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# Effects of inlet flow distribution evenness on outlet water quality from multiple parallel-arrayed sedimentation basins

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**ABSTRACT**

This study evaluates the effects of the evenness of the flow distribution from the open channel between a rapid mixing basin and multiple parallel-arrayed flocculation/sedimentation basins on the water quality. The results of the tracer tests in an actual domestic water treatment plant showed that modifying the hydraulic structure of the distribution channel could improve the evenness of the flow distribution by ~50%. The results of turbidity measurements for each sedimentation basin also showed that a more even flow distribution reduces the turbidity of the settled water by more than 25%.

*Keywords:* Evenness of flow distribution; Multiple parallel-arrayed flocculation/sedimentation processes; Tracer test

## 1. Introduction

Parallel-arrayed process reactors with the same geometrical shape and function have been widely used in water and wastewater treatment plants. In water treatment plants, the incoming flow should be evenly distributed to the process units, especially for a series of successive lateral basins. Distribution channels are commonly used to distribute the flow from the rapid mixing basins into the flocculation basins (Fig. 1). In addition, the outlet flow from the sedimentation basins is distributed through weirs or orifices in the open channel to multiple parallel-arrayed filtration processes.

In wastewater treatment plants, the pipes from the aeration tanks to the multiple circular sedimentation basins are symmetrically designed and constructed to evenly distribute the outlet flow from the aeration processes. However, in the case of drinking water treatment plants (Fig. 1), the flocculation and sedimentation basins downstream of the rapid mixing process are generally designed and constructed to be rectangular in shape and are arranged in parallel. Several hydraulic structure modifications, such as changing the weir elevation, tapering the channel to keep the Froude number constant, and slightly adjusting the elevation of each weir while tapering the channel, have been suggested to reduce the uneven flow distribution in a basic open-type channel [5]. The retention time will be considerably different from the designed value in the flocculation/sedimentation basin and other locations that are constructed as a package if the inlet flow to each flocculation/sedimentation basin is not evenly distributed. The lower velocity and longer retention time in a basin with a flow rate lower than the designed value will accelerate the particle deposition in the sedimentation basin. Meanwhile, the higher horizontal velocity and the shorter retention time in a basin with a flow rate higher than the designed value could yield re-floating sludge [1]. The higher flow rate and velocity increase the surface loading rate, which makes it impossible for particles to settle within the sedimentation basin [4]. Determining design factors, such as the inlet structure, sectional geometry, length, outlet size, and shape, is very important in obtaining an even flow distribution in an open channel. The fluid behav-

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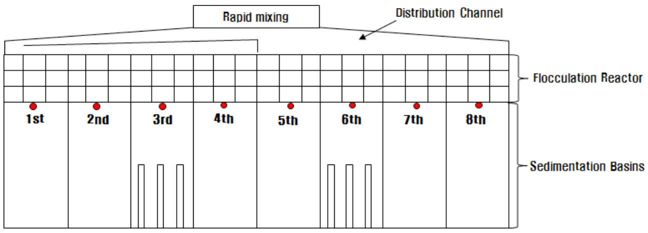


Fig. 1. Rapid mixing, distribution channel, and flocculation and sedimentation basins (top view).

iors, particularly in the case of a distribution channel, are very complicated that a 3D analysis should be performed to predict the actual flow phenomena. Accordingly, a serious error may occur if this kind of hydrodynamic problem is analyzed using a 1D time function or 2D code based on shallow water theory [2]. These have been designed using trial-and-error methods based on experiments because of the complexity of most hydraulic constructions. Lee et al. suggested a simple method that involved the installation of a longitudinal baffle with orifices in the main flow direction to achieve an even flow distribution in an open channel. They also performed computational fluid dynamics (CFD) simulation of an internal baffle design and wet tests of a small-scale open channel (1/8 scale) to prove the method efficiency. The equalities of the flow distributions in the modified channels in their study were up to 30% higher than those in a conventional channel [6]. However, the verification test of their idea was limited to the laboratory scale. They were not able to reveal the effects of the evenness of the flow distribution from the open channel between a rapid mixing basin and the multiple parallel-arrayed flocculation/sedimentation basins on water quality.

