Study the Effect of Ogee Stepped Spillway on Stream Reaeration

Dr. Heikal G. E.,
Teacher in Environmental Department
Faculty of Engineering – Zagazig University

Abstract **-The oxygen transfer at a hydraulic structure happens by self-aeration through the spillway and by flow aeration in the hydraulic jump downstream of the hydraulic structure. Spillways with their water-air controlling mechanisms are important not only for their structural properties but also for their effects on stream ecology. Spillway types also affect the efficiency of aeration. Decisions on the types of spillway should be made by taking the environmental conditions and flow rates into consideration.**

This paper investigated the aeration efficiency of ogee stepped spillway model in a large laboratory flume at inclination angle (α = 40°). Dissolved oxygen concentrations were measured versus different discharges in range (4.6-24.6) L/s. The results indicated that ogee stepped model is very efficient at oxygen transfer because of the strong turbulent mixing associated with substantial air bubbles entrainment. DO concentration changes are shown to depend on the flow types and discharge rates. The highest aeration efficiency was achieved in the case of the lowest discharge rate equal 4.6 L/s with average percentage 59%

Keywords: dissolved oxygen, ogee stepped, re-aeration, aeration efficiency.

1. INTRODUCTION

The concentration of dissolved oxygen is an important indicator of water quality because aquatic life lives on the dissolved oxygen in the water. 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. The primary reason for this accelerated oxygen transfer is that air is entrained into the flow in the form of a large number of bubbles. These air bubbles greatly increase the surface area available for mass transfer. The physical process of oxygen transfer from atmosphere acts to replenish the used oxygen. This process is termed re-aeartion or aeration. Hydraulic structures can increase dissolved oxygen levels by creating turbulent conditions where small air bubbles are carried into the bulk of the flow.

The objective of this study was to investigate the effects of aeration caused by ogee stepped spillways, in a laboratory model flume, and in relation to flow type and discharge rate.

2. MECHANISMS OF ENTRAINMENT OF AIR BUBBLES:

Stepped flows are characterized by the strong turbulent mixing, the large residence time and the substantial air bubble entrainment. Air bubble entrainment is caused by turbulence fluctuations acting next to the air-water free surface. Through this interface, air is continuously tapped and released. Air entrainment occurs when the turbulent kinetic energy is large enough to overcome both surface tension and gravity effects. The turbulent velocity normal to the free surface must overcome the surface tension pressure, and be greater than the bubble rise velocity component for the bubbles to be carried away Chanson, H. (2002)[5].

Stepped flows can be classified into skimming flow, transition flow, and nappe flow. For narrow steps or larger discharges such as the design discharge the water skims over the step corners and recirculating zones develop in triangular niches formed by the step faces and the pseudo-bottom, as shown in Fig. (1). In skimming flow the water flows as a coherent stream over the pseudo-bottom formed by the step corners. For a range of intermediate discharges, a transition flow regime takes place. The dominant feature is stagnation on the horizontal step face associated with significant splashing and a chaotic appearance.

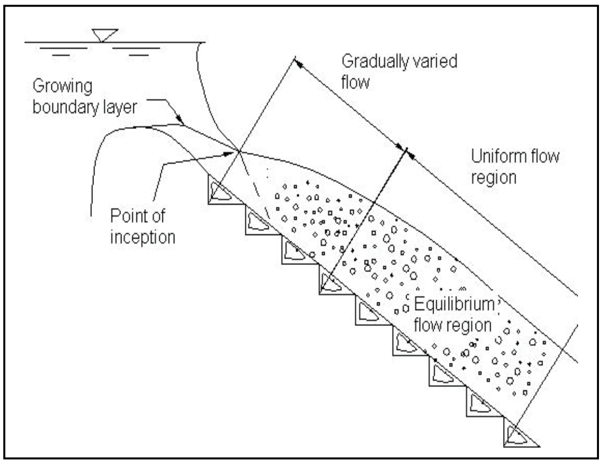

Fig. (1) Skimming flow regime

For nappe flow the steps act as a series of overfalls with the water plunging from one step to another Fig. (2).

