High-Performance Aerating Weirs for Dissolved Oxygen Improvement

Gary E. Hauser[1], M. ASCE and Doug I. Morris[2]

Abstract

New concepts in aerating weir design are being explored for improving dissolved oxygen in tailwaters downstream from hydropower projects with oxygen-deficient releases. Reliable design procedures are being developed from experiences of the Tennessee Valley Authority (TVA) and other utilities in a project sponsored by the Electric Power Research Institute (EPRI). The project includes laboratory and prototype field experiments to fill gaps in existing knowledge. This paper is intended to update water resources professionals on the project.

Introduction

With proper design, aerating weirs represent a highly efficient, reliable, low-maintenance technology for dissolved oxygen (DO) improvement in hydropower releases. TVA now routinely considers weirs, along with other technologies, in achieving its goals for reservoir release improvement (Adams and Brock, 1993). As described by EPRI (1990), reliable design guidance for aerating weirs has been lacking. Considerable aeration literature exists for conventional linear weirs, but results are occasionally conflicting and the weirs tested were designed for purposes other than aeration. Recent research on weir innovations such as the "labyrinth" and the "infuser" is improving our understanding of the aeration processes associated with such weirs, leading to more predictable, closer-tolerance designs over a range of weir types. TVA is serving as a utility test site, under EPRI-sponsorship, to demonstrate aerating weir technology and to develop reliable design procedures for the hydropower industry. This three-year project includes development of a design manual, in which available data were supplemented with laboratory testing of experimental weirs and new field testing of prototype weirs. The project, started in 1993, will culminate in a design manual for aerating weirs to be published in 1996.

[1]Technical Specialist, TVA Engineering Laboratory, P.O. Drawer E, Norris, Tennessee 37828
[2] Project Manager, Electric Power Research Institute, P.O. Box 10412, Palo Alto, California 94303

An interim manual, published in early 1995, is currently available to the hydropower industry (Hauser, 1995).

Three types of weirs were considered in this research: the conventional linear weir; the labyrinth weir, which assumes a repetitive "W" shape in plan view; and the infuser weir, which is a broadcrest weir that allows vertical flow through a series of transverse slots in its crest. Prototype labyrinth and infuser weirs have been constructed by the Tennessee Valley Authority, and labyrinth weirs have been constructed by Georgia Power (GP) and the Guadalupe-Blanco River Authority (GBRA). Photographs of weirs for which prototype test data are now available are shown in Figure 1.

Laboratory Testing

The aeration potential of conventional linear weirs constructed normal to river flow is well documented by Nakasone (1987), Avery and Novak (1978), Kobus and Markofsky (1978), and Wilhelms et al. (1992). In hydropower situations, use of a linear weir for aeration is often not prudent because the specific discharge (turbine flow per unit length weir) exceeds acceptable limits for safety. Recirculation in weir plunge pools is notorious for entrapment of unwary river users. Also, the specific discharge is generally well beyond the optimal range for aeration. Specific discharge is reduced with a labyrinth weir, which provides extended crest length in a sawtooth alignment in the river channel. Labyrinth weirs can therefore reduce the recirculation intensity to a safe level while creating more optimal conditions for aeration. However, labyrinth weirs can be costly to construct, due in part to the crest length required for safety.

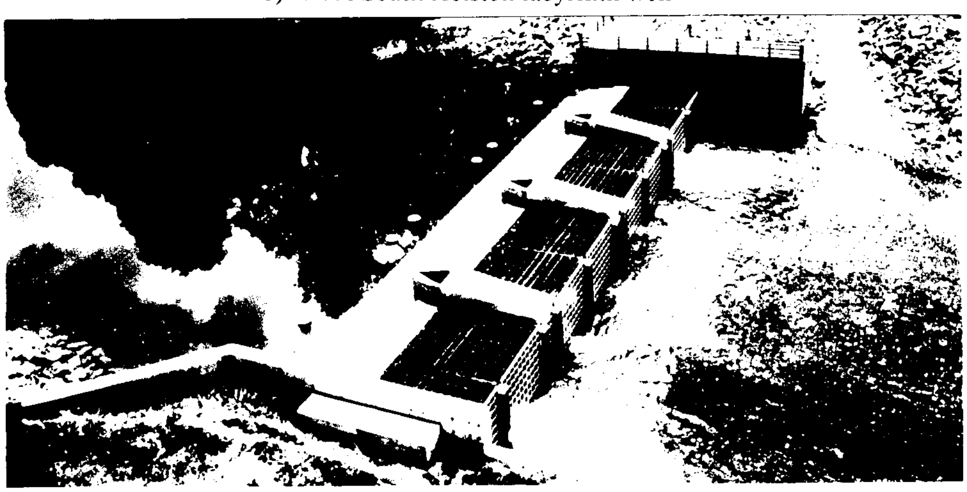
The primary goal of the laboratory testing was to explore issues not fully addressed in the literature. It was necessary to explore crest modifications to reduce the length, and hence the cost, of labyrinth weirs; plunge pool depth effects, because of the complex interactions between bubble residence time and turbulence; and labyrinth shape effects. Laboratory tests consisted of a qualitative screening phase and a quantitative aeration testing phase.