The present study conducted a detailed evaluation of the effect of an even flow distribution on the water from a structurally modified distribution channel. This channel was designed as symmetrical and constructed in an S_WTP (water treatment plant) (Fig. 1). The flow distribution equality in the modified channels was investigated through CFD simulation and lab-scale experiments in a previous research [6]. The quality of the water from each outlet of the eight parallel-arrayed sedimentation basins herein was periodically and continuously detected for two weeks from June 7–22, 2011 to quantitatively and experimentally evaluate the effectiveness of the even flow distribution.

## 2. Theoretical background

Fig. 2 shows the top view of an open-type distribution channel with a constant width and energy line occurring in the case of a relatively lower Froude number (Fr << 0.1) within the channel. In this case, the inlet water flowing through the channel and its head loss increase because of friction from the side and bottom walls. Therefore, the outlet flow rate decreases as the orifice's distance from the inlet increases (Fig. 2). The head at the end (right side, Fig. 2) is higher than that near the inlet (left side, Fig. 2) when the average velocity and Froude number are relatively higher. The most important criterion for these controversial phenomena is the Froude number. The Froude number represents the ratio of the inertia force and the gravity force or that of the average velocity and the surface wave transfer velocity.

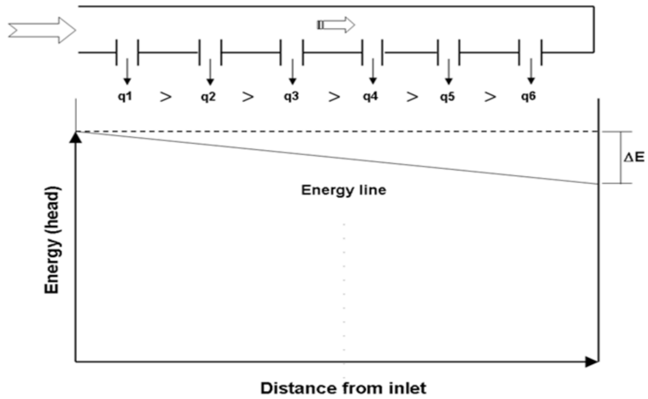


Fig. 2. Energy line grade of an open-type distribution channel (top view).

Aside from the "step method," methods of achieving an even flow distribution in an open channel have also been introduced in a few studies. The "step method" proposed by Chao and Trussel in 1980 has been widely used in the design of an open-type distribution channel [3]. In Fig. 2, the outlet flow ($q_*$; * = 1, 2, 3, 4, 5, and 6) from each orifice can be calculated using Eq. (1) as follows:

$$q_* = C_d \cdot a \cdot \sqrt{2 \cdot g \cdot H} \tag{1}$$

where $a$ is the orifice's cross-sectional area; $C_d$ is the flow coefficient; $g$ is the gravity acceleration; and $H$ is the upper water level.

In this method, the flow distribution to each basin (flocculation/sedimentation basin) is determined by proceeding step-by-step from the downstream end of the channel to the upstream end, where the flow enters. Several modification approaches, including changing the weir elevation, tapering the channel to maintain a constant Froude number, and slightly adjusting the elevation of each weir while tapering the channel, have also been proposed to improve the evenness of the flow distribution in an open-type channel [5]. However, an even flow distribution could not be achieved in most channels designed using the "step method" or modifications. Moreover, the uneven distribution primarily occurred because of the abrupt turn of the flow direction caused by inadequate inlet geometry. This phenomenon has seriously impaired the treatment efficiencies [2,7].

