The Effect of Hydraulic Structure on Aeration Performance Case Study: Stepped Cascade with End Sill

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ABSTRACT

Cascade aeration has been utilized as a hydraulic structure for years which has proven to be the least costly aeration system in replenishing dissolved oxygen. The aeration performance of the cascade structure with end sill has been investigated in a large laboratory cascade structure which has been designed and constructed at Al-Mustansiriya university in environmental hydraulic .An empirical equation to predicting the oxygen transfer efficiency for different models of cascade structure with end sill was correlated. The results indicated that l/h and s/h were a significant effect on the aeration efficiency of cascade structure.

Keywords: Hydraulic structure, Stepped cascade , End sill ,Aeration, Oxygen transfer

1-Introduction

Aeration or re-aeration is the physical process of oxygen transfer or oxygen absorption from the atmosphere acts to replenish the used oxygen. Aeration is one of the fundamental parameters required to maintain dissolved oxygen for the aerobic bacteria that feed on organics whether in treatment facilities or in streams and rivers (A. Baylar, 2010). (Metcalf & Eddy, 2003).Hydraulic structures increase the amount of dissolved oxygen in a river system, even though the water is in contact with the structure for only a short time . The same quantity of oxygen transfer that normally would occur over several kilometers in a river can occur at a single hydraulic structure (A. Baylar, 2010).

Aeration efficiency (E_{20}) of hydraulic structures has been studied by many investigators.. Within the last few years there has been a growing interest in the air entrainment by water jets plunging into pools(A. Baylar, 2010). Tebbutt et al. (1977) presented some aeration data for stepped cascades with nappe and skimming flows. Since they conducted the experiments in small-size facilities, reduced free-surface aeration was present of Essery et al. (1978) studied nappe flow in pooled stepped cascades. Novak (1994) compared a cascade as investigated by Essery et al. (1978) with a cascade of pools and a single jet/pool configuration. Toombes and Chanson (2000) and Chanson and Toombes (2000) considered aeration in small-slope stepped cascades. Chanson and Toombes (2002) conducted gas–liquid interface measurements in stepped cascade. Recently, Baylar et al. (2007a, b,2009), Baylar and Emiroglu (2003b, 2005,2006), Emiroglu and Baylar (2003a,), have conducted many studies to investigate air/water flow ratio (Q_a/Q_w) and aeration efficiency (E_{20}) in cascade structure . Gulliver and Wilhelms (1992) have stated that an upstream DO deficit of greater than 2.5 mg/l is normally required for accuracy in an oxygen-transfer efficiency measurement. Wormleaton and Soufiani (1998) found that the oxygen transfer efficiency, E, is sensibly independent of the upstream DO deficit.

Y. B. M. Heza et al (2008) investigated the feasibility of using aeration weir systems in agricultural drains receiving domestic sewage to increase its quality by increasing the dissolved oxygen content (DO).

Stepped chutes have become popular in recent years mainly due to the intrinsic low cost and the speed of construction. In a stepped chute, the provision of steps can produce significant energy dissipation . The flow on stepped chutes can be in either nappe or skimming flow regimes (Emiroglu, M. E., & Baylar, A. 2003a). Rajaratnam (1990), Chamani and Rajaratnam (1994), Chanson (1994a,b; 1996), and Chamani and Rajaratnam (1999a,b) have focused mainly on characteristics of nappe flow and skimming flow over stepped chutes. There are not found any published analytical or physical studies of the dissolved oxygen levels produced in cascade structure with end sill. The basic goal of this study is to characterize the cascade efficiency for different cascade geometries, and the effect of varying l/h and s/h.