Qualitative Screening

Qualitative screening was performed to identify weir modifications to reduce the length (and cost) of labyrinth weirs without sacrificing safety or aeration efficiency. Previous work by Hauser (1991) indicated that safe levels occur in weir plunge pools at specific discharges less than about 0.14 m^2/s. If weir modifications could provide safe overflow conditions at higher specific discharges without sacrificing aeration, the crest length and therefore cost of the labyrinth weir could be substantially reduced. A weir crest that could safely aerate at 0.28 m^2/s, for example, would require half the crest length.

a) GBRA Canyon labyrinth weir

b) TVA South Holston labyrinth weir



c) TVA Chatuge infuser weir

Figure 1. Photographs of Prototype Aeration Weirs

To screen basic weir alternatives for subsequent quantitative testing, a simple linear weir and nine basic weir modifications were evaluated qualitatively in a TVA laboratory channel (2.4-m high by 2.4-m wide) at specific discharges of 0.28 m^2/s and higher. The weir modifications were evaluated for safety, air entrainment, bubble zone characteristics, hydraulic efficiency, constructability, and ability to pass debris. Subjective observations regarding safety were obtained in the laboratory plunge pool from volunteer swimmers equipped with safety lines. Weir modifications included the following:

tailwater blocks	blocks fixed to the channel bottom downstream of the weir, proposed to enhance safety by dissipating the energy of the recirculation
cascade/step	a single step below the weir crest, proposed to break up the overflow before it plunged to reduce momentum of submerged jets that drive recirculation
slotted weir crest	boards attached vertically to a simple weir, extending above its crest to create vertical slots (i.e., serration) in the crest, proposed to enhance tailwater safety by creating locally "weak" zones of recirculation in the tailwater, and to enhance DO uptake by increasing the air/water contact area and nappe turbulence
alternating depth slotted weir crest	same as the slotted weir crest, except a deep and a shallowslot were used in an alternating pattern, proposed to increase the irregularity of the crest flow pattern
infuser flap	grating strip fastened horizontally at the weir crest, spanning the width of the laboratory channel, so that most of the flow travels through the grating, with some flowing over the grating for self-cleaning. proposed to act as a short infuser deck to break overflow jets into highly turbulent nappes
crest fins	rectangular flaps protruding horizontally downstream from the weir crest, spaced at intervals along the weir crest, proposed to spread the overflow, reducing the effective specific discharge, increasing the air/water contact area, and creating a nonuniform flow distribution in the tailwater to locally disrupt recirculation zones
flip bucket fins	similar to the crest fins, except fitted with flip bucket troughs at the downstream edges, and set at alternating angles below the horizontal, proposed to spread the overflow, reducing energy per unit length of the nappe and increasing the air/water contact area and time of exposure to the atmosphere
serpentine crest	semi-circular sections attached to the weir crest in a serpentine pattern in plan view, proposed to increase effective crest length on a shortened weir wall
tailwater jet	low-level horizontal orifices in weir, proposed to increase tailwater safety by sweeping out recirculation zones below the weir

Based on test observations, the infuser flap was considered most favorable of the nine modifications for safely reducing the length of the labyrinth weir. It was effective in breaking up recirculation, had a negligible effect on overflow efficiency, entrained significant air, was easy to construct, and was deemed the safest by the volunteer swimmer. Minor maintenance may be required to clear the grating of debris. The slotted weirs were the next most favorable. Constructability and air entrainment appeared promising, especially with the alternating depth slotted weir. Debris could pose a serious problem with all slotted weirs. The flip buckets could be made equally favorable with the slotted weirs with further modification to minimize the expense of construction, and they are more hydraulically efficient and less subject to debris problems. The tailwater blocks, cascade/step, crest fins, serpentine crest, and tailwater jets did not warrant further testing, due primarily to poor tailwater safety, impact on aeration, and/or potential expense arising from constructability issues.

