Potential impact of severe weather on hydraulic performance of a field-scale wastewater treatment plant: A case study of baffle-based pond

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Abstract—Water pollution is a relevance problem in Thailand's water resources management. Overall, the current status of the surface water of Thailand is moderate to good quality except that of the central Chao Phraya watershed which deteriorates. This fact indicates that the environmental management policy and wastewater treatment infrastructure of the country may need to be improved for enhancing efficiency in wastewater and stormwater treatment. Focusing on the latter issue, despite significant wastewater contributions from domestic and industrial sectors, establishing and maintaining their wastewater treatment plants need utmost responsibilities and must be ready for challenges from climate variation influences. However, the excessive cost is still a vital issue in developing wastewater treatment infrastructure, therefore, improving and modernizing the existing structures can be more useful alternatives. On a field scale, waste stabilization ponds with baffles (WSPBs) configuration can be one of the possible solutions to the mentioned issue. However, generalizing the structure to fit various sites and finding the optimal design remains a challenge. In developing know-how for a country with different climatic regions like Thailand, the impacts of environmental factors like severe weather, unusually heavy rainfall on hydraulic performance and caring capacity of the pond should also be included. In this study, we conduct a numerical experiment of hydraulic flow of WSPBs via a sophisticated Navier-Stoke model. Several hydraulic flow scenarios associated with severe weather conditions have been used to drive the model. Finally, the optimal design of WSPBs will be evaluated. This research could help benefit the communities related to water pollution management and provide an understanding of wastewater infrastructure design.

Keywords—wastewater treatment; hydraulic performance; baffles; porous media fliter

I. INTRODUCTION

Waste stabilization ponds (WSPs) are open basins designed for removing pathogens from wastewater collected from the sewerage system of urban, agricultural and industrial units. Using natural processes such as sunlight exposure, sedimentation, hydraulic flow and physical-chemical factors (including temperature and pH) to remove pathogens is the mainconcept of this technology. However, controlling hydraulic efficiency of the ponds is the most suggested approach for design, operation and maintenance basis of pathogen removal in WSPs. Mostly, guidance may suggest maintaining theoretical hydraulic retention time (HRT) of the pond for receiving an optimal level of treatment performance. Systems with significantly long hydraulic retention times can contribute certainly influences on pathogen removal in WSPs. Because longer reside of wastewater in WSPs may enhance treatment performance of pathogens and pollutants by higher sedimentation and longer contact with sunlight. Consequently, discharging of slowest growing microorganisms (necessary for an anaerobic process) and spreading of helminth eggs and coliforms are disrupted. Recently, impacts of hydraulic retention times (HRTs) and pond depths on the reduction of pathogens have been reported by [1].

ControllingHRT is such beneficial guidance for operating/designing WSPs, but in reality, this may be a difficult doing. Because factors such as constantly changing flow rate, hydraulic dead space and hydraulic short-circuiting, channeling effect, sludge accumulation, inlet/outlet configurations, etc. can effect hydraulic efficiency in the ponds. As hydraulic problems of WSPs is considered, the improving scheme such as baffles is commonly used in WSPs.Therefore, waste stabilization pond with baffles (WSPBs) is also a widely used configuration in the opened-wastewatertreatment system.Because of the balance between the received treatment performance and the cost. Generally, both concrete and earthen structures are usedfor installing baffles in WSPs. Moreover, basins separated by baffles can be applied such a primary treatment sequentially i.e. anaerobic ponds, facultative ponds and maturation ponds. However, the function of the pond can be the sub-optimal level as some hydraulic behaviors i.e. short-circuiting and dead space occurs. The first behavior can arise when applying small baffle geometric ratios i.e. small inlet size and overuse numbers of baffles while the second one is the result of the reversal flow cell or eddy. The increment of fluid momentum is a driver of the latter phenomena. Hence, both pond geometries and flow rates are involved in treatment inefficiency.Besides, most of WSPs are established in the opened natural areas where the influence of weather conditions (temperature, rainfall, evaporation and wind) or even the consequences of stochastically synoptic conditions (severe rain and strong wind) can be important. The latter condition can naturally induce large stormwater magnitudes flowing through the WSPs.

