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Oxygen Transfer through Air Entrainment in Riparian Riffles: A Case Study of Seomjin River, Korea

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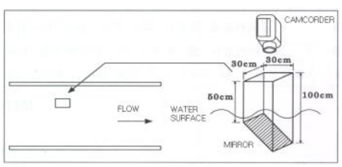
Graphical abstract



Abstract

Field investigation on the oxygen transfer through the air entrainment, the riffle geometries, and the relationships between the efficiency of the oxygen transfer and the hydraulic parameters in the riparian riffles were performed. Investigation of the air entrainment and measurements of the oxygen transfer in the riffles were conducted. Types of bed height in the riffles were upward convex. Slopes of the water surface and the river bed were steeper at the downstream rather than at the upstream part. Air entrainment occurred more frequently in the edged gravels rather than in the round and edgeless gravels, and it was formed mainly from behind the trailing edges of the gravels. Oxygen transfer was found to be proportional to the flow velocity, the flow discharge, and the Froude number, but not closely related to the particle diameter. Average value of oxygen transfer in the riffles of the study area was about 0.085, which shows good habitat condition for the aquatic creatures.

Keywords: Oxygen transfer; air entrainment; riffle; flow velocity; Froude number

■1.0 INTRODUCTION

A riffle is a short, relatively shallow and coarse-bedded length of stream over which the stream flows at higher velocity and turbulence than a pool. Riffles are usually caused by an increase in a stream bed's slope or an obstruction in the water.

Riffles are instrumental in the formation of meanders, with deeper pools forming alternately. Although simple fluid flow suggests slower flow in deeper water and faster flow over riffles, the true flow pattern at pool and riffle waters is often tumbling, helicoidal or turbulent[1].

Riffle-pool formations are well developed in the environmentally sound and meandering channels and they are important for fish habitats. Most of fishes can inhabit mainly in the riffles at daytime, and can rest or sleep in the pools at night. The riffle is characterized by the high flow velocity, the steep bed slope and the shallow water depth. The pool is located at the curved part of the stream channel and is characterized by the relatively low flow velocity and the higher water depth.

Riffles are the shallower, faster moving sections of a stream with fast current where the water surface collides with rocks. They are important to fish habitat since the abundant dissolved oxygen can be stored in the water. As water rushes over the rocks it adds oxygen.

Riffles consist of gravel and cobble-sized stone arranged at distinct intervals in shallow streams. Gravel riffles promote the formation of stable substrate in channels that have been modified or otherwise heavily impacted by development. Gravel substrate provides productive habitat for aquatic organisms and areas for fish to spawn.

Since the riffles are characterized by high flow velocity and shallow depth, they have relatively high Froude number ranging between 0.5-0.8, but sometimes have value larger than unity, which represents the supercritical flow and the hydraulic jump[2]. Riffles have high bed slopes and large size of gravels, and hence the oxygen transfer through air entrainment is actively made into riffles, which has the similar results as an aeration enhancement by macro-roughness in in-stream cascades or stepped weirs[3]. Dissolved oxygen will be enhanced and with this effect, plenty of algae, aquatic insects and fish can inhabit in the riffles.

Many streams have been modified to improve their capacity to convey the flood flow. This has most often been achieved by straightening the channel alignment and lowering the streambed to increase the channel slope and the flow velocity. Although these practices greatly improve the efficiency of the flood control, this kind of channel modification degrades the stream's water quality and destroys the aquatic habitat. Recently, the river restoration works considering ecological habitats have been thought to be important, so the hydraulic studies on the ecological features of the riffles for the effective design of river restoration must be conducted[2].

This paper performed the ecological features of the riparian riffles. It presents the hydraulic analysis on the oxygen transfer through air entrainment, and the relationships between the efficiency of the air entrainment and the hydraulic parameters of the riffles. Investigation of air entrainment and the measurement of the oxygen transfer in the riffles were performed to determine the relationships between the air entrainment and the hydraulic parameters such as flow velocity, flow discharge, Froude number and particle diameter.

2.0 SAMPLING SITES FOR RIPARIAN RIFFLES

Field survey of the sampling sites for the riparian riffles was conducted at Seomjin River flowing through the mid-part of Korea (Figure 1). This river is environmentally sound and well conserved which is not affected by the artificial human activities, and hence the naturally meandering riffle-pool formations are well developed.