Quantitative Aeration Tests

Based on qualitative screening, the infuser flap and the alternating depth slotted crest (nicknamed the "picket fence") were selected for quantitative testing. In addition, four labyrinth configurations were tested to evaluate shape effects. Figure 2 shows the 1-bay wide labyrinth tested, along with 2-bay and 4-bay alterations using the same crest length. Centerline length of the 1-bay labyrinth was 9.1 m, and the downstream bay width was 3.2 m. A similar 1-bay narrow labyrinth was also tested with a bay width 60 percent of that of the 1-bay wide labyrinth. Tests were conducted in a 3.5-m wide outdoor flume at Colorado State University (CSU) where low DO water is seasonally available from a nearby reservoir. All test weirs stood 2 m above the channel floor. Tests included three drop heights, five flows, and two plunge depths, as outlined in Table 1.

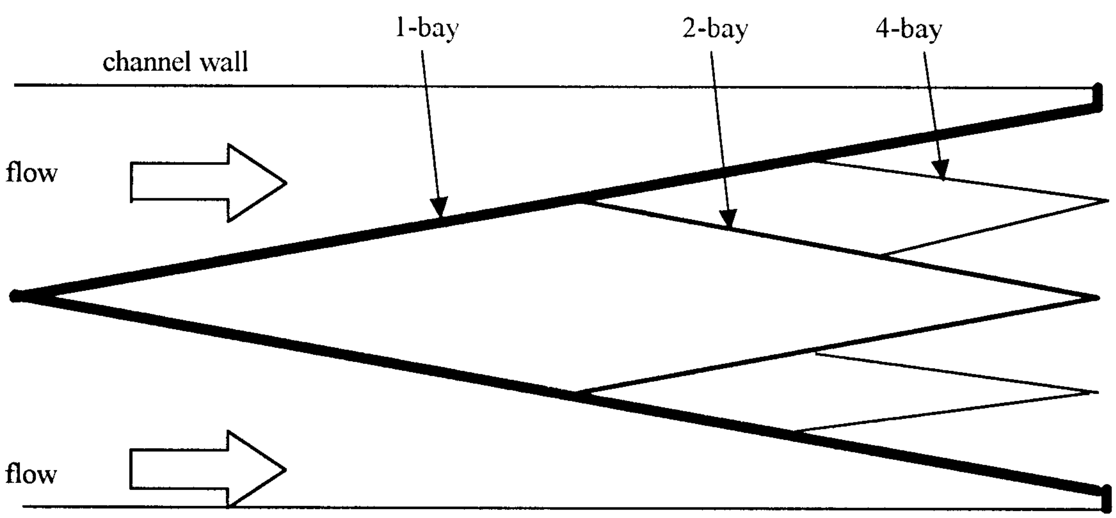


Figure 2. Labyrinths in Quantitative Lab Testing

Results from all 1994 quantitative tests are summarized in Figure 3 as aeration efficiency normalized to 15°C, E_{15}, versus drop height (water level difference across weir). Aeration efficiency is defined as the fraction of the upstream oxygen deficit that is removed by the weir. An aeration efficiency of zero indicates no oxygen transfer takes place, while an aeration efficiency of 1.0 indicates complete oxygen transfer to saturation. The legend in Figure 3 describes each data point, and the (S) or (D) designation shows whether the test involved shallow or deep plunge depths, respectively.

