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RESEARCH PAPER

An Experimental Investigation on Aeration Performance of Sharp-crested Weirs: Discharge Effect

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Abstract: In this experimental study, the aeration performance of weirs was investigated regarding the discharge effect. Experiments were conducted at a 90º V-notch weir with drop heights ranging from 0.35-0.535 m and unit discharges ranging from $3x10^{-2}$ to $6.33x10^{-2}$ m^2/s and E_{20} varied in the range of 0.13-0.23. A positive correlation has been established between the discharge rate of a unit and the efficiency of aeration. This correlation has been mathematically defined using a power function that takes into account the drop height and the unit discharge. It has been determined that the aeration efficiency is directly proportional to the 3/4 power of the drop height and the 1/3 power of the unit discharge. The predictive accuracy of the proposed empirical formula has been evaluated by comparing it with other empirical formulas based on their average relative error values. Furthermore, when the drop height is assumed to be equal to the head loss, it has been observed that the dependence of hydraulic jump aeration efficiency on head loss continues for weirs. This finding suggests that the primary factor influencing the process is the presence of free-surface macro turbulence.

Keywords: Discharge effect, dissolved oxygen, drop height, self-aeration, sharp-crested weir.

İnce Kenarlı Savaklardaki Havalandırma Verimliliğinin Deneysel Olarak İncelenmesi: Debi Etkisi

***Sorumlu yazar:**
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Öz: Bu deneysel çalışmada savakların havalandırma performansı debi etkisi altında incelenmiştir. Bu amaçla, düşme yükseklikleri 0,35-0,535 m arasında ve birim genişlikten geçen debinin 0,03-0,063 m^2/s aralığında değişen 90° üçgen ince kenarlı bir savakta deneyler yapılmıştır. Deneysel verilerin analizi sonucu, birim genişlikten geçen ile havalandırma verimliliği arasında pozitif bir korelasyon bulunmuş ve ortaya çıkan ilişki, düşüm yüksekliği ve debinin fonksiyonu olarak tanımlanmıştır. Önerilen ampirik formülün tahmin kapasitesi diğer ampirik formüllerle ortalama bağıl hata değerleri açısından karşılaştırılmıştır. Ayrıca düşüm yüksekliğinin yük kaybına eşit olduğu varsayıldığında, hidrolik sıçramdaki havalandırma verimliliğinin yük kaybında olan bağımlılığının ince kenarlı savakta da geçerli olduğu gözlemlenmiştir.

Anahtar kelimeler: Çözünmüş oksijen, debi etkisi, doğal havalandırma, düşüm yüksekliği, ince kenarlı savak.

INTRODUCTION

In the hydrosphere, dissolved oxygen (DO) is one of the most important water quality parameters for the aquatic biota and environmental issues (Gulliver et al., 1998). For example, DO quantity directly affects the fish activities such as spawning and migrating; hence, for a good abundance of fish population and species diversity, DO concentration is recommended to be higher than 5 mg/L (Giller & Malmqvist, 1998; Welch & Jacoby, 2004). However, in streams DO content generally has low levels resulting from wastewater diffusion from point and non-point sources, in which chemical reactions like nitrification and oxidation of organic matter deplete the DO content of the water. Therefore, the self-aeration mechanism which means a transfer of oxygen from air into water is an important phenomenon for regaining the lost dissolved oxygen. At hydraulic structures, aeration efficiency is compted with the equation proposed by Gamenson (1957):

$$E = \frac{C_u - C_d}{C_s - C_u} = \frac{Total\ Oxygen\ Transfer}{Potential\ Maximum\ Oxygen\ Transfer} \quad (1)$$

The aeration efficiency, denoted as E, encompasses a spectrum ranging from 0, indicating the absence of aeration, to 1, representing complete downstream saturation. C_u and C_d symbolize the dissolved oxygen concentrations at the upstream and downstream sections of a hydraulic structure, respectively, while C_s signifies the mass concentration of dissolved oxygen in a state of full saturation. Equation (1) has been derived from Fick's Law.

