

# JOURNAL OF THE HYDRAULICS DIVISION

## ENVIRONMENTAL EFFECTS OF HYDRAULIC STRUCTURES<sup>a</sup>

By the Task Committee on Environmental Effects of Hydraulic Structures  
of the Committee on Hydraulic Structures of the Hydraulics Division

### INTRODUCTION

**Objectives.**—The Hydraulic Structures Committee stated these Task Committee objectives:

1. Define what structure types should be selected for study in view of current research activity and potential effects on the environment.
2. Provide a general survey of how hydraulic structures interrelate with their environment.
3. Make recommendations to the Hydraulic Structures Committee for future task or full committees to examine specific problem areas.

At its initial meeting, the Task Committee considered these objectives and discussed possible approaches to them. While the Task Committee recognized the immediate need for solutions to specific environmental problems confronted by design engineers, they also recognized that the overall perspective or philosophy of the entire project or system of projects must be seriously considered by planning engineers. Even though this overall analysis of the long-range and far-reaching environmental impacts is often beyond the traditional responsibility of the design engineer, the Task Committee recommends that this general overview of environmental effects be kept in mind.

### CATEGORIES OF HYDRAULIC STRUCTURES AND ENVIRONMENTAL EFFECTS

Appendix I is the Task Committee's attempt to list the categories of hydraulic structures. Appendix II categorizes environmental effects as physical, chemical, and biological effects on water, land, and air systems. The table should be

Note.—Discussion open until July 1, 1978. To extend the closing date one month, a written request must be filed with the Editor of Technical Publications, ASCE. This paper is part of the copyrighted Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, Vol. 104, No. HY2, February, 1978. Manuscript was submitted for review for possible publication on November 7, 1977.

<sup>a</sup>Presented at the August 4-7, 1976, ASCE 24th Annual Hydraulics Division Specialty Conference, held at Purdue University, West Lafayette, Ind.

self-explanatory. Other effects possibly should be listed; however, this includes the parameters that realistically may occur as a result of engineering actions.

#### HOW HYDRAULIC STRUCTURES INTERRELATE WITH ENVIRONMENT

Inspection of Appendices 1 and 2 and the subcategories that could be added suggest the very large number of possible combinations between specific hydraulic structures and specific environmental effects. Numerous approaches have been used to "pair-up" an action with an environmental consequence. The references listed in Appendix IV give information on various assessment approaches. All of these methods are dependent on human judgment and are thus subject to the effects of bias. The Battelle Columbus approach (6), for example, relies on the assignment of number values (Environmental Impact Units) to water resource development projects. Numbers were assigned by an interdisciplinary

TABLE 1.—Construction of Example Matrices

Hydraulic structure (1)	Environmental Effects		
	Water (2)	Land (3)	Air (4)
Reservoir	Salinity	Salt	Evaporation
Selective outlet (epilimnion)	Phosphate	Sedimentation	Humidity
Outlet energy dissipator	Nitrogen	Erosion	
Spillway intake channel	Iron	Slides	
Spillway energy dissipator	Manganese	Terrestrial animals	
Power plant tailrace	Dissolved oxygen	Plants	
Bridges	Supersaturation		
	pH		
	Turbidity		
	Temperature		
	Sedimentation		
	Fecal coliform		
	Phytoplankton		
	Zooplankton		
	Fish		
	Benthic organisms		

research team and are assumed to be applicable on a nationwide basis. This inherent inflexibility would seem to invite criticism of the method. However, with the assignment of numbers on a case-by-case basis, the framework of the Battelle Columbus approach could be applicable.

Most assessment methods use matrices in some form, which are also subject to bias. However, the Task Committee felt that the use of matrices would be an acceptable approach, and would have general utility for planners and designers of hydraulic structures. Furthermore, it was recognized that the ultimate objective is identification of significant effects. A discussion among peers would probably serve to identify most of the significant effects; however, it was felt that a more general systematic approach is necessary to insure that the identified

effects are truly significant and that some significant effects have not been overlooked.

**Examples of Matrix Construction.**—Inclusion of all the hydraulic structures and all the environmental effects would result in a matrix with thousands of elements. For construction of example matrices, the Task Committee opted to use lists of seven hydraulic structures common to storage projects and 24

CAUSAL FACTORS	ENVIRONMENTAL CONDITION AFFECTED																										
	WATER												LAND						AIR								
	Downstream:	Salinity	Phosphate	Nitrogen	Iron	Manganese	DO	Supersaturation	pH	Turbidity	Temperature	Sedimentation	Fecal coliform	Phytoplankton	Zooplankton	Fish	Benthic organisms	Salts	Sedimentation	Erosion	Slides	Terrestrial animals	Plants	Evaporation	Humidity		
Reservoir		2	2	2	1	1	3	3	3	2	2	2	2	2	2	3	3	2	4	2	4	4	3	1	3	3	
Selective outlet (epilimnion)		2	2	2	2	1	3	3	3	2	2	2	2	2	2	3	3	2	4	2	4	4	3	1	3	3	
Outlet energy dissipator		4	2	4	2	2	1	3	1	2	4	4	4	4	4	2	2	2	1	4	4	2	2	4	4	3	3
Spillway intake channel		4	4	4	4	3	3	4	4	4	4	4	4	4	4	2	2	2	4	4	4	4	4	4	4	4	4
Spillway energy dissipator		4	4	4	4	4	3	3	4	2	4	1	4	2	2	2	2	1	4	4	2	2	4	4	1	1	1
Powerplant tailrace		4	2	4	2	3	3	1	1	1	2	4	2	2	2	2	2	2	4	4	3	4	4	4	3	3	3
Bridges		4	4	4	4	4	4	4	4	3	4	3	4	4	4	4	4	4	4	4	1	4	4	4	4	4	4