Fig. 3 shows that installing a longitudinal baffle with orifices within an open distribution channel causes the inlet water to turn at the end of the right side. As a result of friction, the water level at the left side would be higher than that at the right side as the inlet water flow runs from left to right. The water level gradient reverses after the main flow turns at the end of the right side and runs from right to left. The water level above each outlet orifice can be kept constant because the water passes through the orifices in the internal baffle. A comparison of Fig. 3 with Fig. 2 also shows that the average velocity in the case of the former can

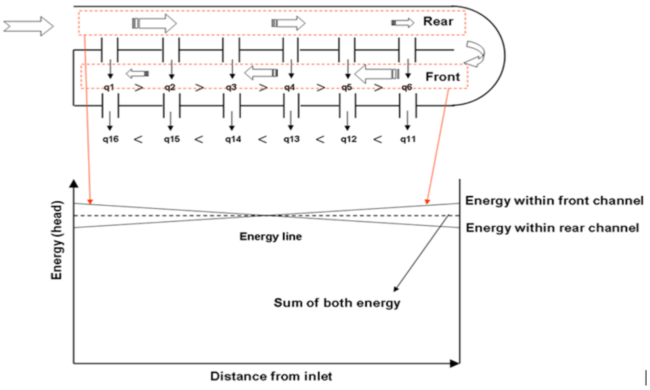


Fig. 3. Energy line grade of a double-baffled-type distribution channel (top view).

be twice that in the case of the latter even though the two channels have the same theoretical retention time because the cross-sectional area decreases to half. Micro-flocs are expected not to settle within the distribution channel because of the increased velocity.

The tracer tests herein were performed to compare the hydraulic behaviors within the distribution channel. The residence time distributions (RTD) can be obtained by a tracer test. The test consists of an instantaneous injection of a known quantity of a conservative substance (e.g., slats, fluorescent dye, etc.) at the distribution channel inlet and the subsequent monitoring of the tracer concentration with time at the outlet section [8]. The hydraulic behavior can be directly assessed from the comparison of the RTD functions. However, the direct interpretation of these functions is not always simple. Therefore, some hydraulic indices are usually extracted from the tracer test results (e.g., RTD curves) so that the analysis can become less qualitative. The hydraulic indices are usually divided into two categories as follows: short-circuit and mixing indicators [8,9]. Table 1 summarizes the hydraulic indices used in this study.

Table 1
Hydraulic indices

| Categories | Index | Definition |
|---|---|---|
| Short-circuit indices | $t$ | Mean retention time calculated from the cumulative RTD curve [10] |
| | $t_{10}$ | Period of time necessary for 10% of the mass of the tracer injected at the inlet to reach the outlet of the flocculation basin [8] |
| | $t_{50}$ | Period of time necessary for 50% of the mass of the tracer injected at the inlet to reach the outlet of the flocculation basin [8] |
| | $t_{90}$ | Period of time necessary for 90% of the mass of the tracer injected at the inlet to reach the outlet of the flocculation basin |
| | $t_p$ | Time in which the maximum concentration (peak concentration) was detected at the unit outlet [8] |
| | $t_g$ | Time in which the RTD curve centroid was shown |
| | $(t_g - t_p)/t_g$ | Thirumurthi's index — represents how far $t_p$ is from $t_g$ [8] |
| Mixing indices | Morril index | Ratio between $t_{10}$ and $t_{90}$ [8] |
| | Modal index | Ratio between $t_p$ and theoretical retention time |

Fig. 4. Actual distribution channel and flocculation basins in S_WTP.

## 3. Materials and methods

### 3.1. Distribution channel and tracer test

Fig. 4 shows photographs of the actual distribution channel and the flocculation basins operated in S_WTP. Different water colors resulted from the uneven flow distribution from the existing channel. Fig. 5 presents the top views of the rapid mixing, distribution channel, and flocculation and sedimentation processes in the domestic S_WTP along with the detailed geometry and shape of the internal baffle and orifices installed from the 1–4th flocculation/sedimentation basin. The baffle and orifice were installed to experimentally compare and evaluate the effects of even distribution on the water quality. The internal baffle installed on the left side was a polypropylene double frame. The full-scale internal baffle and orifices shown in Fig. 5 were designed and installed on April 7, 2011 based on the results of numerous laboratory wet tests and CFD simulation work on their geometry design. A paper has already published the results of these laboratory wet tests and CFD simulations. Hence, they were excluded from the present report [6]. During the comparative experiments, a total of eight flocculation/sedimentation basins were used for treatment at a constant rate of ~12,600 m$^3$ h$^{-1}$. The flow rate in each basin could theoretically be calculated as 1,575 m$^3$ h$^{-1}$. The tracer tests were performed for two days (April 12–13, 2011) to verify the CFD simulation results and evaluate the differences in the flow rates of the eight flocculation basins. Fluorosilicic