$$\frac{dC}{dt} = Ka(C_S - C) \qquad (2)$$

The rate of mass transfer, denoted as dC/dt, is influenced by the mass transfer coefficient, represented as K. The mass transfer coefficient is dependent on the diffusion coefficient of the gas being transferred, as stated by Muntz & Roberts (1989), as well as the turbulence structure of the flow, as mentioned by Kawase & Moo-Young (1992). Another factor in the equation is the ratio of the total surface area of the bubbles to the overall volume of the air-water mixture, denoted as a. Additionally, C represents the concentration of the dissolved gas. The term "self-aeration" refers to the process of oxygen transfer from air to water, which has significant implications for the environment and ecology of polluted streams (Zhao, et al., 2022). It is worth noting that hydrodynamic processes that facilitate self-aeration, such as hydraulic jumps, plunging jets or waterfalls, and stepped channels, also share the common property of being utilized as energy dissipaters in hydraulic structures. Consequently, it is anticipated that there exists a positive correlation between energy dissipation and aeration efficiency, as suggested by Kucukali & Cokgor (2009).

At weirs, highly turbulent flow and turbulence mixing mechanisms at the receiving pool generate an air-water interface area which ensures the gas transfer process (Ervine et al., 1980). Weirs are commonly used to improve the water quality of streams (Van der Kroon et al., 1969; Watson et al., 1998; Rajwa-Kuligiewicz et al., 2016), as well as to record flow rates. Yet, studies about oxygen transfer at weirs demonstrate that the aeration performance is directly proportional to the drop height (Table 1). In Table 1, E_{20} is the aeration efficiency at 20 ºC, h is the drop height, d_c is the critical depth over a waterfall, q is the unit discharge, and d_p is the pool depth. Re is the Reynolds number and calculated from Re = q/υ, υ is the kinematic viscosity of water; Fr_j is the Froude number of the waterfall and calculated from $Fr_j = (8gh^3/q^2)^{0.25}$, in which g is the acceleration of gravity.

It could be seen from the existing studies in the literature that there isn't a common correlation between the discharge and aeration efficiency of falling water at sharp-crested weirs (Table 1). For instance, in Avery & Novak (1978) formula, with the increase of discharge at a constant drop height, oxygen uptake decreases; on the other hand, in Nakasone (1987) formula aeration efficiency is positively related to discharge up to a certain limit, above this limit discharge was negatively related with unit discharge (Table 1). Accordingly, existing studies indicate that the weir aeration process under different discharges is uncertain. This experimental study aims to investigate the aeration performance of weirs in terms of discharge effect. For this purpose, systematic experiments were carried out at a 90º V-notch weir for several discharges.

Table 1. Aeration efficiency empirical formulas at weirs.

Reference	Formula	Remarks
Gameson (1957)	$E_{20} = 1 - (\frac{1}{1+0.62h})$	Obtained from a field study of numerous polluted streams in England
Avery & Novak (1978)	$E_{20} = 1 - \left[\frac{1}{1+(0.24\times10^{-4}\times Fr_j^{\ 1.78}\times \mathrm{Re}^{0.53})}\right]^{1.115}$	Obtained at a small-scale experimental set-up: 0.6 L/s < Q < 5.8 L/s
Markosfky & Kobus (1978)	$E_{20} = 1 - \left[\frac{1}{1+0.1Fr_j^{\ 1.2}}\right]^{1.115}$	Valid under fully turbulent (i.e Re > 10^5) conditions
Nakasone (1987)	For q $\leq$ 0.065m³/s.m: $E_{20} = 1 - \exp\left[-2.61\times(h+d_c)^{1.31}\times q^{0.428}\times d_p^{\ 0.310}\right]$ for q > 0.065 m³/s.m: $E_{20} = 1 - \exp\left[-0.28\times(h+d_c)^{0.31}\times q^{-0.363}\times d_p^{\ 0.310}\right]$	Valid for ($h+1.5d_c$) $\leq$ 1.2 m
Kim & Walters (2001)	$E_{20} = 1 - \frac{1}{1+0.453Fr_j^{\ 0.453}\times h^{1.117}\times(\frac{d_p}{h})^{0.475}}$	Experiments flow conditions: $0.046 \leq q \leq 0.139\ m^3/s.m$