The riffle is located upstream of the pool and is characterized by high flow velocity (0.6 m/s-1.2 m/s) and shallow water depth (0.2 m-1.0 m). Water surface looks as white waves by aeration due to macro-roughness. The run is located downstream of the pool and is characterized by low flow velocity (0.3 m/s-0.8 m/s) and large water depth (0.8 m-1.2 m). Water surface appears as weak and consecutive transverse wrinkles. The pool is located at the curved part of the stream channel and is characterized by the relatively low flow velocity (0.2 m/s-0.5 m/s) and the large water depth (1.0 m-2.5 m) shown in Figure 2[4].

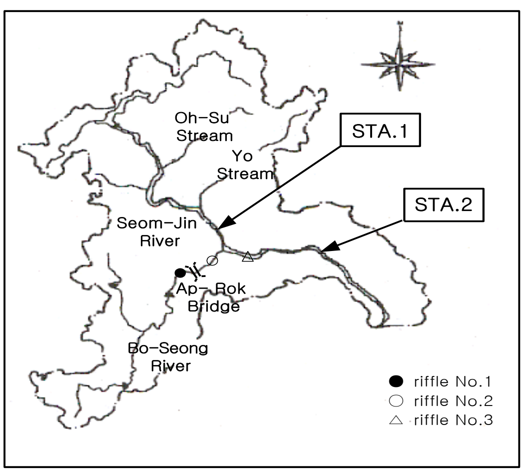
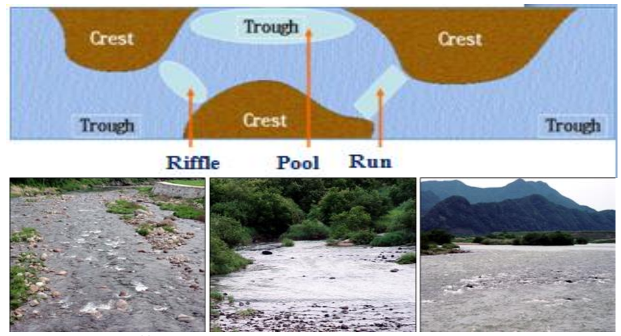


Figure 1 Sampling sites of Seomjin River



(a) Riffle (b) Pool (c) Run

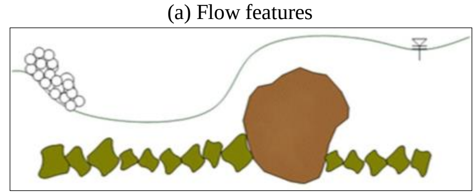
Figure 2 Formation of riffles and pools

It can be seen that the riffle-pool formations are well developed in this river reach. Riffle formations will promote aeration enhancement and oxygen transfer associated with substantial air entrainment, which leads to the good conditions of water quality and habitat. The flow types of riffles take narrower and longer shape compared with those of pools. The reason is that the pools are located at the meandering section, while the riffles are located at the straight part between the pools.

To investigate the influence of hydraulic characteristics on the air entrainment, the following three sampling riffle sites as the areas of substantial aeration and abundant dissolved oxygen were selected. Two sampling sites are located at the downstream part of Bo-Seong River, which is the branch of the main Seomjin River, and one site is located downstream of the confluence of the main river. In these sites, the riverbeds are covered with gravels and the flow velocity is 1.0 m/s-1.2 m/s, which shows the typical features of the riffles.

Riffle No. 1 is located 700 m upstream of the Ap-Rok Bridge. A steep riffle characterized by the shallow water depth (0.5 m-0.7 m) and the high flow velocity (1.0 m/s-1.1 m/s) is formed at this reach. Upstream part of the riffle is characterized by the mild bed slope and the undular wave types. Downstream part of the riffle is characterized by the steep bed slope and the hydraulic jump 0.5 m-1.0 m behind the large stone (Figure 3). The river bed is covered with gravels and air entrainment is dominant. The width and length of the riffle are 7.2 m and 21.8 m, respectively.

(a) Flow features

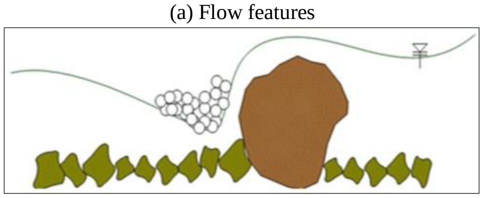


(b) Schematic diagram

Figure 3 Riffle No. 1

Riffle No. 2 is located 1 km downstream of the Ap-Rok Bridge. A steep riffle is also formed and air entrainment occurred. The bed slope is relatively high and covered with gravels. The hydraulic jump occurs directly from behind the large stones (Figure 4). Plenty of algae are attached to the bed gravels, which provide the good habitat for aquatic insects and fishes. The width and length of the riffle are 7.5 m and 3.4 m, respectively.