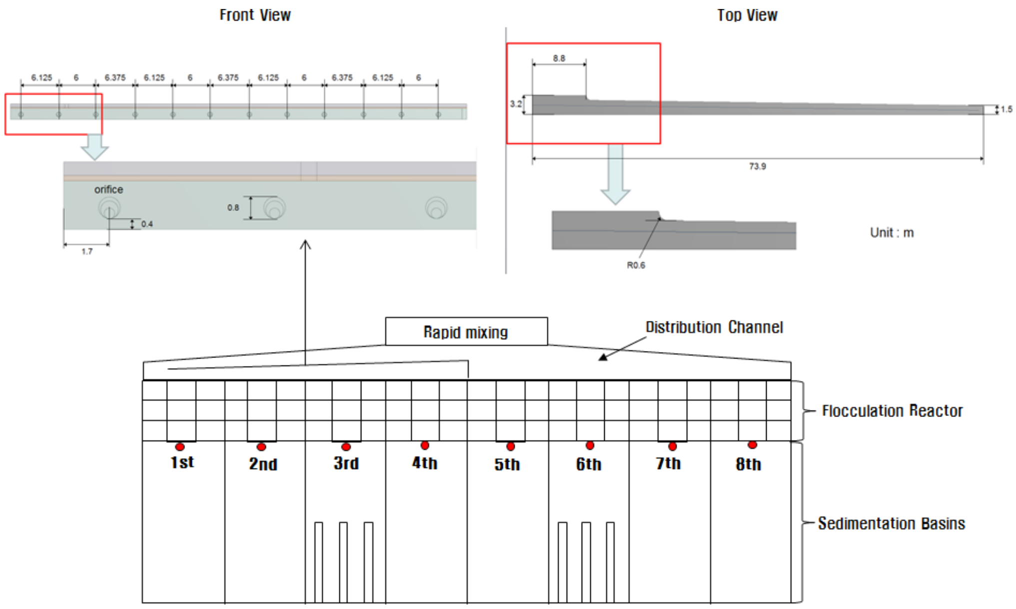


Fig. 5. Geometry and shape of the subject distribution channel in S_WTP (the internal baffle was installed on the left-hand side within the distribution channel to compare the turbidity in effluents from the eight sedimentation basins).

acid ($H_2SiF_6$; fluorine concentration: 25%, specific gravity: 1.27) was used as the tracer matter for these comparative experiments. Approximately 120 L of this tracer matter was injected into a gauging well ahead of the rapid mixing tank using the "pulse input" method. The gauging well and the rapid mixing tank were connected by a 1,200 mm pipe. The travel time was less than 20 s, which could be disregarded when calculating each total retention time for flocculation. The eight small red dots in Fig. 5 mark the sampling points in the flocculation basin outlets. Each point was located 1 m from the surface layer of the central basin point. The fluorine concentration in each sample was measured using a spectrophotometer (DR 2010, HACH, US) at a sampling interval of 2 min. A total tracer test was performed for 160 min, which was approximately twice the theoretical flocculation basin retention time (i.e., 74 min). Vertical paddle-type flocculators were used for flocculation in S_WTP. Each sedimentation basin was equipped with nine flocculators. All of the orifices were fully opened not only during the tracer test but also for the entire two weeks to measure the settled water turbidity from each sedimentation basin.

