# Aeration performance of weirs

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## Abstract

The concentration of dissolved oxygen (DO) in the waters of rivers and streams is very important to the quality and existence of aquatic life. Hydraulic structures increase the amount of DO in a river system, even though the water is in contact with the structure for only a short period of time. The same quantity of oxygen transfer that normally would occur over several kilometres 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 air bubbles which greatly increase the surface area available for mass transfer. Plunging overfall nappes from weirs are a particular instance of this, and the aeration properties of such structures have been studied widely in the laboratory and field over a number of years. This paper looks at the aeration performance of weirs having different cross-sectional geometry. It is demonstrated that the aeration efficiency of the triangular notch weir generally is better than for the other weirs.

## Nomenclature

| | |
|---|---|
| a | the specific surface area (A/V), or surface area per unit volume |
| A | surface area associated with the volume V, over which transfer occurs |
| b | crest width of weir |
| C | DO concentration |
| $C_d$ | DO concentration downstream of a hydraulic structure |
| $C_s$ | saturation concentration |
| $C_u$ | DO concentration upstream of a hydraulic structure |
| E | transfer efficiency at the measured water temperature |
| $E_{20}$ | transfer efficiency at 20°C |
| f | term to adjust from 20°C to T°C |
| h | drop height |
| H | tailwater depth |
| $K_L$ | liquid film coefficient for oxygen |
| L | the experimental channel width |
| Q | weir discharge |
| r | oxygen deficit ratio |
| s | difference between crest and top of weir |
| t | time |
| T | water temperature |
| W | difference between base and crest of weir |

## Introduction

Currently there is much emphasis on water quality and maintaining water quality parameters in our freshwater hydrosphere (rivers, lakes, and reservoirs). Dissolved oxygen (DO) concentration is one of the most widely cited parameters. DO is often used as an indicator of the quality of water used by humans or serving as a habitat for aquatic flora and fauna. It is maintained by many natural chemical and biological processes that either increase or decrease local oxygen concentrations. Respiration by aquatic life serves to reduce DO, as does biodegradation of organic material in the sediments, along with a host of other oxygen-consuming chemical reactions. Photosynthesis by aquatic plant life can be a significant source of oxygen to a water body, as can oxygen exchange with the atmosphere.

Weir aeration occurs in rivers, fish hatcheries and water treatment plants. Often, the hydraulic head is naturally available and incurs no operating cost. In some cases, however, weir aeration is economically competitive with alternative aeration technology such as surface aeration, even when energy costs for pumping the water are included.

Before breaking up into drops, the flow over a weir or waterfall would be classified as a free nappe, as shown in Fig. 1. Typically most of the oxygen transfer is accomplished in this type of structure during the breakup of the nappe, and the subsequent collision of the free nappe with the bottom of the channel. If the free nappe plunges into a downstream water pool, air entrainment and turbulence will contribute to oxygen exchange. In addition, the depth of the downstream water pool can enhance the absorption because of the increased hydrostatic pressure on the entrainment of air bubbles. Avery and Novak (1978) found that the transfer efficiency is at its maximum at a tailwater depth of approximately 0.6 times the drop height, indicating that a trade-off exists between bubble residence time, pressure and turbulence levels. Oxygen absorption efficiencies vary widely, but for low-head overflow weirs, efficiencies of up to 70% have been measured.

Gameson (1957) was the first to report on the aeration potential of weirs in rivers. Since then a number of laboratory investigations into weir aeration have been carried out, notably Van der Kroon and Schram (1969a;b), Apted and Novak (1973), Avery and Novak (1978), and Nakasone (1987). Investigations have also been reported on the aeration performance of existing hydraulic structures and these are reviewed by Wilhelms et al. (1992). Gulliver and Rindels (1993); in particular, problems associated with field measurements of oxygen transfer and the degree of uncertainty involved are discussed. Much of this work has dealt with straight weirs and free overfalls, among other structures, and none has concentrated specifically on the aeration performance of differently shaped weirs.