1 - Variable may be increased by causal factor  
 2 - Variable may be decreased by causal factor  
 3 - Variable may be either increased or decreased by causal factor  
 4 - Variable unaffected by causal factor

FIG. 1.—Causal Factors Affecting Environmental Conditions after Ellis (7) (with Number Coding Indicating Nature of Relationship)

CAUSAL FACTORS	ENVIRONMENTAL CONDITION AFFECTED																									
	WATER												LAND						AIR							
	Downstream:	Salinity	Phosphate	Nitrogen	Iron	Manganese	DO	Supersaturation	pH	Turbidity	Temperature	Sedimentation	Fecal coliform	Phytoplankton	Zooplankton	Fish	Benthic organisms	Salts	Sedimentation	Erosion	Slides	Terrestrial animals	Plants	Evaporation	Humidity	
Reservoir		1	1	1	2	2	1	2	1	1	1	1	1	1	1	2	2	1	1	1	1	1	3	2	3	3
Selective outlet (epilimnion)		1	1	1	1	1	2	1	2	1	2	2	2	2	2	2	2	1	3	3	2	2	3	3	3	3
Outlet energy dissipator		3	2	1	1	1	3	2	3																	
Spillway intake channel																										
Spillway energy dissipator																										
Powerplant tailrace		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Bridges																										

1 - Strong relationship  
 2 - Moderate relationship  
 3 - Weak relationship  
 Blank - Zero or negligible relationship

Note: An alternative approach would be a system using shaded circles to indicate strength of relationship, such as ●, ○, ◐, etc.

FIG. 2.—Causal Factors Affecting Environmental Conditions after Ellis (7) (with Number Coding Indicating Strength of Relationship)

effects associated with the environment downstream from an impoundment, as listed in Table 1.

The reader will note that the chosen parameters are not necessarily identical to the lists of Appendices 1 and 2; this may well be the case when one begins to construct a matrix for a specific application.

Ellis (7) provides a basic approach for construction of matrices. Examples are shown in Figs. 1, 2, 3, and 4 using the Task Committee's elements. Fig. 1 relates causal factors (hydraulic structures) to environmental conditions affected. Ellis indicated the existence of a relationship by the presence of a dot (or any similar mark); the Task Committee instead used a numbering system

CHANGED ENVIRONMENTAL CONDITION		ENVIRONMENTAL CONDITION AFFECTED																								
		Downstream:																								
		Salinity	Phosphate	Nitrogen	Iron	Manganese	DO	Supersaturation	pH	Turbidity	Temperature	Sedimentation	Fecal coliform	Phytoplankton	Zooplankton	Fish	Benthic organisms	Salts	Sedimentation	Erosion	Slides	Terrestrial animals	Plants	Evaporation	Humidity	
WATER	Salinity																									
	Phosphate																									
	Nitrogen																									
	Iron																									
	Manganese																									
	DO																									
	Supersaturation																									
	pH																									
	Turbidity																									
	Temperature																									
	Sedimentation																									
	Fecal coliform																									
	Phytoplankton																									
Zooplankton																										
Fish																										
Benthic organisms																										
Salts																										
Sedimentation																										
Erosion																										
Slides																										
Terrestrial animals																										
Plants																										
Evaporation																										
Humidity																										

FIG. 3.—Interaction among Environmental Conditions (with Dots Indicating Existence of Relationship) after Ellis (7)

to indicate the nature of the relationship. A second matrix, Fig. 2, uses the same elements, with numbers denoting the strength of relationship. Using blank spaces to indicate a zero relationship is not recommended, as it may lead to confusion about whether an element has been considered. Fig. 3 relates changed environmental conditions to environmental conditions affected. This is simply to identify the effects a changed environmental condition might have on other environmental conditions. Again, the use of blanks may lead to confusion. A fourth matrix, Fig. 4, relates changed environmental conditions to the human activities affected, which is a logical end point for any assessment procedure.

Readers may rightly disagree with the relationships, etc., indicated by the Task Committee on the matrices. Each decision includes underlying assumptions, and different persons will use different assumptions. Matrices, in most cases,

CHANGED ENVIRONMENTAL CONDITION		HUMAN ACTIVITY AFFECTED
WATER	Downstream:	
	Salinity	Water-based recreation
	Phosphate	Land-based recreation
	Nitrogen	Irrigated agriculture
	Iron	Dry-land agriculture
	Manganese	Transportation
	DO	Commercial fishing
	Supersaturation	Navigation
	pH	Manufacturing and processing
	Turbidity	Domestic water supply
	Temperature	Energy production
	Sedimentation	Mgt. waste disposal
	Fecal coliform	Construction
	Phytoplankton	Mining
	Zooplankton	Food processing
Fish		
Benthic organisms		
Salts		
Sedimentation		
Erosion		
Slides		
Terrestrial animals		
Plants		
Evaporation		
Humidity		

FIG. 4.—Environmental Conditions Affecting Human Activities (with Dots Indicating Existence of Relationship) after Ellis (7)

CAUSAL FACTORS	ENVIRONMENTAL CONDITION AFFECTED																									
	Downstream:	Salinity	Phosphate	Nitrogen	Iron	Manganese	DO	Supersaturation	pH	Turbidity	Temperature	Sedimentation	Fecal coliform	Phytoplankton	Zooplankton	Fish	Benthic organisms	Salts	Sedimentation	Erosion	Slides	Terrestrial animals	Plants	Evaporation	Humidity	
Reservoir		10	10				5	5	5	10			2	2	5	2								1	1	
Selective outlet (spillway)		10	10	10	10	10	5	5	5	10			2	2	5	2								1	1	
Outlet energy dissipator																										
Spillway intake channel																										
Spillway energy dissipator																										
Powerplant tailrace																										
Bridges																										

AB = positive effect  
 A/B = negative effect  
 / = no effect  
 A = magnitude (strength of the effect)  
 B = importance (significance)

AB = flagged for attention

FIG. 5.—Task Committee Consideration for Method of Determining whether Effect Is Positive or Negative towards Environment and USGS (8) Method for Ranking Magnitude and Importance (only Partially Completed)

would probably be backed up by narrative discussion of each element, including a list of assumptions used. The Committee's purpose here is to show alternate methods.