### *3.2. Turbidity measurement*

The effluent turbidity from each of the eight sedimentation basins was measured for approximately two weeks from June 7–22, 2011 to experimentally evaluate the effects of the evenness of the flow distribution for the multiple parallel-arrayed flocculation/sedimentation basins on the water quality. The turbidity in the field was measured every day at 11:00 AM for two weeks. The usefulness of installing the internal orifice baffle to modify the existing distribution channel could be examined in an actual, full-scale plant by comparing the turbidities of the effluents from the first four sedimentation basins with those from the last four. The turbidity was measured using a turbidimeter (Model 2100P, HACH, US). Table 2 shows the geometry and operating conditions based on the designed flow rate.

Table 2
Detailed geometry and operating conditions of the sedimentation basin in S_WTP

| Parameters | Hydraulic conditions (flow rate 425,000 $m^3$ $d^{-1}$) |
|---|---|
| Length/width ratio | 4.4 |
| Width/height ratio | 4 |
| Length/height ratio | 17.7 |
| Velocity (m $s^{-1}$) | 0.0076 |
| Wetted perimeter (m) | 3 |
| Reynolds number (Re) | 18,091 |
| Froude number (Fr) | $2.12 \times 10^{-6}$ |
| Surface loading rate (m $d^{-1}$) | 36.9 |
| Weir loading rate ($m^3$ $m^{-1}$·$d^{-1}$) | 229 |
| Upward velocity ($m^3$ $m^{-1}$·$d^{-1}$) | 77.7 |

## 4. Results and discussion

### *4.1. Tracer test results*

Figs. 6 and 7 show the concentration curves (*C*-curves) as the results of the tracer tests for the 1–4th and 5–8th flocculation basins, respectively. The tracer recovery ratio was 96.5%. Therefore, the results of the conducted tracer tests were reliable.

Tables 3 and 4 present the corresponding retention time ($t$), $t_{10}$, $t_{50}$, $t_{90}$, $t_p$, $t_g$, Thirumurthi's index, and Morril and

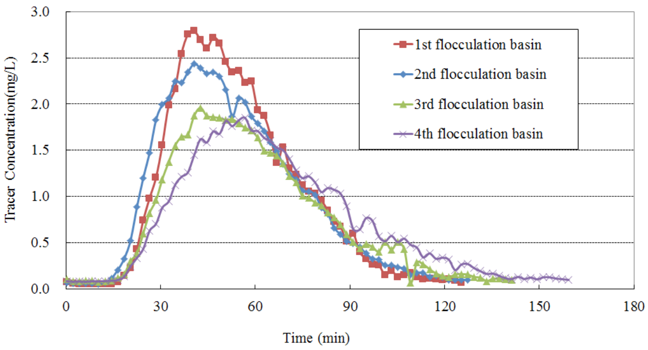


Fig. 6. Results of the tracer tests for the 1st to 4th flocculation basins.

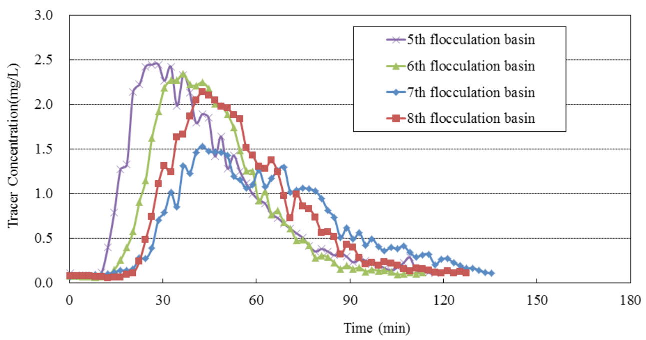


Fig. 7. Results of the tracer tests for the 5th to 8th flocculation basins.

