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2-D modeling to understand the design configuration and flow dynamics of Pond-In-Pond (PIP) wastewater treatment system for reuse

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Table of Contents

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Abstract

Water reuse for irrigation is increasingly recognized as an essential and economical strategy in areas with water scarcity. A simple, low cost, low-maintenance, and highly efficient Pond-In-Pond (PIP) treatment system can be used for wastewater reuse. PIP is a treatment technology in which two types of ponds -- anaerobic and aerobic -- are combined into a single pond and consists of a deeper inner section entirely submerged within the outer pond. Previous studies on PIPs and PIP-like systems have reinforced the potential for reuse through promising performance results with BOD removal over 80% and a reduction in land area requirements by approximately 40%. Yet, no prior efforts have been made to understand the performance mechanism of such systems. This study makes use of two, 2-D modeling tools in developing a fundamental understanding of PIP flow dynamics and the expected performance. The modeling results showed that the PIP configuration offers improved flow-diversion along with reduced flow velocity. Additionally, the PIP retained approximately 17% more ($p<0.05$) particles than the traditional pond with most of the particles concentrated within the inner pond. Lower velocity and the higher solids retention in the PIP thus allowed for better treatment performance compared to traditional ponds. The findings from this study can be used as preliminary data for future in-depth investigations of the PIP system leading toward effective and optimal designs. This will help address the major societal concern of water scarcity with low-cost and effective wastewater treatment.

Keywords: wastewater reuse; irrigation; sustainability; pond-in-pond; pond configuration; 2-D modeling

1. Introduction

Wastewater is increasingly recognized as an important water, energy, and nutrient resource [1, 2, 3, 4]; reclamation and reuse of such water is much more economical than finding new sources of water [5, 6]. Reuse for irrigation is often viewed as a positive means of recycling water and offers two major benefits – 1) wastewater reuse improves the environment as it reduces the amount of waste (treated or untreated) discharged into water courses, and 2) conserves water resources by lowering the demand for freshwater [7, 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, 11]. Many sources of wastewater are readily available and are produced within close proximity of the crop production operations, thus potentially large volumes of water can be reused [12, 13]. If our crop production systems can adapt to using reclaimed water, we will be able to sustain and possibly increase crop production for a much longer time [14] while continuing to provide adequate potable water.

For land application systems, the effluent quality is less stringent, usually 2-3 times higher than that required for stream discharge [15, 16] thus, the need for expensive advanced wastewater treatment facilities can be diminished through reuse. Considering the reduced cost in treatment plant construction for reuse systems, billions more in capital costs could be saved in the future as the population continues to grow. Several feasibility studies [17, 18, 19, 20] have been completed to quantitatively evaluate economic, environmental and resource availability of water-reuse projects, and the results from such studies have concluded water reuse as a profitable option even under conservative measures. But only 6% in the US [21] and less than 3% globally [22] is reclaimed for beneficial use. This situation exists due to the perceived difficulty of reusing wastewater for agricultural purposes and the lack of a single best treatment technology of wastewater for reuse.

1.1. Wastewater treatment systems

Pond treatment systems have been widely used for treating wastewater because they are lower in capital construction costs as compared to conventional mechanical systems [23, 24, 25, 26, 27]. Ponds used for treating municipal wastewater range from aerobic to facultative to anaerobic [28] and several procedures have been developed to design these various types of ponds [29, 30, 31, 32, 33, 34, 35]. Numerous studies [16, 36, 37] have been done on different pond systems and existing design criteria and their limitations. Many of these pond designs have been in existence for decades, yet there is a lack of design specifications with respect to pond performance. Also, there exist strong contradictory viewpoints regarding pond dimensions as they relate to pond performance [16]. 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.

One of the potentially viable and sustainable treatment technologies could be a simple, low-cost, and low-maintenance natural treatment system known as Pond-In-Pond (PIP). The PIP is a treatment technology in which the two types of ponds--anaerobic and aerobic--are combined into a single pond [16, 28, 38]. The PIP system combines the functionality of two different ponds and provides more efficient conversion of wastewater, including high-strength waste, to end products through the synergistic relationships of the various microorganisms' present. The deeper pond submerged inside the outer shallower pond provides the anaerobic environment required for more complete conversion of complex organic matter. The outer pond with an aerobic surface helps control the odor and allows for aerobic digestion of the volatile fatty acids produced by the anaerobic process. The previous study by the authors [16] provides a detailed discussion of the need for the PIP; and their later article [39] evaluates the applicability of the PIP for effluent reuse in irrigation through analysis of performance data for ponds with similar configurations.

1.2. Pond-In-Pond

The initial concept of the PIP was first considered by Stone [40] in which a small, deeper sub-basin was placed within one corner of a much larger basin. This concept was further advanced by Oswald [38] when 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. Other researchers [28, 41, 42] later adopted the system for treating various types of wastewater ranging from municipal to industrial to animal waste. Thus, far, the concept of the PIP system has been practiced in multiple locations in USA and some other nations such as India, New Zealand, Australia, and Ethiopia [36].

The PIP concept has been adopted for multiple purposes such as stream discharge, energy and nutrient recovery, and reuse of effluent on land application sites. Evaluation of existing PIP and PIP-like systems shows an average BOD removal above 80% while reducing the land area requirements for the pond by approximately 40% [39]. Yet, there has not been significant progress in the identifying design characteristics or configuration of such systems. The latest advances in pond design have been the use of mechanistic modeling tools to describe the process [43, 44, 45, 46, 47]. The use of mechanistic models on traditional pond systems have helped design engineers better understand the flow dynamics and the effects of pond configuration on the treatment performance [48, 49, 50] .

Proper understanding and knowledge of the design configuration and flow dynamics of the PIP will aid in addressing the existing knowledge gap on the PIP. The objective of this research, therefore, is to evaluate the configuration of the PIP to provide basic guidelines for selecting design parameters for such ponds. Additionally, this research aims to simulate the effects of having a deeper basin inside a larger, shallower basin through mechanistic analysis on the PIP configuration. The modeling results will contribute to the understanding of the flow behavior, velocity pattern, and particle distribution in the PIP thus providing a fundamental understanding of why the PIP configuration offered better performance compared to traditional ponds. To the authors' knowledge, this study is the first attempt to investigate the PIP systems using the 2-D modeling approach.

