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Reaeration at Low-Head Hydraulic Structures

*by Steven C. Wilhelms
Hydraulics Laboratory*

*John S. Gulliver, Kenneth Parkhill
University of Minnesota*

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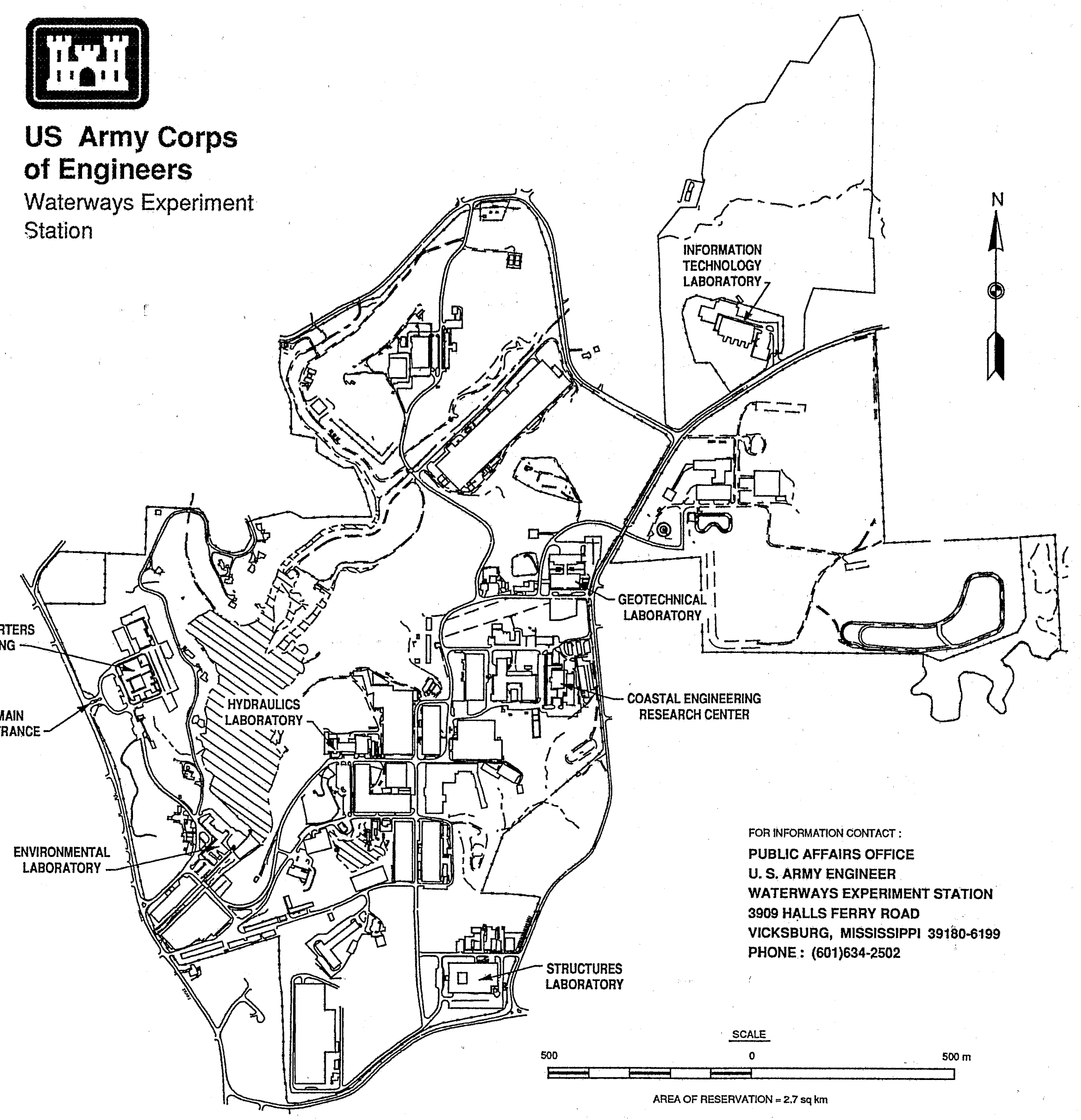

FOR INFORMATION CONTACT:
PUBLIC AFFAIRS OFFICE
U. S. ARMY ENGINEER
WATERWAYS EXPERIMENT STATION
3909 HALLS FERRY ROAD
VICKSBURG, MISSISSIPPI 39180-6199
PHONE: (601)634-2502