EXPERIMENTAL SET-UP

Experiments were conducted within a glass-walled and concrete-bottomed horizontal rectangular flume measuring 0.5 m in width, 0.45 m in depth, and 12.30 m in length (Figure 1). The flow in the flume was supplied by a header tank standing at a height of 1.12 m, which in turn received water from a 5.7 m^3 chamber through a 7.5 kW pump situated below the tank. Upstream of the flume, a 90-degree V-notch weir was employed both for measuring discharge and as a self-aerator in the experiments (Figure 1). The weir plate thickness is in the order of 2 mm (ISO, 2008). The flow rate was regulated through a valve located adjacent to the pump, while the depths of flow were determined using pointer gauges with a precision of 0.2 mm. The pool depths were controlled by a sluice gate positioned 6.5 m from the starting point of the channel. Furthermore, great emphasis was placed on ensuring optimal pool depth conditions, wherein the penetration depth of bubbles was less than the pool depth. Consequently, any influence of pool depth on aeration efficiency values was eliminated (Avery and Novak, 1978).

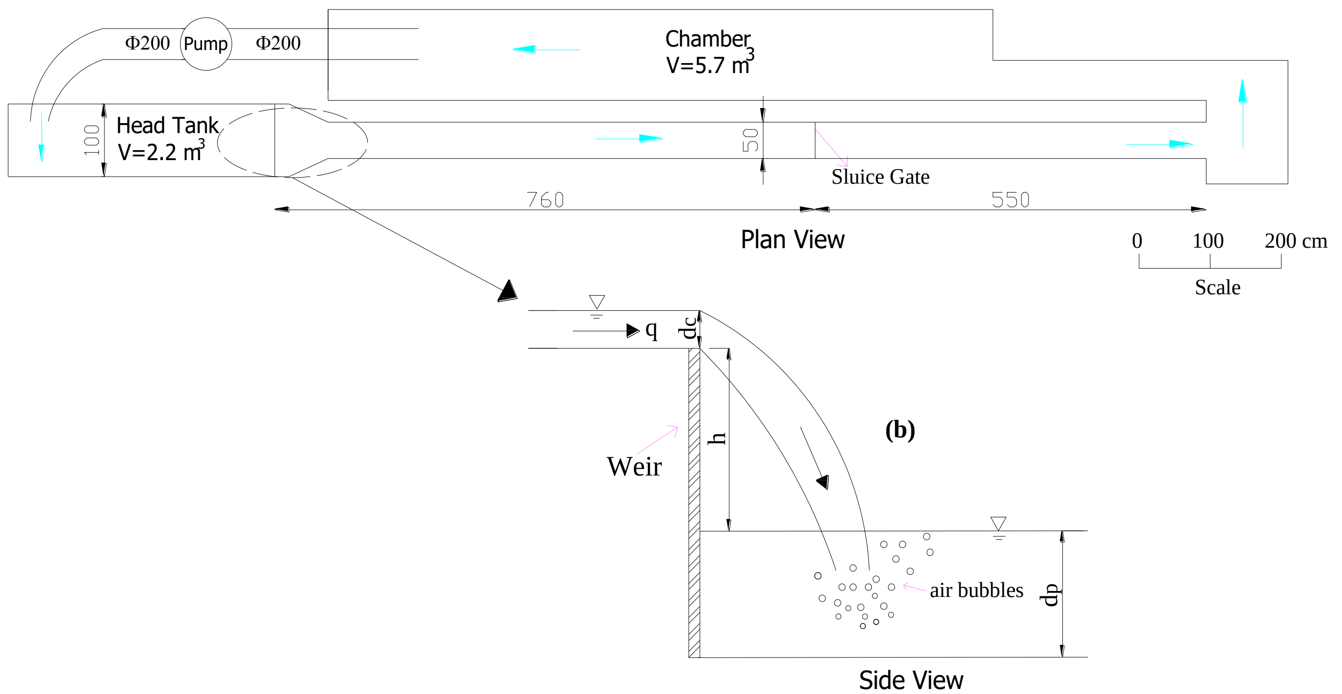

Figure 1. (a) Plan view of the experimental set-up. (b) sketch of the weir aeration process.

Simultaneous measurements of dissolved oxygen (DO) were conducted at both the upstream and downstream locations of the weir. These measurements were carried out using handheld oxygen meters (Model WTW Oxi 330i), which boast an accuracy of ±0.5% for oxygen concentration and ±0.1% for temperature within the range of 0-19.99 mg/L DO and -5 to +50 ºC, respectively. The experiments employed the air calibration technique, and the oxygen probe had a sampling rate of 1 Hz. In order to deplete the DO concentration of the descending water, Sodium Sulfide and Cobalt Chlorite were introduced into the chamber as catalysts. The aeration efficiencies were determined using Equation (1), and then adjusted to a standard temperature of 20 ºC using the formula developed by Gulliver & Rindels (1990):