2. Pond-In-Pond design parameters

Oswald [51] adopted the idea of the PIP and introduced a preliminary design guideline. The PIP consists of an inner deeper section as an isolated volume where wastewater solids are collected and remain allowing for more complete degradation of the complex organic matter. One of the simplest design techniques is the septic tank criteria. The inner pond must be sized to have a minimum of 2 days hydraulic retention time. The outer pond is designed with a minimum retention time of 15 to, preferably, 20 days [51], with longer retention times used as the climate changes from warmer to colder temperatures.

Another design technique proposed is the anaerobic loading criteria [51]. This approach takes into consideration the volume for non-degradable materials and grit volume in the inner pond. The maximum permissible organic loading into the ponds is determined based on the

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percentage of solids in the sludge. The volume of the inner pond is the sum of volume required for settleable solids, inert ash volume, and grit volume for the estimated service life of the pond. The outer pond is designed similarly to the septic tank approach. Figure 1 shows the plan and sectional view for the PIP system including some basic design configuration parameters.

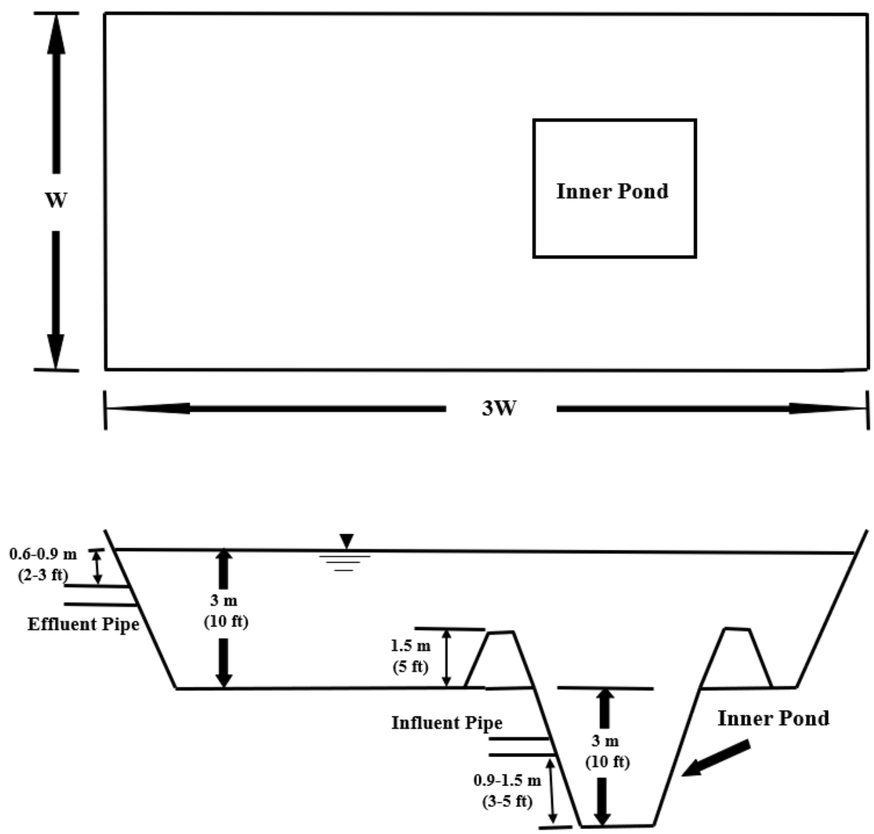

Figure 1: Plan (top) and profile (bottom) of a PIP system (Depths shown are relative)

2.1. Pond configuration

In general, the inner pond is typically designed for a 2-day retention time and with a volume adequate for holding settleable solids, inert ash volume and grit volume for the estimated service life of the pond. Whereas the outer pond is typically designed for a retention time of 10 to 20 times the inner pond retention time, with larger values for cold regions [51].

The inner pond can be of any shape depending on the site conditions. However, based on the design guideline for clarifiers, frusto-conical shapes with sloping sides may provide additional performance benefits [52]. The slope helps reduce the up-flow velocity as the wastewater rises in the pond thus promoting separation of finer solids. The solids then agglomerate and fall to the bottom of pond and undergoes anaerobic degradation. In addition, the reduced bottom area concentrates and reduces the volume of sludge handling thereby reducing the disposal and handling costs [53].

The top surface area for the inner pond is kept small enough, typically 0.1 to 0.16 hectares (0.25 – 0.4 acres), to prevent mixing. The up-flow velocity is typically kept under 2 m/day (6 ft/day) to optimize sedimentation and to prevent most helminth ova and ova cyst from leaving the inner pond [51]. Additionally, the inner pond includes a berm at the top on all sides. These berms act as a barrier to the mixing of the contents of the inner pond that can be caused by seasonal temperature stratification of the water and subsequent wind. Further, these berms serve as a baffle and provides flow diversion thus reducing short-circuiting. The change in direction due to the berms separates the larger mass of sludge flow by inertia similar to that in a clarifier [52]. The pond area and height for these barriers, however, depends on the prevalent wind velocity in the region and can vary.

2.2. Pond depth and orientation

The existing PIP systems typically have depths between 4 m (13 ft) to more than 6 m (20 ft) for the inner pond and about 3 to 5 m (9 to 15 ft) for the outer pond [16, 28, 39, 42]. In addition to more complete degradation of organic matter, the increased depth also provides better control of vegetation and better inhibition of insect breeding. Ponds with shallow depths (<6 ft) have high risk of nuisance and odor problems [54]. The increased pond depth allows for a reduction in the area required for wastewater treatment thus reducing the land area requirements and the capital cost for the system. There exists a strong contradiction on optimal depth for such systems, specifically the inner pond, and a study by the EPA [36] on pond design for the last few decades shows an increasing trend in the adopted depths from about 3 - 4 m (9 – 13 ft) to about 6 - 7 m (19 - 23 ft) in recent years.

The aspect ratio of the pond is often 3:1 for the length: width. This ratio, however, largely depends on the site conditions and can vary accordingly. The inner pond is preferably located on the downwind side of the predominate wind rose for two major reasons – 1) to prevent short-circuiting of the influent and 2) to push the floatable materials away from the outlet. The other important factor in pond design is the location of inlets and outlets and they should be placed to avoid the short-circuiting of the influent. The recommended effluent pipe location is 0.5 to 1 m (2 - 3 ft) below the water surface to avoid discharge of floatable material in the effluent while the influent is introduced into the inner pond 1 to 1.5 m (3 - 5 ft) off the bottom with a concrete pad beneath to prevent erosion of the soil and promote mixing. Gentle mixing of the influent (near the bottom) encourages flocculation of very fine particles [55] and prevents fine solids from escaping into the outer pond.

