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Research Note

Effect of step geometry and water quality on efficiency of cascade aeration

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Abstract. In this paper, the effect of step geometry with five different tread values from 0.40 m to 0.60 m with an increment by 0.05 m, and three different types of water, namely potable, non-potable, and recycled water, on aeration efficiency of stepped cascade aeration was studied. Detailed experimental investigations were carried out for different hydraulic loading rates of 0.005 m^2/s to 0.035 m^2/s. All the experiments were conducted for nappe flow condition. Results revealed that the overall aeration efficiency at standard conditions (E_{20}) approaches the maximum for $t/h = 4$, number of steps were 12 with a hydraulic loading rate of 0.02 to 0.025 m^2/s for potable and non-potable water. In the case of recycled water, maximum efficiency was achieved for $t/h = 3.67$. Results also revealed that stepped cascade aeration was a very suitable option for enhancing DO content in treatment of waste water before discharging it to water bodies to save aquatic life.

1. Introduction

Aeration was found to be one of the important techniques employed in water and wastewater treatment process, which enabled supply of oxygen from gaseous phase to liquid phase. In the case of nappe flow, the energy dissipation occurs by the break-up of jet in the air. In the case of skimming flow, the flow is in an organized stream supported by the recirculation fluid. It was found from experiments that skimming flow occurred when the ratio of critical depth to the height of the step (d_c/h) was greater than 0.8 and smaller values of d_c/h caused nappe flow [1]. In stepped cascade system, water is permitted to fall on series of steps and during this process, bubbles are formed which lead to dragging of air from the atmosphere. Stepped cascade system was used to remove color and taste caused by volatile oil, carbon dioxide, hydrogen sulphide, and volatile organic compounds such as chlorine and methane in the potable water treatment process [2]. Stepped cascade flow is characterized by its large residence time, vibrant mixing, and substantial air bubble entrainment. Fluctuation in turbulence acts next to air-water free surface and causes the air bubble entrainment which is responsible for continuous tapping and releasing of air. It was observed that flow due to gravity played a vital role in the air entrainment process [3]. Experiments were carried out on stepped cascade aeration system to investigate the effect of air entrainment [4] and hydraulics of nappe flow [5], predict transition from nappe to skimming flow [6], and propose the condition for nappe flow [7]. Previous research works, conducted by [8-17], focused on hydraulic aspects of cascade system and the existence of relationship between flow rate and step geometry

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on aeration was reported. Appreciable results were obtained in the experiments conducted for removing the pollutants from grey water using cascade aeration and bio filtration. Good removal efficiency of ions concentration and COD is witnessed in the experiments [18]. Experiments were also conducted to study the combinational effect of stepped cascade system with limestone trickling filter in removal of toxic matters like Polychlorinated biphenyls (PCB's), Petroleum products and Phenols [19]. An attempt at numerical modeling of stepped cascade with end sill and high roughness is made using Volume Of Fluid (VOF) multiphase flow model [20]. The application of stepped cascade along with trickling filter filled with thermo-stone removed the concentration of toxic matters in the range 0.074 nm-0.156 nm [21]. The stepped cascade system has become very versatile in recent years because of its speedy construction. It is also proved that the system is a cost effective aeration system in replenishing dissolved oxygen. From the available literature, it is understood that previous studies focused on hydraulic properties of water and step geometry. Hence, in the present work, effect of stepped cascade aeration on water quality, especially waste water after post-treatment, was considered. The adaptability of the cascade system in such situations was also studied.

