations

From the design calculations, estimating a median land price of USD 1880/acre (USD 4665/ha) [53] in the West Texas region and USD 4250/acre-ft (USD 3.4/m³) for excavation costs [54]. An additional 50% was added for areas in both ponds and wetlands to allow for sloping walls, driveways, and setbacks.

There was a projected yield of 7.2 tons/acre-year (17.8 tons/ha-year) [55], USD 217/ton of alfalfa hay in Texas [55], and a historical difference in Consumer Price Index (CPI) and Producer Price Index (PPI) of 0.60% [56] to compare the cash flow between inflation and producing goods over time.

3. Results

Based on the design premises, both systems were modeled and designed to achieve their goals: (1) polish and discharge the effluent in a stream, and (2) store and irrigate an alfalfa crop. Thereafter, the land application design selection and financial evaluation were performed.

3.1. Stream Discharge System

As a result of the design calculations and assumptions, a total of two Pond-in-Ponds were implemented. The PIP dimensions (Figure 3) were 240 m in length, 80 m in width, and 3 m in depth, and the anaerobic pit was designed with a 6 m depth. The first was implemented in year 0 of operation and the second one after 5 years of operation to handle the growing influent flow until year 20. Based on those dimensions and the adjusted kinetic coefficient, a 40 mg/L effluent concentration and below would be achieved throughout the lifespan of the system, considering the flow variations and ponds' construction.

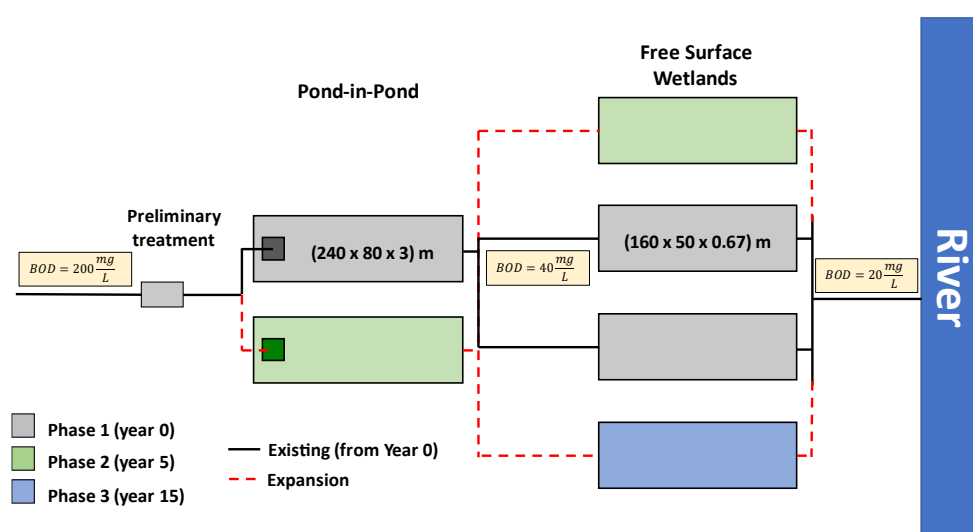


Figure 3. Stream discharge system conceptual design representing a preliminary treatment, comprising a screening process, Pond-in-Ponds reducing the wastewater BOD under 40 mg/L, and the free water surface wetlands polishing the effluent under 20 mg/L to discharge in a surface water.

For the second system, the constructed wetland with free water surface, the dimensions designed were 160 m in length, 50 m in width, and 0.67 m in depth. The filling material considered had 0.65 porosity, and the flows were calculated for summer and winter conditions. The first two cells were designed to be implemented in year 0 of operations, a third one in year 5, and a fourth one in year 15. The calculated dimensions should provide 20 mg/L of BOD consistently throughout the lifespan of the treatment system, below the 30 mg/L BOD concentration for effluent discharge in streams, according to the regulatory limit for nature-based systems in Texas [45].

3.2. Agricultural Reuse System

For the land application system, the PIP system was the same as the previous system designed for the stream discharge system. The land application design was decided upon the evaluation between the two proposed alternatives, TCEQ and TTU methods. The decision was based on reducing the storage volume, which has the biggest impact on the capital costs, and increasing the irrigation area, to increase the crop production and the operational revenue. The TTU method outperforms the TCEQ method in both aspects, with a 16% larger crop area and 42% less storage volume needed (Table 1).