3. Mechanistic analysis of PIP configuration

The effects of having a deeper basin inside a larger basin was evaluated using 2-D modeling simulation tool. To confirm the validity of the modeling results, the simulation was performed using two different modeling tools – 1) SToRM (System for Transport and River Modeling), available in iRIC [56] and 2) TELEMAC-2D available as a solver package in

TELEMAC-MASCARET [57]. The SToRM model offers improved visualization capabilities while the TELEMAC-2D is best known for its increased compatibility in parameter definition. Both models use the two-dimensional, depth-averaged equations, also referred to as the shallow water equations (SWEs), to simulate surface waters [57, 58]. Depth averaged modeling has been widely used in rivers, lakes, estuaries, and coastal flows, and has been shown to effectively predict flow features.

3.1. Model Development

To comply with the boundary definitions required by the 2-D modeling, the inner pond of the PIP was located at the influent edge such that water flows directly into the inner pond and overflows to the outer pond (Figure 2) compared to the configuration shown in Figure 1. The depths for inner and outer pond sections in the PIP modelled were kept as 6m (20 ft) and 3m (10 ft), respectively. The straight-sided berm around the inner pond was designed at a height of 1.5 m. The influent was fed into the inner pond while the outlet was located at the opposite side of the outer pond. In comparison, the traditional pond was provided with a uniform depth of 3 m (10 ft), and the inlet/outlet were located at two opposite ends of the pond (Figure 2).

For all the simulations, a constant discharge of 10 m^3/s was used as an inflow boundary condition, and a fixed stage of 6 m (20 ft) was used as the outflow boundary condition. The cross-sectional areas for inlet and outlet were approximately 5 m^2 [5 m width with 1 m of water depth] resulting in an approximate mean inlet velocity of 2 m/s. Figure 2 shows the water depths for the PIP and traditional pond.

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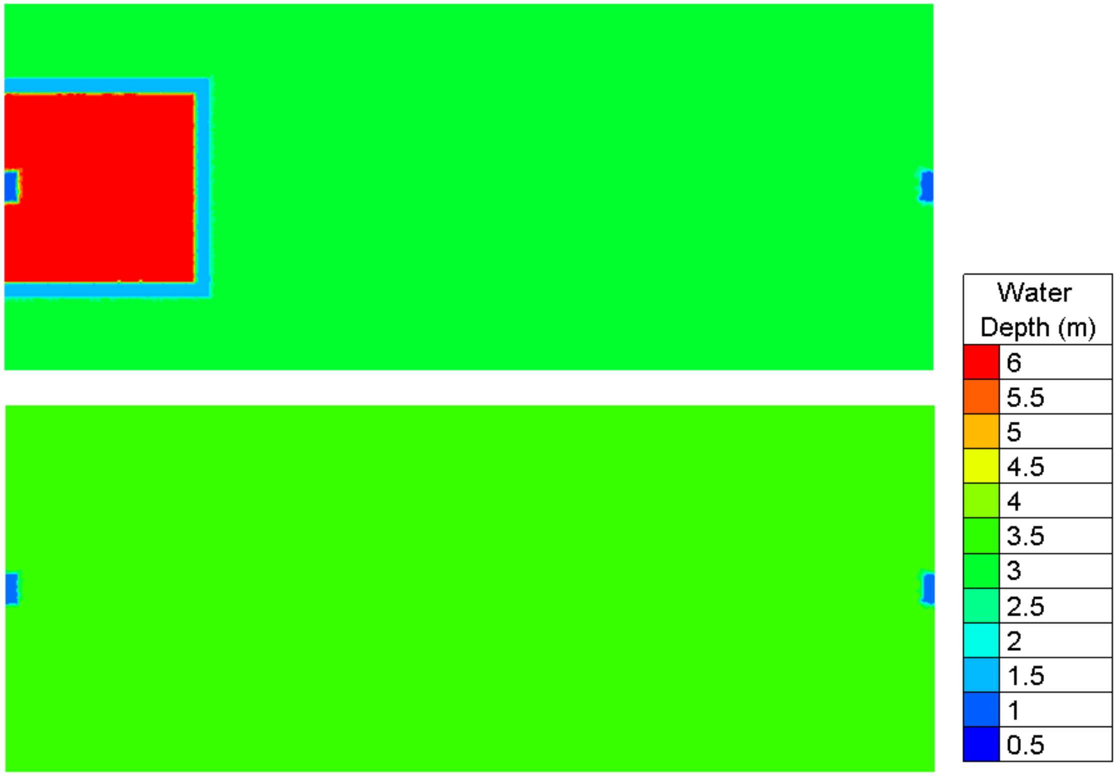

Figure 2: Water depths for the PIP (top) and traditional pond (bottom)

3.2. Results and discussion

3.2.1. Velocity Profile

Figure 3 illustrates the velocity magnitude for both the PIP and traditional pond configurations. In the PIP, the higher incoming velocity is dissipated within the inner pond with significantly reduced velocity in the outer pond as energy is lost when water flows from inlet into the deeper basin and then upward toward the shallow region. The rapid change of flow rate from the inlet into the inner basin and the existence of the berms around the inner basin increase the energy dissipation due to irregular circulation created by velocity jets throughout the inner basin [59, 60]. As a result, the velocity of the water is reduced significantly with better balanced and more stable flow moving into the outer shallow region of the PIP [61]. Such distribution of velocity in the PIP contributes to the higher settling of suspended particles. Conversely, within

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the traditional pond, the incoming higher velocity is propagated over a longer distance with nothing causing a shift in the momentum, thus maintaining a higher velocity of flow toward the outlet [60]. The higher velocity leads to increased particles exiting from the outlet before they can settle. Additionally, a similar run was performed for the traditional pond with a uniform depth of 6 m to evaluate the effects of difference in volume (though negligible as compared to the pond area) between the PIP and the 3 m deep conventional pond. No difference in the flow pattern was observed and the incoming higher velocity dispersed along the pond length as in the pond with a 3 m depth. The results further confirms that the flow dynamics and the reduced velocity in the PIP is primarily due to the configuration of the PIP rather than the increased depth alone.