(a) Flow features

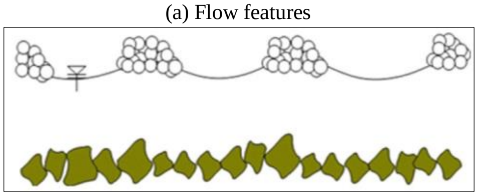


(b) Schematic diagram

Figure 4 Riffle No. 2

Riffle No. 3 is located 5 km downstream of the Ap-Rok Bridge and is characterized by the steep riffle and air entrainment. The water surface appears as consecutive wrinkles as shown in Figure 5. The bed slope is relatively high and the riverbed is covered with gravels. The width and length of the riffle are 6.5 m and 3.7 m, respectively.

(a) Flow features



(b) Schematic diagram

Figure 5 Riffle No. 3

Measured values of the riffle size are shown in Table 1. Here, b and B are widths of the riffle and channel, respectively and L is the length of the riffle. Definitions of these values are shown in Figure 6.

Table 1 Shape of riffles

Properties	b(m)	L(m)	B(m)	b/B(-)	L/b(-)
No. 1	7.2	21.8	46.2	0.156	3.028
No. 2	7.5	3.4	88.7	0.085	0.453
No. 3	6.5	3.7	86.4	0.075	0.569

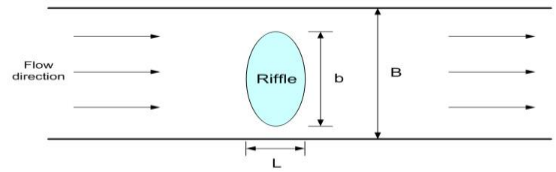


Figure 6 Definitions of riffle shape

Long type of a riffle corresponds to L/b larger than 1.0, and wide type of corresponds to L/b is smaller than 1[5]. From the results of the Table 1, No. 1 riffle is the long type and No. 2 and 3 riffles are wide type.

Shape clearness of the shoreline of gravel bars is shown in Figure 7. The shoreline takes an asymmetry shape. Round part of region 1 takes an unclear shoreline due to erosion and lowering of the river bed, while region 2 shows the clear shoreline due to deposition of sediments.

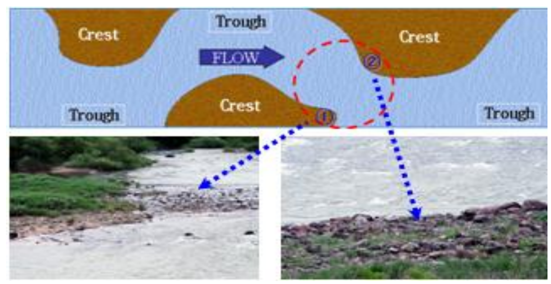


Figure 7 Shoreline shape of gravel bar

■3.0 SLOPE OF WATER SURFACE AND RIVER BED ALONG FLOW DIRECTION

Slopes of the water surface and of the river bed along flow direction were measured using Total Station (Sokkia Set 2100) and the staff (5 m long) as shown in Table 2. These slopes were measured by three 20 m long flowlines from the reference line at the upper stream (Figure 8). They were measured by 2 m intervals. Height of the reference line is appointed as zero. Here, *D* is the measured distance from the reference line, *Hs* is the height of water surface, *Hb* is the height of the river bed.