Draining excess wastewater to nearby hydrological system cannormallybe designed for combined sewer overflows (CSOs). If such approachis included in the combined sewer system, the effect of stormwater can be separated from the WSPs. However, the impact of the approach may occur such as severe contamination in the adjacent environmental system. For achieving minimal waste and contamination, the CSOs may essentiallyneed to be dischargedto the WSPs. This condition implies that the interference of the instantaneous hydrological process (severe surface runoff) of the plants can dominate over the designed hydraulic function of the WSPs. The consequences of this phenomenon may not be considered because of some reason (the treatment performance of the WSPs may partially maintain). However, if the treatment performance of the WSPs dropped by severe surface runoff, its impacts may rapidly spread to the vicinity ecologic system. If this problem cannotbe overlooked, an efficient scheme solving the problem is always required. Besides, the insight physical processes and impacts of the mentioned issue should be sought.

To reduce the effects of severe weather on wastewater infrastructures efficiently, improving and modernizing existing infrastructure may needto be focused. For an open system such as WSPs, the role of baffles can be one of the possible solutions to improve theirhydraulic control. However, generalizing the structure to fit various topography and finding the optimal design remains a challenge. In developing know-how for a country with different climatic regions like Thailand, the impacts of environmental factors like severe weather, unusual high rainfallamount onWSPBs hydraulic performance and caring capacity should also be included.

In this study, we conduct a numerical experiment of hydraulic flow of WSPBs via a sophisticated Navier-Stoke model. Several hydraulic flow scenarios associated with severe weather conditions have been used to drive the model. Finally, the optimal design of WSPBs will be evaluated. This research could help benefit the communities related to water pollution management and provide an understanding of wastewater infrastructure design.

II. METHODOLOGY

A. WSPB design

In designing WSPBs, the rectangular pond with the transversal four [2] and six baffles [3] are frequently suggested as an efficient configuration for achieving the best hydraulic performance. Expectantly, the best treatment performance may also be received. However, based on the fact that linear relationship of hydraulic performance (HP) and treatment performance (TP) is not guaranteed. Thus, higher/lesser baffle geometric ratios such as 2 and 8may also be applied for improving/ensuring the treatment performance. However, misapplications of those configurations are also possible if the associated hydrodynamic behaviors have never been well analyzed. This may cause the inefficient design of the WSPBs.

For improving the above process, the hydrodynamic perspective given from numerical simulation can be significantly beneficial. Thus, we endeavor to make a numerical study investigating advantages and limitations and as well finding the improving approaches for the WSPBs. In the current study, the transverse 2 and eight baffles are selected to be the WSPB configurations (Fig. 1). To compare the hydraulics behaviors of those configurations to the conventional WSP, the flow solution of the unbaffled pond are also investigated. We also consider the effects of the inlet (spillway) constructed at the end of the baffles. Thus, the effect of changing the inlet sizes is to be examined. We define the hydraulic retention time (HRT) for operating the pond to be five days. Therefore, the associated incoming flow rate and volume of the pond are 29000 cubic meter/day and 150000 cubic meters, respectively.

We determine the advantage of the applied WSPBs by the minimal appearance of the dead space or the eddy cells in the pond. For testing WSPBs limitation, we consider the hydraulic response associated with mitigation of overtop or flooding during the severe flow rate. Besides, the possible way to mitigate such effect is also considered. In doing so, first, steady-state solutions driven by different flow rates would be numerically investigated. These solutions would help in determining the possible characteristic of the dead space subject to the baffle configurations and flow rates. Besides, we can provide a proper boundary condition for unsteady-state calculations. The schemes for potentially improving the hydraulic performance at the operatingHRT or even in the cases under severe flow rate conditions are also determined.Details are presented in the next section.