Modal indices derived from the test results. As mentioned earlier, the distributed inlet flows to the 1–4th flocculation/sedimentation basins might be more even than those to the 5–8th basins. The standard deviations of the calculated short-circuit index values for the 1–4th basins were 27–50% less than those for the 5–8th basins. The differences of the mean retention time ($t$), $t_{10}$, and $t_{50}$ were close to 50%, while those of $t_{90}$, $t_p$, and $t_g$ were smaller at 27%. The deviation value gradually decreased because the *C*-curves (Figs. 6, 7) from the tracer tests exhibited the long tail in a later time. The deviation differences could confirm that the evenness of the inlet flows to the 1–4th flocculation/sedimentation basins improved by ~50% compared to that for the 5–8th basins. The tracer exit time (i.e., 11.8 min) at the 2nd basin was the earliest for the first four basins, whereas that (i.e., 19.8 min) at the 4th basin was the latest. The tracer exit time (9.7 min) at the 5th basin was the earliest for the last four basins, which had a relatively uneven inlet flow, whereas that (21.2 min) at the 8th basin was the latest. The Thirumurthi's index values for the 1–4th basins were calculated as 0.14–0.29 (dimensionless). Meanwhile, those for the 5–8th basins were 0.23–0.42. These differences might have an effect on the water quality and treatment performance for multiple parallel-arrayed processes.

In the aspect of mixing indexes, slight difference was observed among the basins even though slightly higher Modal index values were calculated for the 1–4th basins. Consequently, modifying the distribution channel structure by installing an internal orifice baffle affected these actual, multiple, full-scale parallel-arrayed flocculation/sedimentation basins.

Table 3
Hydraulic indices of the 1st to 4th flocculation basins

| No. of basins | 1st | 2nd | 3rd | 4th | Standard deviation |
|---|---|---|---|---|---|
| $t$ (min) | 54.9 | 53.6 | 58.3 | 65.8 | 5.5 |
| $t_{10}$ (min) | 32.6 | 29.0 | 32.6 | 34.5 | 2.3 |
| $t_{50}$ (min) | 51.4 | 49.3 | 55.1 | 61.3 | 5.3 |
| $t_{90}$ (min) | 79.0 | 81.4 | 90.1 | 101.5 | 10.0 |
| $t_p$ (min) | 40.6 | 40.6 | 42.6 | 57.0 | 7.9 |
| $t_g$ (min) | 55.7 | 53.2 | 59.7 | 66.4 | 5.8 |
| $(t_g - t_p)/t_g$ | 0.27 | 0.24 | 0.29 | 0.14 | |
| Morril index | 0.41 | 0.36 | 0.36 | 0.34 | |
| Modal index | 0.55 | 0.55 | 0.58 | 0.77 | |

Table 4
Hydraulic indices of the 5th to 8th flocculation basins

| No. of basins | 5th | 6th | 7th | 8th | Standard deviation |
|---|---|---|---|---|---|
| $t$ (min) | 43.7 | 54.9 | 56.1 | 69.2 | 10.4 |
| $t_{10}$ (min) | 27.5 | 32.6 | 34.6 | 38.8 | 4.7 |
| $t_{50}$ (min) | 43.2 | 50.7 | 59.7 | 63.8 | 9.3 |
| $t_{90}$ (min) | 67.3 | 81.2 | 97.1 | 99.1 | 15.1 |
| $t_p$ (min) | 28.5 | 36.6 | 42.6 | 50.7 | 9.4 |
| $t_g$ (min) | 48.9 | 57.3 | 62.9 | 65.6 | 7.4 |
| $(t_g - t_p)/t_g$ | 0.42 | 0.36 | 0.32 | 0.23 | |
| Morril index | 0.41 | 0.40 | 0.36 | 0.39 | |
| Modal index | 0.39 | 0.49 | 0.58 | 0.68 | |

### *4.2. Results of the turbidity measurement*

This study aimed to experimentally evaluate the effects of the evenness of the flow distribution on the overall water quality for actual, multiple, full-scale parallel-arrayed flocculation/sedimentation basins. The water turbidity from each outlet of the eight parallel-arrayed sedimentation basins was periodically detected for two weeks to accomplish this goal. Fig. 8 shows the turbidity measurement results for the eight sedimentation basins from June 7–22, 2011. During the experiments, the total inlet flow into the eight sedimentation basins was fixed at 12,600 $m^3 h^{-1}$. Half of that flowed into the 1–4th basins. The rest flowed into the 5–8th basins. The raw water turbidity from the Paldang Dam was measured and found as 1.54–3.81 NTU. The temperature was ~14 °C. S_WTP used poly-aluminum chloride ($Al_2O_3$ = 10%), which is a commercial coagulant product. Fig. 8 and Table 5 show that the measured turbidities of the effluents from the 1–4th basins were below 0.8 NTU, whereas those from the 5th to 8th basins were ~1.0 NTU. These apparent experimental results can be attributed to two reasons. First is the deviation