This paper describes an experimental investigation into the aeration performance of weirs, and in particular, the effect of varying the shape of the weir (Fig. 2). The shape of the weir dictates

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the behaviour of the nappe. This, in turn, is believed to alter the air entrainment and contact time in both the nappe itself and the downstream water pool and, hence, the aeration performance of the weir.

## Background

Oxygen is a highly volatile compound with a gas-water transfer rate that is controlled entirely by the liquid phase. Thus, the change in oxygen concentration over time in a parcel of water as the parcel travels through a hydraulic structure can be expressed as:

$$\frac{dC}{dt} = K_L \frac{A}{V}(C_s - C) \tag{1}$$

where:

- $C$ = DO concentration
- $K_L$ = liquid film coefficient for oxygen
- $A$ = surface area associated with the volume V, over which transfer occurs
- $C_s$ = saturation concentration, or the dissolved oxygen concentration at which equilibrium with the gas phase is achieved
- $t$ = time.

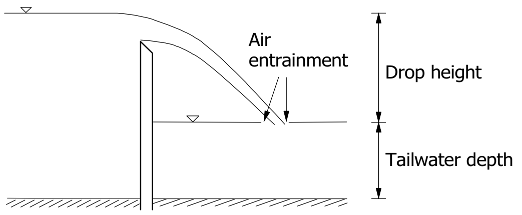
The term A/V is often called the specific surface area, a, or surface area per unit volume. Eq. (1) does not consider oxygen sources and sinks in the water body because their rates are relatively slow compared to the oxygen transfer that occurs at most hydraulic structures due to the increase in free-surface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

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

$$E = \frac{C_d - C_u}{C_s - C_u} = 1 - \frac{1}{r} \tag{2}$$

where:

- u and d = subscripts indicating upstream and downstream locations, respectively
- r = oxygen deficit ratio.



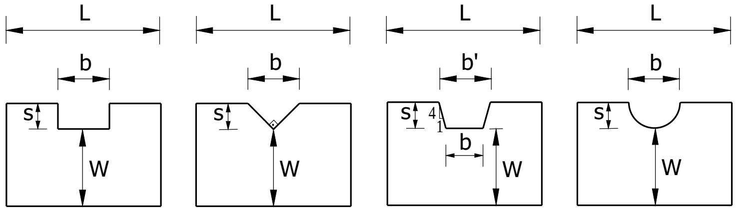




***Figure 1 (top left)***
*Free nappe over weir*

***Figure 2 (bottom left)***
*Weir cross-sections used for experiments*

A transfer efficiency value of 1.0 means that the full transfer up to the saturation value has occurred at the structure. No transfer would correspond to E = 0.0. The saturation concentration in distilled, deionised water may be obtained from charts or equations. This is an approximate value because the saturation DO concentration for natural waters is often different from that of distilled, deionised water due to the effects of salinity.

In this study, the saturation concentrations were determined by the chart of McGhee (1991) (Table 1). The salinity effect was minimised by using tap water with a low salt concentration.

## Factors affecting aeration efficiency

The oxygen transfer that occurs at a given structure is sensitive to water temperature, water quality, tailwater depth, drop height, weir discharge and DO deficit.

### Water temperature

Oxygen transfer efficiency is sensitive to water temperature, and investigators have typically employed a temperature correction factor. For hydraulic structures, the most frequently used temperature correction factor has been that of Gameson et al. (1958). Some investigators have chosen to use an Arrhenius-type of water temperature correction (Holler, 1970). Gulliver et al. (1990) applied the theories of Levich (1962), Hinze (1955), and Azbel (1981) to mass transfer similitude and developed the relationship:

$$1 - E_{20} = (1 - E)^{1/f} \tag{3}$$

where:

- $E$ = transfer efficiency at the water temperature of measurement
- $E_{20}$ = transfer efficiency at 20°C.
- $f$ = the exponent described by:

$$f = 1.0 + 0.02103\,(T - 20) + 8.261 \times 10^{-5}\,(T - 20)^2 \tag{4}$$

### Water quality

The presence of surface active agents, organic substances and suspended solids in water has been responsible for affecting the aeration process. Surface active agents in particular appear to modify the process by reducing surface tension, forming diffusion-inhibiting films at the air-water interface, and affecting the hydrodynamic characteristics of the flow. The effect of water quality often is generalised by the use of a "water quality factor" in equations for the deficit ratio, for instance Gameson (1957) and Markofsky and Kobus (1978). Avery and Novak (1978) used a similar constant to allow for the effects of different concentrations of sodium nitrate in their water.

**TABLE 1**
**Saturation values of dissolved oxygen in fresh- and seawater exposed to an atmosphere containing 20.9% oxygen under a pressure of 760 mm of mercury**

| Temperature (°C) | DO (mg/ℓ) for stated concentrations of chloride, mg/ℓ | | | | | Difference per 100 mg/ℓ chloride |
|---|---|---|---|---|---|---|
| | 0 | 5.000 | 10.000 | 15.000 | 20.000 | |
| 0 | 14.62 | 13.79 | 12.97 | 12.14 | 11.32 | 0.0165 |
| 5 | 12.80 | 12.09 | 11.39 | 10.70 | 10.01 | 0.0140 |
| 10 | 11.33 | 10.73 | 10.13 | 9.55 | 8.98 | 0.0118 |
| 15 | 10.15 | 9.65 | 9.14 | 8.63 | 8.14 | 0.0100 |
| 20 | 9.17 | 8.73 | 8.30 | 7.86 | 7.42 | 0.0088 |
| 25 | 8.38 | 7.96 | 7.56 | 7.15 | 6.74 | 0.0082 |
| 30 | 7.63 | 7.25 | 6.86 | 6.49 | 6.13 | 0.0075 |

The salt content of tap water used for all of the experiments reported in this paper was low and was monitored constantly during the experiments to ensure that there was no build-up of residues caused by the deoxidant chemicals which were added to the water. Therefore, the results were not affected by the presence of any chemicals or pollutants.

### Tailwater depth

The residence time of entrained air bubbles in a water body directly affects the oxygen mass transfer. The residence time is related to the bubble flow path and, hence, the bubble penetration depth into the downstream water pool. Tailwater depth is thus an important factor with regard to weir aeration and aeration efficiency generally increases with increasing tailwater depth. There is a limit, however, because the penetrating air-bubbles will not reach infinite depths. For each combination of discharge and fall height, there is an approximate maximum depth to which the bubbles penetrate, thus limiting the aeration efficiency and possibly even defining its maximum value. Avery and Novak (1978) found that the optimum tailwater depth of weirs should be approximately 0.6 times the drop height so as to ensure maximum aeration efficiency. They further indicated that the aeration efficiency remained stable for tailwater depths greater than 0.6 h. For consistency, all tests reported in this paper were carried out under these conditions. In all of the experiments for all four weir cross-sections the writers observed that air bubbles did not generally reach the floor of the downstream water pool.

### Drop height

The oxygen transfer that occurs at weirs is sensitive to drop height across the structure. Initially, a nappe with a relatively smooth surface issues from the weir and air entrainment takes place mainly at the surface of the downstream water pool. As the drop height increases, the surface of the nappe first becomes rough and then begins to oscillate during the fall, entraining air. This results in greater air flow into the downstream water pool. With increasing drop height, the nappe eventually breaks up into discrete droplets. The breakup of the nappe reduces its penetration depth into the pool and, hence, also the depth of the biphasic zone. This effectively reduces contact time $t_c$ between the bubbles and the surrounding water, and so aeration is observed to be less effective. It should be noted that the "breakup length" of the nappe (i.e. the difference in level between the weir sill and the point of breakup) is not at all well-defined and the nappe breaks up over a considerable length.