Generally speaking nappe flow is observed for low discharges and wide steps.

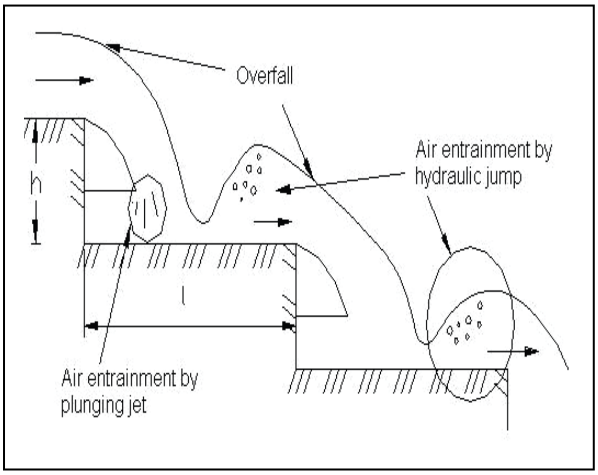

Fig. (2) Nappe flow regime

3. STREAM REAERATION PROCESS:

Reaeration process and dispersion into water essentially is governed by the processes of molecular diffusion, turbulent mixing, or both. The mass balance equation relating the instantaneous rate of change in DO concentration (dc/dt) to the rate of oxygen mass transfer can be expressed as

$dC/dt = K_L A/V (Cs – C)$ ……………..…(1)

where C is DO concentration, K_L is liquid film coefficient for oxygen, A is surface area associated with the volume, V, over which transfer occurs, Cs is saturation concentration, and t is time.

The term A/V is often called the specific surface area or surface area per unit volume. Equation 1 does not consider sources and sinks of oxygen in the water body because their rates are relatively slow compared to the oxygen transfer that occurs at most hydraulic structures due to the increase in free-surface turbulence and the large quantity of air that is normally entrained into the flow.

The predictive relations described herein all assume that Cs is constant and determined by the water-atmosphere partitioning. If that assumption is made, Cs is constant with respect to time and the oxygen transfer efficiency (aeration efficiency), E, may be defined as (Gulliver et al. 1990) [7]:

$E = (C_d – C_u) / (C_s - C_d) = 1 – 1/r$ ……(2)

where u and d are subscripts indicating upstream and downstream locations, respectively, and r is the oxygen deficit ratio $[(C_s – C_u)/(C_s – C_d)]$. E a transfer efficiency value of 1.0 means that the full transfer up to the saturation value has occurred at the structure and No transfer would correspond to E = 0.0. 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.

Comparative evaluations of oxygen uptake at hydraulic structures require that aeration efficiency should be corrected to reference temperature. To provide a uniform basis for comparison of measurements, the aeration efficiency is often normalized to a 20˚C standard. Gulliver et al. (1990) [7] proposed the following equation describe the influence of temperature.

$E_{20} = 1 - (1 - E)^{1/f}$ ………… (3)

Where E = aeration efficiency at actual water temperature; E_{20} = aeration efficiency at 20˚C; and f = exponent described by

$f = 1.0 + .02103\,(T - 20) + 8.261 * 10^{-5}(T - 20)^2$ …………………..…..(4) In this study, the aeration efficiency was normalized to 20˚C using Eq. (3).

4. EXPERIMENTAL ARRANGEMENT:

A series of laboratory experiments were run on reference model which has smooth face and ogee stepped model. All experiments conducted at hydraulics laboratory in Faculty of Engineering-Zagazig University in a prismatic rectangular open channel, 0.30 m wide and 0.47 m deep, in which the steps were installed at 4 m of the inlet of the flume to grantee steady flow. The total length of the flume channel is 15.6 m. Water was pumped from the storage tanks to the flume channel. The discharge passing through the feeding pipe was measured by means of a pre-calibrated rectangular sharp-edged weir. Water entered the flume through an inlet part with its bed 1.25 m above the laboratory floor. The discharge was measured by using an orifice meter, which is installed in the feeding pipe line between two flanges. The slope of the reference model and the ogee stepped model, defined as inclination angle α was equal to 40◦. The step height of the ogee stepped model was equal to 1.5 cm, so the number of steps of the ogee stepped model was 12 steps. All experimental runs were carried out with discharges ranging between 4.6 and 24.6 L/s as 10 values.