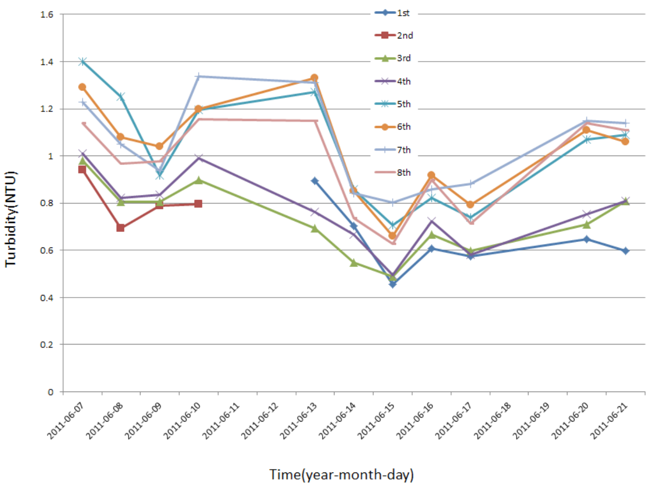


Fig. 8. Results of the turbidity measurements from the eight sedimentation basins.

Table 5
Average turbidities measured for comparison

| No. of basin | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th |
|---|---|---|---|---|---|---|---|---|
| Turbidity (NTU) | 0.64 | 0.80 | 0.73 | 0.77 | 1.03 | 1.03 | 1.05 | 0.97 |
| Average (NTU) | 0.735 | | | | 1.02 | | | |

of the retention times in each basin. The shortest and longest retention times were detected at the 5–8th basins, respectively. The anaerobic reaction and sludge re-floating can deteriorate the settled water quality in basins with relatively short and long retention times. The second reason is the difference in the Thirumurthi's index values. The short-circuit index values for the 1–4th basins were over 50% less than those for the 5–8th basins. Short-circuit implies that at least some of the fluid follows a different path from the intended one through the reactor and exits after a shorter time than the desired retention time [9,10]. It can be concluded from these results that a more even flow distribution reduced the settled water turbidity by more than 25%. This study proved that the overall treatment performance could severely deteriorate, as previous researchers pointed out, if the inlet flow to the actual, multiple parallel-arrayed processes is not even [4]. A methodology to enhance the evenness of the flow distribution for the multiple parallel-arrayed processes was also proposed and experimentally verified.

## 5. Conclusions

This study was conducted to experimentally evaluate the effects of the evenness of the flow distribution in an open channel between a rapid mixing basin and the multiple parallel-arrayed flocculation/sedimentation basins on water quality. This goal was accomplished by performing comparative tracer tests and periodic turbidity measurements for the full-scale, actual flocculation and sedimentation basins, respectively. The study's findings are summarized as follows:

1. The results of the comparative tracer tests showed that the evenness of the inlet flow to the first four flocculation/sedimentation basins (modified) improved by ~50% compared to that for the last four basins (existing). Modifying the distribution channel structure by installing an internal orifice baffle affected these actual, multiple, full-scale parallel-arrayed flocculation/sedimentation basins.
2. The results of the turbidity measurements demonstrated that the more even flow distribution reduced the settled water turbidity by more than 25%. The overall treatment performance could severely deteriorate if the inlet flow to the actual, multiple parallel-arrayed processes was not even. Moreover, a methodology to enhance the evenness of the flow distribution for the multiple parallel-arrayed processes was proposed and experimentally verified in this study.

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