Ellis points out that the use of the matrices can be expanded so that additional information can be stored within the elements. This approach was considered further by the Task Committee, as explained herein. It is also important to note that the factors and conditions can be coded with a numbering system, allowing computer storage and retrieval, with associated routines for manipulation of data.

The U.S. Geological Survey (USGS) method (8) ranks magnitude and importance of the relationship, on a scale of 1 to 10 on a single matrix. For example, the matrix element for the relationship between a selective outlet in the epilimnion and the level of dissolved oxygen in the downstream channel would be designated as 10/10, showing the highest ranking in both magnitude and importance. Also, a matrix element for the relationship between the reservoir and the downstream manganese level (5/10) would show that this is a very important relationship (10), but that the magnitude is only of moderate strength (4).

Fig. 5 is still another approach, using both the USGS method for ranking magnitude and importance and a Task Committee idea for denoting whether the effect is positive or negative. The matrix also shows a method to flag certain elements for special attention, which is an adaptation from the Battelle Columbus approach (6). For example, the relationship between selective outlet works and downstream temperature is very strong in both magnitude and importance, the effect is positive towards the environment, and the element is flagged for attention because temperature is especially important in the environment.

Finally, the matrix could be used to denote important references for detailed information on the relationship by simply placing reference numbers in the matrix elements.

The various uses of the matrix approach described herein will hopefully serve to demonstrate the possible utility of this approach. The kinds and quantity of information to be stored would seem to be limited only by imagination and the time available for coding the information. The degrees of generality or detail can be determined by the user. Submatrices for finer detail could be considered for those elements showing significant relationships.

**Task Committee Approach.**—Because of the broadness of the subject, as discussed previously, the Task Committee decided to choose an example as a demonstration of application of the method to any hydraulic structure. Also, this particular example is probably of primary importance to most designers of hydraulic structures and is generally what the Hydraulic Structures Committee had in mind when they developed the Task Committee objectives.

#### EXAMPLE—EFFECTS OF IMPOUNDMENT ON DOWNSTREAM WATER QUALITY

The example includes the effects of the reservoir, spillways, outlets, turbines, and energy dissipators.

**Impoundment Effects Survey.**—In order to gather basic data for the example, a questionnaire was sent to 15 professionals in various branches of engineering and biology. Four responded with completed questionnaires, four responded

but were unable to complete the questionnaires, and seven failed to respond. In addition, two Task Committee members completed questionnaires.

The six complete responses covered 60 reservoirs in several regions (see Table 2). The categories of various water uses downstream from these impoundments are also indicated.

Experience with these reservoirs by the responders varied from 1 to 30 years. Several generalizations were drawn from the results.

**The Nature of Impoundment Effects.**—Responses to the questionnaires provided the following general observations for various water quality parameters.

Distinct temperature effects were reported in the Southwest where water temperatures were found to decrease from natural stream conditions. Approximately one-half (8 of 19) of the Southeastern reservoirs also caused decreases in water temperatures. In the Northwest, run-of-the-river reservoirs had no effect on downstream temperature conditions. Other reservoirs in the Northwest, Southeast, and other parts of the country were reported to cause increases,

TABLE 2.—Summary of Reservoirs from Questionnaire Responses by Region and Use

Region of United States (1)	Number of reservoirs (2)	Number of Reservoirs Used to Support						
		Warm-water fishery (3)	Cold-water fishery (4)	Recreation (5)	Water supply <sup>a</sup> (6)	Cooling water (7)	Irrigation (8)	Waste assimilation (9)
Northwest	28	23	28	28	2	18	28	28
Southwest	4	0	4	4	4	0	4	4
Southeast	19	6	13	18	5	2	0	6 <sup>c</sup>
Others <sup>b</sup>	9	1	7	9	4	4	2	1
Total	60	30	52	59	15	24	34	39

<sup>a</sup>Municipal and industrial water supply.

<sup>b</sup>Includes miscellaneous unnamed reservoirs in the Northwest, Midwest, Southeast, and East.

<sup>c</sup>Changed from "1" to "6" by a Task Committee member.

decreases, or show no effect, depending on the season of the year. The effect of the impoundments, in general, was to dampen the natural seasonal temperature cycles, increasing fall-winter temperatures and decreasing spring-summer temperatures. Cold water fisheries, throughout the country, were reported to be improved or created downstream from reservoirs. Recreation also improved where temperatures increased. The exception to these statements was the Southwest where three of four cold water fisheries were degraded as was recreation because of cold water discharges. (Southwestern Fisheries were actually improved because of the impoundment, but the improvement was the result of effects other than temperature.) Decreases were observed in downstream turbidity and suspended solids in all regions on which data were received. Increases were reported below a few reservoirs in the Northwest (2 of 28) and in the Midwest and Southeast (2 of 24). No effects were reported below many Northwestern reservoirs.

Turbidity was reported to have no effect on most fisheries. Some reservoirs in the Northwest and all reservoirs reported in the Southwest did improve downstream fishery resources. Recreation throughout the country was either improved or not changed as a result of changing turbidity.