2. Materials and methods

Experimental model for the rectangular stepped cascade aeration system consisted of two tanks, called stilling basin and collecting tank, fitted on the upstream and downstream sides, respectively. Both tanks were made up of steel. The size of the upstream tank was 0.60 m × 1.20 m × 1.0 m and downstream tank was 0.60 m × 0.60 m × 0.60 m. Both tanks were connected by a sloped waist arrangement made up of steel frame, on which RCC precast slab was placed to provide a firm base for construction of steps. Steps were constructed using brick masonry to reflect the reality of the field. Perspex sheets were used as side walls of the stepped cascade system to facilitate better visualization from outside when experiment was on. A 5 HP capacity monoblock pump was used to lift the water from the collection tank to the tank in the upstream side. A magnetic flow meter, capable of measuring 0.040 m^3/s with an accuracy of 0.0001 m^3/s, was used to measure the rate of flow. Two dissolved oxygen meters (HANNA make - model HI 9146) were used to measure concentration of dissolved oxygen in the measuring locations (one at upstream tank and the other at downstream tank) of the stepped cascade system by inserting probes to a depth of 0.20 m [13]. The calibration of DO meters was daily done by air calibration method in ambient air conditions. Three readings were taken at the upstream and downstream locations for each and every sample and average value was used for the analysis. The total height of the stepped cascade system used in the present work was 1.80 m. Experiments were conducted for three different qualities of water, namely Potable Water (PW), Non-Potable Water (NPW), and Recycled Water (RW). The water, collected from the Reverse Osmosis (RO) plant in SASTRA university campus, was designated as PW. The water quality parameters of PW were fulfilling its requirements. The water collected from the bore well of SASTRA university was named NPW. It had higher chloride content and total dissolved solids. However, BOD and COD of NPW were well within the permissible limit. The water collected from effluent treatment plant was designated as Recycled Water (RW). It had higher values of water quality parameters exceeding permissible limit. For each and every type of water, readings were taken for two different heights of steps (0.15 m and 0.18 m) with five different treads of steps (0.40 m, 0.45 m, 0.50 m, 0.55 m, and 0.60 m). In total, there were 210 trials performed in the present work. Potable and non-potable water was added with 10 mg/l of sodium sulfite and 0.010 mg/l of cobalt chloride for the purpose of deoxygenation to maintain 1 mg/l of DO concentration. Since no reduction in DO concentration was observed in recycled water due to the addition of chemicals, no deoxygenation was performed as recycled water, collected from the effluent treatment plant, contained higher TDS and surface agents. It retarded the process of deoxygenation even after the addition of Sodium Sulfite. Figure 1 shows the experimental model used for the present research work. Table 1 lists the design parameters adopted in the experiment. Table 2 provides the chemical characteristics of different types of water used in conducted experiments. Taking the effect of temperature into account, the following equation was used to find the aeration efficiency at a standard temperature of 20°C [22]. Table 3 provides the calculation of $[d_c/h]$ for the steps used in this experiment, i.e. 0.15 m and 0.18 m for various hydraulic loading rates.

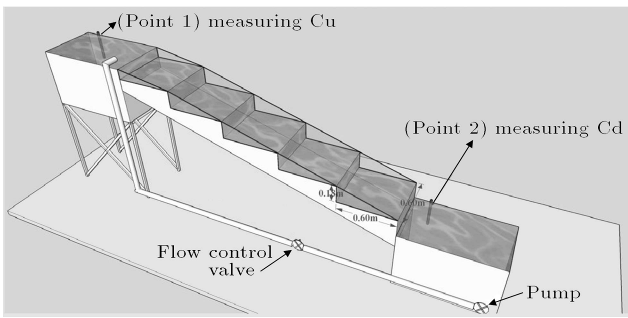

Figure 1. Experimental model for the laboratory stepped channel.

Table 1. Design parameters used in the experiment.

S. no	Independent	Range	Dependent
01.	Hydraulic loading rate (m^2/s)	0.005, 0.01, 0.015, 0.02, 0.025, 0.03 and 0.035	
02.	Rise of each step (m)	0.15 and 0.18	
03.	Tread of each step (m)	0.60, 0.55, 0.50, 0.45 and 0.40	Aeration efficiency (E_{20})
04.	Width of the channel (m)	0.60	
05.	Total height of the system (m)	1.80	
06.	Number of steps	12 and 10	

Table 2. Chemical properties of the used water.

Parameter	Potable Water (PW)	Non-Potable Water (NPW)	Recycled Water (RW)
pH	7.5	8.77	9.2
Temperature (°C)	26.2	28.2	29.3
TDS (mg/l)	30	1800	930
Salinity (mg/l)	102	670	1023
Chloride (mg/l)	81	385	120
DO (mg/l)	6.00	6.40	4.90
COD (mg/l)	10	12	170
BOD (mg/l)	0	2	65

Table 3. Dimensionless discharges (d_c/h) based on flow per unit width and step height.