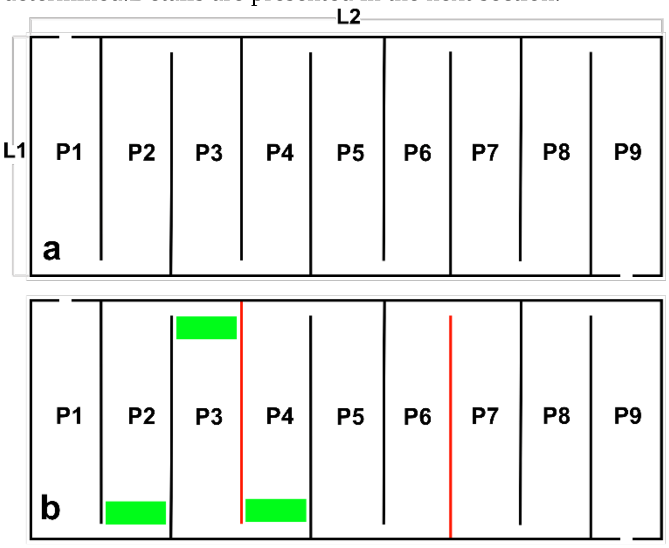

Fig. 1. a: Schematic of WSP geometry and baffle configuration. b: The same shape except for filters (green rectangular areas) applied to the sub-basin number 2,3 and 4. Red lines indicate positions of the twoelevated baffles. L1/L2=1/2.6.

B. Design for improvement schemes

Because of the impact of hydraulic dead space in the WSPBs is depended on the characteristic of the eddy cells. Hence, the practices in suppressing such phenomenon would consider being one ofthe efficient improving schemes. We speculate that constructing a porous-media-like filter near the jet flow of the pond may efficiently suppress the development of the eddy cells. However, calculating that flow problem cannot be easily performed. Importantly, the proprietary software (porous-shallow water solvers or CFD) is significantly expensive. We aim to investigate the cheaper approach by applying the hydrodynamic opensource software such as SCHISM [4]. Alternatively, we apply the array of circular obstacles [5] to the WSPB domain for representing the ideal porous-media-like filter effect. The placement of the filters are presented in Fig. 1b. For managing the overflow condition, the effect of baffle elevation including the filteris considered.

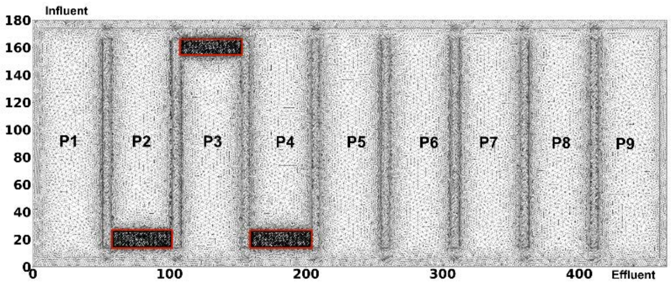

Fig. 2. Computational domain (triangular grids) designed for the SCHISM model. The porous-media-like filters are located inside in the red rectangle.

C. Effect of stormwater

Theoretically, the flow problem of the WSPBs induced by the geometric effect can be avoided during the engineering design process if the insight hydrodynamic mechanisms are understood. Instead, the effect of the uncertainty in flow rate is more difficult to manage than the geometric effect. For the tropic region, this problem would be intensified for the open WSP system. The important source of instantaneous high flow rate can naturally be surface runoff/excess rainfall originated in the watershed area adjacent to the WSPs. Under the condition of high rainfall intensity over the sufficiently large watershed area with saturated soils (or impervious land cover), high surface runoff rate can possibly discharge to the supported WSPs. If this is the case, the hydraulic retention time (HRT) supporting the biochemical process of the wastewater treatment cannot be maintained.Establishing schemes for efficiently managing this issue remains a challenge for the relevance communities. However, understanding the development of the dead space and other flow behaviors subject to the instantaneous flow rate with different WSPBs configuration would be beneficial in designing an efficient scheme. We aim to study this issue by performing the hydrodynamic simulation of the WSPBs under unsteady flow rate. Thus, the synthetic varying flow rate (Fig. 3) associated with the heavy rainfall effect is designed and applied in the simulation.