Taste and odor increased or decreased, was not affected, or had unknown effects. Some increases were reported in the Southeast, but most reservoirs caused no effect. Decreases were observed in taste and odor in the Southwest.

Effects on taste and odor in the Southwest resulted in improved conditions for recreational, municipal, industrial, and irrigation uses.

Salinity (TDS) effects were reported to be unknown in most of the Northwest. A few Northwestern reservoirs and all of the Southwestern reservoirs caused decreases. Increases, decreases, and no effect were all reported in the Southeast.

Effects on total and orthophosphate were unknown throughout the Northwest, Midwest, and most of the Southeast. Decreases were reported below the remaining Southeastern reservoirs and below all of the Southwestern reservoirs.

Effects on total nitrogen were reported to be unknown through the Southeast and much of the Northwest. Increases were reported below those Northwestern reservoirs with known effects. Decreases were reported for all Southwestern Reservoirs.

Effects on ammonia were unknown in the Northwest, East, and most of the impoundments in the Southeast. Increases were reported in the Southwest and downstream from some Midwestern and Southeastern reservoirs.

Effects on nitrate concentrations were unknown throughout the Northwest, East, and most of the Southeast. Some reservoirs in the Southeast and all considered in the Southwest caused decreases in downstream nitrate concentrations.

Dissolved nitrogen gas concentration was reported to increase downstream from nearly all reservoirs in the Northwest and Northeast. The effects on dissolved nitrogen gas in other parts of the country (Southeast and Southwest) were almost entirely unknown. One reservoir of 19 considered in the Southeast was known to cause increases in downstream dissolved nitrogen gas concentrations.

Most of the surveyed northwestern reservoirs caused degradation in downstream fisheries because of the nitrogen gas changes.

Dissolved oxygen (DO) concentrations decreased below almost all (22 of 28) reservoirs in the Southeast, Midwest, and Southwest. Dissolved oxygen concentrations increased downstream from almost all reservoirs in the Northwest and Northeast.

In the cases where DO was increased, improved conditions were reported for various water uses, and in those cases (the Southeast and Southwest) where DO was decreased, degraded conditions were reported.

Effects on pH in the Northwest and Southeast were mostly unknown. Southwestern impoundments either caused increases or decreases in downstream pH conditions.

Effects on iron and manganese were unknown for most reservoirs; however, significant concentration increases were observed below some reservoirs in all parts of the country. These increases caused degraded conditions for fisheries and municipal and industrial water supplies.

The effects of impoundments on fecal coliform were reported to be unknown throughout the country. (However, several reports in the literature indicate that

total coliform concentrations decrease below most reservoirs.)

The productivity and species diversity effects for phytoplankton, zooplankton, and benthos were unknown throughout the country for most reservoirs. Four of 32 reservoirs in the Northwest and East showed some increase in both productivity and species diversity for all three parameters. Southwestern reservoirs also increased productivity and diversity for both phytoplankton and zooplankton.

Fish productivity and fish diversity effects were unknown across most of the country; however, some reservoirs in the Northwest and most of the reservoirs in the Southwest caused increases in fish productivity and diversity. The latter was a result of the introduction of a number of species by a State Game and Fish Department.

**Other Observations.**—The preponderance of unknown effects on several parameters suggests a recommendation that more data should be collected on these parameters.

CAUSAL FACTOR	ENVIRONMENTAL CONDITION AFFECTED (Downstream)																									
	Temperature	Turbidity/suspended solids	Taste/odor	Salinity (TDS)	Total phosphate	Ortho phosphate	Total nitrogen	Ammonia	Nitrate	Dissolved nitrogen gas	Dissolved oxygen	pH	Iron and manganese	Fecal coliform	Aquatic plants	Productivity	Species diversity	Zooplankton	Productivity	Species diversity	Benthos	Productivity	Species diversity	Fish	Productivity	Species diversity
Impoundment	3	2	1	4	2	2	3	1	2	1	3	4	1	2		3	3		3	3		2	2		3	3
	Nature of relationship																									
	1 - Variable may be increased by causal factor																									
	2 - Variable may be decreased by causal factor																									
	3 - Variable may be either increased or decreased by causal factor																									
	4 - Variable unaffected by causal factor																									
	x - Effect unknown																									
Impoundment	1	2	3	3	1	1	3	x	x	1	1	x	3	2		2	2		3	3		2	2		1	1
	Strength of relationship																									
	1 - Strong relationship																									
	2 - Moderate relationship																									
	3 - Weak relationship																									
	x - Effect unknown																									

FIG. 6.—Results of Impoundments Effects Survey in Matrix Form

The variable nature of the questionnaire responses may justify a conclusion that results drawn from a composite of questionnaires are rather weak for the majority of parameters, and that simple opinion might do as well. Since strong general conclusions cannot be drawn, evaluation on a case-by-case basis seems necessary. For the benefit of those hydraulic engineers who may not be familiar with the behavior of water quality in reservoirs, a brief discussion of this topic is presented in Appendix III.

In general, water quality of impoundment releases is affected by: (1) Physical characteristics of the reservoir, such as residence time in the impoundment and depth; (2) depth of outlets; (3) impoundment operation, such as for hydroelectric power generation, flood control, or water supply; (4) meteorology; (5) topography surrounding the reservoir; and (6) the quality of inflow to the reservoir, which is dependent on geology of the area, types of land use, and

municipal and industrial waste discharges.

Downstream effects generally resulted in improved conditions more than degraded conditions for the various uses. Exceptions were: effect of temperature on warm-water fishery, effect of total nitrogen on cold-water fishery, effect of dissolved nitrogen gas on all fisheries, effect of DO on recreation (may be connected to fishery), effect of pH on recreation and irrigation, and the effects of biological parameters on fishery. Obviously, the direction of change will determine the effect on most of the uses.

