US Army Corps
of Engineers

Water Quality Technical Note MS-01
May 1995

Improvement of Reservoir Releases by Aeration

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Purpose

This technical note presents the background and calculational procedures for evaluating several reservoir aeration techniques that are part of the spreadsheet AERATE. Selection of options from the main menu of AERATE guides the user through the program's activities and, when necessary, to submenus for inputting variables needed for calculations. Each of the program's menu options is described, along with the computational formulas and input variables.

Background

The thermal stratification that occurs at most reservoir projects can create problems with release water quality. If the hypolimnion becomes sufficiently isolated from the surface, oxygen-demanding processes in the hypolimnion can cause anaerobic conditions to develop. Many times this results in the reduction and dissolution of iron and manganese and the production of hydrogen sulfide. The withdrawal and release of this hypolimnetic water will result in low or zero dissolved oxygen (DO) concentrations in the tailwater. Additionally, the soluble iron, manganese, and hydrogen sulfide may create water quality problems downstream.

Several methods of treatment can eliminate or mitigate the release water quality problem by improving the water quality in the reservoir, modifying the withdrawal outlet location and thereby changing which water is withdrawn and released from the reservoir, treating the release water to eliminate the poor quality as the flow passes through the outlet structure, or treating the release water in the tailwater area.

These methods can be generally categorized into three areas: in-reservoir, in-structure, and downstream techniques. Examples of in-reservoir techniques include the deployment of a diffused aeration or oxygenation system to oxygenate the hypolimnion, installation of a localized mixing system to dilute hypolimnetic releases with epilimnetic water, and the installation of an alternate withdrawal device that would skim higher quality epilimnetic water rather than withdraw hypolimnetic water. If the releases are made through hydroturbines, the installation of a turbine venting capability is an example of an in-structure alternative. Once released, the water may be treated downstream with a diffused aeration or oxygenation system or by spillage over an aeration weir.

Computational Formulas

AERATE includes procedures to calculate the requirements for an in-reservoir aeration system using air or molecular oxygen. Also included are calculations that account for the oxygen uptake due to a turbine venting system. The diffused air/oxygen calculations can also be applied for a tailwater aeration system. Lastly, the oxygen uptake created by an overflow weir in the downstream area is included. The alternatives can also be used in combinations. Each of these formulas is described below.

For sizing an in-reservoir or tailwater aeration system, the hypolimnetic DO, target DO, and water flow are required. The rate of oxygen injection required to meet the target DO (accounting for absorption efficiency) is calculated with the following mass balance:

$$O_2(required) = \alpha_1 \frac{\left(DO_{target} - DO_{hypolimnion}\right)Q}{E} \tag{1}$$

where

$O_2\,(required)$ = required oxygen, lb/hr

α_1 = conversion to pounds/hour

DO_{target} = target release DO, mg/L

$DO_{hypolimnion}$ = oxygen concentration in the lake hypolimnion, mg/L

Q = flow rate of water through hypolimnion for release, cfs

E = oxygen absorption efficiency

The oxygen absorption efficiency E is the proportion of available oxygen that is absorbed as the bubble plume rises through the water column. Equation 2 (Price and Tillman 1991) is included in the spreadsheet computation and provides a means of estimating absorption efficiency.

$$E = 0.61D_d \tag{2}$$

where D_d is the depth of the diffuser system in feet.

The flow rate of air required to supply the oxygen calculated with Equation 1 is computed with Equation 3, as follows.

$$Q_{air} = \alpha_2 \frac{O_2(required)}{\beta \gamma_{air}} \tag{3}$$

where β is 0.21 (fraction of oxygen in air), γ_{air} is the specific weight of air (in lb/ft^3), and α_2 converts the units to cubic feet/minute.

The spreadsheet will calculate the release DO from hydroturbines with a venting system. The calculations are based on the assumption that the venting system uses hub deflectors as a means of aspirating air into the discharge and that the air flow has been optimized for maximum DO uptake. For these conditions, the oxygen uptake is calculated based on a reaeration efficiency E_T of 30 percent (Wilhelms, Schneider, and Howington 1987):

$$DO_{release} = DO_{penstock} + E_T\left(DO_{sat} - DO_{penstock}\right) \tag{4}$$

where

$DO_{release}$ = release DO, mg/L

$DO_{penstock}$ = DO concentration of withdrawal water in penstock, mg/L

E_T = 0.30

DO_{sat} = oxygen saturation concentration as function of water temperature, mg/L

Note: Penstock DO and release temperature can be estimated with SELECT, the numerical model of selective withdrawal (Davis and others 1987).