Each experiment was started by filling the storage tank with tap water and adding Na_2So_3 and $CoCl_2$ for chemical deoxygenation. During the experiments, DO concentrations were measured at five main sampling points of the ogee stepped model; at the inlet of the flume (S_1), just before the stepped cascade model (S_2), after the hydraulic jump (S_3), at the ninth meter of the flume length (S_4) and at the outlet of the flume (S_5). DO measurements were taken using calibrated portable Jenway Model 9170 oxygen meter at the locations identified in fig. (3). The DO meter was 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.

During the experiments, water temperature was measured by the portable Jenway Model 9170 oxygen meter itself. Since the saturation concentration of oxygen is 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 20˚C standard using equation (3).

5. Results and Analysis:

In this study, the values of the aeration efficiency of ogee stepped model were obtained depending on discharge (Q) compared with its values for the smooth face model which is the reference model. The following section presents and discusses DO concentrations and aeration efficiency results. The aeration efficiency (E_{20}) of the ogee stepped model will be investigated in three phases; the first dissolved oxygen concentration was measured just before the ogee stepped model and after the hydraulic jump which perform ($E(2)_{20}$), the second, dissolved oxygen concentration was measured just before the ogee stepped model and at the outlet of the flume which perform ($E(4)_{20}$) and the third, the overall aeration efficiency $E(20)_{overall}$ of the ogee stepped model were investigated when dissolved oxygen concentration was measured just before the ogee stepped model and at the outlet of the flume.

Fig. (4) presents the relationship between discharge versus the dissolved oxygen concentrations of the ogee stepped model in compare with the reference model at inclination angles ($\alpha=40^{\circ}$). Generally, Fig. (4) shows that dissolved oxygen concentration decreases with the increase of the flow rate. It also obtained that at fixed discharge the dissolved oxygen concentration of ogee stepped model is higher than its value of reference model.

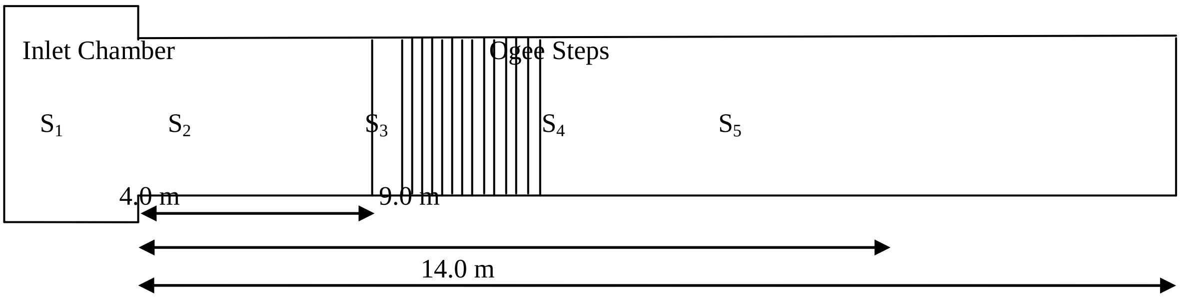

Figure (3): Different locations of sampling of the stepped cascade models along the length of the flume