2- Aeration Process

Oxygen transfer and dispersion into water essentially is governed by the processes of molecular diffusion, turbulent mixing, or both. At the water surface it requires a difference in active partial pressures between the air and water. Lewis and Whitman (1924) suggested that two laminar films or layers lie on either side of the air-water interface. Both films offer resistance to the passage of oxygen molecules into the water. However, for a slightly soluble gas, such as oxygen in water, the resistance of the waterside is very much the greater of the two, effectively controlling the transfer process. The mass transfer rate (dm/dt) of gas molecules across an interface is known to be proportional to the concentration gradient across the interface, and this can be expressed as:

$$\frac{dm}{dt} = \frac{dC}{dt} = K_L \frac{A}{V} (C_S - C) \qquad (1)$$

where C is DO concentration(ML^{-3}), K_L is liquid film coefficient for oxygen (LT^{-1}),A (L^2) is surface area associated with the volume, V(L^3), over which transfer occurs, C_s is saturation concentration (ML^{-3}), and t is time (T). The term A/V is often called the specific surface area, a, or surface area per unit volume (L^{-1}).

The predictive relations described herein all assume that C_s is constant and determined by the water-atmosphere partitioning. If that assumption is made, C_s is constant with respect to time, and the oxygen transfer efficiency (aeration performance), E, may be defined as (Gulliver et al. 1990):

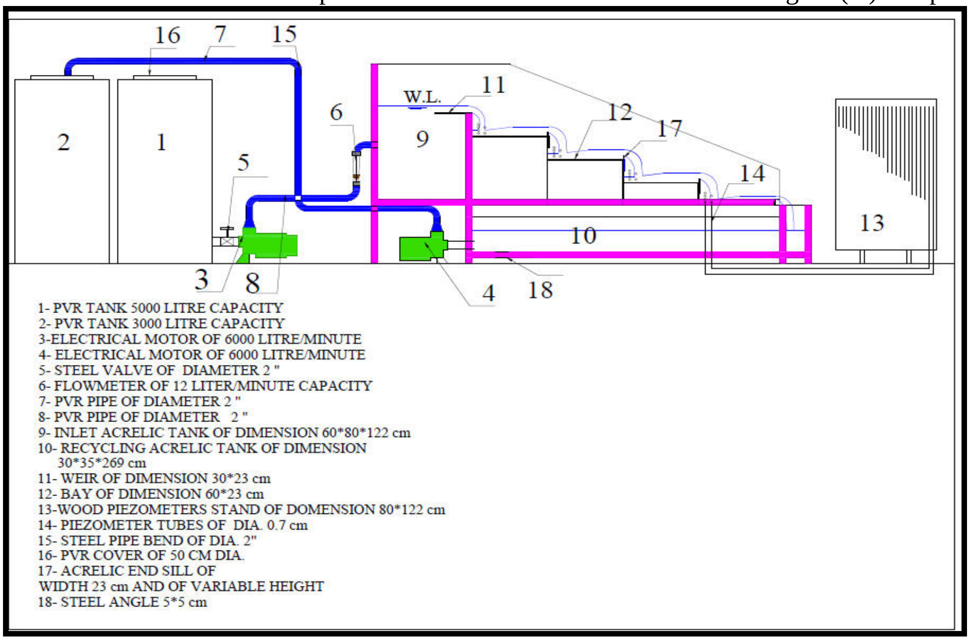
$$E = 1-\frac{1}{r} = \frac{Cd-Cu}{Cs-Cu} \qquad (2)$$

where u and d are subscripts indicating upstream and downstream locations, respectively, and r is the oxygen deficit ratio [($C_s - C_u$)/($C_s - C_d$)].

The saturation concentration in distilled, deionized water may be obtained from charts or equations. This is an approximation because the saturation DO concentration for natural waters is often different from that of distilled, deionized water due to the salinity effects. In this study, the saturation concentrations were determined by the chart of McGhee (1991).

3-Experimental Arrangement and Experiments

The lab-scale model consist of inlet PVR tank , inlet pump, transparent methacrylate cascade structure , recycling tank , recycling pump and outlet PVR tank connected to each other by galvanized cast iron pipes , fittings and flow meter .The schematic representation of lab- scale unit is shown in figure (1) and plate (1).