$$1-E_{20}=(1-E_T)^{1/f_T} \qquad (3)$$

where E_{20} denotes aeration efficiency at 20 ºC, E_T aeration efficiency at water temperature T_w, and f_T is a constant and calculated from Equation (4):

$$f_T=1+0.02103(T_w-20)+8.261x10^{-5}(T_w-20)^2 \qquad (4)$$

RESULTS AND DISCUSSION

Experimental conditions and test results are presented in Table 2. In the experiments drop heights varied between 0.35-0.535 m for q values ranging from $3x10^{-2}$ to $6.33x10^{-2}$ m^2/s. E_{20} got values between 0.151-0.256 and had the highest value at h=0.535 m and q=$6.33x10^{-2}$ m^2/s test condition (Table 2).

Table 2. Detail of experimental conditions and results.

Test No	Q (m^3/s)	q (m^2/s)	d_c (cm)	d_p (cm)	h (cm)	h/d_c	E_{20}
1	0.0195	5.42E-02	18.0	19.5	49.0	2.72	0.212
2	0.0195	5.42E-02	18.0	31.0	35.5	1.97	0.150
3	0.0195	5.42E-02	18.0	23.5	43.0	2.39	0.179
4	0.0195	5.42E-02	18.0	27.3	39.2	2.18	0.169
5	0.0195	5.42E-02	18.0	29.0	37.5	2.08	0.165
6	0.0253	6.33E-02	20.0	18.0	53.5	2.68	0.236
7	0.0253	6.33E-02	20.0	19.5	49.0	2.45	0.217
8	0.0253	6.33E-02	20.0	22.4	46.1	2.31	0.212
9	0.0253	6.33E-02	20.0	26.3	42.2	2.11	0.188
10	0.0253	6.33E-02	20.0	31.5	37.0	1.85	0.160
11	0.0253	6.33E-02	20.0	20.2	51.0	2.55	0.221
12	0.0129	4.22E-02	15.3	18.0	45.8	2.99	0.171
13	0.0129	4.22E-02	15.3	16.8	49.0	3.20	0.179
14	0.0129	4.22E-02	15.3	28.0	35.8	2.34	0.141
15	0.0129	4.22E-02	15.3	23.8	40.0	2.61	0.160
16	0.0072	3.00E-02	12.1	17.2	48.6	4.02	0.160
17	0.0072	3.00E-02	12.1	20.6	40.0	3.31	0.146
18	0.0072	3.00E-02	12.1	25.6	35.0	2.89	0.131
19	0.0072	3.00E-02	12.1	19.5	43.1	3.56	0.150