Flow rate per unit width ($m^3/s/m$)	Dimensionless discharge	
	For step height of 0.15 m	For step height of 0.18 m
0.005	0.0911	0.0759
0.01	0.1446	0.1205
0.015	0.1894	0.1578
0.020	0.2295	0.1912
0.025	0.2663	0.2219
0.030	0.3007	0.2506
0.035	0.3332	0.2777

Oxygen transfer efficiency (E_T) for a hydraulic structure at any temperature, T (°C), was expressed by the following equation:

$$E_T = \frac{[C_d - C_u]}{[C_s - C_u]}, \tag{1}$$

where:

E_T Transfer efficiency at actual water temperature;

C_d Concentration of DO in the downstream (mg/l);

C_u Concentration of DO in the upstream (mg/l);

C_s Saturation concentration (mg/l).

$$E_{20} = \left[1 - (1 - E)^{\frac{1}{f}}\right], \tag{2}$$

where E_{20} is aeration efficiency for 20°C; f is exponent described by:

$$1 + 0.02103(T - 20) + 8.261x10^{-5}(T - 20)^2, \tag{3}$$

and T is ambient temperature in °C.

Chanson (2002) proposed an equation for nappe flow condition, which was followed in the present research work and is given below:

$$\left(\frac{d_c}{h}\right) \leq 0.89 - \left(\frac{h}{L}\right), \tag{4}$$

where:

$\frac{d_c}{h}$ Dimensionless discharge;

$d_c = \left(\frac{q_w^2}{g}\right)^{\frac{1}{3}}$ Critical depth in a rectangular channel (m);

q_w Hydraulic loading rate (discharge per unit width)(m^2/sec);

h Height of steps (m);

L Length of steps (m).

3. Results and discussion

3.1. Effect of step geometry

The variations of overall aeration efficiency (E_{20}) with respect to a non-dimensional parameter (d_c/h) are depicted in Figures 2-4 for the height of step = 0.15 m, and in Figures 5-7 for the height of step = 0.18 m, respectively. The variation of aeration efficiency E_{20} with a non-dimensional parameter (d_c/h) increases with increase in (d_c/h) up to certain values beyond which it has shown reverse trend. It was applicable for both the heights of step of 0.15 m and 0.18 m. It might be due to the following reasons. A decline trend was observed in the aeration efficiency when the flow was subjected to increased hydraulic loading rate and

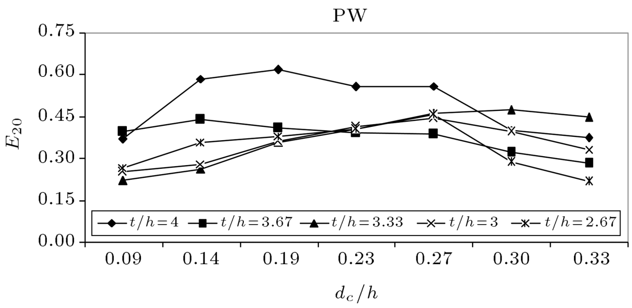

Figure 2. Aeration efficiency of potable water with respect to d_c/h for 0.15 m of rise.

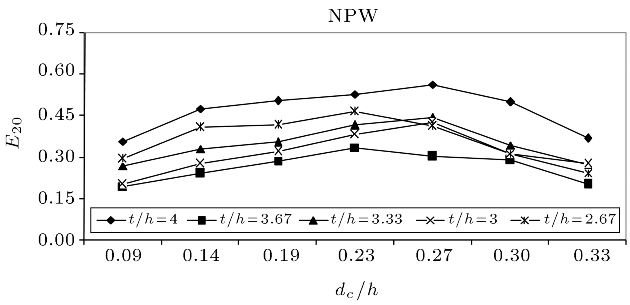

Figure 3. Aeration efficiency of non-potable water with respect to d_c/h for 0.15 m of rise.