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REAERATION AT LOW-HEAD HYDRAULIC STRUCTURES

PART I: INTRODUCTION

Background

1. Presently, one of the most cited water quality parameters in the freshwater hydrosphere (rivers, lakes, and reservoirs) is dissolved oxygen (DO). The oxygen concentration in surface waters is a prime indicator of the quality of that water for human use as well as use by the aquatic biota. Many naturally occurring biological and chemical processes use oxygen, thereby diminishing the DO concentration in the water. The physical process of oxygen transfer or oxygen absorption from the atmosphere or air bubbles acts to replenish the used oxygen. This process is termed reaeration.

2. Low-head hydraulic structures within the US Army Corps of Engineers are generally associated with navigation projects. These structures are usually "run-of-the-river" and are used to maintain a constant upstream pool elevation. The oxygen transfer in these deeper, slower pools is lower than that of the open river. Biological and chemical oxygen demands may accumulate and concentrate in the impoundment and thereby degrade the DO concentration in the stored water because of the excess demand compared to reaeration potential. Without sufficient reaeration, release of this water may pose an environmental and water quality concern.

3. Some hydraulic structures exhibit remarkable reaeration, while others do very little to increase DO. If the DO in releases is lower than desired or required, operational or structural modifications or artificial aeration can be employed to improve the release DO concentration. The design engineer will be faced with the need to evaluate the oxygen transfer characteristics of existing conditions at a hydraulic structure for comparison with the characteristics of a proposed modification. As in any engineering application, it is imperative to possess a clear definition of the processes that affect water quality and the expected change as a result of implementing the particular improvement technique. Hence, the potential impacts of alternative techniques on the reaeration processes must be thoroughly understood and quantified.

4. In the past, the focus of interest in gas exchange at hydraulic

structures has been the transfer of atmospheric gases: absorption of oxygen to replace DO used by aquatic processes and the absorption of nitrogen, potentially resulting in nitrogen supersaturation. More recently, however, the desorption of volatile organics or toxics that may be dissolved in the water has become important. The air-water transfer of any chemical is called gas transfer because the chemical is a gas in one of the two phases. In general, the physical processes that influence oxygen absorption also affect the transfer of any dissolved volatile compound. Thus, it becomes even more important for the design engineer to possess a thorough understanding of (a) the physics of gas transfer, (b) the quantification of gas transfer, (c) the important physical processes, and (d) the hydraulic conditions that can enhance or degrade gas transfer.

Objective and Scope

5. The objective of this report is to familiarize field engineers with the oxygen transfer process and the oxygen transfer characteristics of various low-head hydraulic structures. The physics of gas transfer are conceptually explained and the mathematical description of the gas transfer process is developed. The important physical processes and their impact on the variables in the gas transfer equation are identified. The hydraulic conditions that contribute to these physical processes are described and applied to oxygen transfer, or reaeration.

6. It is hoped that field engineers, when familiar with the conceptual descriptions provided in this report, can qualitatively evaluate the oxygen transfer characteristics at a structure based solely on observed hydraulic conditions, e.g., they will be able to estimate whether the structure, upon testing, would exhibit a large or small degree of gas transfer. With the mathematical description of oxygen transfer at a "generic" type of structure and an understanding of how hydraulic conditions contribute to oxygen transfer, field engineers should be able to "bracket" or roughly estimate the transfer that is occurring at a specific structure.

7. The hydraulic structures at most low-head projects usually consist of a gated sill, gated low-head spillway, and a fixed- or adjustable-crest weir. The gas transfer analyses reported herein emphasize these "generic" types of structures. More complete descriptions of the geometry and flow

conditions at these structures are given in Part IV, "Hydraulics at Various Structures."

PART VI: SUMMARY AND CONCLUSIONS

56. Gas transfer or reaeration is considered a first-order reaction process and can be conveniently described by

$$E = \frac{(C_f - C_i)}{(C_s - C_i)} = 1 - \frac{D_f}{D_i} = 1 - \exp\left(-k_L \frac{A}{V} t\right) \qquad \text{(8 bis)}$$

The important physical processes that impact gas transfer are included in this formulation in the following manner: The effect of turbulent mixing is reflected by the liquid film coefficient k_L . The impact of surface area available for gas transfer, which must include the surface area of entrained air bubbles, is represented by the specific area term A/V . Enhanced gas absorption due to the effects of hydrostatic pressure on plunging aerated flow is included as a pressure modification of the saturation concentration C_s . The time of contact over which gas transfer can occur is t .