<u>Figure (1):</u> Schematic representation of lab-scale unit

The primary PVR tank of 5000 liter capacity connected to a pump which is of 600 l/min pump flow rate . The pump has been connected to flow meter by control valve for flow control . The cascade structure was constructed from three parts . The first part is a settling transparent methacrylate tank of dimension (0.8m*0.6m*1.25m),the second part is transparent methacrylate cascade steps of dimension (2.44m* 0.23m* 1.25m) , the third part is a recycling transparent methacrylate tank of dimension (2.44m*0.3m *0.25m). Each part was made from a frame of iron angle connected to each other by welding and transparent methacrylate.

In the settling tank a weir of 0.3 meter length and 0.23 m width was constructed and calibrated to measure the discharge . The laboratory model is depicted in plate (1). The recycling tank is connected to the outlet tank by a recycling pump of discharge= 600 l/min.

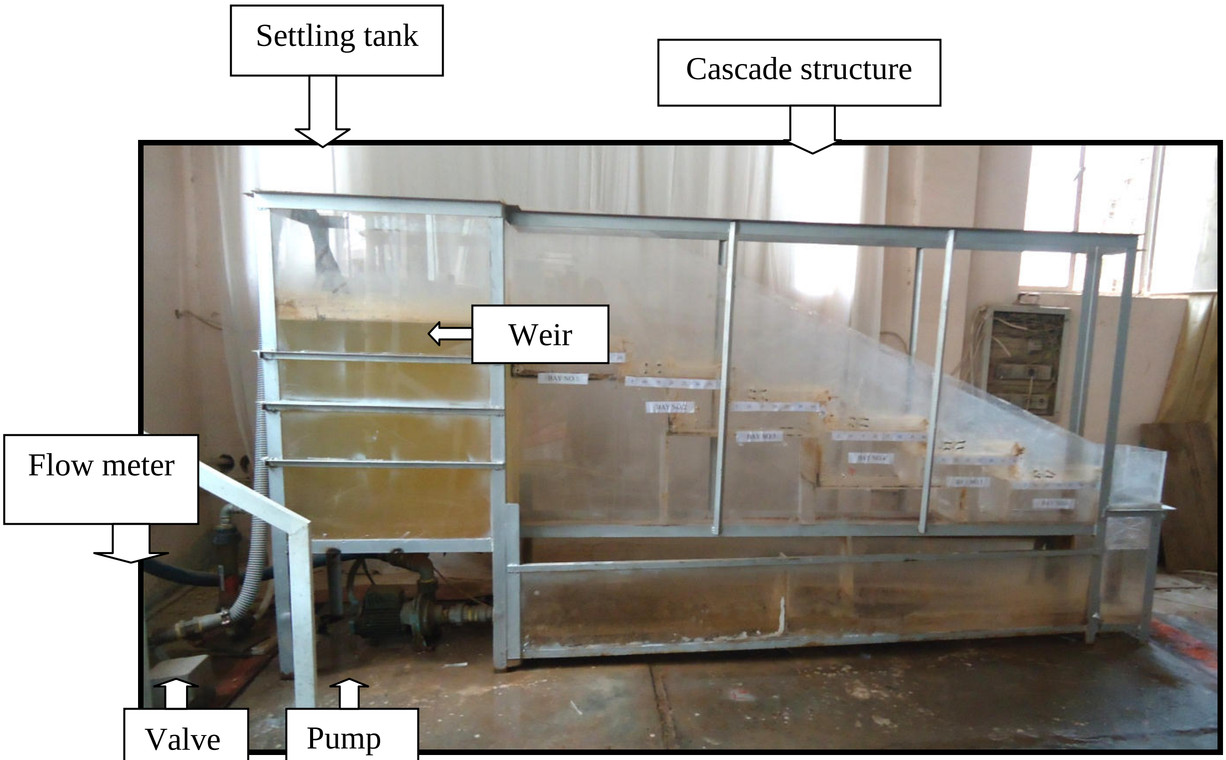


Plate (1): General arrangement of laboratory unit

During the experiments, a digital thermometer was used to measure water temperature. Since the saturation concentration of oxygen is a strong function of temperature, the aeration efficiency is also temperature dependent. To provide a uniform basis for comparison of different systems ,the aeration efficiency is often normalized to a 20°C standard. Gulliver et al. (1990) proposed the following equation to describe the influence of temperature:

$$E_{20}=1-(1-E_T)^{1/1.0+0.02103(T-20)+8.26*10-5(T-20)2} \quad (3)$$

where E_T is oxygen transfer efficiency at the water temperature of measurement and E_{20} is oxygen transfer efficiency at 20°C. In this study, the aeration efficiency was normalized to 20°C using equation 3. Two cases of cascade were experimented