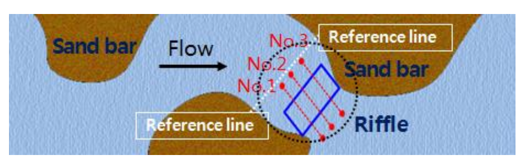


Figure 8 Reference line and three flowlines

Table 2 Height of water surface and river bed

Region	*D* (m)	*Hs* (EI.m)	*Hb* (EI.m)	*D* (m)	*Hs* (EI.m)	*Hb* (EI.m)
No. 1	2.0	-0.06	-0.75	12.0	-0.24	-0.52
	4.0	-0.08	-0.51	14.0	-0.28	-0.62
	6.0	-0.12	-0.53	16.0	-0.45	-0.76
	8.0	-0.09	-0.49	18.0	-0.47	-0.84
	10.0	-0.21	-0.54	20.0	-0.54	-0.94
No. 2	2.0	-0.04	-0.67	12.0	-0.26	-0.53
	4.0	-0.04	-0.66	14.0	-0.24	-0.62
	6.0	-0.13	-0.54	16.0	-0.46	-0.79
	8.0	-0.10	-0.46	18.0	-0.51	-0.83
	10.0	-0.23	-0.59	20.0	-0.54	-0.94
No. 3	2.0	-0.02	-0.69	12.0	-0.24	-0.43
	4.0	-0.06	-0.72	14.0	-0.18	-0.60
	6.0	-0.10	-0.52	16.0	-0.49	-0.72
	8.0	-0.09	-0.42	18.0	-0.48	-0.83
	10.0	-0.18	-0.49	20.0	-0.54	-0.94

Figure 9 shows the results of the height of water surface and river bed taken from Table 2. These results revealed that the types of bed height in the riffles are upward convex. Slopes of the water surface and the river bed are steeper at the downstream rather than at the upstream part.

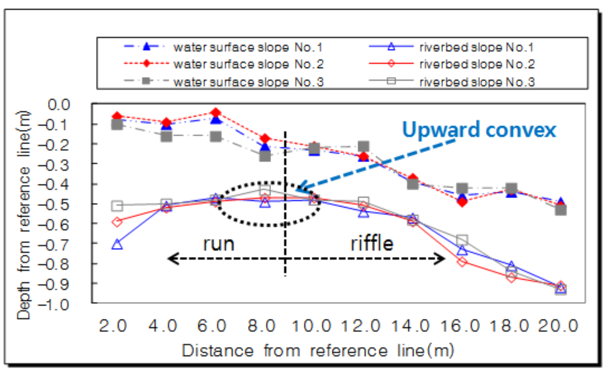


Figure 9 Height of water surface and river bed

■4.0 INVESTIGATION AND MEASUREMENT OF AIR ENTRAINMENT

Submerged photographing was used to investigate the air entrainment. As shown in Figure 10, the hexagonal box made with transparent acryl plate and a mirror attached to the inclined bottom was prepared. The digital video camcorder was installed inside the hexagonal box for submerged photographing. Observation areas were illuminated by the strong light to get clean views[6].

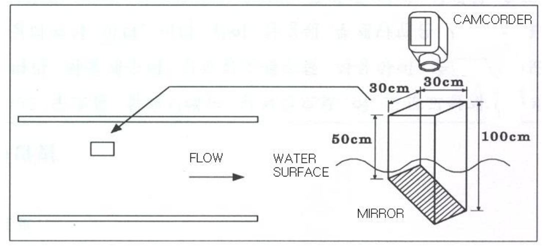


Figure 10 Experimental apparatus for submerged photographing

Measured points in the riffles were two (upstream and downstream of the riffle) along the flow direction, and four along the transverse direction, and hence eight points were selected. The points were numbered from upstream to downstream and from right to left consecutively. Distance between points along the flow direction is 20 m and the distance between points along the transverse direction is 2 m (refer to Figure 11).

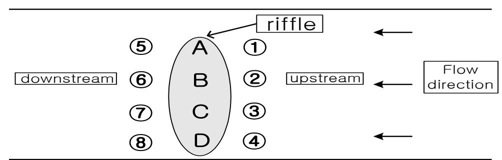


Figure 11 Measured points in riffle sites

Tables 3, 4 and 5 show the measured values of the water quality and the hydraulic parameters at riffle No. 1, 2 and 3, respectively. Here, *DO*(mg/l) is the concentration of the dissolved oxygen, *pH* is the potential of hydrogen, T(℃) is the water temperature, *V*(m/s) is the average value of the flow velocity, *H*(m) is the average value of the water depth, q(m^2/s) is the flow discharge per unit width, D_{50}(cm) is the mean value of the particle diameters of the bed materials and *Fr* is the Froude number.