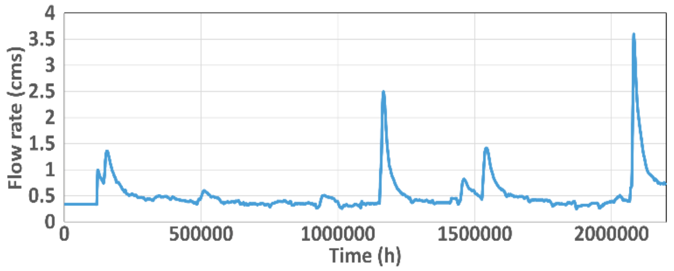

Fig. 3. Synthetic input flow designedfor WSP operation and representingstormwater influence

The characteristic of the mentioned flow rate is given from long duration of rainfall with sufficient intensity (20-30 mm/hr) induced by the active intertropical convergence zone and monsoon trough predominate over Thailand. Within the saturated soil condition, even small catchment area adjacent to the WSPBs can generate the high surface runoff flow. Further details of the simulation are presented in the next section.

D. Computational details

From the WSP design schemes detailed in the previous sections, the associated computational domains can be developed and presented in Fig.2. It is noted that the vertical geometry of the sub-basin number P1 of the domain is characterized by uniform depth of 3.5 meters (referenced from the pond bank elevation) while the shallower depth of -2.5 meters is rather applied to the rest basin. The elevation of the baffle edges and the banks surrounding the pond are 0.5 and 0.0 meters, respectively.However, the effects of the higher/shorter baffle edges are also tested for the purpose mentioned in section *A*. Besides, the effect of the inlets will be examined by changing the spillway height.

For performing the steady-state calculation, the setups are prescribed by constant flow rate for both inlet and outlet positions. The considered flow rates are in the range of 0.3-2.5 cms. Interpreting the solution of these experiments would determine the associated hydraulic properties subject to the operating HRT and other considered conditions. Besides, the most efficient configuration would be suggested.For including the porous-media-like filter effect in the calculation for section *B*, we locate the geometry of the circular obstacle array (Fig. 3b) in the computational domain. It is noted that the two different sizes of the obstacle diameters (0.15 and 0.5 meters) with mostly staggered arrangement are implemented in the calculations. For differentiating the effect of the filters form the other influences, their placements are only near the inlets of the P2, P3 and P4 basins (Fig.1 b). We consider that the predominance of the phenomenon mentioned in section *C* may contribute an inefficiency of WSP operation under the severe weather condition. Thus, the simulation setups for the section *A* and *B* (Fig. 2) are duplicatedbut the driving force is instead the varying flow signal characterizing the magnitude for WSP operation and stormwater influence (Fig. 3). It is noted that the open boundary condition at the outlet of the domain is prescribed with the free surface (zeta) derived from flow information of the steady-state solutions.All flow problems will be solved by the SCHISM solver [4].

III. RESULTS

A. Hydraulic flow structure

In Table 1 and Fig. 4, the characteristics of hydraulic flow given by different configurationsare summarized and presented. The structureof plug flowseems to appear in the ponds with WSP+8Bs+Inlet1 (Fig. 4a and c) setting and unbaffledpond (Fig. 4b) while large hydraulic dead spaces occur in the two baffles pond.