1- For Case 1 the stepped cascade weirs are designed and constructed from three steps each step of dimension 0.6m*0.23 m and of height 0.2 m The end sill of variable height (35,60,80,100 mm) have been tested .

2- For Case 2 The cascade step of dimension (0.4m *0.23m) and of 0.1 m height. The end sill of variable height (40,50 mm) have been tested.

The discharge was measured by means of a rotometer which has been installed in the supply line. The slope of the stepped chute, defined as l/h was equal to 3.0 for case 1 (α = 18.43°), 4.0 for case 2 (α = 14.036°). All experimental runs were carried out with discharges ranging between 1 and 4 l/s in 7 steps.

Each experiment was started by filling the storage tank with marginal water and the characteristics of the marginal water as shown in Table was measured.The salt content of marginal water used for all of the experiments reported in this paper was low and was monitored constantly during the experiments to ensure there was no buildup of residues caused by the deoxygenation chemicals added to the water. Therefore, the results were not affected by the presence of any chemicals or pollutants.

DO measurements at the upstream and downstream of the stepped chute were taken using calibrated portable HANNA Model HI 9142 oxygen meters at the locations identified. Measurements were made by submersing the probe to a depth of approximately 0.20 m at sampling points. The DO meters were calibrated daily according to local atmospheric pressure, prior to use, by the air calibration method. Calibration procedures followed those recommended by the manufacturer. The calibration was performed in humid air under ambient conditions. From equation 2 it can be seen that the measurement of transfer efficiency becomes quite sensitive to measurement errors with a low upstream DO deficit.

4- Results and Analysis

The aeration efficiency of stepped cascade were obtained depending on cascade inclination angle (α), sill height (s),
discharge (Q) and chemical oxygen demand of aeration performance of experiments COD . Aeration efficiency results (E_{20}).Tables 1-6 shows the results of experiments for cases 1,2

Table (1): Results of experiments of Case 1 with end sill =35 mm

Discharge	PH U/S	PH D/S	EC U/S	EC D/S	TDS U/S	TDS D/S
1	6.82	6.85	1034	1023	515	509
1.5	6.83	6.86	1027	1017	512	508
2	66.83	6.9	1020	1011	509	506
2.5	6.94	7.07	1006	999	502	499
3	7.06	7.24	993	990	496	493
3.5	7.04	7.06	998	995	498	496
4	7.03	7.09	1002	999	500	497

Table (2): Results of experiments of Case 1 with end sill =60 mm

Discharge	PH U/S	PH D/S	EC U/S	EC D/S	TDS U/S	TDS D/S
1	7.66	7.77	1038	1047	527	516
1.5	7.49	7.47	1040	1041	528	520
2	7.32	7.37	1042	1035	521	516
2.5	7.31	7.37	1055	1048	535	523
3	7.3	7.36	1066	1062	555	531
3.5	7.28	7.34	1064	1061	540	534
4	7.27	7.32	1063	1061	537	531

Table (3): Results of experiments of Case 1 with end sill =80 mm

Discharge	PH U/S	PH D/S	EC U/S	EC D/S	TDS U/S	TDS D/S
1	7.41	7.53	1025	1084	566	544
1.5	7.41	7.47	966	1074	538	509
2	7.4	7.42	907	1064	453	533
2.5	7.3	7.38	967	1046	584	523
3	7.22	7.33	1028	1028	525	514
3.5	7.40	7.47	1067	1048	551	524
4	7.62	7.78	1106	1066	587	534