**Matrix of Survey Results.**—Fig. 6 shows a matrix, similar to those of Figs. 1 and 2, summarizing the results of this survey. Where the survey results were ambiguous, the matrix elements reflect experience of the Task Committee.

#### CONCLUSIONS

1. Although the Task Committee recognized the broad aspects of environmental considerations in planning, major emphasis was placed on defining a method that could be used to evaluate effects of specific structures at specific locations.

2. An overview of potential environmental effects of hydraulic structures was developed in the form of categorized lists of hydraulic structures and environmental effects.

3. Various matrix forms were demonstrated to show a potential method of relating hydraulic structures and environmental effects.

4. An example, believed to be of practical importance to designers of hydraulic structures, was chosen. The example, "Effects of Impoundment on Downstream Water Quality," was developed by issuing a survey questionnaire. Response was poor; however, the survey results, along with the experience of the Task Committee, were used to develop a matrix.

5. The survey results and matrix showed the difficulty in trying to frame general conclusions and affirmed that analyses may have to be site specific.

6. Formation of a matrix should be useful in determining data requirements to complete an assessment of environmental effects. It might also help identify parameters with negligible effect to be deleted from monitoring programs, which tend to be very expensive.

#### RECOMMENDATIONS

1. Site specific matrices should be developed for assessment of environmental impact of hydraulic structures. Both references and field data can be used to complete matrix elements.

2. In developing site-specific analyses, care must be taken to avoid overlooking effects that might originate at structures upstream. Furthermore, long-term effects must be considered which may not be immediately apparent. The effects of policy, such as wild rivers versus hydroelectric development, must also be taken into account.

3. No additional task or full committees are recommended. The magnitude of a comprehensive analysis of environmental effects of hydraulic structures suggests that a firm, university, or agency would require staff and funding for its accomplishment. The task would be beyond the capability of part-time committees or task groups.

4. The questionnaire survey suggested the need for more field data on the environmental effects of reservoirs. Field research programs should be encouraged. However, the literature should also be surveyed carefully to make full use of existing information.

#### ACKNOWLEDGMENTS

The assistance of the following personnel of the Tennessee Valley Authority, Chattanooga, Tenn., is gratefully acknowledged: Mr. Richard Toussaint in evaluation of various matrix schemes, Mr. Malcolm Babb and Mr. David Bruggink in development of the questionnaire on environmental effects of impoundments, Mr. Bruggink and Mr. John Higgins in evaluating the results of the questionnaire, and Mr. Babb in preparation of the appendix on behavior of water quality in reservoirs.

This report is respectfully submitted by the Task Committee on Environmental Effects of Hydraulic Structures of the Committee on Hydraulic Structures of the Hydraulics Division.

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#### APPENDIX I.—CATEGORIES OF HYDRAULIC STRUCTURES

- I. Hydrologic structures (infiltration galleries, drains, wells, drain inlets, culverts, bridges, hydraulic mining structures, detention dams, storage tanks, etc.)
- II. Streamflow structures (bridges, culverts, revetments, mill ponds, conveyance channels, check dams, ground-water recharge, beaches, boat ramps, etc.)
- III. Regulatory structures (dams, reservoirs, navigation lock filling and emptying systems, energy dissipation structures, sediment and chemical control structures, channel stabilization structures, collection and diffusion structures, pumps and turbines, flow measurement or control structures, fish ladders, etc.)
- IV. Conveyance structures (pressure conduits, free-surface conduits, canals, etc.)
- V. Irrigation and drainage structures (diversions, intakes, distribution systems, laterals, pipelines, division works, turnouts, wasteways, settling basins, bridges, fish control structures, drainage systems, etc.)
- VI. Urban features (streets, drains, septic tanks and leaching fields, water supply systems, sewers, etc.)
- VII. Industrial structures (cooling towers, outfalls, pipeline crossings, conveyance structures, treatment structures, mooring structures, mining, bridges, etc.)
- VIII. Wastewater treatment facilities (plain sedimentation tanks, aeration basins, sand filters, trickling filters, land treatment, activated sludge treatment, mains, lift stations, bar screens, settling tanks, measuring stations, outfalls, sludge treatment, disposal, disinfection, etc.)

- IX. River utilization structures (dams, levees, revetments, dikes, floodways, shipping channels, locks, docks, cooling for thermal power plants, etc.)
- X. Estuarine structures (breakwaters, jetties, marinas, docks, floodways, levees, erosion controls, revetments, outfalls, seafood production and processing, thermal power plants, etc.)
- XI. Coastal structures (seawalls, jetties, dikes, dune stabilization, piers, moorings, breakwaters, thermal power plants, tidal control, tidal power plants, reefs, submerged pipelines, outfalls, etc.)
- XII. Offshore structures (moorings, pipelines, drilling platforms, power plants, dredge spoil waste sites, ocean mining, etc.)

#### APPENDIX II.—LIST OF ENVIRONMENTAL EFFECTS

##### Water

1. *Chemical* categories for environmental effects: Dissolved solids; Organic nitrogens; Nitrate-nitrite; Ammonia; Phosphates; Orthophosphate, or reactive with molybdate with no prior digestion; Sulfide, oxides of sulfide; Silica; Iron; Manganese; Heavy metals; Trace elements; Total organic carbon; BOD; DO; Percentage of dissolved nitrogen saturation; Organics; pH; Alkalinity; Acidity; Pesticides; PCB's (polychlorinated biphenyls); Potassium; Calcium; Magnesium; Chloride; Fluoride; Radioactive isotopes; and Other toxic substances.