An in-reservoir aeration system can be combined with a turbine venting system. For this combination, the oxygen uptake with the turbine venting system is maximized, thereby minimizing the oxygen requirements of the in-reservoir aeration system. Given the oxygen release target as $DO_{release}$ in Equation 4, AERATE uses Equation 4 to compute the minimum penstock DO that will allow achievement of the release target. The required oxygen and air are computed with Equation 1, based on increasing the hypolimnetic DO to the minimum penstock DO just calculated.

Release DO may also be improved by installing a low-head aeration weir downstream of the discharge area. The oxygen uptake for flow over the weir is computed with Equation 4 where E_T is computed with (Avery and Novak 1978).

$$E_T = 1 - \left(\frac{1}{1 + 0.64 \times 10^{-4} F_j^{1.787} R^{0.533}} \right)^{1.1149} \tag{5}$$

where F_j is the Froude number of the jet, given by

$$F_j = \frac{(2g)^{0.25} H^{0.75}}{q^{0.5}}$$

and g is the acceleration of gravity (32.2 ft-sec^{-2}) and R is the Reynolds number of the jet defined by

$$R = \frac{q}{2\nu}$$

where ν is the kinematic viscosity.

Installation of an aeration weir can also be combined with turbine venting and an in-reservoir aeration system. The spreadsheet maximizes the oxygen uptake for the weir and turbine venting system before computing the oxygen required of the in-reservoir aeration system.

Spreadsheet Operation

To execute the spreadsheet in QuattroPro, the file AERATE.WQ1 must be opened. AERATE guides the user through the spreadsheet activities with options on the main menu (Figure 1) for AERATE, VENT, WEIR, COMBINE, QUIT THIS MENU, SAVE THIS WORKSHEET, and EXIT QPRO. To choose an option on the main menu, press the first letter, highlight the option name with directional keys and press ENTER, or click the option name with a mouse. If AERATE, VENT, WEIR, or COMBINE is chosen, the program goes to a submenu and allows the user to input variables to make calculations.

AERATE
VENT
WEIR
COMBINE
QUIT THIS MENU
SAVE THIS WORKSHEET
EXIT QPRO

Figure 1. Main menu

The submenus (Figure 2) for AERATE, VENT, AND WEIR are identical, with options for INPUT VALUES, PRINT RESULTS, RETURN TO MAIN MENU, QUIT THIS MENU, and SAVE THIS WORKSHEET. These screens are designed to input variables and obtain results for air or oxygen flow rates for a diffused aeration system, release DO due to turbine venting, and release DO with turbine venting and an overflow weir.

INPUT VALUES
PRINT RESULTS
RETURN TO MAIN MENU
QUIT THIS MENU
SAVE THIS WORKSHEET

Figure 2. Sub menu for AERATE, VENT, and WEIR

If COMBINE is chosen from the main menu, a submenu appears that has four combinations using a diffused aeration system, turbine venting, and an overflow weir. These are AERATE + VENT, AERATE + WEIR, VENT + WEIR, and AERATE + VENT + WEIR. To choose an option on this menu, press the number, highlight the option name with directional keys and press ENTER, or click the option name with a mouse. This menu also has options for RETURN TO MAIN MENU, QUIT THIS MENU, and SAVE THIS WORKSHEET (Figure 3).

1. AERATE + VENT
2. AERATE + WEIR
3. VENT + WEIR
4. AERATE + VENT + WEIR
5. RETURN TO MAIN MENU
6. QUIT THIS MENU
7. SAVE THIS WORKSHEET

Figure 3. Sub menu for COMBINE

INPUT VALUES
PRINT RESULTS
COMBINE MENU
RETURN TO MAIN MENU
QUIT THIS MENU
SAVE THIS WORKSHEET

Figure 4. Sub menu for combinations of AERATE, VENT, and WEIR

If one of the "combinations" is chosen, another menu appears that is similar to the submenus for AERATE, VENT, and WEIR, with the added option of returning to COMBINE MENU (Figure 4).

The following shows what information is necessary to run the spreadsheet program and how to use each of the menu options.

Input Values

To input variables for calculation, choose INPUT VALUES by pressing the letter I, highlighting INPUT VALUES and pressing ENTER, or clicking INPUT VALUES with a mouse.