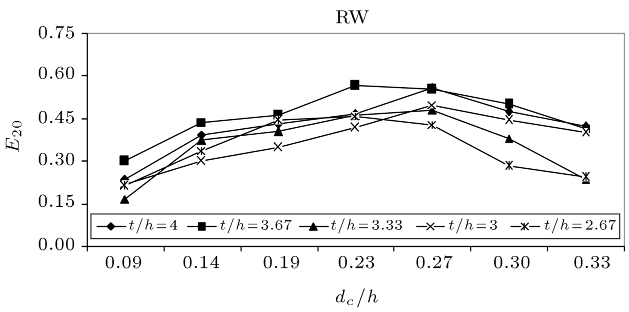

Figure 4. Aeration efficiency of recycled water with respect to d_c/h for 0.15 m of rise.

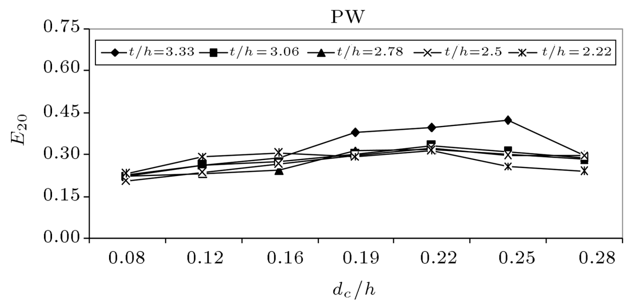

Figure 5. Aeration efficiency of potable water with respect to d_c/h for 0.18 m of rise.

this could be due to transition from nappe to skimming flow and width of the channel. It was also seen that for a particular height of step, size of tread played a role in deciding about aeration efficiency. Higher efficiency was observed for smaller values of tread.

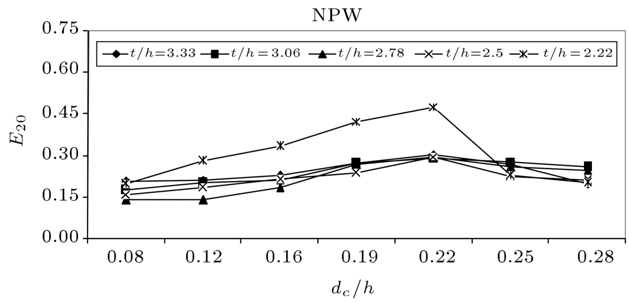

Figure 6. Aeration efficiency of non-potable water with respect to d_c/h for 0.18 m of rise.

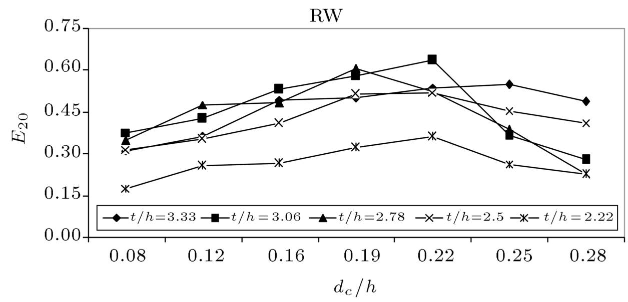

Figure 7. Aeration efficiency of recycled water with respect to d_c/h for 0.18 m of rise.

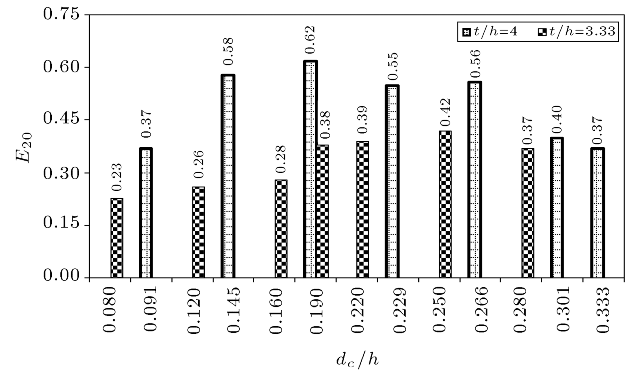

Figure 8. Effect of step geometry on the overall aeration efficiency.