Table 3 Measured data in riffle site No.1

Properties		DO (mg/l)	PH (-)	T (℃)	V (m/s)	H (m)	Q (m^2/s)	D_{50} (cm)	Fr (-)
No.1	1	8.06	7.03	21.0	0.601	0.51	0.307	4.40	0.269
	2	8.08	6.94	20.9	0.713	0.53	0.381	4.38	0.313
	3	8.11	7.00	20.8	0.668	0.53	0.354	5.18	0.293
	4	8.08	7.02	21.0	0.804	0.51	0.407	4.91	0.359
	5	8.07	6.87	21.0	0.827	0.35	0.290	4.60	0.446
	6	8.13	6.94	21.1	0.831	0.58	0.483	5.33	0.348
	7	8.17	6.96	20.8	1.013	0.69	0.701	5.27	0.389
	8	8.20	6.70	21.0	1.103	0.81	0.893	5.06	0.391

Table 4 Measured data in riffle site No.2

Properties		DO (mg/l)	pH (-)	T (℃)	V (m/s)	H (m)	q (m^2/s)	D_{50} (cm)	Fr (-)
No.2	1	7.97	6.90	20.2	0.857	0.40	0.343	9.83	0.403
	2	8.01	6.99	20.2	0.752	0.57	0.426	8.94	0.318
	3	8.04	6.99	20.1	0.990	0.50	0.495	7.50	0.447
	4	8.01	7.01	20.0	0.704	0.64	0.452	7.47	0.281
	5	8.02	7.50	20.0	0.839	0.46	0.386	7.44	0.424
	6	8.05	7.17	20.2	0.548	0.53	0.290	1.26	0.212
	7	8.09	7.52	20.2	0.584	0.59	0.342	2.24	0.243
	8	8.13	7.80	20.6	0.710	0.62	0.440	1.08	0.287

Table 5 Measured data in riffle site No.3

Properties		DO (mg/l)	pH (-)	T (℃)	V (m/s)	H (m)	q (m^2/s)	D_{50} (cm)	Fr (-)
No.3	1	8.01	6.58	21.0	0.547	0.34	0.186	9.64	0.301
	2	8.07	6.61	21.2	0.612	0.57	0.347	7.98	0.259
	3	8.02	6.57	21.5	0.920	0.59	0.543	8.74	0.384
	4	8.05	6.82	21.0	0.814	0.50	0.404	8.14	0.367
	5	8.02	6.58	21.1	0.826	0.84	0.690	9.50	0.287
	6	8.10	7.64	21.0	1.004	0.94	0.944	7.84	0.331
	7	8.14	6.97	20.8	0.682	0.52	0.355	8.22	0.302
	8	8.11	7.75	21.0	0.747	0.44	0.329	8.59	0.360

■5.0 RESULTS AND DISCUSSIONS

Figure 12 shows the occurrence of air entrainment observed using the above-mentioned method of submerged photographing in 4.0[2].

Figure 12 Air entrainment behind trailing edge of gravels

Air entrainment occurred mainly from behind the trailing edges of the gravels due to flow separation, which is the similar results to the air entrainment behind step edge shown in Figure 13[7]. It occurred behind the edged gravels more frequently rather than behind the round and edgeless ones. Air bubbles were formed and swept in the downward direction becoming larger in volume and were finally broken. Abundant dissolved oxygen seemed to be stored at regions of breaking of air bubbles, and this would give the good habitat condition.

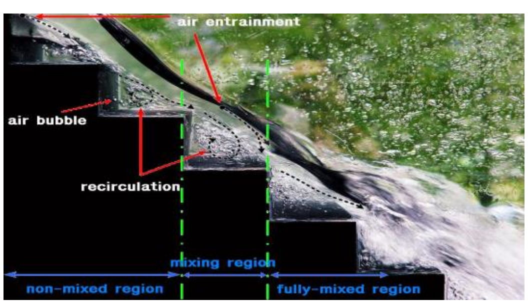
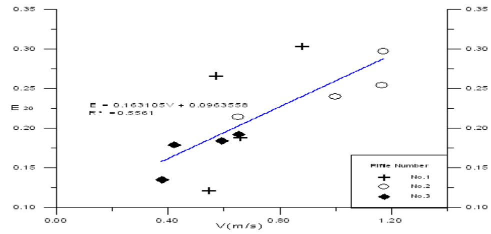
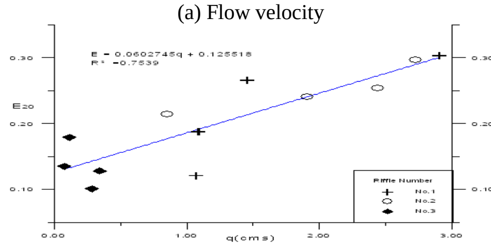