MAJOR FLOW BEHAVIORS OF THE WSP CONFIGURATION

Configuration	HRT condition	Flow behavior
WSP+8Bs+Inlet1	5 days	Mostly plug flow
WSP+8Bs+Inlet2	5 days	Small dead space
WSP+2Bs+Inlet1	5 days	Large dead space
WSP+2Bs+Inlet2	5 days	Large dead space
WSP+8Bs+Inlet1	0.7 days	Medium dead space
WSP+8B+Inlet1+filter	0.7 days	Partially plug flow
Unbaffled WSP	5 days	Mostly plug flow
Unbaffled WSP	0.7 day	Mostly plug flow

[a] Noted that WSP is stabilization pons, B is a baffle, the cross section areas for the Inlet1 and Inlet 2 are 2.5 and 1.5 square meters, respectively.

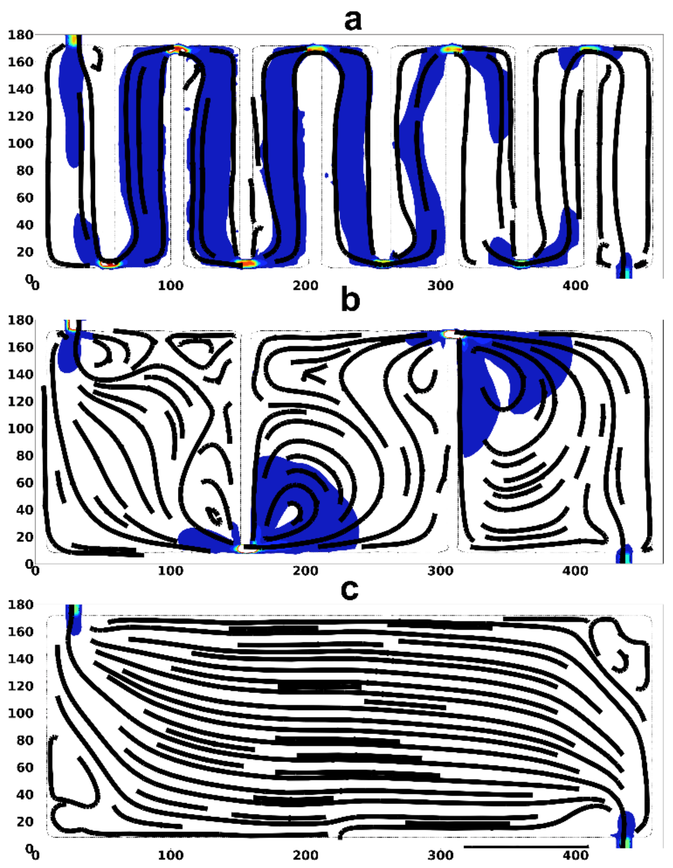

Fig. 4. Flow magnitudes and overlaid streamlines subject to the baffle configurations and the HRT condition of 5 days. a: 8 baffles. b: 2 baffles. c: Unbaffled pond. The min/max values of the contour are 0.001 and 0.25 m/s. The inlet size is 2.5 square meters.

Because plug flow is one of the most important hydraulic features for treatment performance of WSPs, hence, we suggest that the function of the pond with eight baffles is more efficient than that of the two baffles and unbaffledponds. The importance of the latter configurations is disregarded because they potentially induce large hydraulic dead spaces and short-circuiting (Fig. 1b and c).However, the effective inlet is strictly required for effectively applying the eight baffles pond. At the operating HRT (5 days), we have found that the effect of the inlet size of 2.5 square meters can efficiently reduce the sizeof eddy cells. By considering the mentioned results, the most advantageous configuration for the operating HRT can be assessed as the WSP+8Bs+Inlet1.

Inaddition, some issue for the best configuration may need to be considered as the higher flow rates become influenced. In that situation, the flow rates should directly change the HRT of the pond. Besides, the treatment processes may also be disrupted by the effect of the large dead space or large eddy cells developed in the WSP. This problem may disappear if the baffle height decrease, however, another situation such as overtopping flow on the baffle tops may occur.

The embankment over the baffles of the WSP+8Bs+Inlet1 configurationmay benefit for reducing flood level. However, the dead space problem should normally return. The practices in suppressing such phenomenon are determined.Nonetheless, we have found that a scheme related to hydrodynamic filters can help manage that problem efficiently. Besides, the suggestion for the efficient use of the filteris speculated. The corresponding details are revealed inthe *C* section.