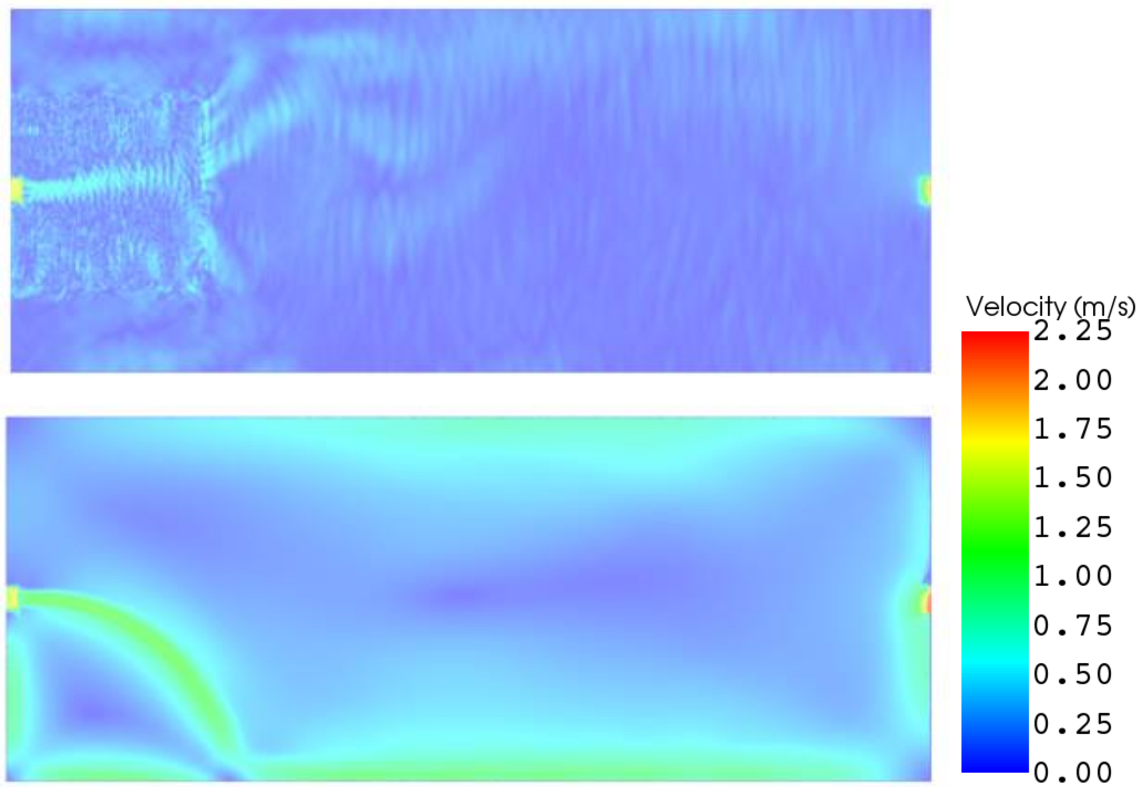

Figure 3: Velocity profile plot from SToRM simulation for PIP system (top) and traditional basin (bottom)

A similar velocity profile was obtained using the TELEMAC-2D simulation as shown in Figure 4. Both modeling tools provided similar results with similar velocity profiles and magnitude as can be seen from Figures 3 and 4. As these modeling tools have been used for the first time in simulating pond-like structures, the two models were used to verify the results. The confirmatory results from both models validate the accuracy and reliability of each of the models for application in future studies on pond systems. Comparisons between two models at different simulation times are provided as supplementary figures in Appendix A (Figure A1 and Figure A2). The supplementary file consists of velocity profile plots for SToRM and TELEMAC-2D

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runs at different simulation times where similar transient flows can be observed throughout the entire simulation period.

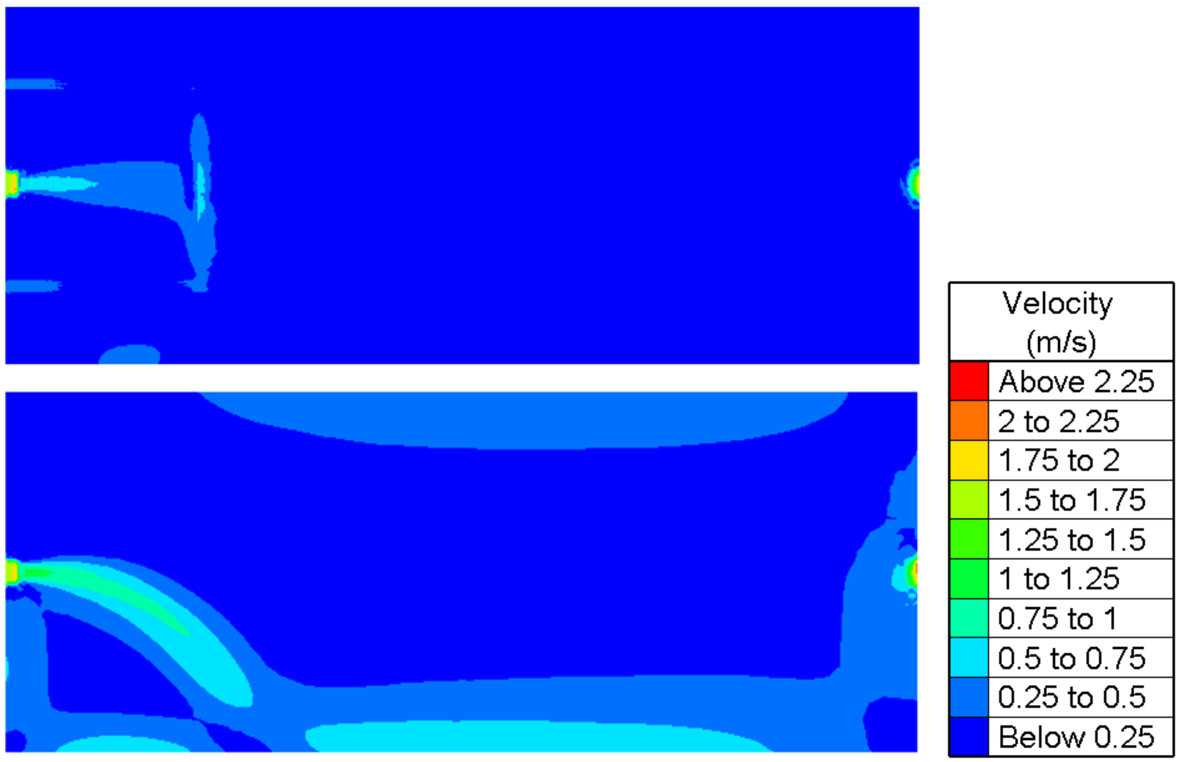

Figure 4: Velocity profile plot from TELEMAC -2D simulation for PIP system (top) and traditional basin (bottom)

Figure 5 shows the corresponding velocity vectors (direction of flow) for the PIP and the traditional pond. The flow is channelized in the traditional pond and it is also observed that the higher velocity in the traditional pond caused the shift of flow toward one edge of the pond creating a rotational movement at the corner of the pond. As high velocity water moves from larger pond area to the small cross-section at the outlet, not all flow can change the direction to exit from the outlet. The flow thus gets diverted back to the entrance of the pond following the path of least resistance (toward one of the edges) in order to increase its specific energy thereby

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allowing the incoming flow to pass through the outlet. This diversion causes water circulation through the pond to the inlet forcing the flow jet to bend toward the edge. Bending of flow creates the vortex at the corner of the pond. Such areas will reduce the effective treatment volume of the pond inhibiting the pond performance due to suspension of the particles caused by vortices. Whereas the flow in the PIP is more uniformly distributed in the outer pond with minimal disturbance as it exits with much lower velocity from the inner pond.