Figure 13 Air entrainment behind step edge

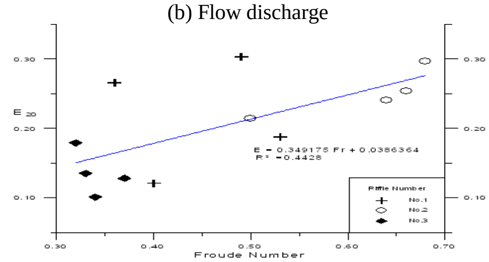
Figure 14 shows the quantitative relationships between the efficiency of the oxygen transfer (E_{20}) and the hydraulic parameters of flow velocity (*V*), flow discharge (*Q*), Froude Number, and particle diameter (*D*). These relationships were taken from Tables 3, 4 and 5.



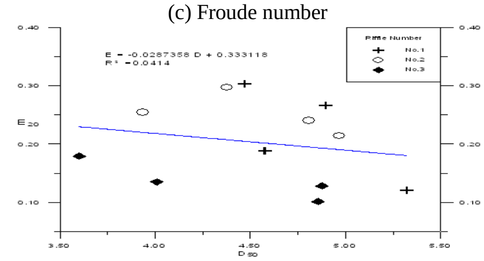
(a) Flow velocity



(b) Flow discharge



(c) Froude number



(d) Particle diameter

Figure 14 Relationship between oxygen transfer efficiency and flow parameters

Here the riffle numbers 1, 2 and 3 were mentioned in 2.0. The efficiency of the oxygen transfer, *E*, was defined as follows (Avery and Novak, 1978).

$$E = (C_d - C_u)/(C_s - C_u) \qquad (1)$$

where, C_d and C_u are concentrations of the dissolved oxygen measured at downstream and upstream points, respectively, and C_s is the saturated concentration of the dissolved oxygen.

Since the oxygen transfer is affected by water temperature, *E* is substituted by E_{20} (Gullivers *et al.*, 1990);

$$\frac{\ln(1-E_T)}{\ln(1-E_{20})} = 1.0 + \alpha(T-20) + \beta(T-20)^2 \qquad (2)$$

where, E_T and E_{20} are the efficiencies of oxygen transfer at a temperature of *T*ºC and a reference temperature of 20ºC, respectively. The symbols α and β are constants given α =0.02103 ºC^{-1} and β=8.621×10^{-5} ºC^{-2}. In Figure 14, E_{20} was evaluated per unit length to relate them to the hydraulic parameters quantitatively.

As can be seen in Figure 14, Oxygen transfer was found to be proportional to the flow velocity, the flow discharge and the Froude number. But it was not found to be proportional to the particle diameter of the bed materials, which can be seen from the fact that air entrainment occurred more frequently behind the edged gravels rather than behind the round and edgeless ones. Therefore, it is related to the particle shape of the bed materials rather than to the particle size.

The efficiency of the oxygen transfer is more related to the flow discharge than to the Froude number as shown in (b) and (c) in Figure 14.[8] shows that oxygen transfer increase when the flow depth decrease. Their relationship was not clarified exactly in this study, since the flow depth was proportional to the flow discharge but inversely proportional to the Froude number. Also, the variation of water level, which is proportional to the oxygen transfer[9] was found to increase with flow velocity and the particle size of bed materials. Relationships between variation of water level and oxygen transfer must be investigated quantitatively through the site measurements and the hydraulic model tests.

Data revealed that average value of oxygen transfer, E_{20} in the riffles of the study area was about 0.085, which shows good efficiency compared with results of smooth chute[10] and shows good habitat condition for aquatic creatures due to storage of abundant dissolved oxygen.

■6.0 CONCLUSIONS

The following conclusions are drawn from this study:

a. Types of bed height in the riffles were upward convex.
b. Slopes of the water surface and the river bed were steeper at the downstream rather than at the upstream part of the riffles.
c. Air entrainment occurred in the edged gravels more frequently rather than in the round and edgeless one, and it occurred mainly from behind the trailing edge of the gravels.
d. Oxygen transfer was found to be proportional to the flow velocity, the flow discharge and the Froude number. It was closely related to the flow velocity and the flow discharge more than to the Froude number, but was not proportional to the particle diameter.
e. Average value of oxygen transfer in the riffles of the study area was about 0.085, which shows good habitat condition for aquatic creatures.

Acknowledgement

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