HYDRAULIC RESEARCH IN TRANSITION: THE EVOLVING ROLE OF HYDRAULIC STRUCTURES - FROM DEVELOPMENT TO MANAGEMENT OF WATER

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INTRODUCTION

Throughout its illustrious history, the Bureau of Reclamation has focused its efforts on creating a life-sustaining environment in the once barren West. Reclamation was established in 1902 and since that date has constructed over 220 large dams. Reclamation's hydraulic research started in the early 1930's and played a key role in developing innovative designs and establishing standards for many hydraulic structures. In the early years, Reclamation's applied hydraulic research dealt with dam structures such as spillways, outlet works, and their energy dissipators. Over time the research expanded to include hydraulic equipment and various conveyance systems for irrigation and municipal and industrial water supplies, Rhone (1990).

Reclamation's hydraulic structures research in the period from 1930 through the 1970's resulted in world class technological advancements in water resource development as documented in publications such as *Design of Small Dams* (1960) and Engineering Monograph No. 25, "Hydraulic Design of Stilling Basins and Energy Dissipators" (1958). As public values shift from an emphasis on water resource development to management of western waters, our hydraulic research program has maintained a contemporary focus. This evolution in hydraulic research from water development to water management has led to an emphasis on technology development for protecting the public and the infrastructure developed in the past, encouraging water conservation, and emphasizing environmental restoration on regulated river systems. This paper will describe emerging areas of hydraulic research for protecting hydraulic structures and utilizing hydraulic structures to manage the water resource in an environmentally and economically sound manner.

PROTECTING THE INFRASTRUCTURE - DAM SAFETY

The Department of the Interior's (DOI) dam safety program is administered by Reclamation. A component of the program is the development of new technologies (applied research) to cost-effectively solve dam safety problems. Inadequate spillway capacity is one of the primary reasons dams fail. Reclamation's dam safety research focuses on hydraulic investigations performed in the Water Resources Research Laboratory (WRRL). Alternative spillway designs, fuse plug concepts, and overtopping protection concepts are investigated. The safety improvements, innovative new design concepts and construction cost savings realized from this research have been significant.

INCREASED SPILLWAY CAPACITY - LABYRINTH SPILLWAYS

Reclamation has used labyrinth spillways on existing dams where the discharge capacity of a spillway is insufficient or where a reservoir must be enlarged. Research on the labyrinth spillway concept produced design criteria that were applied to augment the spillway capacity at Ute Dam on the Canadian River, New Mexico, and generated significant savings in field construction cost. Ute Dam spillway was constructed for $10 million, a $24 million cost savings over the estimated $34 million cost for a traditional gated structure. Houston (1982) described laboratory sectional flume studies and a 1:80 scale model of the full labyrinth spillway, figure 1. The 9-m-high, 14-cycle spillway had a length magnification ratio of 4 and a flow magnification ratio of 2.4.

Figure 1. - View of the 1:80 scale model of the 14-cycle, 9-m-high Ute Dam labyrinth crest passing 15 500 m^3/s.

EMERGENCY SPILLWAY CONCEPTS - FUSE PLUGS

Pugh (1984) defines a fuse plug as ". . . an embankment designed to wash out in a predictable and controlled manner when the capacity in excess of the normal capacity of the service spillway and outlet works is needed." A number of laboratory embankments, 0.15- to 0.38-m high and 2.7-m long at scales of 1:10 and 1:25, were tested in the WRRL to develop fuse plug spillway design criteria. Figure 2 illustrates a typical laboratory fuse plug investigation. Fuse plug designs have been selected for the dam safety Corrective Action Plan on the Verde River in Arizona: Horseshoe and Bartlett Dams. The fuse plug for Bartlett Dam is designed with an erosion resistant invert and abutment structure and will pass 10 100 m^3/s. Three erodible embankment sections will operate in sequence. The Horseshoe Dam fuse plug is designed to pass 6850 m^3/s through three 44- to 52-m-long openings 6.0-m to 7.9-m high, figure 3.

The documented construction cost savings of $150 to $300 million on the Verde River Dams are an example of the significant benefits resulting from this hydraulic research.

OVERTOPPING EMBANKMENT PROTECTION CONCEPTS

Flood flow overtopping an embankment is considered unacceptable. However, hydraulic research in recent years has greatly advanced the concept of embankment protection systems, not only for low dams (under 15-m high), but now for high dams as well. Frizell and others (1994) have reported on recent cooperative research funded by DOI dam safety, the Electric Power Research Institute (EPRI), and Colorado State University (CSU), which has resulted in design criteria development for concrete step overlay protection for embankment dams. Studies were completed in Reclamation's WRRL as well as tests performed in a large-scale, outdoor overtopping facility at CSU. The 1.5-m-wide, 15-m-high outdoor test facility subjected tapered blocks to unit discharges as high as 3.2 $m^3/s/m$, figure 4. The 35-cm-long by 5-cm-high by 60-cm-wide blocks are placed in an overlapping pattern on filter material. The blocks are designed to aspirate water from the filter layer through small drainage slots formed in each block. The block shapes developed through these studies are effective for a range of embankment slopes.