Table (4): Results of experiments of Case 1 with end sill =100 mm

Discharge	PH U/S	PH D/S	EC U/S	EC D/S	TDS U/S	TDS D/S
1	7.01	7.1	1037	1034	516	510
1.5	7.04	7.08	1030	1027	515	510
2	7.06	7.06	1026	1021	513	508
2.5	7.11	7.09	1024	1024	513	508
3	7.13	7.20	1023	1028	513	507
3.5	7.1	7.22	1031	1029	518	514
4	7.08	7.34	1039	1030	524	515

Table (5): Results of experiments of Case 2 with end sill =40 mm

Discharge	PH U/S	PH D/S	EC U/S	EC D/S	TDS U/S	TDS D/S
1	7.36	7.32	978	925	475	460
1.5	7.27	7.32	953	922	469	460
2	7.19	7.32	929	920	463	461
2.5	7.23	7.28	930	924	464	462
3	7.24	7.26	931	929	465	463
3.5	7.26	7.27	926	922	462	462
4	7.28	7.28	922	918	460	460

Table (6): Results of experiments of Case 2 with end sill =50 mm

Discharge	PH U/S	PH D/S	EC U/S	EC D/S	TDS U/S	TDS D/S
1	7.36	7.56	1085	1055	542	524
1.5	7.28	7.42	1086	1075	542	535
2	7.22	7.28	1087	1095	543	546
2.5	7.23	7.27	1087	1090	542	545
3	7.24	7.26	1087	1084	542	543
3.5	7.2	7.25	1091	1088	543	545
4	7.18	7.24	1095	1092	545	546

The COD range (32-50) mg/l.

Figures (2-7) represent aeration efficiency E_{20} for Case 1,2 for different models

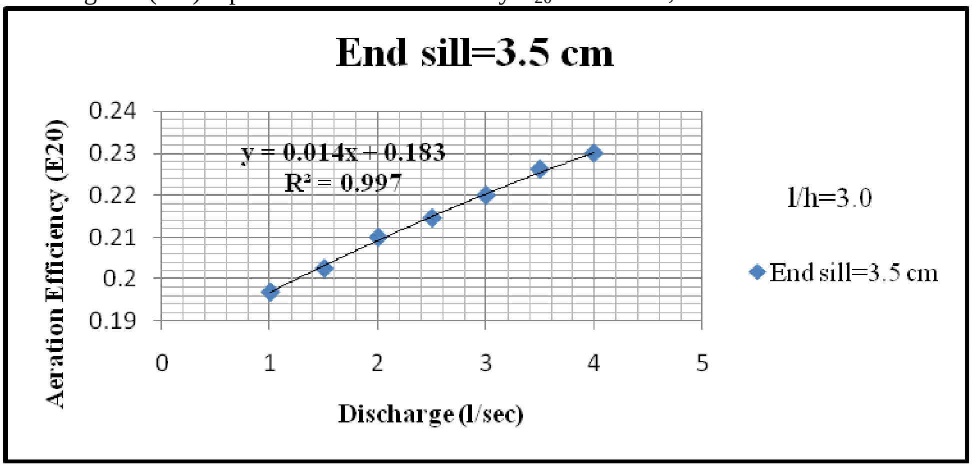


Figure (2): Relation between discharge and aeration efficiency for case No.1 model No.1