In Figure 2, the aeration efficiency is shown as a function of the drop height. The figure reveals that the values exhibit scattering around a linear line, thus indicating the influence of a second parameter on the process. This particular parameter is believed to be the unit discharge. In Figure 3, the E_{20} values are plotted against the drop height for various unit discharges. It is noteworthy that even when the drop height remains constant, an increase in the unit discharge leads to an increase in E_{20}. Furthermore, Figure 3 demonstrates that E_{20} is primarily determined by the drop height and secondarily influenced by the unit discharge. By employing non-linear regression analysis on the experimental data points, it was determined that the power function provides the best fit for the data:

$$E_{20} = 1.06 \times h^{0.77} \times q^{0.34} \qquad (R^2 = 0.98) \qquad (5)$$

Furthermore, E_{23} exhibits an inverse relationship with both surface tension and kinematic viscosity. This is due to the necessity of overcoming surface tension effects in order to facilitate the transfer of gas between air and water (Kobus, 1991; Ervine, 1998). Moreover, lower values of Reynolds number result in a reduction of turbulence fluctuation velocities (Wei & Willmarth, 1989).

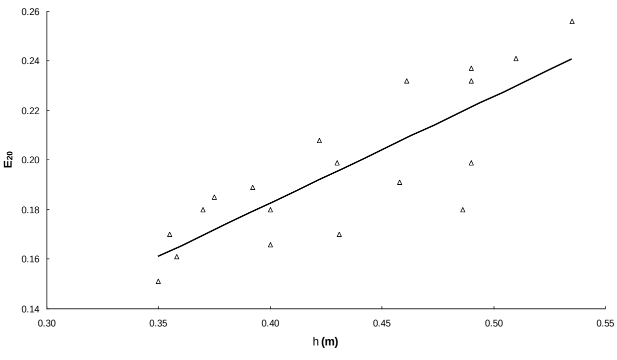

Figure 2. Aeration efficiency E_{20} versus fall height h.

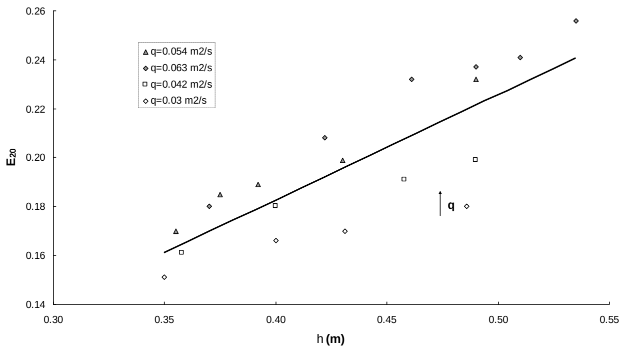

Figure 3. Variation of aeration efficiency as a function of fall height at various unit discharges.

On the other hand, E_{20} is directly proportional to the specific weight γ because the pressure exerted on the entrained bubbles will increase with γ, which in turn enhances the quantity of transferred oxygen from bubbles to solution (Markofsky & Kobus, 1978; Urban et al., 2005). Showing these statements in a mathematical form:

$$E_{20}\ \alpha\ \frac{Q \times h \times \gamma}{\sigma \times \upsilon} = \frac{(m^3/s)\times m \times (N/m^3)}{(N/m)\times(m^2/s)} = Dimensionless \qquad (6)$$

yields a dimensionally homogenous equation. Water's physical properties are known for a constant temperature and pressure at 20 ºC: $\gamma = 9789\ N/m^3;\ \sigma = 0.0728\ N/m;\ \upsilon = 1.003\times10^{-6}$ (Streeter & Wylie, 1981), substituting these terms in Equation (6) one obtains:

$$E_{20}\ \alpha\ 13.46\times10^{10} \times Q \times h \qquad (7)$$

Based on experimental results the inter-relationship between the E_{20}, Q, and h expressed with a power function, hence:

$$E_{20} = a\,13.46\times10^{10} q^b h^c \qquad (8)$$

These experimental coefficients were found as: $a = 7.87\times10^{-12}, b = 0.24, c = 0.73$. Beyond q > 0.1 m^2/s, which represents the fully turbulent conditions (Kobus, 1991) E_{20} could be independent of q. Further, Toombes & Chanson (2005) results supported this statement. The proposed empirical formula in Equation (8) is valid for $q < 0.1\ m^2/s$. Figure 4 shows the plot of predicted versus observed aeration efficiency values. It can be seen from the figure that, Equation (5) made good predictions, only two points lie outside the ±5 % error bands, and the average relative error (ARE) is found 2.5% which is less than the practically acceptable 5%. The relative error of each experimental point is calculated with:

$$\mathrm{Re}lative\ error = \frac{\left|E_{predicted} - E_{observed}\right|}{E_{observed}} \times 100 \qquad (9)$$

Also, the proposed empirical formula prediction capacity is compared with the other empirical formulas in terms of their average relative error values. Interestingly, the best prediction is made by Gamenson's (1957) formula, related only to the fall height, among other formulas (Figure 4). Consequently, the trend is best fitted by the correlation of Gamenson10 with ARE=%9.1, Avery and Novak (1978) with ARE= %18.8; Nakasone (1987) with ARE= %22.5.

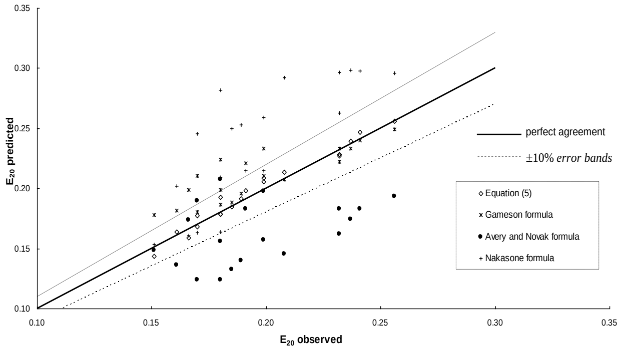

Figure 4. Results of the proposed empirical formulas and comparison with the other formulas.

Based on experimental results, a direct relation was found between the discharge and aeration efficiency. Furthermore, Nakasone (1987) proposed an empirical equation to determine the aeration length of a weir:

$$L_a = 2.69 \times 10^{-4} \times h^{0.134} \times q^{0.666} \qquad (11)$$

in which, L_a denotes the aeration length and higher values of L_a will generate higher aeration efficiencies (Nakasone, 1987) and in this equation, aeration efficiency is directly proportional to drop height and discharge with a power function. Further, Kucukali & Cokgor (2020) developed an empirical formula for estimating the aeration efficiencies of hydraulic jumps in terms of energy loss based on 49 series experiments conducted at the same channel shown in Figure 1. In the study, relevant parameters represent the degree of turbulence, and most of the researchers pointed out that free-surface macro turbulence is the main mechanism enabling oxygen transfer (Kobus, 1981; Sene et al., 1994; Chanson, 1996; Ervine, 1998). Based on the experimental results, least square fitting gives the following expression for the aeration efficiency of hydraulic jumps (Kucukali, 2006):

$$E_{20} = 0.77 \times \Delta H^{0.73} \times q^{0.24} \qquad (R^2 = 0.97) \qquad (12)$$

Additionally, in the case of weirs where the drop height is assumed to be equal to the head loss, thereby achieving optimum pool depth conditions (Apted & Novak, 1973), the values of aeration efficiency were shown as a function of head loss for both hydraulic jumps and weirs (Figure 5). It is evident from Figure 5 that a similar pattern observed for hydraulic jumps continues for weirs, and this positive correlation between aeration efficiency and head loss can be attributed to the increase in turbulence levels. These findings align well with the theories proposed by Higbe (1935) and Dankwerts (1951), which suggest that the rate of mass transfer is dependent on the surface renewal facilitated by large-scale organized eddy motions near the free surface, which are influenced by the turbulence characteristics of the flow.