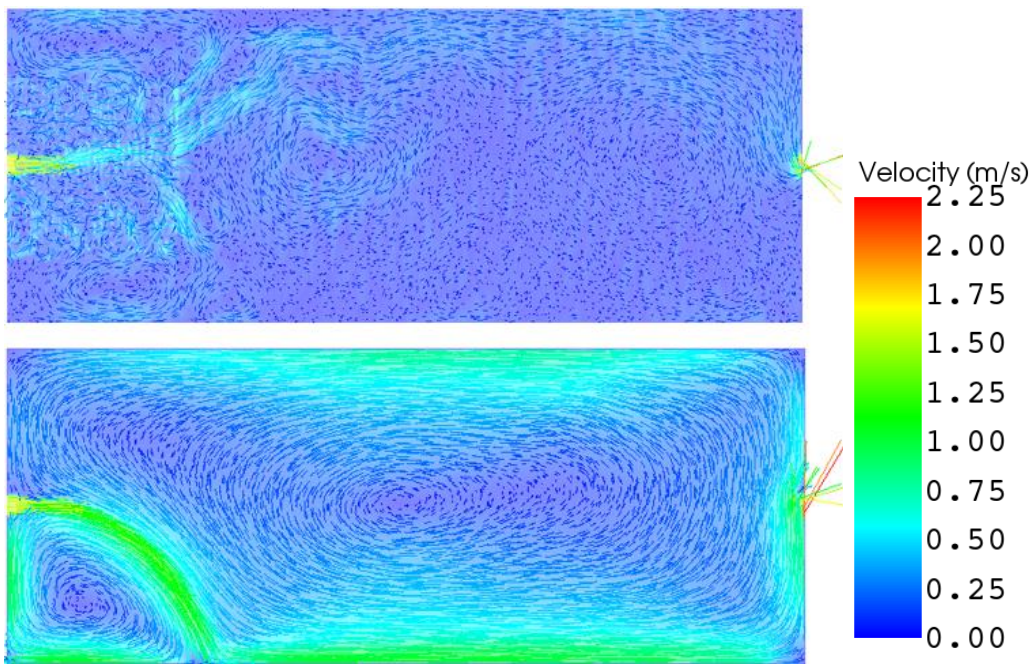


Figure 5: Velocity vector plot from SToRM simulation for PIP system (top) and traditional basin (bottom)