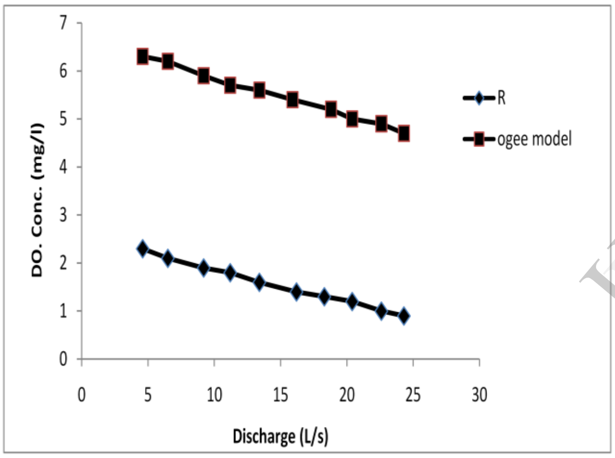

Fig. (4) comparison of DO concentrations of the reference and ogee models

The previous result agreed with Emiroglu and Baylar (2006) [6] investigated the self-aeration in smooth and stepped chutes. The experiments were conducted in a prismatic rectangular chute with 0.30 m wide and 0.50 m deep. Water was pumped from the storage tank to stilling tank, from which water entered the chute through an approach channel, with its bed 0.75 m above the laboratory floor. The discharge was measured by means of a flow meter installed in the supply line. All experimental runs were carried out in unit discharges ranging between 16.67 and 166.67 L/s.m.

For smooth chute, downstream channel was 3.0 m long, 0.60 m wide and 0.60 m deep. The slope of the smooth chute was varied as 8.40°, 10.82°, and 12.94°. A flip bucket with lip angle of 45° was placed at the downstream end of the smooth chute. For stepped chute, downstream channel was 3.0 m long, 0.35 m wide and 0.45 m deep. The slope of stepped chute was varied as 14.48°, 18.74° and 22.55°. For all slopes tested, steps with h equal to 5, 10, and 15 cm were used. Emiroglu and Baylar (2006) [6] reported that stepped chutes are very efficient means of aeration, that had the greater values of aeration efficiency than the smooth chutes with or without flip bucket. This is due to the strong turbulent mixing, the large residence time and the substantial air bubble entrainment.

Fig. (5) shows the relationship between discharge versus the aeration efficiency $E(2)_{20}$ which performed just before the ogee stepped model and after the hydraulic jump with regard to the reference model.

It describes that the aeration efficiency $E(2)_{20}$ decreases with the increase of the flow rate. It is also cleared that $E(2)_{20}$ at Q=4.6 L/s in ogee stepped model equal 0.73, while $E(2)_{20}$ at the same discharge in reference model equal 0.25. It also observed at fixed discharge that aeration efficiency in ogee stepped model is higher than the reference model (which is smooth).

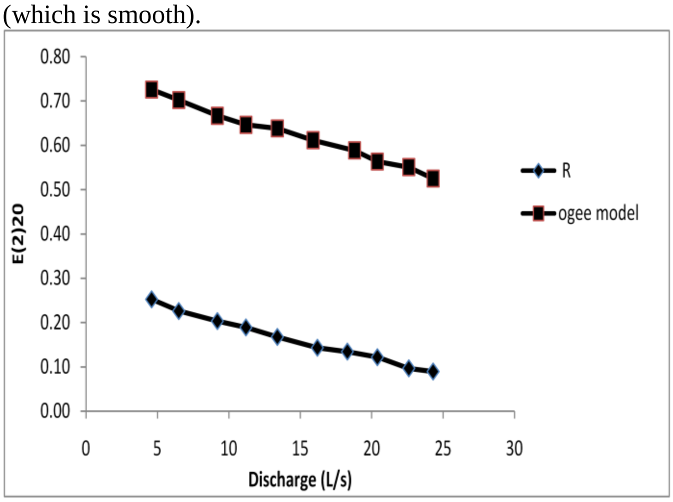

Fig. (5) Comparison of aeration efficiency before the models and after hydraulic jump of the reference and ogee models

The previous result agreed with Baylar et al. (2006) [2] investigated the aeration performance in stepped spillways. All experiments were conducted in a prismatic rectangular chute channel, 0.3m wide and 0.5m deep. The test channel used was 3.0m long, 0.3m wide and 0.45m deep. Channel angles were 30°, 40°, and 50° with step heights of 5, 10, 15cm respectively. All experimental runs were carried out with discharges ranging between 5 and 50 l/s. The results indicate that, for all chute angles, a tendency towards the nappe flow regime occurs at low discharges. In addition, a tendency towards the skimming flow regime was observed at high discharges. This showed that nappe flow has higher aeration efficiency than skimming flow.