If calculating for AERATE, the following data (Figure 5) are necessary for input:

WORKSHEET TO CALCULATE RELEASE DO FOR A DIFFUSED AERATION SYSTEM ****TO RETURN TO MENU AFTER DATA INPUT, PRESS ESC**** ****IF QUIT MENU IS CHOSEN, PRESS ALT-M TO RETURN TO MENU**** INPUT VARIABLES	
DEPTH, ft	40
FLOW RATE, cfs	1,200
HYPO DO CONCENTRATION, mg/l	0
RELEASE DO, mg/l	1.77
RESULTS	
REQUIRED AIR, cfm	2,075.2
REQUIRED O2, lbs/hr	1,964.1

Figure 5. Diffused aeration system

DEPTH	Depth of diffuser, ft
FLOW RATE	Release discharge flow rate, cfs
HYPO DO CONCENTRATION	Dissolved oxygen concentration in hypolimnion or in release water without aeration, mg/L*
RELEASE DO	Target release dissolved oxygen, mg/L
*Withdrawal water quality can be estimated with SELECT (Davis and others 1987).	

The program then calculates the results for

REQUIRED AIR	Required air flow rate, cfm
REQUIRED O_2	Required oxygen flow rate, lb/hr

The information needed to calculate for VENT (Figure 6) is:

WORKSHEET TO CALCULATE RELEASE DO DUE TO TURBINE VENTING	
INPUT VARIABLES	
PENSTOCK DO, mg/l	RELEASE TEMP, °C
3.0	50.0
RESULTS	
	WITH VENTING
RELEASE DO, mg/l	3.8

Figure 6. Turbine venting

PENSTOCK DO	Penstock dissolved oxygen concentration, mg/L*
RELEASE TEMP	Release temperature, °C*
*Withdrawal water quality can be estimated with SELECT (Davis and others 1987).	

with results of

RELEASE DO	Release dissolved oxygen, mg/L

To calculate for WEIR (Figure 7):

WORKSHEET TO CALCULATE RELEASE DO WITH AN OVERFLOW WEIR				
INPUT VARIABLES				
WEIR LENGTH	HEAD DIFF	FLOW RATE	PENSTOCK DO	REL TEMP
ft	ft	cfs	mg/l	°C
900.0	4.0	1,200.0	4.0	16.0
RESULTS				
	WITH WEIR			
RELEASE DO, mg/l	6.7			

Figure 7. Overflow weir

WEIR LENGTH	Weir length, ft
HEAD DIFF	Head differential, ft
FLOW RATE	Release discharge flow rate, cfs
PENSTOCK DO	Penstock or release dissolved oxygen concentration, mg/L*
REL TEMP	Release temperature, °C

with results of

WITH WEIR	Dissolved oxygen concentration of releases after flow over the aeration weir, mg/L

As stated above, if COMBINE is chosen from the main menu, the user has four combinations from which to input data and obtain results for a diffused aeration system, turbine venting, and an overflow weir. The information needed to calculate for a diffused aeration system and turbine venting, AERATE + VENT, is as follows (Figure 8):

WORKSHEET TO CALCULATE COMBINED DIFFUSED AERATION & TURBINE VENTING		
INPUT VARIABLES		
PENSTOCK DO, mg/l	RELEASE T, °C	DEPTH, ft
1.0	20.0	50.0
FLOW RATE, cfs	TARGET DO, mg/l	
5,000	5.0	
RESULTS		
RELEASE DO, mg/l	5.0	
REQ AIR, cfm	8,639.5	
REQ O2, lbs/hr	8,176.7	

Figure 8. Combined diffused aeration system and turbine venting

PENSTOCK DO	Penstock or release dissolved oxygen concentration, mg/L*
RELEASE TEMP	Release temperature, °C
DEPTH	Depth of diffuser, ft
FLOW RATE	Release discharge flow rate, cfs
TARGET DO	Target release dissolved oxygen, mg/L

* Withdrawal water quality can be estimated with SELECT (Davis and others 1987).

The calculated results are

RELEASE DO	Release dissolved oxygen concentration, mg/L
REQ AIR	Required air flow rate, cfm
REQ O_2	Required oxygen flow rate, lb/hr

For a combination of a diffused aeration system and overflow weir, AERATE + WEIR (Figure 9):

WORKSHEET TO CALCULATE RELEASE DO WITH AERATION SYSTEM & OVERFLOW WEIR			
INPUT VARIABLES			
WEIR LENGTH, ft	HEAD DIFF, ft	FLOW RATE, cfs	DEPTH, ft
100	4.0	1,200	40
TARGET DO, mg/l	PENSTOCK DO, mg/l	REL TEMP, °C	
5.0	3.0	25.0	
RESULTS			
REL DO, mg/l	5.0		
REQ AIR, cfm	878		
REQ O2, lbs/hr	831		