57. The unknowns in this equation often dictate that reaeration measurements be conducted to determine the gas transfer efficiency. The transfer efficiency can then be related to the physical processes through empirical relationships and regression analyses. Several alternatives are available for measurement of gas transfer. Direct in situ measurement of dissolved oxygen with polarographic probes is usually the most convenient. However, based on uncertainty analysis, a DO deficit of at least 2.5 mg/ℓ (when saturation is 8.0 mg/ℓ) is required for accurate analysis. Often, the DO is not sufficiently low to permit an accurate analysis. When this is the situation, alternative gas transfer tracers must be used in measurements for gas transfer. In situ methane gas shows the highest potential for general application in reaeration field studies.

58. Generally, low-head structures can be categorized into four groups: (a) free-surface flows, such as flow in a channel or on a spillway or ogee crest without a tailwater plunge pool; (b) submerged flows, such as discharge under a submerged gate; (c) free jets, such as flow over a sharp-crested weir; and (d) transitional flows, where free-surface flows or jets interact with a pool of water resulting in plunging flow or a hydraulic jump. The hydraulics of each group differ dramatically and, consequently, the gas transfer characteristics are significantly different. However, an understanding of the hydraulics and the resulting gas transfer characteristics of each type of structure can permit limited extrapolation to other hydraulic structures. The observations reported herein show that gated and ungated ogee crests demonstrate gas transfer efficiencies up to nearly 100 percent. Submerged flows without air entrainment can result in efficiencies up to 40 percent. Sharp-crested overflow weirs or jets demonstrate efficiencies up to 70 percent. Transitional flow conditions, which include several or all of the other types of flow conditions, have shown reaeration efficiencies of up to nearly 100 percent.

59. Several sources of observed data were assembled and, after screening through an uncertainty analysis, are included in the appendices of this report. Predictions from eleven equations that describe gas transfer efficiency at various types of structures were compared to this comprehensive database. Although there are inadequacies in the models currently used for prediction of gas transfer, the equations listed in Table 3 were the most successful for given types of structures.

Table 3

Suggested Predictive Equations

Structure Type	Predictive Equation	Standard Error	Source
Ogee Crests	$E_{20} = 1 - \exp\left(\frac{-0.2625h}{1 + 0.2153q} - 0.2034H\right)$	0.16	Rindels and Gulliver (1991)
Gated Sills	$E_{20} = 1 - \frac{1}{\left(1 + 666N_f^{-3.33}\right)}$	0.14	Pruel and Holler (1969)
Sharp-crested Weirs	$E_{20} = 1 - \left(\frac{1}{1 + 0.64 \times 10^{-4} F_j^{1.787} R^{0.533}}\right)^{1.1149}$	0.17	Avery and Novak (1978)
Gated Conduit Outlets	$E_{20} = 1 - \exp(-0.1476h)$	0.31	Wilhelms and Smith (1981)

60. Standard error estimations for the equations of Preul and Holler (1969) and Rindels and Gulliver (1991) may be too low. Much of the sill and ogee spillway database included in this report was used in the regression of the two equations, and the paucity of accurate alternative data sources closely tailors these equations to this evaluation. While the compilation of accurate data is not simple, further field investigations are needed to define the performance of predictive equations.

61. In their efforts to predict the impact of hydraulic structures on levels of dissolved gases in river systems, many researchers sought to create equations that provide accurate estimates of transfer efficiency. Unfortunately, the development of each equation was limited by the size of the database that a researcher had available and the difficulty encountered in deriving a theory from first principles. As a result, many equations are useful only for specific types of structures under particular conditions, i.e., the domain of accuracy for the parameters used in the equation is relatively small. The relatively large deviations between the measured transfer efficiencies and the values computed from the predictive equations are understandable because of the size and diversity of the observed data. Consequently, a large uncertainty is associated with the prediction of an oxygen transfer efficiency from these equations. Field measurements are still the most consistent means of determining oxygen transfer characteristics.