Table 1. Summary on land application methods comparison.

Parameters	TCEQ	TTU	Units
Irrigation area	205 (83)	238 (96)	Acre (ha)
Storage volume	308 (378,000)	179 (221,000)	ac-ft (m ³)
HRT in storage tank	100	58	days

Therefore, for the land application design using the TTU method (Figure 4), a storage pond with 125 acre-ft or 1.5×10^5 m³ was designed with a square configuration and a superficial area of 27,500 m² (165 m × 165 m; water dimensions), an 8 m depth, and a sloping wall of 1:3. The land application site for the crop irrigation was designed to be 238 acre or 9.6×10^5 m² (96 ha).

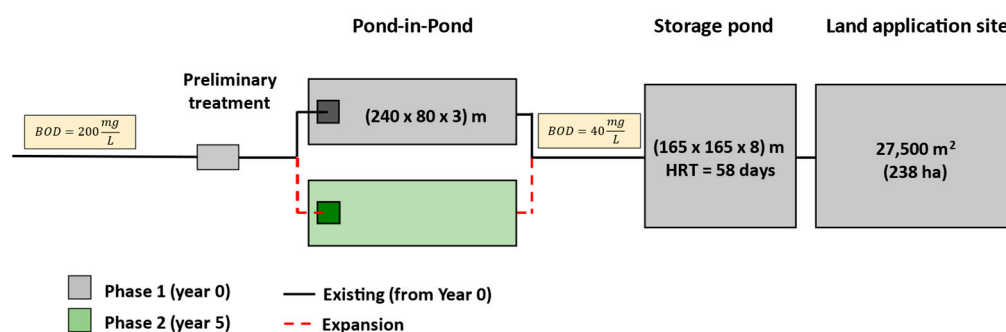


Figure 4. Agricultural reuse system conceptual design representing a preliminary treatment, comprising a screening process, Pond-in-Ponds reducing the wastewater BOD under 40 mg/L, a storage pond to provide year-long water for irrigation and the land application system used to produce alfalfa with reused water.

In addition to the BOD analysis, which is the major requirement from regulatory standards in Texas, the simulated nitrogen uptake was 82% of the potential uptake by alfalfa. This simulation provides evidence that there would be no nitrogen contamination to groundwater due to plants' nitrogen consumption. Lastly, the salts balance performed indicated that the expected crop yield decrement would be under 3%, which is within the recommended range [49].

3.3. Financial Analysis and Cash Flow Projection

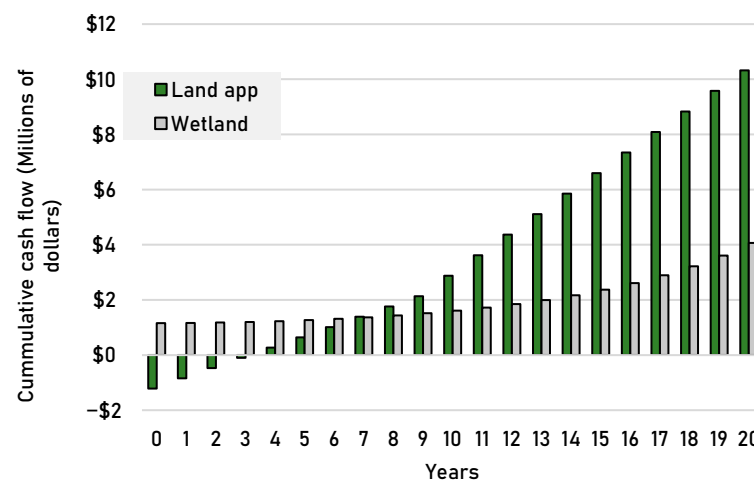
The cost estimation was based on the areas and volumes and is summarized in Table 2. The PIPs have a higher area and volume than the constructed wetlands, which led to higher land and excavation costs. The stream discharge system had a total cost of USD 428,000, while the agricultural reuse system totaled USD 1,585,000, which is over three times the discharge system.

Based on the estimated 7.2 ton per acre-year (17.8 ton per ha-year) alfalfa yield, the land application system would produce 1715 tons of alfalfa per year, on average. At a price of USD 217 per ton, the median for the study area, the average revenue would be over USD 372,000 per year, which would be doubled after year 10, with the projected system expansion.