Further increase of tread values showed a reverse trend in efficiency. From the effect of step geometry, it was understood that increase in height of step from 0.15 m to 0.18 m resulted in reduction in efficiency. It was due to increase in number of steps for lesser height of 0.15 m. Since more number of steps was used for 0.15 m height of step, aeration efficiency got accelerated and was very much effective.

To understand the effect of step geometry on overall aeration efficiency of stepped cascade aeration system, a typical example is explained in the following lines by taking the result of potable water. The results are discussed for a step tread of 0.60 m with heights of 0.15 m and 0.18 m, respectively, as shown in Figure 8. The results were compared for almost closer values of d_c/h. For a flow rate of 0.009 m^3/s, the aeration efficiency with step height of 0.15 m was found to be 0.62, whereas for step height of 0.18 m, it was found to be 0.28. This difference in aeration efficiencies due to step geometry is significant. However, for the highest d_c/h value, the effect of step geometry pronounces less due to increase in hydraulic loading rate where flow is subjected to transition stage.

3.2. Effect of water quality

For potable water, the maximum efficiency of 62% was observed for $t/h = 4$ with $d_c/h = 0.189$ for 0.15 m height of a step. It was also observed that for a hydraulic loading rate from 0.005 to 0.025 m^2/s, the aeration efficiencies were good and further increase of flow led to transition zone; hence, there was a reverse trend. There was not much variation in aeration efficiency from $t/h = 4$ to 3.33 and further reduction of these values showed a higher reduction in efficiency which was due to decrease in tread values below 0.45 m where sufficient space was not available for aeration process. In a similar sense, for $t/h = 3$ with a hydraulic loading rate of 0.005 m^2/s, a minimum efficiency of 15% was observed. As the turbulence, directly related with velocity and spreading of water on step, was like thin film over the larger area, the performance of cascade system for low hydraulic loading rate was found to be very low. In general, flow with lower velocity will lead to greater residence time of the cascade and will result in greater air transfer. But, the geometry of the cascade was unable to produce greater turbulence and hence lesser efficiency. Improved performance of cascade systems was observed for hydraulic loading rate 0.01 m^2/s and 0.015 m^2/s. It was due to formation of hydraulic jump within the tread and ultimately yielded sizable quantity of aeration. However, the efficiency of cascade aeration significantly improved when hydraulic loading rate increased to 0.02 m^2/s and 0.025 m^2/s. By further increase in hydraulic loading rate to 0.03 and 0.035 m^2/s, the efficiency was found to be low when compared with efficiency for hydraulic loading rates of 0.02 m^2/s and 0.025 m^2/s. With increased velocity of flow on the cascade, the residence time and aeration efficiency decreased. It was evident from the above results that step geometry was optimized based on hydraulic loading rate and considered to be the main governing parameter in the design stage.

In the case of non-potable water with a height of step = 0.15 m, more aeration efficiency was achieved for $t/h = 4$ and for other t/h values, the efficiency was found to be less. Increase in d_c/h up to 0.266 increased the aeration efficiency for all t/h values and further increase in d_c/h showed a reverse trend. It was due to increased hydraulic loading rate. Also, similar trend was observed for a height of 0.18 m. Maximum efficiencies of 56% and 47% were observed for heights of steps 0.15 m and 0.18 m, respectively.

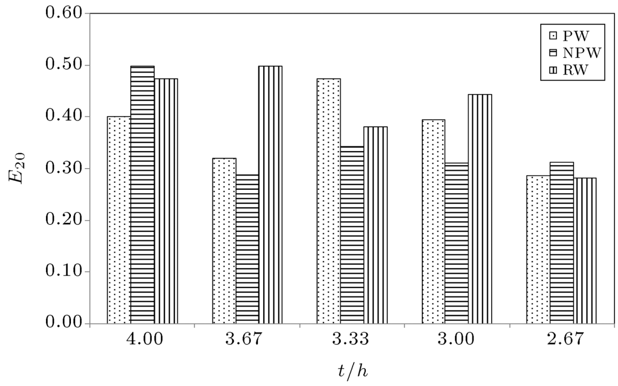

Figure 9. Effect of water quality on the overall aeration efficiency.