B. Stormwater effect

Previously, the flow behavior representing the function of the WSP associated with the most efficient configuration (WSP+8B+Inlet1)is presented. In this section, the response of the configuration to the severe weather is focused. It is noted that the effect of the weather condition is input to the model as the unsteady flow rate. Performing the simulation with this driving force would benefit the study forextracting the flow behaviors after the effect of the external condition decays. The corresponding results of the section are shown in Fig. 5.

As the peak flow rate (2.5 cms) of the stormwater passes through the pond with the WSP+8B+Inlet1 setting, the large eddy cells can develop near the inlet of each sub-basins of the pond (Fig. 5a). Since the stormwater flow decreases and the operating flow dominates, the eddy cell sizes turn to be smaller but it can remain in some sub-basin for 24.0 hours (the corresponding graphicis not shown).

If another configuration such the WSP+8B+Inlet2 is instead applied, the size of the remaining eddy can be wider (the corresponding graphicis not shown). This effect may turn the pond function to be inefficient.Potentially, the severe stormwater or the instantaneously high flow rate may turn the WSPBs function to be under the optimal level.

Generally, the WSPBs may be designed with a small inlet for keeping a small HRT. Since the instantaneous flow rate becomes significantly high, the overtopping flow on the baffle edges can occur.The simulation of this case is performed via the WSP+8B+Inlet2 configuration, but the lower baffle edges are instead replaced. The result of this experiment is shown in Fig. 5b.As seenin Fig. 5b,mostly, the flow across the baffle edges with higherflow magnitude.

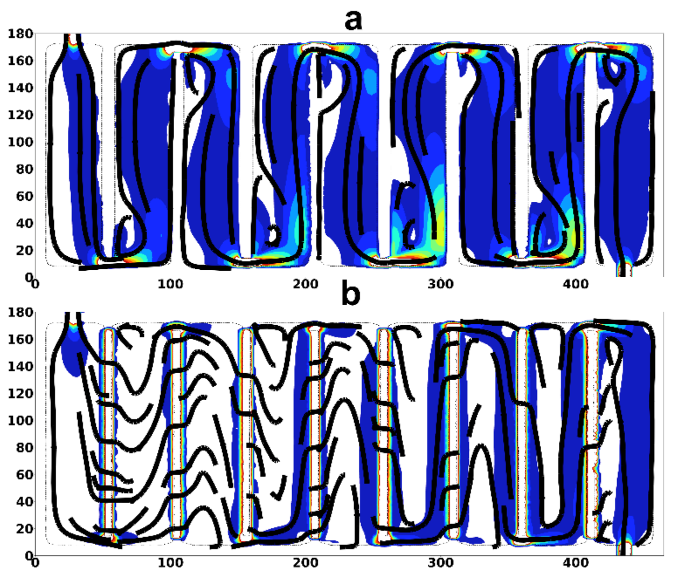

Fig. 5. Same as Fig.4 except for only the eight baffles and the HRT becomes 0.7 days. a: The most efficient configuration. b: The smaller inlets with lower baffle edges.The min/max values of the contour are 0.02 and 0.25 m/s.

Focusing on Fig. 5b, although the flow pattern in the pond (smaller inlets and lower baffle edges)tend to agree with minimal appearance of the hydraulic dead space, however, the flow path is instead shorter than that of another configuration. Such flow behavior should also potentially induce short-circuiting condition. This condition would also be an essential factor inthe reduction of the WSP efficient. If this situation becomes intensified in real WSPs, some pollutant can remain high concentration at the outlet. Besides, it may induce strong erosion condition on the baffle edges. Hence, finding improvement schemes for the above issues may be needed. In the current study, some advantage of CFD knowledge such as staggered cylinder arrays is applied to be an improvement practice for the problem. The results are revealed next.