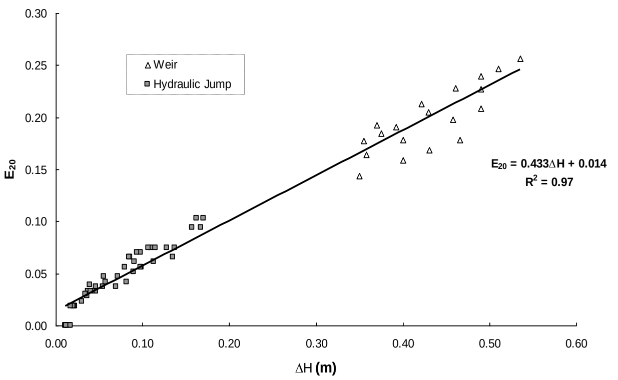

Figure 5. Variation of aeration efficiency as a function of head loss at a hydraulic jump and weir.

CONCLUSION

Based on the experimental results, a positive correlation was found between the unit discharge and aeration efficiency at weirs and this formula is valid under $q < 0.1$ m^2/s. The proposed equation made good estimations; only two out of a total of 19 readings lie outside the ±5 % error bands and the average relative error (ARE) is found 2.5% which is less than the practically acceptable 5%. Also, the proposed empirical formula prediction capacity is compared with the other empirical formulas in terms of their average relative error values, and the best prediction is made by Gamenson's (1957) formula among other empirical formulas in the literature. Additionally, by assuming a drop height equal to head loss, it was observed that hydraulic jump aeration efficiency dependence on head loss continued for weirs indicating the free-surface macro turbulence's main role in the process.

REFERENCES

Apted, R.W. & Novak, P. (1973). Oxygen uptake at weirs. *Proceedings of 15th IAHR Congress*, Istanbul, Türkiye, 177-186.

Avery, S. T. & Novak, P. (1978). Oxygen transfer at hydraulic structures. *J. Hydr. Div., ASCE, **104***(11), 1521-1540.

Dankwerts, P.V. (**1951)**. Significance of liquid-film coefficients in gas absorption. *Industrial and Engineering Chemistry*, ***43***(6), 1460-1467.

Ervine, D.A., Mckeogh, E. & Elsawy, E.M. (1980). Effect of turbulent intensity on the rate of entrainment by plunging water jets. *Proc. Inst. Civ. Engrs*., ***2***, 425-455.

Ervine, D.A. (1998). Air entrainment in hydraulic structures: a review. *Proc. Instn Civ. Engrs Wat., Marit. & Energy*., ***130***(5), 142-153.

Giller, P.S. & Malmqvist, B. (1998). *The biology of streams and rivers, Oxford University Press*, Great Britain.

Gulliver, J.S., Wilhelms S.C. & Parkhill, K.L. (**1998**). Predictive capabilities in oxygen transfer at hydraulic structures. *Hydr. Engrg.,* ASCE, July, 664-671.

Gulliver, J.S. & Rindels, A.J. (**1990**). Indexing gas transfer in self-aerated flows. *J. Envir. Engrg., ASCE,* ***116***(3), 503-523.

Gameson, A.L.H., Vandyke, K.G. & Ogden, C.G. (**1958**). The effect of temperature on aeration at weirs. *Water and Water Engrg*., Nov, 489-492.

Higbe, R. (**1935**). On the adsorption of a pure gas into a still liquid during short period of exposure. *Transactions, American Institute of Chemical Engineers*, **31**, 365-390.