Figure 9. Combined diffused aeration system and overflow weir

WEIR LENGTH	Weir length, ft
HEAD DIFF	Head differential, ft
FLOW RATE	Release discharge flow rate, cfs
DEPTH	Depth of diffuser, ft
TARGET DO	Target release dissolved oxygen, mg/L
PENSTOCK DO	Penstock or release dissolved oxygen concentration, mg/L*
REL TEMP	Release temperature, °C*
*Withdrawal water quality can be estimated with SELECT (Davis and others 1987).	

with results of

REL DO	Release dissolved oxygen concentration, mg/L
REQ AIR	Required air flow rate, cfm
REQ O_2	Required oxygen flow rate, lb/hr

For a combination of turbine venting and overflow weir, VENT + WEIR, the information needed is (Figure 10):

WORKSHEET TO CALCULATE RELEASE DO WITH TURBINE VENTING AND OVERFLOW WEIR				
INPUT VARIABLES				
WEIR LENGTH	HEAD DIFF	FLOW RATE	PENSTOCK DO	REL TEMP
ft	ft	cfs	mg/l	°C
900.0	4.0	1,200	4.0	16.0
RESULTS				
	W/VENT & WEIR			
REL DO, mg/l	7.7			

Figure 10. Combined turbine venting and overflow weir

WEIR LENGTH	Weir length, ft
HEAD DIFF	Head differential, ft
FLOW RATE	Release discharge flow rate, cfs
PENSTOCK DO	Penstock or release dissolved oxygen concentration, mg/L*
REL TEMP	Release temperature, °C*
* Withdrawal water quality can be estimated with SELECT (Davis and others 1987).	

with results of

W/VENT & WEIR	Release dissolved oxygen concentration, mg/L

Input variables required for a combination of a diffused aeration system, turbine venting, and overflow weir, AERATE + VENT + WEIR, are (Figure 11):

WORKSHEET TO CALCULATE RELEASE DO WITH AERATION SYSTEM, TURBINE VENTING AND OVERFLOW WEIR			
WEIR LENGTH, ft	HEAD DIFF, ft	FLOW RATE, cfs	DEPTH, ft
100	4.0	1,200	40
TARGET DO, mg/l	PENSTOCK DO, mg/l	REL TEMP, °C	
5.2	2.0	25.0	
RESULTS			
REL DO, mg/l	5.2		
REQ AIR, cfm	187		
REQ O2, lbs/hr	177		

Figure 11. Combined diffused aeration system, turbine venting, and overflow weir

WEIR LENGTH	Weir length, ft
HEAD DIFF	Head differential, ft
FLOW RATE	Release discharge flow rate, cfs
DEPTH	Depth of diffuser, ft
TARGET DO	Target release dissolved oxygen, mg/L
PENSTOCK DO	Penstock or release dissolved oxygen concentration, mg/L*
REL TEMP	Release temperature, °C*

with results of

RELEASE DO	Release dissolved oxygen concentration, mg/L
REQ AIR	Required air flow rate, cfm
REQ O_2	Required oxygen flow rate, lb/hr

For some situations with combinations, the release target may be achieved without aeration. In such cases, the release DO is calculated without aeration, asterisks are placed in the results for Required Air and Required O_2, and a message appears that states "TARGET ACHIEVED W/O AERATION SYSTEM."

The required input data for AERATE, VENT, WEIR, and COMBINE are entered to the spreadsheet in the shaded areas shown in Figures 5-11. It should be noted that the user cannot work anywhere else in the spreadsheet except in the locations for INPUT VARIABLES when the INPUT VALUES menu option has been chosen. Pressing ESC returns the user to the spreadsheet menu.

Print Results

To print the tables showing the input variables and the results, press the letter P, highlight the letter P and press ENTER, or click PRINT RESULTS with a mouse. This will print the table with the input variables and the results.

Quit This Menu

The QUIT THIS MENU option bypasses the menu and goes directly to the spreadsheet. This allows the user to change formulas within the spreadsheet to meet specific requirements, if desired. To return to the menu, press ALT-M (the ALT key pressed simultaneously with the letter **M** key).

Return to Main Menu

When RETURN TO MAIN MENU is chosen, the AERATE spreadsheet goes from one of the submenus back to the main menu.

Combine Menu

This options appears on the submenu when one of the "combinations" is chosen. Instead of going back to the main menu, this options returns the user to the COMBINE submenu.

Save This Worksheet

This option saves any changes or input in the spreadsheet.

Exit QPro

EXIT QPRO saves the spreadsheet and exits the software program.

Obtaining This Program

AERATE was designed to run on a 386, 486, or Pentium IBM-compatible personal computer using QuattroPro Version 4.0. Copies of this spreadsheet can be obtained by sending a preformatted 5-1/4-in. or 3-1/2-in. floppy diskette to the U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-HS-L, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

References

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