The results of Fig. (5) indicate that the nappe flow regime lead to greater aeration efficiency than the other flow regimes. In nappe flow regime, the oxygen transfer on each step of the ogee stepped model which results from the flow aeration and mixing in the free-falling nappe, at the plunge point and possibly at the downstream of the hydraulic jump. In other words, the reason for greater aeration efficiency in nappe flow regime can be explained with the high level of turbulence, the large residence time and the substantial air bubbles entrainment.

The relationship between Froude number for the ogee stepped model and the aeration efficiency $E(4)_{20}$ which performed along the total length of the flume compared with the reference model is presented in fig.(6), the increase of Froude number increases the aeration efficiency $E(4)_{20}$. It is noticed that the ogee stepped model achieves the higher aeration efficiency than the reference model. It also noticed that at fixed Froude number the aeration efficiency of the ogee stepped model increases more than its value of the reference model. It refers to the strong turbulent mixing which is function into air bubble entrainment.

The main reason for the previous result that Froude Number has a major effect in dissipating energy as it is a function in velocity. So the increase of the velocity increases the strong turbulence mixing which increases the aeration efficiency.

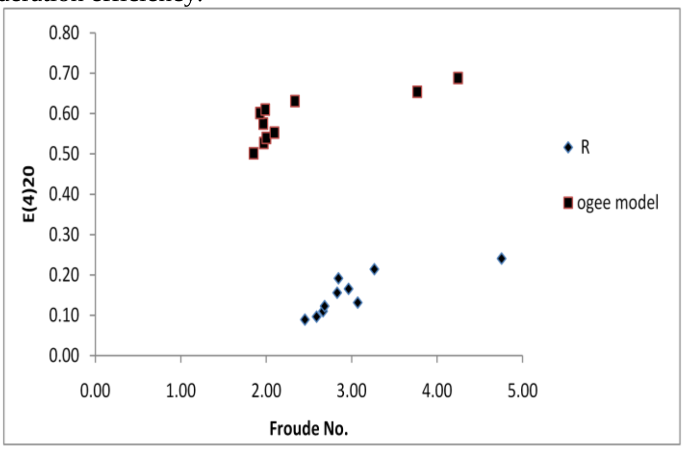

Fig. (6) relationship between froude number and aeration efficiency along the flume channel of reference and ogee models

The previous results agreed with Kavianpour and Masoumi (20080 [8] that investigated the energy dissipation over stepped spillway and its influence on aeration efficiency. The study showed that water flowing over a stepped spillway can dissipate a major proportion of its energy. The steps increase significantly the rate of energy dissipation. As Froude Number increases, the energy dissipation of the flow increases which increase the turbulent mixing and air bubbles entrainment.

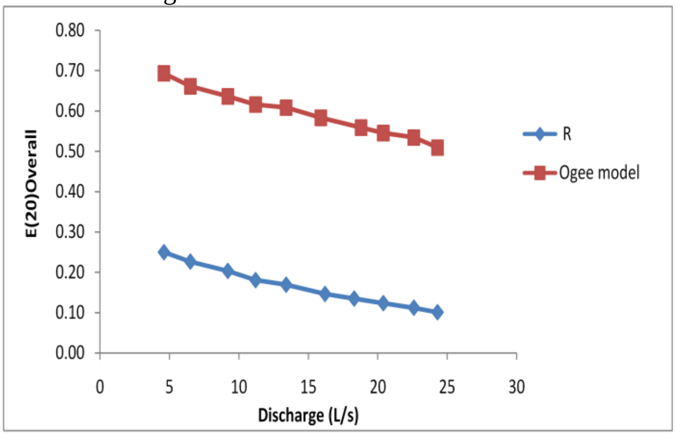

Fig. (7) comparison of aeration efficiency along the flume channel of the reference and ogee models