2. *Biological* categories for environmental effects: Phytoplankton; Zooplankton; Fish—warm and cold; Eutrophication; Aerobic bacteria; Anaerobic bacteria; Fecal coliforms; Benthic organisms; Waterfowl; Other aquatic animals; Attached aquatic plants—algae and macrophytes.

3. *Physical* categories for environmental effects: Turbidity; Light penetration; Temperature; Sedimentation; Taste; Floating material; Odor; and Color.

##### Land

1. *Biological* categories for environmental effects: Terrestrial animals; Amphibians; Birds; Insects; Bacteria; Plants—shoreline and flood plain; and Other.

2. *Physical* categories for environmental effects: Sedimentation; Erosion; and Esthetics.

##### Air

*Physical* categories for environmental effects: Sprays; Odors; Temperature; Dust; and Gases.

#### APPENDIX III.—BEHAVIOR OF WATER QUALITY IN RESERVOIRS

The following is a brief discussion of selected water quality parameters generally of concern to typical water users downstream from dams. This is not intended to be a complete, detailed exposition of all aspects of these parameters or the numerous interrelationships and reactions in which they may be involved. Instead, an attempt has been made to provide the hydraulic engineer with: (1) A concise definition of the parameter; (2) a brief description of the important changes which these parameters may undergo as a result of impoundment effects; and (3) a summary of major interactions with other water constituents which significantly affect water quality.

**Temperature.**—Water temperature plays an extremely important role in controlling many hydraulic, chemical, and biological phenomena occurring in impounded water as well as exerting a direct influence on many water users downstream from reservoirs. Deep reservoirs with long detention times generally have the effect of cooling the discharged waters. This may be advantageous in some cases in maintaining a cold-water fishery downstream from the dam. However, in many western states this cooling effect may be excessive. Even cold-water fish have a difficult time surviving in such waters and the use of this water for swimming is unusual. Important considerations in evaluating the temperature of releases include the absolute temperature range and the rate of temperature change. All biological organisms exhibit a certain behavior pattern within a range of temperatures for which survival is possible. Furthermore, most organisms will not tolerate rapid changes in temperature. Also, hourly, daily, and yearly temperature variations may all be important quality criteria for certain downstream water users.

Temperature also affects many complex processes occurring in the reservoir which determines the quality of the discharged water. The rate of chemical and biochemical reactions is directly related to temperature. A common rule of thumb for many biochemical reactions is that for a rise of 10° C the reaction rate doubles. A more subtle effect of temperature upon water quality results from the phenomenon of thermal stratification. Temperature directly affects the density of water. Down to a temperature of 4° C, water becomes more dense with cooling and settles to the bottom of deep reservoirs. Between 0° C and 4° C water actually becomes less dense as it cools. During the summer months, reservoirs are usually stratified with respect to temperature so that three zones are formed. The upper zone is known as the epilimnion. It is generally characterized by well-mixed aerobic conditions. Temperature is relatively constant within the depth of the epilimnion. The lowermost zone near the bottom is known as the hypolimnion. It is characterized by cold-water temperatures (down to 4° C) and minimal mixing. Depletion of the dissolved oxygen concentration in this zone also may result. Depleted oxygen conditions in turn can give rise to numerous biological and chemical reactions that degrade discharge water quality.

The difference in temperature (density) between the hypolimnion and epilimnion creates the thermocline which serves as a boundary that resists mixing between the other two zones. As a result, little dissolved oxygen from the epilimnion is transferred to the hypolimnion to replace that used in chemical reactions and metabolism of organisms.

Reservoirs begin the process of thermal stratification in the spring. In the fall, thermal stratification is destroyed as the reservoir cools and, except for very deep reservoirs, mixing of the entire water column takes place. Factors affecting the duration and degree of thermal stratification include the physical dimensions of the reservoir, inflow and outflow characteristics, meteorological variables, and certain water quality parameters such as high concentrations of suspended and dissolved solids.

**Turbidity/Suspended Solids.**—Turbidity is related in part to particulate materials (suspended solids) in the water, either inorganic or organic, which tend to reduce the light transmission characteristics of the water. Some of this material may settle from the water, given quiescent conditions and enough time. However,

turbidity can be composed of colloidal matter that will remain suspended in the water for extremely long periods of time. Since turbidity reduces light penetration, algal growth is reduced with increasing turbidity. Suspended solids can clog the gills of fish and cover benthic organisms. In some cases an important part of the cost of municipal and industrial water treatment is that incurred in the removal of suspended solids.

In general, reservoirs tend to reduce the turbidity of the water downstream from the impoundment as compared to the natural stream. This phenomenon is the result of the generally quiescent settling conditions and increased detention time of the water. Turbid water conditions can result, however, immediately below the tailrace of the dam as the result of scouring of the riverbank and channel.

**pH.**—pH is the logarithm of the reciprocal of the hydrogen ion concentration (activity). The pH of most natural waters falls within the range of 6 to 9. The majority of waters are slightly basic due to the presence of carbonate and bicarbonate ions. pH plays an important role in many chemical and biological reactions. pH controls the availability of nutrients for subsequent biological uptake, the resultant products of chemical reactions, the net direction of ion exchange and absorption reactions, and the occurrence of certain chemical species or ionic forms. Associated with the term pH is a consideration of the buffering capacity of the water. Alkalinity is the ability of the water to resist a change in pH upon the addition of a strong acid. On the other hand, acidity is the ability of the water to resist a change in pH upon the addition of a strong base. Extremes in pH as well as rapid fluctuations can have adverse effects on aquatic life.

In low buffered waters intense algal activity can cause wide variations in pH. Anaerobic activities in the hypolimnion of some reservoirs can reduce the pH, resulting in slightly acidic waters.