### Weir discharge

The aeration efficiency for weirs varies with discharge. The aeration efficiency decreases with an increase in discharge. Apted and Novak (1973), Avery and Novak (1978), and Van der Kroon and Schram (1969a; b) show a constant increase in the aeration efficiency with a decrease in discharge. At low discharges, on the other hand, breakup of the nappe is observed as the drop height increases. This leads to reduced penetration and bubble contact time into the downstream water pool and to reduced aeration efficiency.

### Dissolved-oxygen deficit

From Eq. (2) it can be seen that the measurement of transfer efficiency becomes quite sensitive to measurement errors with a low upstream DO deficit. Gulliver and Wilhelms (1992) state that an upstream DO deficit of greater than 2.5 mg/ℓ is normally required for accuracy in an oxygen-transfer efficiency measurement. The primary source of measurement uncertainty was found to be uncertainty in the oxygen-saturation concentration. During summer, when the average saturation concentration is about 7 mg/ℓ in most areas, this specification resulted in an upstream DO of less than 4.5 mg/ℓ. Wilhelms et al. (1992) found that a substantial portion of the oxygen-transfer measurements at hydraulic structures reported in the literature suffered from the low upstream deficit problem. They were dropped from the database because of the unacceptably high uncertainty in these measurements.

Wormleaton and Soufiani (1998) investigated the independence of oxygen transfer efficiency and upstream DO level. A set of readings was taken of the deficit ratio for a rectangular model weir without end contractions, with 320 mm sill width, under constant drop height, discharge, tailwater depth, and temperature conditions. The upstream DO concentration $C_u$ varied over a range of 0 to 80% of its saturation value and a variation in the downstream DO value $C_d$ was noted. The results showed a linear relationship between $C_u$ and $C_d$. DO deficit ratio and hence oxygen transfer efficiency E are independent of the upstream DO value $C_u$.

A relationship between $C_u$ and $C_d$ was derived from Eq. (2) as:

$$C_d = (1\text{-}E)\, C_u + E\, C_s \tag{5}$$

A regression analysis indicated that the best-fit line between $C_u$ and $C_d$ was:

$$C_d\,(\%) = 0.289\, C_u\,(\%) + 69.53 \tag{6}$$

implying that the oxygen transfer efficiency E is 0.711 and $C_s$ is 97.8%, thus confirming that the oxygen transfer efficiency is independent of the upstream DO deficit. It also reinforces the use of oxygen transfer efficiency as a useful indicator of the aeration behaviour of structures.

In this study, sodium sulphite ($Na_2SO_3$) was added to the water to ensure a minimum upstream DO deficit of 2.5 mg/ℓ. Cobalt chloride ($CoCl_2$) was used as the catalyst.

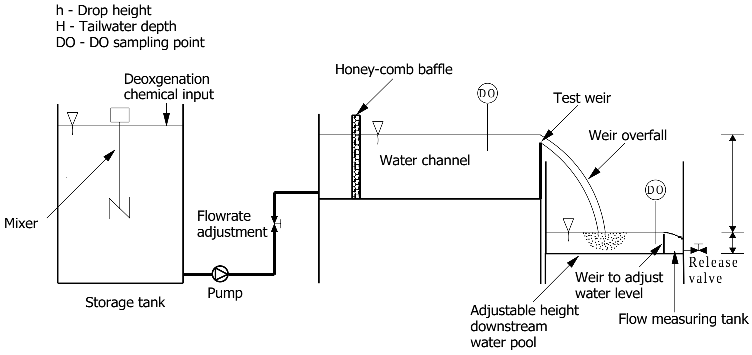



***Figure 3***
*Laboratory weir aeration apparatus*

## Experimental set-up

Aeration experiments were conducted using an experimental channel in the Hydraulic Laboratory at the Civil Engineering Department of Firat University, Elazig, Turkey. A 3 $m^3$ storage tank supplied water to a 3.4 m long, 0.60 m wide and 0.50 m deep channel with a maximum water flow rate of approximately 4 ℓ/s (Fig. 3). The water nappe from the test weir plunged into a downstream water pool, the height of which could be adjusted using a pulley arrangement. The water depth in the downstream water pool was controlled by an adjustable weir. The dimensions of the downstream water pool were 0.6 x 0.6 m.