Fig. (7) shows the relationship between discharge and overall aeration efficiency along the laboratory flume for the ogee stepped model with regard to the reference model at inclination angle (α= 40°). Fig. (7) presents that the overall aeration efficiency $E(20)_{overall}$ decreases with the increase of discharge for the two cases of ogee stepped model and the reference model. It also observes at fixed discharge, the achieved aeration efficiency for ogee stepped model is higher than its value of the reference model along the range of discharge between (4.6-24.6) L/s.

The previous results also agreed with Baylar et al. (2009) [3] studied the influence of channel slope on oxygen content in stepped cascade aerators. For stepped channel, downstream channel was 3 m long, 0.35m wide and 0.45m deep. The slopes of stepped channel were varied as 14.48°, 18.74°, 22.55°, 30°, 40°, and 50°. For all slopes tested, steps height was varied equal to 5, 10, and 15 cm. All experimental runs were carried out in unit discharges ranging between 16.67 and 166.67 m^3/s.m. The results indicated that the aeration efficiency increases as the unit discharge decreases.

Fig. (8) shows the effect of different distances (x) along the flume length represented in sampling points on the enhancement of average DO for the reference model and the ogee stepped model. The results show that the highest increase of the average DO concentration has occurred for the ogee stepped model with an average rise of 5.49 mg/l after the secondary hydraulic jump at x=5.0 m. However the lowest increase in average DO occurred for the reference model where the concentration of DO has risen to 1.55 mg/l at the same position of sampling. This shows that the ogee stepped model would perform the best DO enhancement as more air bubbles have penetrated the water surface leading to an increase of aeration efficiency compared to the reference model. It also noticed that the peak dissolved oxygen concentration achieved after ogee stepped model at the hydraulic jump and decreased slightly by (0.1-0.4) mg/l from its value at the ninth meter of the flume length. It is may be due to the diminishing of air bubbles and the turbulence of the water so the flow turned into steady state. Furthermore, the DO concentrations decrease at the end of the channel because the fine air bubbles could have escaped at the surface of the water such as the results of Chanson and Toombes (2001) [4].

The previous results agreed with Emiroglu and Baylar (2006) [6] who reported that stepped chutes are very efficient means of aeration, which had the greater values of aeration efficiency than the smooth chutes with or without flip bucket.

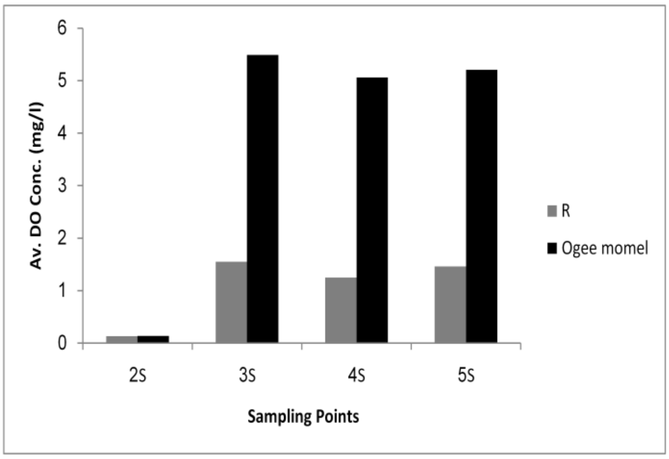

Fig. (8) Comparison of average DO concentrations of the reference and ogee models at the different sampling points

This is due to the strong turbulent mixing, the large residence time and the substantial air bubble entrainment and also agreed with Aras and Berkun (2010) [1] who compared the aeration efficiency of stepped and smooth spillways and the results presented A higher aeration was observed on the stepped spillway because of surface aeration, plunging jet aeration and hydraulic jump aeration.