C. *Effect of the improvement scheme*

In this section, the results of the schemes designed for reducing the impact of the severe stormwaterare presented. The interpretation mainly focuses on the effects of the filters and the baffle edges. The situations are designed to be under the HRT of 0.7 days (under the optimal level). First, the results of the WSP+8B+Inlet1 configuration on the mentioned condition is interpreted. In Fig. 6a, it is seen that the effects of the filters can significantly suppress the development of the eddy cells in the basins of P2, P3 and P4.

The hydraulic flow influenced by the filter ismainly the plug flow. Instead, theflow in the basins without the filters tend to exhibit the large dead space. We speculate that the latter structure can disappear if the more filter structures are applied. Besides, the latterresults may also indicate some advantage/disadvantage of the porous filter-liketreatments suchas the wetland plants which may need to be sufficiently determined for the best efficiency of the application.

We can suggest that the WSP together with the efficient baffles, effective inlet size and the porous media-like filters is the most advantageous configuration for operating the WSP with HRT of 5 days. Even in the flood situation, this structure yet shows a safer condition to operate the WSP than that of the other settings. Assume that othersettings become applied for other purposes (i.e. for keeping the large HRT, performing the complete mixing flow, or even the underestimation of the stormwater effect), the alternate ways (morecheaper or easier) to deal with this situation may need to be explored.

At the end of this section, the result associated with the effect of the schemes for managing the overtopping flow and hydraulic dead space induced by flood conditionis presented. It is noted that the geometry of thepond is duplicated from the WSP+8B+Inlet2 configuration. Previously, the response of such setting is presentedand its response can be explained as the overtopping flow with strong current magnitude on the baffle edges. Here, the effects of the filters and embankment in that setting are seen (Fig. 6b). When particular baffle tops are sufficiently higher (the red lines in Fig.6b), the overtopping flow condition still be found. However, their associatedflow magnitudes reduce.

The effect of the filter may turn the development of the eddy to be the straightflow paths (P3 and P4 basins). However, the large eddy cells and higher flow magnitude appear in the other basins without the filter treatment (P7, P8 and P9 basins). If the completeremoval of the eddy cells are needed, we speculate that increasing the number of baffle and filter region or even rearrangement of these components can efficiently help. Besides, another assist such as changing the inlet design would also be beneficial.These results may suggest one of efficient approaches for managing the hydraulic flow of the WSPBs during the severe stormwater.However, the unexpected effects andoverbalancing of cost and wastewater treatment performance may be received if the related hydraulic behaviors subject to the considered configuration cannot be precisely investigated.

In summary, this study investigated the hydraulic/hydrodynamic behavior of the WSPs under the impact of baffles and the unsteady inflow rates. Wehave found that the number of baffles and drainage channels size can significantly influence the flow characteristics (eddy cell) of the ponds. Therefore, we may design an efficient wastewater treatment pond (minimal appearance of eddy cell) as revealed in the results. When applying the designed treatment pond under an unstable flow rate, the eddy cell may remain in the pond although the flow rate become weaken. We also found that properly installed porous-media-like filters could improve the hydraulic performance (suppressing the eddy cell) of the pond even in the flood condition.