The financial analysis performed to compare both systems with the cashflow projection (Figure 5) shows the benefits of choosing the agricultural reuse system over the discharge system. With a payback period of 3.7 years after the beginning of operations, the crop irrigation needs a short period to fully offset the initial costs invested.

Table 2. Summary of design parameters and estimated costs for each component in both design approaches.

Parameter	Pond-in-Ponds	Constructed Wetlands	Land Application	Units
Area	9.5 (3.8)	2.4 (1.0)	238 (96)	acre (ha)
Storage volume	80 (98,700)	13 (16,000)	124 (153,000)	ac-ft (m ³)
Estimated land cost	27	7	448	\$1000
Estimated excavation cost	340	55	527	\$1000
Estimated total cost	366	62	1219	\$1000

**Figure 5.** Cashflow projection for both projects over a 20-year period. With a high revenue, the land application system proves to be more profitable over the years.

4. Discussion

West Texas is a developing, very agriculture-oriented region with a semi-arid climate that relies on the Ogallala aquifer as its main fresh water source. With the depletion of this water source over the last few decades, this region needs sustainable solutions to approach water scarcity and sustain its growth [57]. Pond-in-Pond technology is proved to be a more efficient solution for wastewater treatment than conventional ponds. PIPs have been used in some municipalities in the region as the main treatment technology [39].

Constructed wetlands are often used as solutions to polish the effluent before stream discharge [58]. Although not evaluated, constructed wetlands also offer additional benefits such as the removal of nutrients like N, P, and emerging contaminants [59]. Although most treatment systems focus on treating the wastewater for stream discharge, the need to augment the water supplies enforced sustainable solutions to overcome water scarcity [60].

Land application systems represent a sustainable approach to reuse water [34]. The TTU method is a slow-rate system that was superior to its counterpart, the TCEQ's method. Since the TTU method uses the vadose zone for storage, it reduces the surface water storage and evapotranspiration, and allows for a larger crop area, which promotes higher crop production [35].

Moreover, the TTU method controls the nitrogen leaching to groundwater which makes it a safer method, as nitrate contamination is a serious public hazard [61], and is especially important in West Texas, characterized by substantial groundwater abstraction, as displayed in Figure 2. Another important aspect that this land application method manages is the salt balance [35]. Salt control is important to avoid an excessive increase in soil salinity, as it has a significant negative impact on crop production [62].

Although wastewater treatment and reuse are consistently presented as a sustainable pathway, often studies lack financial analysis on its impact, especially for agricultural reuse projects. The financial analysis demonstrates that agricultural reuse, often referred to as non-profitable, when compared to industrial reuse, has a high potential to be explored.

As both systems were designed and the costs were analyzed, the agricultural reuse system had a much higher capital cost when compared to the discharge system. But to analyze the projected costs over time, cash flow analysis highlighted the quick payback period, which is often more than 10 years in municipal projects. This reinforces that this agricultural reuse solution is a profitable approach to valuing water, a resource that is usually considered waste after wastewater treatment.

Small-scale irrigation through wastewater reuse offers substantial advantages for local communities and families, providing a sustainable alternative that positively impacts the local economy. Particularly in communities with limited water resources, it becomes a viable solution, addressing water scarcity and bolstering agricultural productivity [63]. To further enhance the relevance and effectiveness of such initiatives, it is crucial to consider local environmental demands, tailor solutions to the specific needs of each community, and align with regional policies [64]. For example, Israel has been a pioneer in wastewater reuse for agriculture, particularly in arid regions [65]. Similarly, California has introduced decentralized wastewater treatment systems to recover water for the irrigation of landscapes [66].

Agriculture requires effective soil nutrient management for plant development. Among the macronutrients, nitrogen and phosphorus are also found in wastewater [67]. Unlike nitrogen, the limited availability of phosphorus (P) underscores the importance of utilizing the nutrient content in treated wastewater. This approach presents a sustainable method for agriculture while addressing the environmental impact of excessive fertilizer use [68]. Also, the implementation of wastewater reuse systems creates economic opportunities within the community and stimulates new job positions [69], especially for businesses involved in wastewater treatment and irrigation infrastructure.