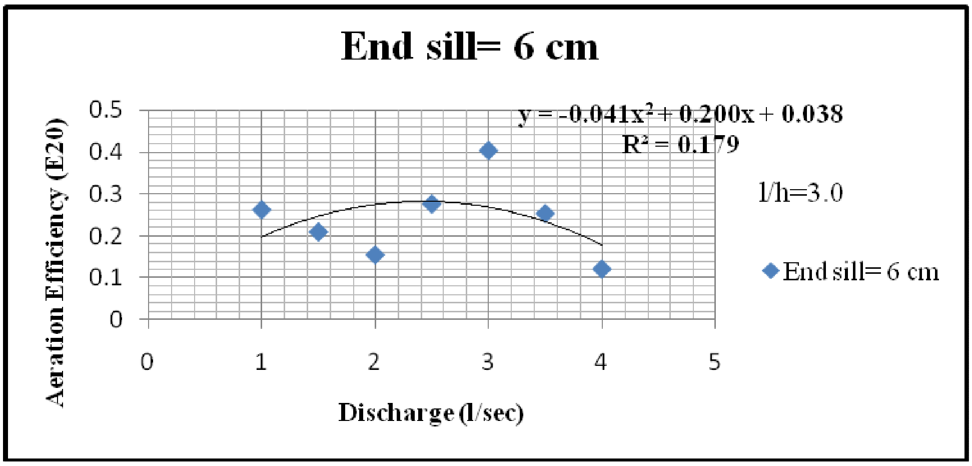


Figure (3): Relation between discharge and aeration efficiency for case No.1 model No.2

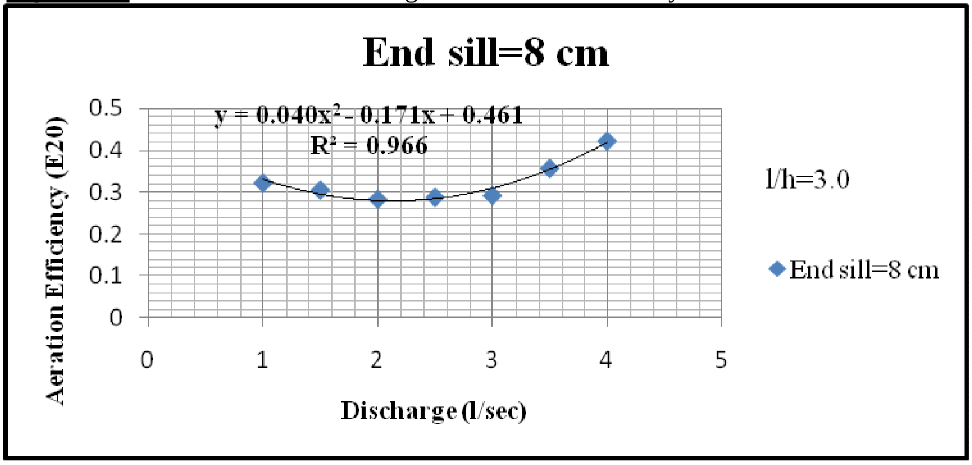


Figure (4): Relation between discharge and aeration efficiency for case No.1 model No.3

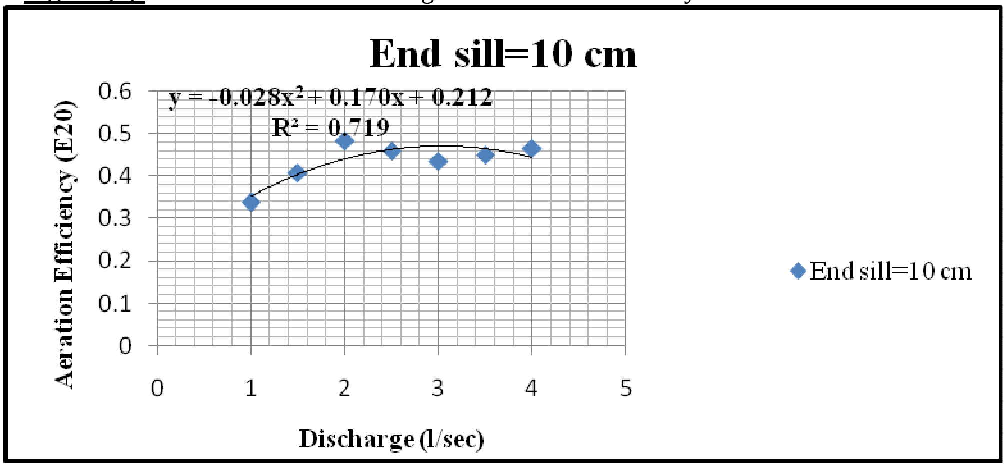


Figure (5): Relation between discharge and aeration efficiency for case No.1 model No.4