Table 1. Test Conditions for Quantitative Aeration Tests (1994)

drop heights:	0.9	1.5	2			(m)
flow rates:						
non-labyrinths	0.09	0.19	0.45	0.9	1.4	(m^3/s)
labyrinths	0.51	1.1	1.7	2.5	3.7	(m^3/s)
plunge depths:	shallow			deep		
non-labyrinths	0.73 - 2.2			1.6 - 3		(m)
labyrinths	0.55 - 1.4					

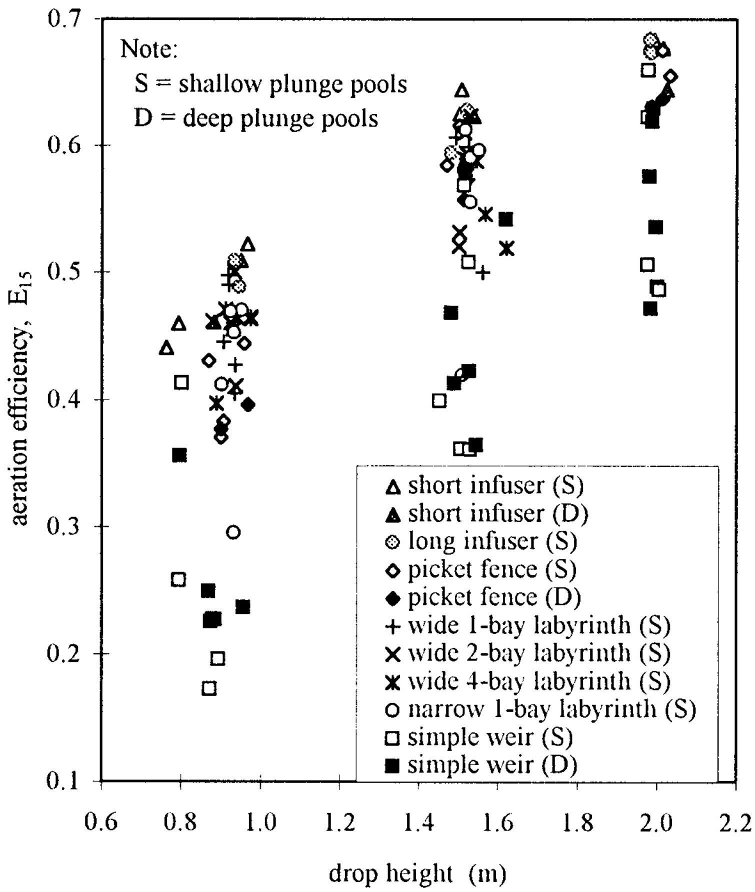


Figure 3. Laboratory Weir Aeration Results

Data from these tests are still being analyzed, but some interesting observations have been made thus far. Figure 3 clearly shows the importance of drop height on aeration efficiency. In rough terms, about 30 percent of the oxygen deficit can be recovered for each meter of drop height. The residual scatter around this tendency is large, however, emphasizing the importance of flow and plunge depth in addition to drop height. Of all lab tests combined, the weir that performed best was the short infuser flap (0.76-m wide) with shallow plunge pool, followed closely by the long infuser flap (1.2-m wide) with shallow plunge pool. The labyrinths and the picket fence were next highest in aeration efficiency. This is especially significant in the labyrinth case because the test flows used for labyrinths were about three times that used for non-labyrinths -- thus, more water was being treated by the labyrinths. The lowest aeration efficiency by far was produced by the simple weir with shallow or deep plunge depths, confirming that there is opportunity for improvement over such weirs. In addition, aeration efficiency with a simple weir is noticeably more sensitive to flow and plunge depth, due to the lack of dissipation of nappe energy and momentum prior to reaching the plunge pool, and due to the uniformity of the nappe as it impinges on the plunge pool. All weirs except the simple weir either broke up or thinned the nappe in some fashion, thereby increasing the air/water contact area. The lab tests also provided strong evidence of the importance of apron conditions below the weirs. A small ledge existed at the base of the weirs in the non-labyrinth tests. When selected tests were repeated without the ledge, considerably higher aeration efficiencies were measured.

Of the three labyrinth configurations tested with the wide downstream opening, the 2-bay labyrinth aerated slightly better than the 1-bay labyrinth, and the 4-bay labyrinth aerated significantly worse than the 1-bay or 2-bay labyrinths. The 1-bay wide labyrinth aerated better than the 1-bay narrow. This suggests there is an optimum arrangement and spacing of the labyrinth bays after overall crest length has been established.

Prototype Field Testing

In 1993 and 1994, field tests were conducted at three prototype aeration weirs: the TVA South Holston labyrinth, the TVA Chatuge infuser, and the GBRA Canyon labyrinth. Physical and operational characteristics of these weirs are summarized in Table 2. DO, temperature, stages, and flows were measured at these weirs with various turbine operations at the upstream dam. Aeration results are summarized as E_{15} versus drop height in Figure 4.