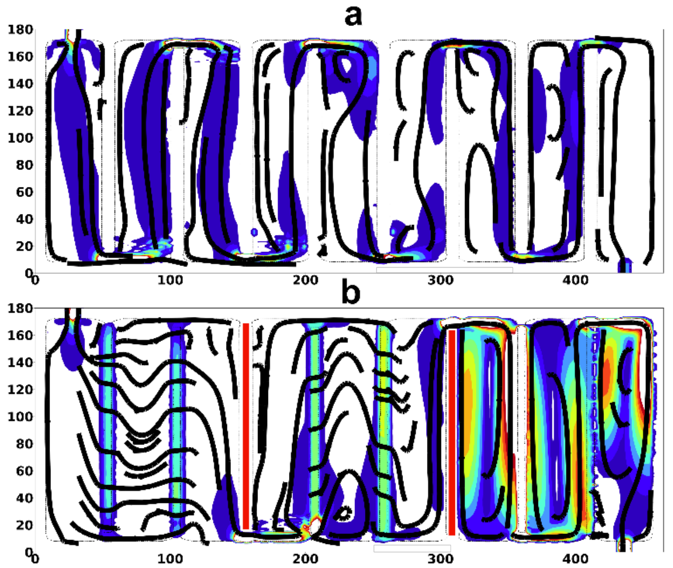

Fig. 6. Same as Fig.5 except for the effect of the filters (a) and the two elevated baffles+filtersare instead applied.

In the context of worldwide water pollution, or even in Thailand, stakeholder involvement may be involved in solving problems effectively. Without this contribution, the ability of other contributors may be ineffective. However, incorrect understanding of the relevant scientific phenomena will reduce the effectiveness of such participation and overall problem resolution. In addition, there may be conflicts. From a scientific standpoint, the strength of science for investigation and adequate knowledge for all stakeholders is an important tool in addressing such issues.Finding a new high-performancewastewater infrastructure, improving efficiency and modernizing the existing system areessential, although they are considered as minor issues in the water pollution problem. Nevertheless, if they are not implemented, the severe problem will always occur.Furthermore, we recognize that awareness and understanding of hydraulic behaviorsand biochemical processes of wastewater treatment can help to reduce conflicts among stakeholders. Occasionally,performance and infrastructure constraints can be important questions during the environmental assessment process for new development projects. The precise answer will suppress the origin of the conflict. Besides, in improving existing infrastructure, a real understanding of the relevant scientific phenomena is essential. One of the most effective approaches to solve these problems is the numerical simulation shown in the present study.

IV. Conclusion

In this study, we conduct a numerical experiment of hydraulic flow of the wastewater stabilization pond with baffles (WSPBs) via a sophisticated mathematical model. Finding an optimal design of WSPBs to reduce effect of severe rainfall is our major objective. Besides, we aim to produce substantial knowledge related to the hydraulic design of WSP for the related communities. Therefore, the effects of baffle configurations, inlet sizes and porous- media-like filters have been investigated. The synthetic flow rate scenarios associated with both of the operating hydraulic retention times (HRT) and severe weather conditions have been used to drive the model. We have found that the number of baffles and inlet size can significantly influence on development of eddy cell (hydraulic dead space) in the ponds. Hypothetically, we can design the best configuration of WSPBs which produce minimal development of eddy cell (the configuration of 8 baffles with the inlet size of 2.5 square meters). However, the efficiency of the configuration become reduced as the effect of surface runoff (excess rainfall) dominates. Besides, the pond can experience flood condition. We also have found that properly installed porous-media-like filter structures could improve pond performance (suppressing the eddy cell) even in flood condition.

Water pollution is a relevance problem in Thailand's water resources management. Overall, the current status of the surface water of Thailand is moderate to good quality except that of the central Chao Phraya watershed which deteriorates. This fact indicates that the environmental management policy and wastewater treatment infrastructure of the country may need to be improved for enhancing efficiency in wastewater and stormwater treatment. Focusing on the latter issue, despite significant wastewater contributions from domestic and industrial sectors, establishing and maintaining their wastewater treatment plants need utmost responsibilities and must be ready for challenges from climate variation influences.However, the excessive cost is still a vital issue in developing wastewater treatment infrastructure, therefore, improving and modernizing the existing structures can be more useful alternatives. On a field scale, waste stabilization ponds with baffles (WSPBs) configuration can be one of the possible solutions to the mentioned issue. Furthermore, generalizing the structure to fit various sites and finding the optimal design remains a challenge. In developing know-how for a country with different climatic regions like Thailand, the impacts of environmental factors like severe weather, unusually heavy rainfall on hydraulic performance and caring capacity of the pond should also be included. Thus, our research would benefit the communities related to water pollution management and provide an understanding of wastewater infrastructure design.

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