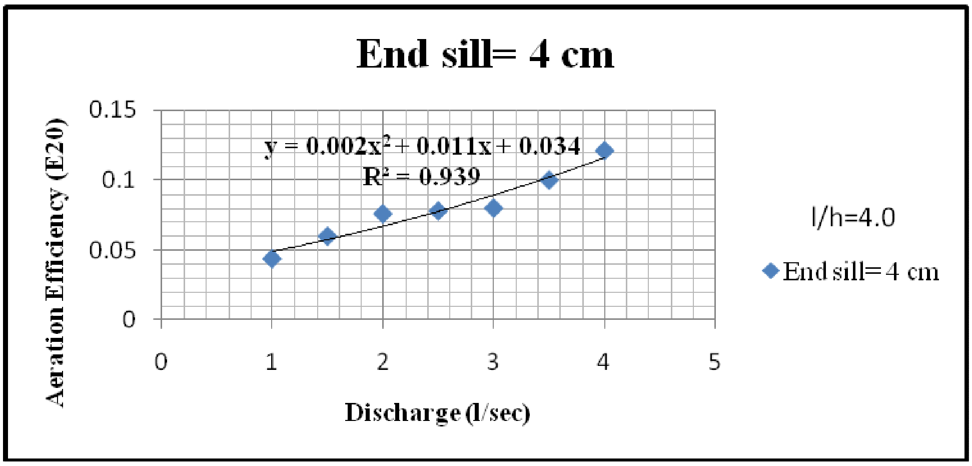


Figure (6): Relation between discharge and aeration efficiency for case No.2 model No.1

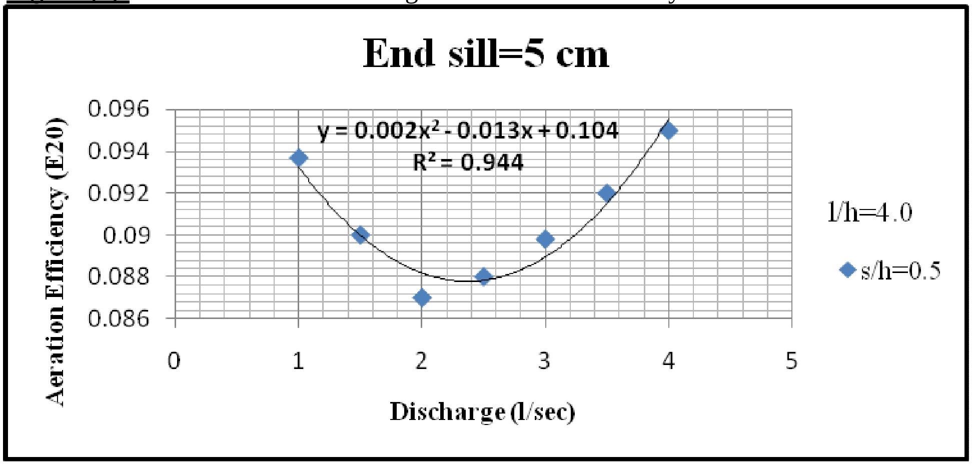


Figure (7): Relation between aeration efficiency - discharge for case No.2 model No.2

Figure 8 represent a comparison between Aeration efficiency E_{20} for case 1,2 for s/h=0.4, and figure 9 represent a comparison between Aeration efficiency E_{20} for case 1,2 for s/h=0.5.

From figures it is clear that case 1 is most efficient than case 2 and case 1 model 4 is most efficient than the other models.