TVA South Holston labyrinth

The South Holston labyrinth includes ten labyrinth bays, each with 64 m of overflow crest length. Weir walls constructed with tongue-and-groove timbers are supported as independent wall sections in a stoplog arrangement using slotted concrete piers at 6-m intervals with concrete midspan supports for the deeper timber members. The South Holston labyrinth weir has been meeting or exceeding aeration targets with minimal operation and maintenance. Aeration tests at this weir showed aeration efficiency (E_{15}) of 65 percent during normal turbine discharge, varying between 55 percent and 70 percent over the range of turbine discharges experienced (14 m^3/s to 68 m^3/s).

Table 2. Physical Features of Prototype Weirs

	TVA S. Holston labyrinth	TVA Chatuge infuser	GBRA Canyon labyrinth
distance downstream of powerhouse (km)	1.9	1.2	0
channel width at weir site (m)	104	35	30
height (m)	2.3	2.9	1
weir crest length (m)	640	30.8	117
drop height (m) headwater to tailwater	1.5	2.3	0.74
turbine capacity (m^3/s)	68	37	17
specific discharge (m^2/s)	0.11	1.2	0.14
head on crest at turbine capacity (m)	0.15	0.76	0.18
plunge pool depth at turbine flow (m)	1.1	1.8	1.9

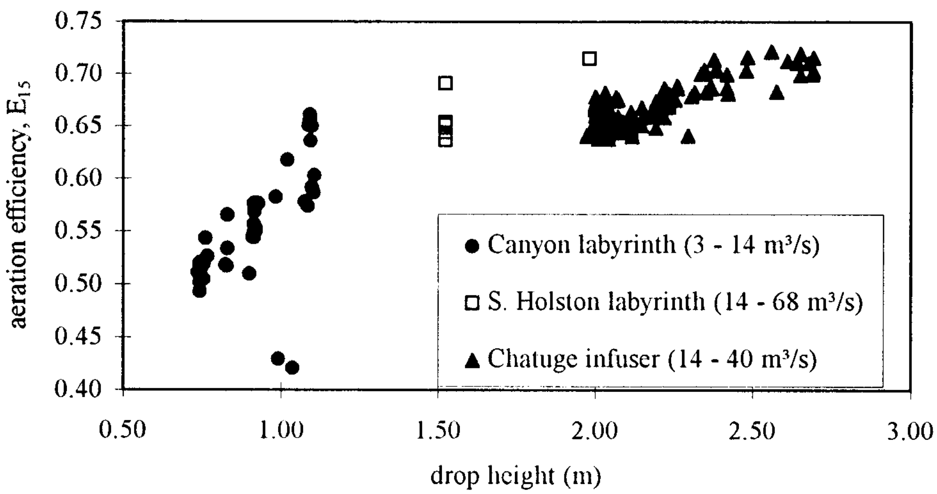


Figure 4. Prototype Weir Aeration Results

TVA Chatuge infuser

The Chatuge infuser is a hollow, broadcrest weir with transverse openings in its crest that allow a series of water curtains to fall through to a plunge pool beneath the crest. Infuser deck openings are the spaces between timbers that support the foot grating on the deck. Deck openings increase in the downstream direction to maintain uniform flow in each slot. The infuser water curtains are turbulent compared to free overfall nappes, increasing the nappe perimeter to flow ratio and increasing aeration efficiency at impingement on the plunge pool. The chamber beneath the infuser deck is ventilated using three open vents in the deck and two abutment vents that allow air to flow easily with minimal losses down under the deck and between the water curtains. The slotted infuser deck is attached to the downstream face of a timber crib filled with loose rock and lined with tongue-and-groove timbers along its upstream face to make it impermeable.

The infuser is better suited for high flow applications than the labyrinth because the public can be easily excluded from the nappe impingement area due to the compactness of the structure. The infuser has disadvantages relative to the labyrinth in regard to higher backwater on the upstream turbine and debris accumulation. Aeration tests of this weir have shown that 63-73 percent of the oxygen deficit is recovered (E_{15}) at turbine discharge flows.