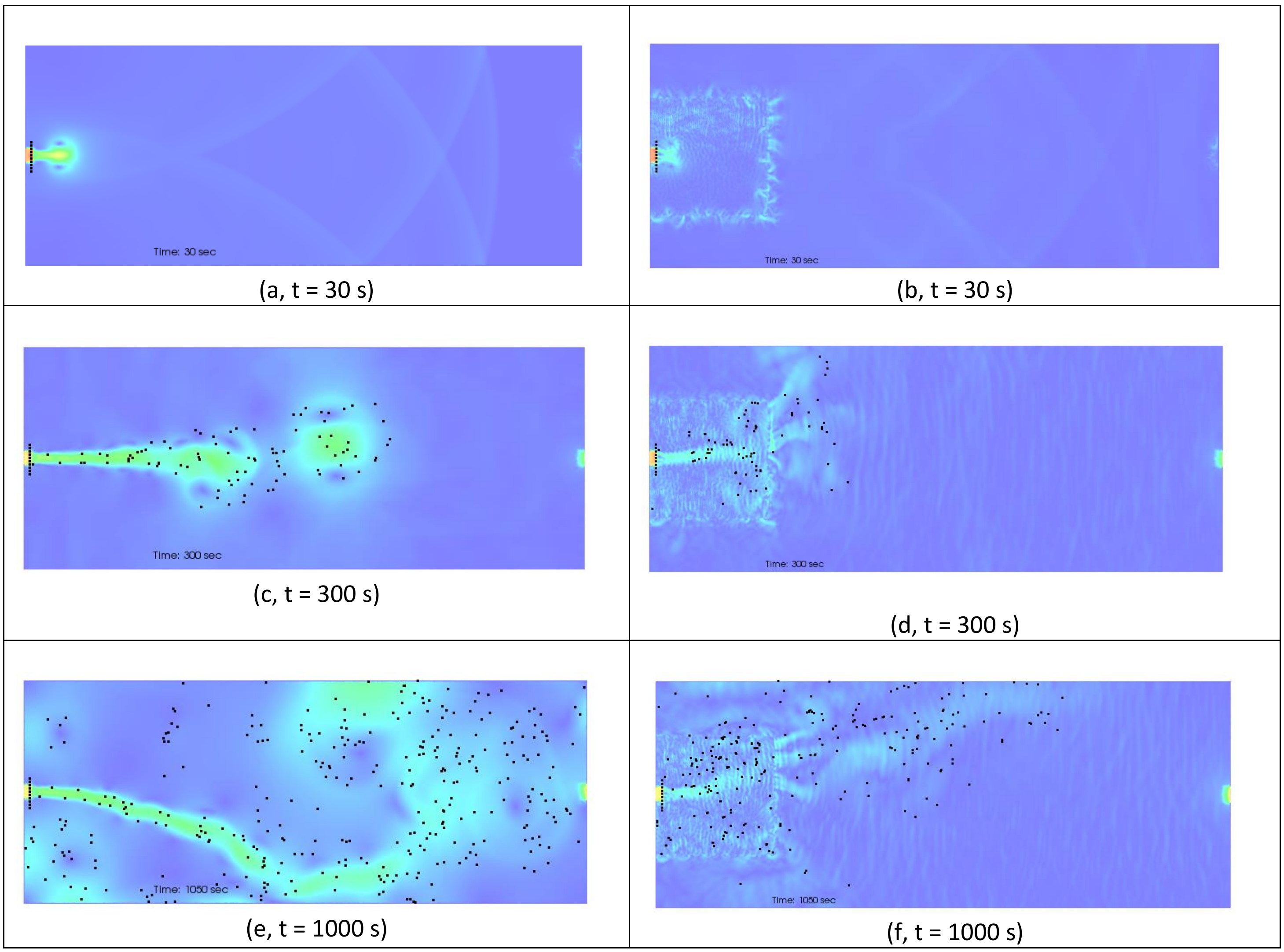
3.2.2. Particle Profile

Next particle movement and distribution within the pond was observed using the particle tracking visualization in the SToRM modeling. Equal numbers of particles (illustration presented for 10 particles) were introduced into both ponds. At every time-step, the same number of new particles continued being added into the ponds. Figure 6 illustrates the distribution of particles in the PIP vs. traditional pond at different simulation times. In the traditional pond, the particles are carried away by the high velocity, and the particles reach the outlet much faster. Whereas, in the PIP, most of the particles are confined within the inner pond and only few particles make their way out. Additionally, the reduced velocity in the outer pond of the PIP inhibits particle movement toward the outlet; and thus the particles tend to settle to the bottom of the pond.

Figure 6a and Figure 6b shows the introduction of particles in the pond. The particles are introduced at the exact same location for both the ponds. After 5 minutes, the particles in the traditional pond have already traveled over half the length of the pond (Figure 6c), whereas in the PIP, the particles have just moved into the outer pond (Figure 6d). At around 16 minutes, the particles in the traditional pond can be seen at the outlet with some particles exiting from the pond (Figure 6e). Whereas, at the corresponding time, the particles in the PIP have just traveled half of the pond length (Figure 6f). It took almost twice the time (approximately 29 minutes) for the particles in the PIP to reach the outlet (Figure 6h) compared to the flow in the traditional pond. Lastly, at the end of the simulation, the traditional pond has particles distributed throughout the pond but with a higher concentration near the outlet and in the circular zone near the inlet (Figure 6i). On the other hand, in the PIP, few particles can be observed at the outlet and most particles are concentrated inside the inner pond (Figure 6j).

The particles count at each time-step was exported from the SToRM model. The exported files consisted of a unique location for each particle along with the total particle count that remained within the pond at a given time-step. Four different cases were used for this analysis where 5, 10, 15 and 25 particles were introduced into the pond. A statistically significant difference ($p<0.05$) in particle retention was observed. In all four cases, it was observed that 16-

18% more particles were retained within the PIP as compared to the traditional pond as shown in Table 1. Based on the higher percentage of retained particles and the reduced velocity in the PIP, it can be assumed that the PIP offers higher potential for particle settlement and, thus, additional treatment. The retention of the particles, however, cannot be considered as settling of the particles in this 2-D simulation.



(a, t = 30 s) (b, t = 30 s)

(c, t = 300 s) (d, t = 300 s)

(e, t = 1000 s) (f, t = 1000 s)

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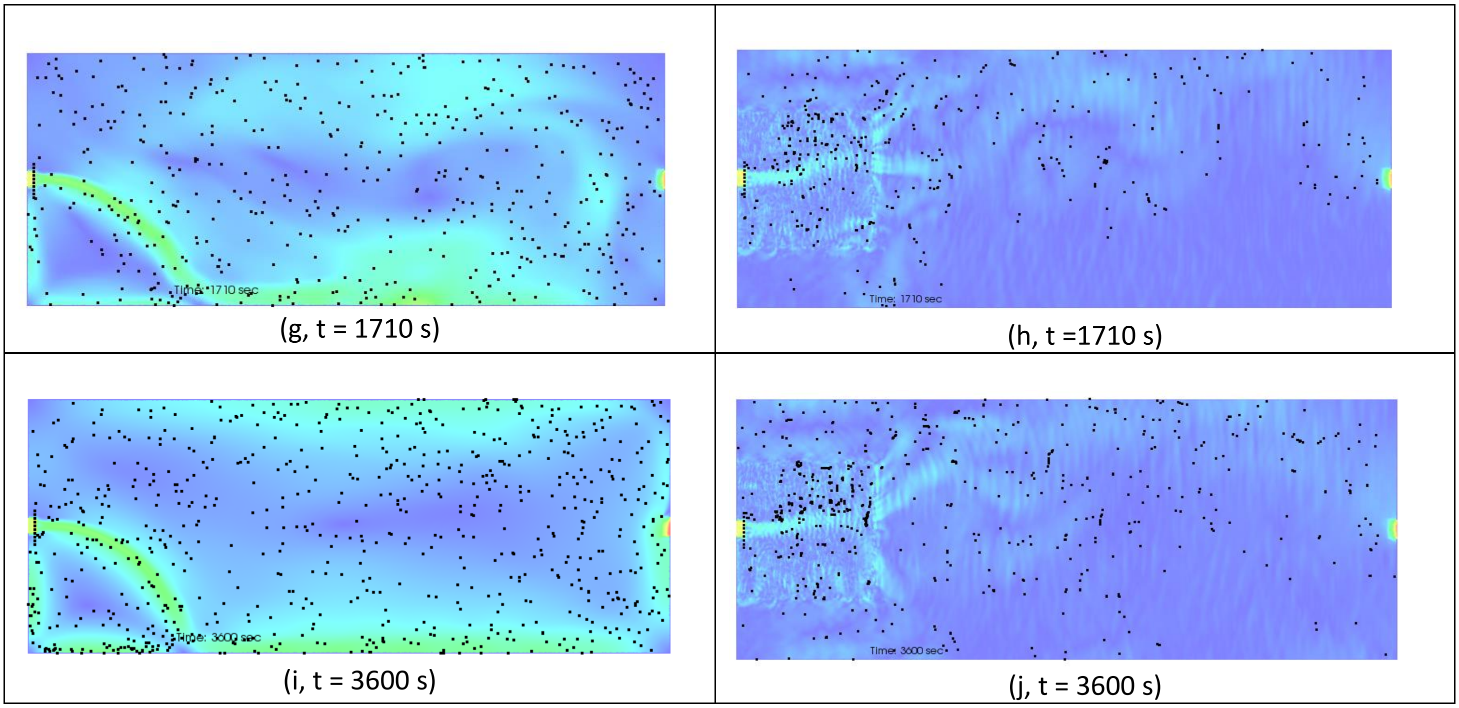

Figure 6: Particle distribution in traditional pond (left) vs. PIP (right) using the SToRM model.