5. CONCLUSION:

Based on the results of this study, the following conclusions can be drawn:

1) It was apparent from the results that skimming flow was observed especially in high discharges.
2) The results showed that aeration efficiency decreased continuously as discharge increased.
3) The nappe flow achieves oxygen transfer better than that of skimming regime.
4) Increasing discharge of flow of ogee stepped model reduces its efficiency in dissipating energy which reduces the turbulent mixing and air entrainment which reduces the aeration efficiency of the flow.
5) The results indicate that the aeration efficiency of nappe flow is higher than for transition and skimming flows. Therefore, ogee stepped spillway can be used as highly effective aerators in streams, rivers, constructed channels, fish hatcheries, water treatment plants, etc.
6) The paper demonstrates that ogee stepped spillway is very efficient means of aeration because of the strong turbulent mixing, the large residence time and the substantial air bubble entrainment. The flow down an ogee stepped chute is much more aerated than on smooth chutes due to a higher degree of turbulence.
7) It was noticed that the peak aeration efficiency achieved after ogee stepped at the hydraulic jump and decreased by (0.1-0.4) mg/l from its value at the ninth meter of the flume length due to the diminishing of air bubbles and the turbulence of the water.

6. LIMITATIONS:

Despite the encouraging results obtained concerning the enhancement of aeration efficiency, the effect of installing ogee stepped spillway in a stream requires further investigation as the following:

- The effect of changing different inclination angle (α) of ogee stepped spillway on enhancement of aeration efficiency.
- Testing the effect of different ogee stepped spillway heights and increasing the number of steps on aeration efficiency in streams.
- Exploring different geometries for the ogee stepped spillway such as increasing height of steps, and width of steps exposed to different flow rates, and its effect on aeration efficiency.
- Studying the performance of ogee stepped spillway at higher flow rates in enhancing dissolved oxygen levels.
- Investigating the effect of stepped cascade on aeration efficiency at sloped channels.
- Making regression analysis to correlate the different dimensions of ogee stepped spillway affecting on dissolved oxygen concentrations to predict the aeration efficiency of ogee stepped for its different geometries, and compare the predicted values to the calculated values from the mathematical relationships.

7. REFERENCES

1. Aras, E. and Berkun, M. (April, 2010). "Comparison of Stepped and Smooth Spillway effects on Stream Reaeration." Water SA. Vol. 36, No. 3.
2. Baylar, A., Emiroglu, M.E., and Bagatur, T. (2006). "An Experimental Investigation of Aeration Performance in Stepped Spillways." Water and Environmental Journal, Vol. 20, pp. 35-42.
3. Baylar, A., Emiroglu, M.E. and Bagatur, T. (Sep., 2009). "Influence of Chute Slope on Oxygen Content in Stepped Waterways." G.U. Journal of Science. Vol. 22, No. 4, pp. 325-332.
4. Chanson, H. and Toombes, L. (Dec., 2001). "Strong Interactions Between Free-Surface Aeration and Turbulence Down a Staircase Channel." 14th Australasian Fluid Mechanics Conference, pp. 841-844.
5. Chanson, H. (2002). "The Hydraulics of Stepped Chutes and Spillways."10th edition, Balkema, Lisse, The Netherlands.
6. Emiroglu, M. and Baylar, A. (2006). "Self-Aeration in Smooth and Stepped Chutes." International Journal of Science & Technology. Vol. 1, No. 2, pp. 105-113.
7. Gulliver JS, Thene JR, Rindels AJ. (1990). "Indexing gas transfer in self-aerated flows." J. Environ. Eng. 116(3):503–523.
8. Kavianpour, M.R., and Masoumi, H.R. (Sep., 2008). "Technical Note: New Approach for Estimating of Energy Dissipation over Stepped Spillways." International Journal of Civil Engineering, Vol. 6, No. 3, pp. 230-237.