Also, similar trend was seen in recycled water as non-potable water, but there was no much variation among efficiencies of different t/h values. Except $t/h = 2.22$, for all the other t/h values, aeration efficiency was above 30% and maximum efficiency was 63% for a height = 0.18 m. For a height of step = 0.15 m, these values were falling between 46 and 57%. Hence, it was inferred that stepped cascade aeration system was effective in recycled water with addition of no chemicals and it was the field reality. The aeration efficiency of recycled water was found to be a little bit less than efficiency of potable and non-potable water; it might be due to the reason that recycled water has sediments, whereas potable and non-potable water does not have this. To understand the effect of water quality on the overall aeration efficiency, Figure 9 depicts the results of aeration efficiency with respect to t/h values for a hydraulic loading rate of 0.03 m^2/s. It was understood from the results that water quality had effect on aeration efficiency and was ranging from 10 to 20%, except for $t/h = 2.67$ (tread = 0.40 m and height = 0.15 m). It was also inferred that aeration efficiency of recycled water under stepped cascade aeration system attracted considerable attention.

3.3. Effect of chemical properties of water on aeration efficiency

From Table 2, it was observed that Total Dissolved Solids (TDS) and Salinity of the NPW and RW were high. Comparing the aeration performances of cascade systems for enhancing DO content of different types of water, potable water was found to be better than the non-potable and recycled water. It might be due to the reason that potable water was free from TDS and salinity, and hence it had better aeration. In case of PW, the minimum and maximum aeration efficiencies were found to be 32 and 62%, respectively, which give an idea about the effectiveness of cascade system in enhancing DO. In case of NPW, these values ranged from 19% to 47% and reduction in efficiency was due to higher values of TDS and salinity with dissolved organic matter. In RW, the difference between maximum efficiency (63%) and minimum efficiency (17%) was found to be more significant than those in other two types of water. Better aeration efficiency was achieved as no deoxygenation was performed for RW before the start of experiment. The initial DO concentration of RW ranges from 4 to 5 mg/l, whereas in cases of PW and NPW, the DO concentration has been set to a value from 1 to 2 mg/l by deoxygenation.

3.4. Comparison of the present results with earlier research

The predictive equation given by Nakasone [23] with combination of fall height, discharge, and tail water depth to analyze the aeration efficiency was compared with our present work. Good agreement in results was not observed. This is due to the hydraulic properties adapted to that equation. The results of the present study were also compared with the results of an earlier study by Moulick et al. It was inferred from their results that aeration efficiency was very high (from 0.8 to 0.9) compared with the present study and it might be due to the difference in quality of water used and scale effect. Moulick et al. (2010) [15] studied a 3 m high stepped cascade system with step height value of 0.6 m, whereas in the present study, the total height of stepped cascade was restricted to 1.8 m with heights of 0.15 m and 0.18 m. Another equation, given by El-Monayeri (2011) [24], was also compared with the present study, which did not establish a good rapport with our results due to higher value of COD.

3.5. Statistical analysis

A regression analysis was made to analyze the results of the experiments, i.e. parameters like d_c/h and r/C_s, to calculate the aeration efficiency (E_{20}). All the parameters considered in this equation are non-dimensional parameters, which will be useful to balance the equation E_{20}. The measured aeration efficiency was compared with values of Eqs. (5)-(7). Good agreement was found between the observed values and predicted values form the developed equation. In addition, confidence level in the correlation was seen in Figure 10. It was also indicated in the comparison of measured and predicted values that they fell well below the upper and lower bound (10% of peak values) lines and hence results were found to be reliable.