The test weir featured four exchangeable weir elements: rectangular weir, triangular notch weir, trapezoidal (Cipolletti) weir, and semi-circular weir as shown in Fig. 2.

Each experiment was commenced by filling the storage tank and adding $Na_2SO_3$ and $CoCl_2$ to increase the upstream DO deficit ($C_s$ - $C_u$) to 2.5 mg/ℓ. The stirrer was installed in the tank to ensure accurate and reproducible water-phase measurements.

During the experiments, DO and temperature measurements upstream and downstream of the weir were taken using a calibrated portable HANNA Model HI 9142 oxygen meter at the locations identified in Fig. 3. The DO meter was calibrated daily, 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.

## Experimental program

The dimensions of the weirs tested are given in Table 2. Each weir configuration was tested under flow rates Q varying from approximately 1.0 to 4.0 ℓ/s in 1 ℓ/s steps. The drop height h, defined as the difference between the water levels upstream and downstream of the weir, was varied between 0.15 to 0.90 m. The depth in the downstream water pool was maintained throughout at greater than the bubble penetration depth to ensure optimum aeration conditions.

**TABLE 2**
**Experimental programme and details**

| Weir type | L (cm) | b (cm) | s (cm) | W (cm) |
|---|---|---|---|---|
| Rectangular weir | 60 | 20 | 10 | 40 |
| Triangular notch weir | 60 | 20 | 10 | 40 |
| Trapezoidal (Cipolletti) weir | 60 | 15 (b'=20) | 10 | 40 |
| Semi-circular weir | 60 | 20 | 10 | 40 |

## Results

An experimental run consisted of establishing target values for Q, h and H within the experimental channel followed by the measurement of T, $C_u$ and $C_d$. Experimental values of $E_{20}$ were calculated from measured values using Eqs. (2) and (3).

The following sections discuss the oxygen transfer efficiency ($E_{20}$) results, which are shown to vary with drop height (h), and discharge (Q) in Fig. 4.

Experiments with all four weir sections indicate that the drop height is the most important factor influencing aeration efficiency. Figure 4 shows the oxygen transfer efficiency observed during experiments as a function of drop height and discharge for four different weir sections. Figure 5 also shows variation in aeration efficiency of four different weir sections with increasing drop height while the change in discharge is constant. All of these graphs show an increase in aeration efficiency with drop height. Generally, a larger drop height leads to greater bubble penetration depths into the downstream water pool and longer contact times $t_c$. This increases aeration efficiency. On the other hand, breakup of the nappe was observed as the drop height increased to more than 90 cm.

The results of experiments involving differing weir discharges were far less significant than those involving drop height. Figure 4 shows that weir discharge influencing oxygen uptake is closely related to the cross-sectional weir geometry. The aeration efficiency of the triangular notch weir was reduced as the discharge increased over the range of drop heights tested. In the other weirs the aeration efficiency was generally greatest for the lowest discharge of 1 ℓ/s and the lowest values of the aeration efficiency were observed for the highest discharge of 4 ℓ/s. For all four weir types breakup of the nappe was observed as the drop height increased for the lowest discharge.

The rectangular weir had the lowest oxygen transfer efficiencies. The greatest oxygen transfer efficiency for this section was 0.37, at a discharge of 1 ℓ/s and a drop height of 0.90 m. The rectangular weir was found to have a relatively poor performance as an aerator.