GBRA Canyon labyrinth

The Canyon labyrinth is a concrete weir that includes two labyrinth bays, each with 59 m of overflow crest length. Aeration tests at this weir showed aeration efficiency (E_{15}) varying between 50 percent and 65 percent over the range of turbine discharges experienced (14 m^3/s to 40 m^3/s). In mapping the DO spatially at this weir, it was found that aeration efficiency between the two bays was about 15 percent higher than along the outside of the two bays.

Summary and Conclusions

All weir modifications tested in the laboratory aerated better than the simple linear weir, suggesting practical opportunity exists for improving on the simple weir. Laboratory testing indicated that a labyrinth weir fitted with a crest modification, such as an infuser flap, can safely and effectively operate at 0.28 m^2/s specific discharge. This is about twice the safety limit proposed for overfall weirs by Hauser (1991). Thus, safe and effective future weir designs are possible with half the weir length of labyrinths constructed to date. There also appears to be an optimal bay separation for labyrinth weirs based on shape effects observed in laboratory tests (2-bay aerated better than 1-bay or 4-bay) and at the Canyon labyrinth data (higher efficiency between its two bays). Apron conditions were found to play an important role in aeration.

Each prototype weir tested was able to remove over half of the oxygen deficit in the hydropower releases, and each was being operated within recognized safety thresholds. With labyrinth weirs, aeration in the overfall occurs at levels consistent with predictions from conventional weir literature. However, additional aeration occurs through the labyrinth bay, causing the total aeration to exceed that of conventional weirs by 20 to 30 percent. This additional aeration is likely due to re-entrainment of bubbles as they are transported to the downstream end of each labyrinth tailwater bay.

Infusers and labyrinths with infuser flaps appear to aerate better than other weir types in shallow tailwaters, likely due to the reduced momentum and higher air entrainment associated with the more broken nappe. Infusers aerate as well as labyrinths yet fit into a much more compact area, easing construction logistics. Labyrinths have the most efficient overflow hydraulics, creating less backwater on upstream turbines and less property inundation during flood flows compared to conventional or infuser weirs. According to cost data from the TVA weirs, an infuser is the more favorable economic choice for river-specific discharge greater than about 2 m^2/s, while the labyrinth is the more favorable choice for discharges less than about 1 m^2/s. In the midrange of 1 m^2/s to 2 m^2/s, the choice will depend on site-specific constraints. A conventional linear weir is probably the most favorable choice for very low discharge applications less than 0.14 m^2/s.

This paper has summarized progress and findings to date. The final design manual will include reliable procedures for predicting aeration performance using the literature, previous field experience, and analyses of the supplemental laboratory and field experiments. The manual will include case studies of the prototype weirs and a discussion of other weir issues such as hydraulics, construction, operation, and cost so that tradeoffs between weirs and other DO improvement technologies can be evaluated.

References

1. Adams, J. S., and W. G. Brock (1993), "A Process for Selecting Options to Improve Water Quality Below TVA Hydro Projects," Proceedings of International Conference on Hydropower, WaterPower 1993.
2. Avery, S., and P. Novak (1978), "Oxygen Transfer at Hydraulic Structures," ASCE, Journal of Hydraulics Division, November.
3. Electric Power Research Institute (1990), "Assessment and Guide for Meeting Dissolved Oxygen Water Quality Standards for Hydroelectric Plant Discharges," GS-7001, Research Project 2694-8, November.
4. Hauser, G. (1995), "Interim Guide for Design of Aerating Weirs," Eletric Power Research Institute Technical Report No. TR-103947.
5. Hauser, G. (1991), "Full-Scale Physical Modeling of Plunge Pool Hydraulics Downstream of a Vertical Weir," TVA Engineering Laboratory, Report No. WR28-1-590-153, Norris, TN, May.
6. Hopping, P. (1994), "Qualitative Screening of Weir Alternatives," TVA Engineering Laboratory, Report WR28-1-590-162, Norris, TN, October.
7. Markofsky, M., and H. Kobus (1978), "Unified Presentation of Weir-Aeration Data," ASCE, Journal of Hydraulics Division, April.
8. Nakasone, H. (1987), "Study of Aeration at Weirs and Cascades," ASCE, Journal of. Environmental Engineering, February.

9. Wilhelms, S., J. Gulliver, and K. Parkhill, (1992), "Reaeration at Low-Head Hydraulic Structures," Technical Report HL-91, US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.