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Table 1: Summary of particles-in and particles retention in the traditional pond vs. PIP

			Traditional Pond		Pond-In-Pond		
Particles-in at each time step	No. of time-steps	Total particles-in	Particles retained	Particles retained %	Particles retained	Particles retained %	% Increase in particles retention
5	121	605	399	66	464	77	16
10	121	1210	779	64	904	75	16
15	121	1815	1145	63	1338	74	17
25	121	3025	1935	64	2282	75	18

4. Summary and conclusions

While many attempts have been made to address the global issues of water shortages, few have considered integrating wastewater reuse and converting those water resources into a safe alternative to freshwater for agricultural irrigation. The integrated approach of natural wastewater treatment along with land application of treated wastewater effluent will provide the world with food while saving potable water for human consumption. Pond-In-Pond (PIP), a simple, low-cost, low-maintenance, and natural system, can provide the necessary level of treatment required for effluent reuse in agriculture. Previous studies on PIP-like configurations have shown the potential for reuse systems through promising performance results with BOD removal of over 80% and a 40% reduction in land area requirements.

The results from the SToRM and TELEMAC-2D models showed that the PIP offers improved flow-diversion with a significantly reduced velocity throughout the pond. The velocity profile and the flow pattern suggest that the PIP configuration has a significant effect on the flow dynamics within the pond and, thus, higher pond performance. The incoming velocity is mostly dissipated within the inner pond of the PIP, and the flow velocity is significantly reduced as it passes toward the outer region. Such reduced velocity inhibits the movement of the particles so more particles would be capable of settling in the PIP as compared to the traditional pond.

Further, as observed from particle distribution plots, most of the particles in the PIP are trapped within the deeper, inner pond of the PIP with fewer particles in the outer region. The settled particles in the PIP undergo anaerobic decomposition under a prolonged solids retention time within the deeper basin of the PIP, thus providing more complete degradation of incoming organic matter.

Modeling the flow dynamics of the PIP is an alternative to the costly field study of the system and can be used to determine a more optimal way to continue this analysis in a 3-D format. In addition, this modeling of the system will allow future research on field sites to be completed more efficiently by identifying specifically the critical components of the system to measure. All of this will then lead to applicable design approaches that can result in the lowest cost with the highest treatment efficiency, thus providing society with a system applicable to more sustainable water reuse.

5. Future recommendations

The 2-D modeling approach has recognized limitations, but it provided an initial understanding of why the PIP system performs better than traditional ponds. Future modeling of the PIP using 3-D computational fluid dynamics is the next logical step in the process of developing an understanding of pond configuration effects on performance. These 3-D results will provide the necessary understanding of how to design the inner pond and the associated berms more

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effectively. Next, the integration of the biokinetics of the treatment process has the potential to contribute to the development of appropriate design procedures for these ponds to be used in any location. Lastly, the integration of a decision-support tool to test strategies for multi-objective optimization will provide a design approach for specific situational needs. Overall, this type of modeling effort will provide a future in which communities can utilize a more sustainable approach to water treatment and reuse that is both environmentally friendly and energy efficient.

CRediT authorship contribution statement

Kushal Adhikari: Conceptualization, Methodology, Formal Analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization.

Clifford B. Fedler: Writing - review & editing, Supervision, Project administration.

Alireza Asadi: Writing - review & editing, Validation, Formal Analysis.

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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, has not received prior publication, and is not under consideration for publication elsewhere.

Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability Statement

The data used in this study can be made available through contact to corresponding author.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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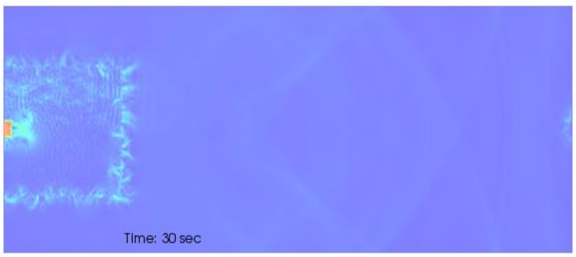
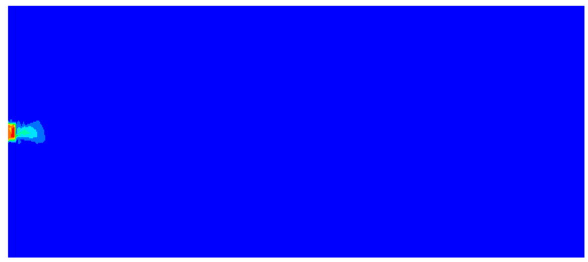
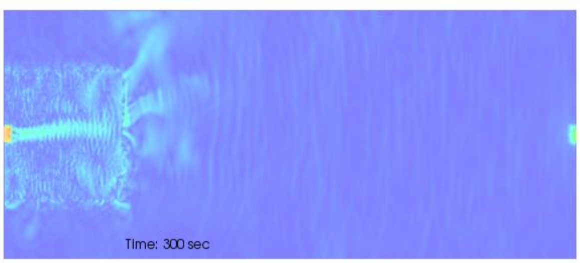
APPENDIX A