#### **SALINITY/TOTAL DISSOLVED SOLIDS**

Salinity refers to inorganic salts dissolved in water. The higher the salt concentration, the more dense the water. Salinity can enter the reservoir in the inflowing water or through ground-water infiltration. The salinity of the reservoir water can also increase as a combined result of high evaporation rates and long detention times. Highly saline water entering a reservoir can establish density stratification patterns similar to that discussed for thermal stratification. In such cases, the mixing of oxygen rich surface waters into oxygen depleted bottom water is inhibited at the interface, named the chemocline. Water of increased salinity may result in discharges that are less desirable as a source for industrial and irrigation users. In addition, the higher the salinity the lower the oxygen saturation concentration for the water.

#### **DISSOLVED OXYGEN**

The dissolved oxygen concentration in water plays an extremely important role in determining the quality of the discharged water. Adequate dissolved oxygen is necessary for the life of fish and other aquatic organisms. The equilibrium concentration of dissolved oxygen resulting when water is in contact

with air is generally known as the saturation concentration. The saturation concentration is directly proportional to atmospheric pressure and inversely proportional to the salinity and temperature of the water.

Ultimately the concentration of dissolved oxygen is equal to the net oxygen sources and sinks affecting the aquatic system. Common oxygen sources include aquatic plant photosynthetic activity and reaeration from the atmosphere.

There basically are eight major types of dissolved oxygen consuming processes in reservoir waters. These include:

1. Biochemical oxygen demand exerted by organisms that oxidize carbonaceous and nitrogenous matter.
2. Phytoplankton, macrophyte, and periphyton respiration.
3. Zooplankton respiration.
4. Fish respiration.
5. Benthic organism respiration.
6. Chemical oxygen demand including oxidation of reduced gases ( $H_2S$ ,  $CH_4$ ) and certain reduced ionic species (iron, sulfides, manganese).
7. Mass transfer reactions including stripping of dissolved oxygen from the water by gas bubbles rising from the bottom muds and diffusion of dissolved oxygen into the bottom muds.
8. Inflow of water low in dissolved oxygen (either via ground water or tributary streams).

It is a complex task to identify the relative importance and magnitude of each of these oxygen sources and sinks. Interactions are common among the various processes. Generalizations are difficult, if not impossible, to make. Each reservoir must be considered separately.

Water conditions considered adverse to many users commonly develop when dissolved oxygen concentrations are reduced to zero (anaerobic conditions). Under these circumstances chemical and biochemical reactions can take place which generate noxious or toxic substances. Although the water can be aerated as it is discharged from impoundments, oxygen consuming reactions can remove the oxygen added in this process. Fish kills can result if the oxygen concentration falls below critical levels and the fish are unable to migrate to water containing high concentrations of oxygen. The critical dissolved oxygen level for fish depends upon the species, life stage, water temperature, and chemical water quality. The makeup of the microbial community in the water as well as the type of benthic organisms in the sediment are also determined by the dissolved oxygen concentration.

#### **IRON/MANGANESE**

These two metals can be conveniently grouped together. Both metals undergo oxidation-reduction reactions that affect their solubility in water. Under certain anaerobic conditions these metals form soluble species that are released into the bulk of the reservoir water from the sediment. If these compounds are not removed by water treatment processes, stains to laundry and plumbing fixtures can result. In addition, iron can impart a bittersweet, astringent taste detectable by some persons at concentrations above 0.3/l. Because of these

problems, drinking water standards limit iron and manganese concentrations to 0.3 mg/l and 0.05 mg/l, respectively. Other adverse effects of these metals include depletion of dissolved oxygen via oxidation reactions downstream from the reservoir discharge and the covering of benthic organisms as the oxidized material settles to the bottom of the stream.

It is common to find iron and manganese concentrations many times higher than critical levels in anaerobic hypolimnion waters. The source of these metals can be from geological outcroppings in contact with the reservoir bottom, from ground-water infiltration, from organic material decomposed by biological action, or from the inflow of tributary streams.

#### PHOSPHORUS

The phosphorus cycle in aquatic systems is extremely complex. The interrelationships of many of the pathways are not completely understood. Generalizations about the relative importance of certain reactions are difficult. For the sake of simplicity, this discussion will be limited to those aspects of the phosphorus cycle having a direct impact upon downstream water users. Phosphorus is an essential nutrient for the growth of plants associated with aquatic systems. Plants represent the primary source of fixed solar energy in these systems and as such serve as the main source of food for high levels of productivity. Plants are capable of exerting a strong influence upon water quality, either by direct interaction with specific chemical systems or by affecting other organisms which in turn interact with a water quality parameter.

Although phosphorus is an essential nutrient for growth, only small amounts are needed as compared with nitrogen and carbon. In many cases, phosphorus availability limits aquatic plant growth. Small increases in the availability of phosphorus can cause large increases in the growth of aquatic plants. The degree to which growth is increased depends upon the relative availabilities of other nutrients required for growth.

The orthophosphate form of phosphorus is readily taken up and assimilated by phytoplankton and periphyton. Other forms of phosphorus (organic polyphosphate) can also be utilized as a source of phosphorus by certain plants.

Reservoirs can act to reduce the phosphorus content of the water discharged from the reservoir as compared to the inflow water. This is the result of phosphorus being incorporated into organic or inorganic compounds that settle to the reservoir bottom. Mechanisms involved in this process include biological uptake and assimilation, chemical precipitation, and physical adsorption. Various processes such as autolysis, zooplankton excretion, and bacterial decomposition in both the water column and in the sediment tend to increase orthophosphate concentrations. However, taken over a long time scale the reservoir represents a phosphorus sink.

Most soluble phosphorus released to the water results from decomposition of the sediments. Under anaerobic conditions high concentrations of inorganic phosphates can occur in the hypolimnion of reservoirs. If this water is then discharged, algal blooms can result downstream from the dam. These can reduce dissolved oxygen concentrations, interfere with water treatment processes, and create unsightly conditions.