ISO. (**2008**). *Hydrometry-Open channel flow measurement using thin-plate weirs*, Geneva, Switzerland.

Kawase, Y. & Young, M.M. (**1992**). Correlations for liquid-phase mass transfer coefficients in bubble column reactors with Newtonian and non-newtonian fluids. *The Can. J. Chem. Engrg.*, ***70***, 48-54.

Kim J. & Walters, R.W. (**2001**). Oxygen transfer at low drop weirs. J. *Envir. Engrg, ASCE*, ***127***(7), 604-610.

Kobus, H. (1991). *Introduction to air-water flows. Air entrainment in free surface flows, I. R. Wood, ed., IAHR Hydraulic Structures Manual, No. 4*, Rotterdam.

Kucukali, S. (2006). *Investigation of hydraulic jumps aeration efficiency in terms of head loss concept*. Ph.D. thesis, Istanbul Technical University, Istanbul, (In Turkish).

Kucukali, S. & Cokgor, S. (2009). Energy concept for predicting hydraulic jump aeration efficiency. *J. Envir. Engrg., ASCE,* ***135***(2), 105-107.

Kucukali, S. & Cokgor, S. (2020). *An experimental ınvestigation of reaeration and energy dissipation in hydraulic jump, M. B. Kalinowska, ed., Recent Trends in Environmental Hydraulics, 127-136, Cham, Switzerland, Springer*.

Muntz, C. & Roberts, P.V. (1989). Gas and liquid phase mass transfer resistances of organic compounds during mechanical surface aeration. *Wat. Res*., ***23***(5), 589-601.

Markosfky, M. & Kobus, H., 1978. Unified presentation of weir-aeration data. *J. Hydr. Engrg., ASCE*, ***104***(4), 562-568.

Nakasone, H. (1987). Study of aeration at weirs and cascades. *J. Envir.Engrg*, *ASCE*, ***113***, 64-81.

Rajwa-Kuligiewicz, A., Bialik, R.J. & Rowiński, P. (2016). *Experimental investigations on the oxygen transfer efficiency at low-head hydraulic structures*, P. Rowiński, ed., *Hydrodynamic And Mass Transport At Freshwater Aquatic Interfaces*, GeoPlanet: Earth and Planetary Sciences. Springer, Cham.

Sene, K.J., Hunt, J.C.R. & Thomas, N.H. (1994). The role of coherent structures in bubble transport by turbulent shear flows. *J. Fluid Mechanics*, ***259***, 219-240.

Streeter, V.L. & Wylie, E.B. (1981). *Fluid mechanics, McGraw-Hill*, Singapore.

Toombes, L. & Chanson, H. (2005). Air-water mass transfer on a stepped waterway. *J. Envir. Engrg., ASCE*, **131**(10), 1377-1386.

Urban, A.L., Wilhelms, S.C. & Gulliver, J.S. (2005). Decay of turbulence downstream of a stilling basin. *J.Hydr. Engrg., ASCE*, ***131***(9), 825-829.

Van der Kroon, G.T.M. & Scharm, A.H. (1969). *Weir-aeration-Part II. H_2O*, ***22***, 538-545.

Watson, C.C., Walters, R.W. & Hogan, S.A. (1998). Aeration performance of low drop weirs. *J. Hydr. Engrg., ASCE*, ***124***(1), 65-71.

Wei, T. & Willmarth, W.W. (1989). Reynolds-number effects on the structure of a turbulent channel flow. *J. Fluid Mech*., ***204***, 57-95.

Welch, E.B. & Jacoby, J.M. (2004). *Pollutant effects in freshwater: Applied limnology, Spon Press*, London and New York.

Zhao,W., Prata, A., Peirson, W., Stuetz, R. & Felder, S. (2022). Reaeration in supercritical open channel flows: An experimental study. *Journal of Hydraulic Engineering*, ***148***, DOI: 10.1061/(ASCE)HY.1943-7900.0002001