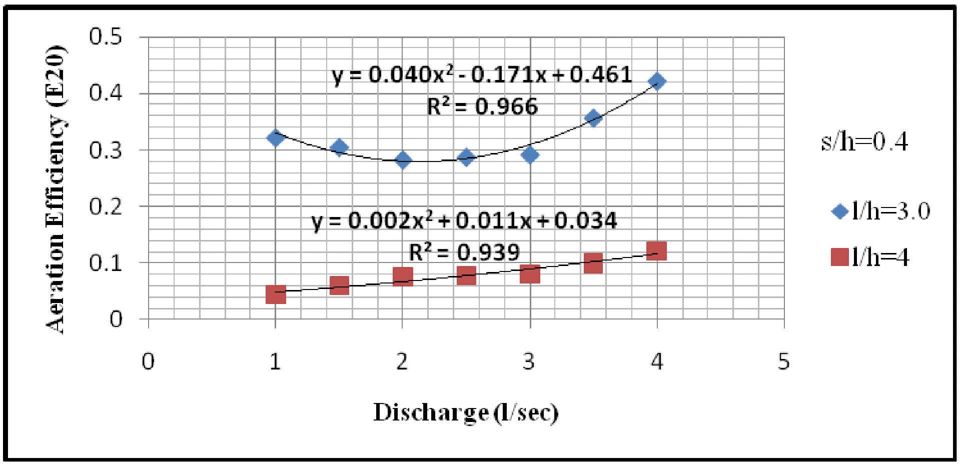


Figure (8): Aeration efficiency- discharge relationship for s/h=0.4 for case No.1 model No.3 and case No.2 model No.1

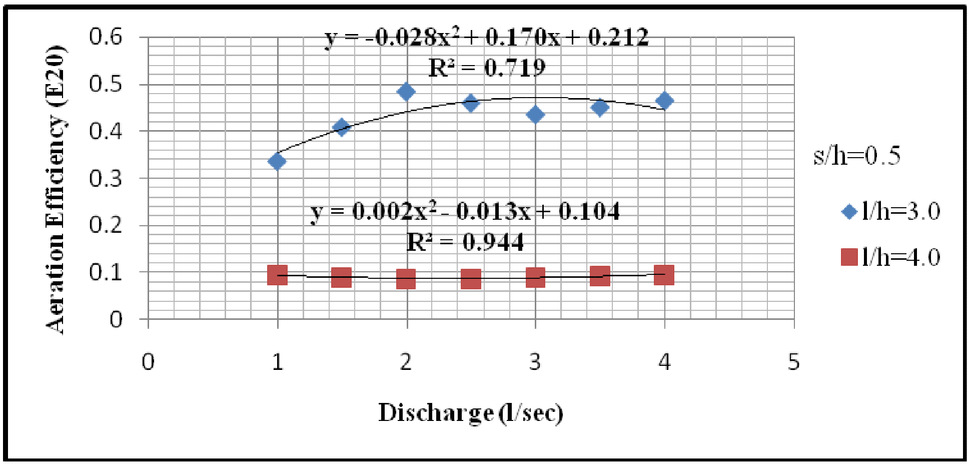


Figure (9): Aeration efficiency - discharge relationship for s/h=0.5 for case No.1 model No.4 and case No.2 model No.2

An empirical correlation predicting oxygen transfer efficiency was developed for stepped cascade. The resulting correlation is given in equation 4:

$$E_{20}=(0.108+2.499*(s/l)^{1.329}/2.69*10^{-11}*(l/h)^{-22.053}*(F*\frac{\frac{U}{S}COD}{\frac{D}{S}COD})^{0.701}) \quad (4)$$; correlation coefficient=85%

where h is the step height (m), l is the step length (m), and F is Froude number , s end sill height (m).

The measured oxygen transfer efficiencies were compared to those predicted with equation 4. Good agreement between the measured oxygen transfer efficiencies and the values computed from the predictive equation was obtained.

5-Conclusions

Set of laboratory experiments have been carried out continuously on stepped cascade with end sill in order to determine aeration performance. An empirical correlation has been developed that predicted the oxygen transfer efficiency for stepped cascade. Based on the findings of this study, the following conclusions can be drawn:

- Nappe flow was observed for all cases and the aeration efficiency of stepped chute with end sill increased with discharge
- For stepped cascade with end sill, the aeration efficiency increased as chute inclination angle increased.
- Additional testing is necessary to assess the effect of aeration efficiency for stepped cascade with end sill when discharge is higher than the largest discharge tested, 4 l/s.
- The COD is an effective factor in aeration efficiency and as COD increases , the aeration efficiency decreased because of pollutant effect of marginal water (COD)

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