**DISSOLVED NITROGEN GAS**

Nitrogen is a biologically inert gas. Under certain conditions, however, nitrogen gas can cause gas-bubble disease in fish. Characteristically these fish develop bubbles under the skin; in the fins, tail, and mouth; behind the eyeballs; and in the vascular system, causing gas embolism and death. Signs of this disease generally occur when fish are exposed to water having saturation levels of greater than about 110% of dissolved nitrogen, though other conditions of stress may cause variability in this critical level. Changes in the percentage saturation can result from a change in temperature or entrainment of air.

Oxygen has been shown to cause signs of gas-bubble disease. However, the onset of the disease occurs at much higher levels of supersaturation as compared to that for nitrogen.

Certain spillway and energy dissipating discharge structures may increase air entrainment and thus supersaturated conditions.

**TASTE AND ODOR**

The water quality parameters of taste and odor concern the human physiological sensations accompanying consumption of and recreation in and around water. There are only four true taste sensations: sour, sweet, salty, and bitter. All other sensations attributed to taste are actually odors acting in conjunction with the taste sensation. Dissolved inorganic salts of iron, zinc, manganese, copper, sodium, and potassium can be detected by taste. Concentrations producing taste range from a few tenths to several hundred milligrams per liter. Reservoirs that increase the salinity or iron and manganese concentration of the discharged water may adversely affect the taste of these waters.

Odors occur in water because of the presence of foreign substances usually organic in nature. However, certain inorganic compounds such as hydrogen sulfide may also cause odor. Taste and odor producing organic compounds may be attributed to the decomposition products of biological materials, synthetic compounds produced by decomposer microorganisms, or compounds produced by algae. These materials may directly impart taste and odor to the water. A compound producing objectionable taste and odor may also develop as a product of the reaction between biologically produced compounds and chlorine in water treatment processes.

**NITROGEN**

The nitrogen cycle in aquatic ecosystems, like the phosphorus cycle, is extremely complex. There are numerous competing and interrelated reactions. Nitrogen is an important component of biological protoplasm. Under certain conditions nitrogen supply can limit the growth of aquatic plants.

Five forms of nitrogen are important to nutrient relationships in aquatic systems. These include nitrogen gas, organic, nitrite, nitrate, and ammonia nitrogen. The basic nitrogen cycle under aerobic conditions begins with the uptake and assimilation of inorganic nitrogen either in the nitrate, nitrite, or ammonia form. Nitrate must be reduced to the ammonia form internally before it can be assimilated into cellular material. This process requires energy. Many organisms preferentially

utilize ammonia in the presence of nitrate. Organic compounds such as amino acids can serve as a nitrogen source for some organisms. However, the ability to use these compounds is not universal.

Recycle of nitrogen in aquatic systems may take place in a number of ways. During metabolic processes many organisms excrete compounds containing nitrogen. This nitrogen may be incorporated into organic compounds or in the ammonia or nitrate form. Upon death of the organism, autolysis and microbial action begin to release nitrogen from the biological material. The ultimate product of these reactions is ammonia. Under aerobic conditions microbial aerobic action oxidizes ammonia to nitrite and then to nitrate. This process is known as nitrification. The nitrite produced in this process usually does not accumulate in large amounts. It is toxic to many organisms and can be readily oxidized to nitrate through chemical reaction with molecular oxygen. It should be noted that both the chemical and biological oxidation reactions utilize dissolved oxygen and can represent an important oxygen sink upon the aquatic system.

Under anaerobic conditions different reactions predominate in the nitrogen cycle. In this case, nitrate is reduced to ammonia and under certain conditions further reduction can take place to produce nitrogen gas. This process is called denitrification.

One other process can play an important role in the aquatic nitrogen cycle. This is the process whereby molecular nitrogen is incorporated into biological material. This process is called nitrogen fixation. It requires a source of energy. The primary group of organisms capable of carrying out this process are the blue-green algae. Under certain conditions this process can represent a major source of nitrogen to the aquatic system.

The effect of reservoirs upon the nitrogen budget of downstream waters is extremely variable. Water discharged from an aerobic epilimnion can have reduced nitrogen concentrations as compared to the stream before impoundment. Soluble nitrogen compounds can be converted to biological mass which settle to the bottom of the reservoir and thus are effectively removed from the system. Nitrification and long detention times can combine to reduce the ammonia concentration of these discharged waters. As a result, the nitrogenous oxygen demand exerted on the downstream water may be reduced.

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**13562 ENVIRONMENTAL EFFECT OF HYDRAULIC STRUCTURE**

**KEY WORDS:** Dams; Environmental effects; Environmental engineering; Environmental factors; Hydraulics; Hydraulic structures; Reservoirs; Water quality; Water resources

**ABSTRACT:** In response to objectives outlined by the Hydraulic Structures Committee, the Task Committee has attempted to: (1) Define what structure types should be selected for study in view of current research activity and potential effects on the environment; (2) provide a general survey of how hydraulic structures interrelate with their environment; and (3) make recommendations for future task or full committees to examine specific program areas. Tables showing categories of hydraulic structures and categories of environmental effects are presented. The Task Committee preference to use matrices as an assessment method is illustrated with several examples. Finally, an example is developed to examine the effects of impoundment on downstream water quality. Data for the example were obtained by a limited survey of engineers and biologists. Results are presented and discussed.

**REFERENCE:** King, Danny L., Chmn., "Environmental Effects of Hydraulic Structures," *Journal of the Hydraulics Division, ASCE*, Vol. 104, No. HY2, **Proc. Paper 13562**, February, 1978, pp. 203-221