t = 30 s

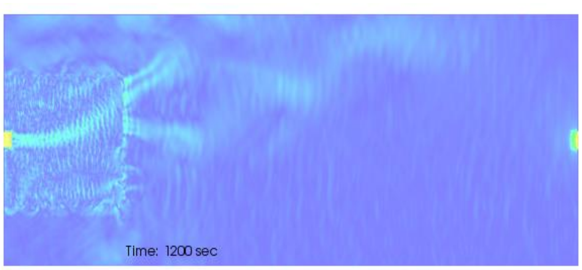


t = 30 s



t = 300 s

t = 300 s



t = 1200 s

t = 1200 s

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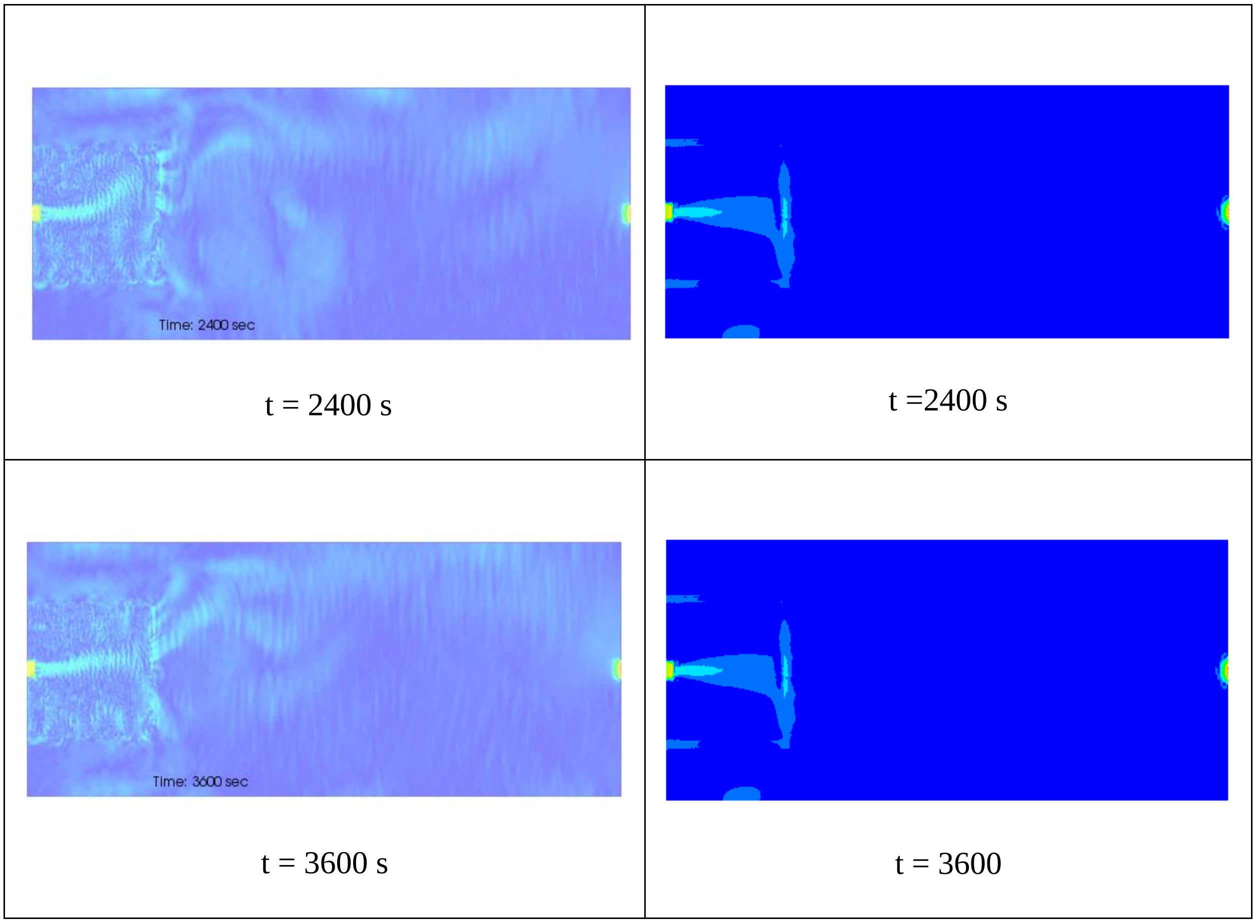

Figure A1: Velocity profile plots for the PIP using SToRM (left) and TELEMAC-2D modeling tools (right) at different simulation times [the color legend is same as in the figures presented in the main text - Figure 3 for SToRM and Figure 4 for TELEMAC-2D].

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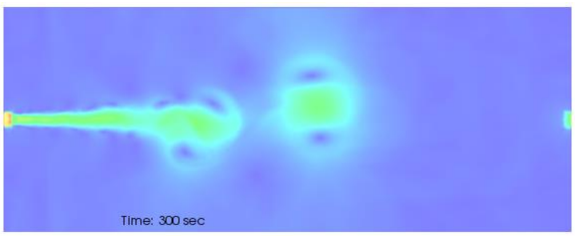
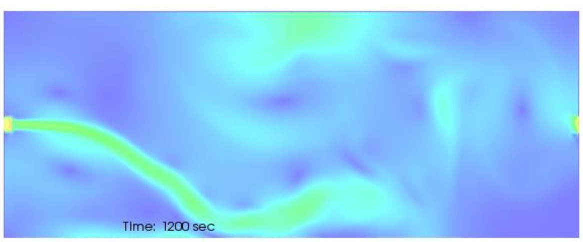
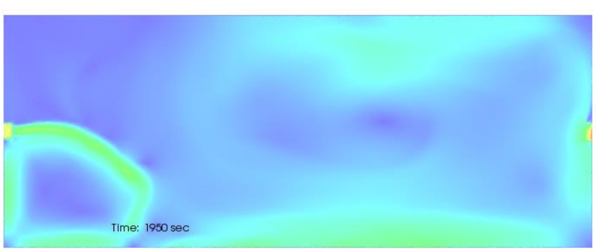
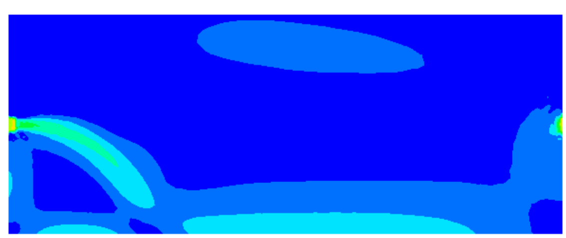
 t = 30 s	 t = 30 s
 t = 300 s	 t = 300 s
 t = 1200 s	 t = 1200 s
 t = 1950 s	 t =1950 s

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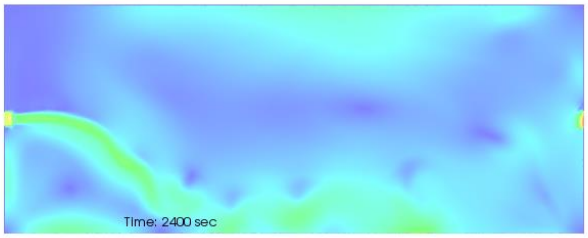
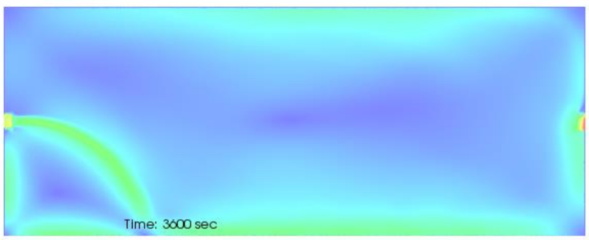
 t = 2400 s	 t = 2400 S
 t = 3600 s	 t = 3600 S

Figure A2: Velocity profile plots for the traditional pond using SToRM (left) and TELEMAC-2D modeling tool (right) at different simulation times [the color legend is same as in the figures presented in the main text - Figure 3 for SToRM and Figure 4 for TELEMAC-2D].