For the trapezoidal weir, the values of oxygen transfer efficiency are in general agreement with the values of the semi-circular weir. The greatest trapezoidal weir and semi-circular weir oxygen transfer yielded an efficiency of 0.41, at a discharge rate of 1 ℓ/s and a drop height of 0.90 m.

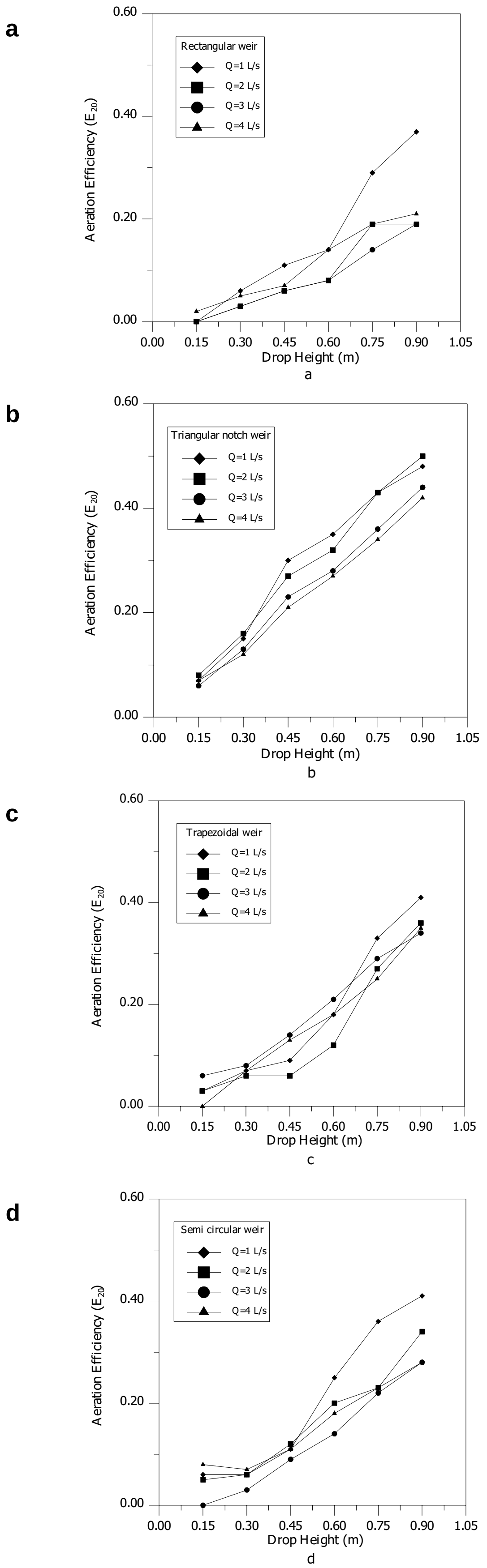



***Figure 4***

*Variation in aeration efficiency with drop height and discharge for (a) rectangular weir; (b) triangular notch weir; (c) trapezoidal (cipolletti) weir; (d) semi circular weir*