From the obtained data for all the three types of water, keeping E_{20} as a dependent variable and function of $\frac{d_c}{h}$ and $\frac{r}{C_s}$, the following equations were developed for PW, NPW, and RW, respectively:

$$E_{20PW} = 0.0119 + 0.0880\frac{d_c}{h} + 1.06\frac{r}{C_s}, \quad (5)$$

$$E_{20NPW} = 0.0175 + 0.0436\frac{d_c}{h} + 1.05\frac{r}{C_s}, \quad (6)$$

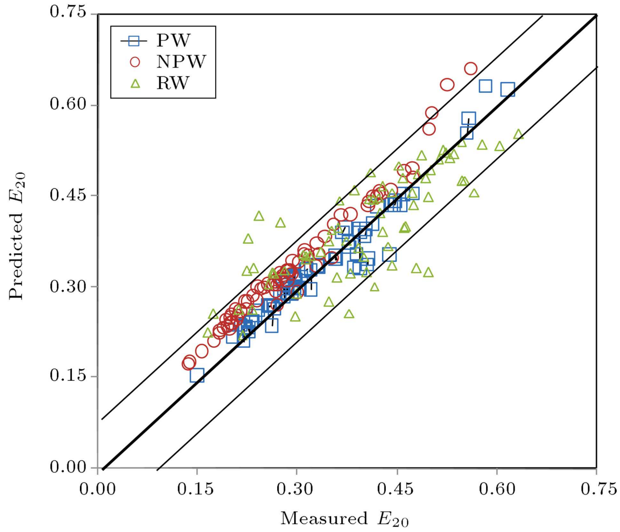

Figure 10. Comparison of the measured and predicted E_{20} values.

$$E_{20RW} = 0.0146 + 0.440\frac{d_c}{h} + 0.829\frac{r}{C_s}, \quad (7)$$

$$\frac{d_c}{h} = 0.04 \text{ to } 0.44, \text{ and}$$

$$\frac{r}{C_s} = 0.80 \text{ to } 1.10.$$

The above equations could be used to predict the aeration performance of the cascade system by slightly varying the geometry and hydraulic loading rates. From the detailed study, it was understood that the aeration efficiency was governed by step geometry, hydraulic loading rate, and also quality of water. Stepped cascade aeration was found to be effective in enhancing DO in recycled water which has shown a positive sign for natural treatment of wastewater before discharging it to water bodies to save aquatic life.

4. Conclusions

From the detailed investigations carried out on rectangular stepped cascade aeration system to study the effect of hydraulic loading rate, d_c/h, height and tread of step, and water quality, the following conclusions were obtained:

- Increase of dimensionless discharge (d_c/h) increased the overall aeration efficiency up to 0.266 and further increase showed a reverse trend which was due to the fact that flow approached transition condition with increased hydraulic loading rate;
- The overall aeration efficiency increased with increase in the number of steps in which better aeration process was on and vice versa;
- The overall aeration efficiency at standard conditions (E_{20}) approached maximum for $t/h = 4$ and

number of steps were 12 with hydraulic loading rate of 0.02 to 0.025 m^2/s for potable and non-potable water. In the case of recycled water, maximum efficiencies were achieved for $t/h = 3.67$ both for 0.15 m and 0.18 m as heights of step;

- Overall aeration efficiency was higher for recycled water among three types of water used. Hence it was concluded that stepped cascade aeration was very suitable for enhancement of DO content.

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Nomenclature

L	Width of channel (m);
C_d	Concentration of DO in downstream (mg/l);
C_u	Concentration of DO in upstream (mg/l);
C_s	Saturation concentration (mg/l);
d_c	Critical flow depth (m);
$\frac{d_c}{h}$	Dimensionless discharge;
E	Transfer efficiency at water temperature (%);
E_{20}	Oxygen transfer efficiency at 20°C (%);
f	Correction factor for temperature;
g	Acceleration due to gravity (m/s^2);
h	Height of the step (m);
K_L	Liquid film coefficient for oxygen;
Q	Flow rate (m^3/s);
q_w	Hydraulic loading rate ($m^3/m/s$);
t	Tread of the step (m);
T	Ambient temperature in °C;
r	Oxygen deficit.

Abbreviations

BOD	Biological Oxygen Demand;
COD	Chemical Oxygen Demand;
DO	Dissolved Oxygen;
HP	Horse Power;
NPW	Non-Potable Water;
pH	Hydrogen ion concentration;
PW	Potable Water;
RW	Recycled Water;
TDS	Total Dissolved Solids;
VOC	Volatile Organic Compounds.

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