Despite the benefits of wastewater reuse, it is essential to acknowledge the oversight in assessing nutrient transport post land application of treated wastewater. This aspect is recommended for a comprehensive understanding of the environmental impact, as effective nutrient management can enhance soil fertility and contribute to sustainable agriculture. Policies and regulations present substantial importance to the widespread implementation of wastewater reuse systems on a global scale [70]. Addressing public health concerns and community resistance is also essential for the successful adoption of wastewater reuse systems [71].

The reuse of wastewater can have environmental, economic, and human health impacts [72]. The economic impact is generally positive, as it increases productivity and reduces costs associated with water and fertilizers. From a health perspective, there may be exposure to pathogens and heavy metals. Environmentally, impacts on the soil can occur due to the introduction of salts, increased microbiological activity, and other chemicals in the soil [73].

These factors must be managed in a reuse project. For example, conventional units of wastewater treatment plants often exhibit elevated levels of pathogens [74,75], even after treatment, requiring an additional disinfection step. Conversely, natural ponds contribute to decreased pathogen concentrations through the action of solar radiation [76]. Nonetheless, depending on the intended application, a disinfection step may still be necessary.

One of the problems that can arise from applying wastewater to land for crop irrigation is bad odor; thus, it is important to stress the importance of wastewater pre-treatment prior to its land application. An excess of suspended solids can cause problems in the irrigation system, i.e., blocking the sprinkler head, and organic matter could lead to an odor nuisance. The recommended limit for biological oxygen demand concentration in land-applied effluent is 100 mg/L [77]. On the other hand, even after treatment, some studies have focused on pharmaceuticals, endocrine disruptors, microplastics, and other

chemicals which may be absorbed by crops irrigated with treated wastewater [72,78,79]. While wastewater reuse presents a sustainable water resource, addressing and mitigating potential risks associated with the presence of these chemicals is still an open topic in science frontiers.

In arid lands, where water scarcity and rising costs pose challenges to traditional agriculture, wastewater treatment and reuse gains even more significance. The nutrient-rich nature of treated wastewater becomes particularly valuable, potentially reducing expenses on external fertilizers and fostering agricultural sustainability.

5. Conclusions

The Pond-in-Pond (PIP) system is an established nature-based wastewater treatment solution focused on small and rural communities. The PIP is known for outperforming conventional ponds, given its superior treatment capacity and reliability over time. But most of the research developed over the years only focused on the technical aspect of the treatment, neglecting the sustainable potential this technology has to offer. This technology also offers resource recovery from the PIP, with the nutrient-rich effluent that can be reused in a more sustainable and safe way for crop irrigation.

This study compared two nature-based methods to treat wastewater and addresses water scarcity in small West Texas communities. The first system analyzed was composed of PIP and constructed wetlands to treat and discharge the effluent wastewater into a stream according to state regulation standards. Alternatively, the second strategy utilizes the potential of the effluent to reuse the water for alfalfa production. Although reuse is commonly referred to as a sustainable option, we analyzed its financial feasibility to prove that not only does it provide a sustainable resource, but it also generates revenue for the municipalities.

The land application water balance method selected was the TTU method, which provides lesser storage and increases the productive crop area, it was superior to the TCEQ's method. Cash flow analysis showed that agricultural reuse would be more profitable over the years by generating income that would pay the increased investments back in under four years. This result reinforces the need to promote this technology in small communities that have limited investment capacity and a shortage of specialized labor.

This study is particularly relevant for arid regions, especially those that struggle with water scarcity, such as the ones in West Texas. Sustainable water practices outweigh traditional methods, demonstrating how innovative approaches can tackle water scarcity worldwide.

Author Contributions: Conceptualization, L.C.S.d.S.J. and C.B.F.; methodology, L.C.S.d.S.J. and D.d.A.C.; writing—original draft preparation, L.C.S.d.S.J. and D.d.A.C.; writing—review and editing, L.C.S.d.S.J., D.d.A.C. and C.B.F. All authors have read and agreed to the published version of the manuscript.

Funding: The second author acknowledges the financial support provided by the Brazilian National Council for Scientific and Technological Development (CNPq).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors acknowledge their respective institutions.

Conflicts of Interest: The authors declare no conflicts of interest.

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