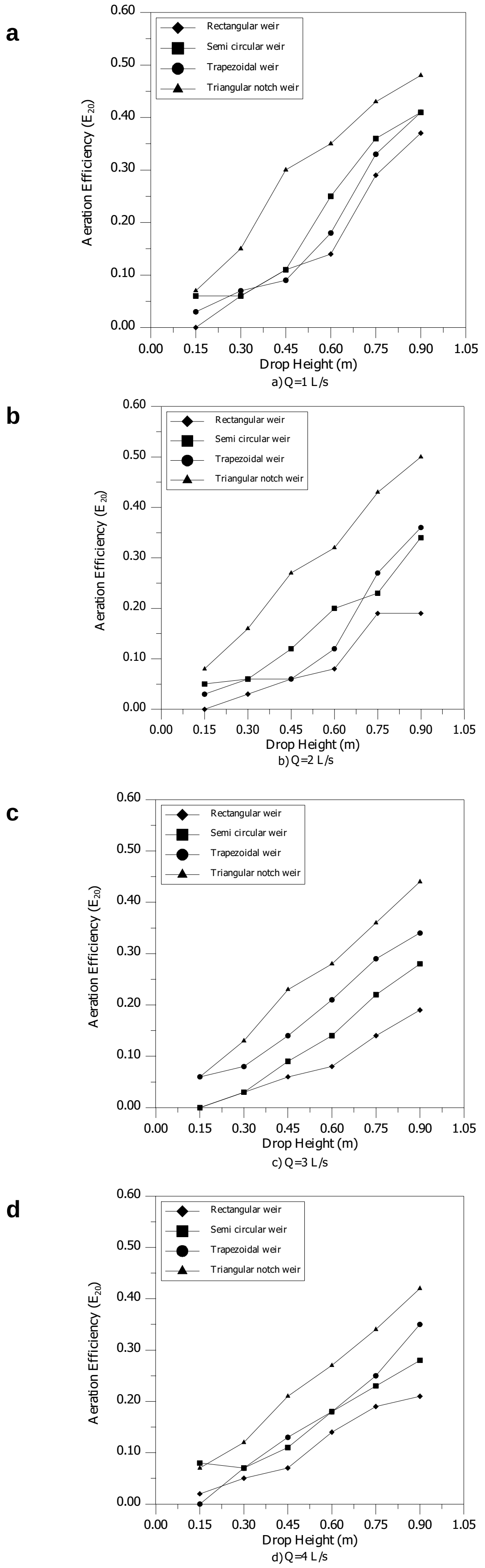



***Figure 5***

*Variation in aeration efficiency of all four weir types with drop height for (a) Q=1 ℓ/s; (b) Q=2 ℓ/s; (c) Q=3 ℓ/s; (d) Q=4 ℓ/s*

The triangular notch weir was found to have the greatest values of oxygen transfer efficiency. The greatest triangular notch weir yielded oxygen transfer efficiencies of 0.50, at a discharge rate of 2 ℓ/s and a drop height of 0.90 m, and 0.48 at a discharge rate of 1 ℓ/s and a drop height of 0.90 m. Aeration efficiency was greatest with the triangular notch weir because in this weir air entrainment and turbulent mixing which contributed to the oxygen exchange were greater than in the other weirs. The primary reason for this difference is the nappe shapes. The weir geometry defines nappe shapes that are unique to each weir, and the oxygen exchange seems to depend strongly on these nappe shapes.

## Conclusions

A series of laboratory experiments has been carried out to measure the aeration performance of different shape weirs over a range of flows between 1 and 4 ℓ/s with drop heights ranging from 0.15 to 0.90 m. The total weir length was kept constant at 0.60 m. The following conclusions may be drawn from the aeration efficiency of weirs:

- The drop height was confirmed to be the most important parameter influencing oxygen transfer at weirs. The aeration efficiency increased with an increase in drop height in all cases.
- The results of experiments involving changing weir discharge were far less significant than those involving drop height. The aeration efficiency of the triangular notch weir was reduced as the discharge increased over the whole range of drop heights tested. In the other weirs the aeration efficiency was generally greatest at a discharge rate of 1 ℓ/s and the lowest values of the aeration efficiency were observed at different discharge values.
- The weir shape has been found to be an important factor influencing the aeration efficiency. The weir geometry defines nappe shapes that are unique to each weir, and the oxygen transfer seems to strongly depend on these nappe shapes.
- The experimental values of the trapezoidal weir for the oxygen transfer efficiency ($E_{20}$) are similar to the values of the semi-circular weir.
- The oxygen transfer efficiency was the highest with the triangular notch weir and lowest with the rectangular weir. Therefore, the rectangular weir would generally not be recommended for aeration purposes.
- Tailwater depth as well as drop height and discharge is important for weir aeration. Therefore, the optimum tailwater depth is 0.6 times the drop height.

## Acknowledgments

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