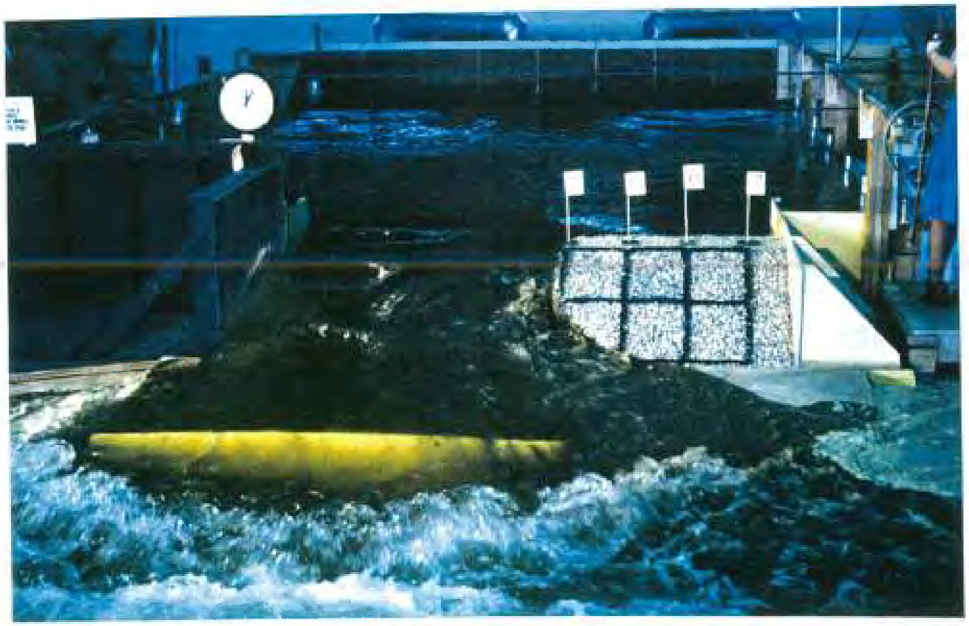

Figure 2. - Laboratory photo showing fuse plug washout process.

Figure 3. - Flow of 4250 m^3/s through the first two sections of the Horseshoe Dam Fuse Plug Model. Scale 1:60.

Figure 4A.- View of flow starting over the 2:1 slope. Blocks are placed in an overlapping fashion on 15 cm of gravel.

Figure 4B. - View of the 1.5-m-wide, 15-m-high test facility at CSU discharging 3.0 m^3/s.

EVALUATING THE EXTENT OF DAM FOUNDATION EROSION

Dam failure can occur when the foundation is undercut or the downstream slope is eroded, eventually causing slumping of the dam crest and failure by overtopping. There are numerous documented instances of extensive erosion damage to spillways, stilling basins, and riverbeds that threaten dam stability. Predicting flow patterns, velocity distributions, material erosion, and other factors of impinging jets in prototype situations is largely beyond the capability of conventional physical and numerical modeling techniques. Reclamation has entered into a multi-year cooperative research and development agreement to develop new technologies for predicting the extent of erosion and scour at dam foundations, specifically at the downstream toe and abutments of dams. The study approach couples hydraulics and geomechanical index concepts and will utilize a laboratory scale model as well as a near-prototype test facility to develop and evaluate a predictive numerical code to estimate the extent of dam foundation erosion. The variety of materials and material properties present in dam foundations indicates the need for an erodibility index which is a product of mass strength, block size, inter-particle strength and relative orientation.

The 3.0-m-wide by 4.0-m-long by 1.8-m-high laboratory model is located in the hydraulic laboratory at the Engineering Research Center, Colorado State University, figure 5. The model is a 1:3 scale representation of the near-prototype facility. A 4.1-cm by 1.0-m-long orifice slot located approximately 1.5 m above the basin tailwater is capable of discharging 18.4 L/s. The near-prototype outdoor facility will have an 11.0-m-wide by 14.6-m-long by 4.6-m-deep basin. A large 12.2-cm by 3.0-m-long orifice located approximately 4.6 m over the basin will be capable of discharging 2.83 m^3/s into the plunge pool basin.

The laboratory and near-prototype studies will scientifically investigate the erosion processes of jacking, dislodging, and transporting foundation material. The test results will provide reliable data to verify the numerical code under development.

Figure 5. - View of 1:3 scale laboratory model with orifice jet discharging into basin.

ENVIRONMENTAL RESTORATION

Water development and environmental interests are striving to coexist in providing today's society with a higher standard of living, while fully protecting environmental resources. In recent years hydropower production and agricultural water supply have been cut back substantially in the U.S. to meet regulatory agency requirements. Rivers regulated for hydropower development, urban and agriculture water supply, and flood control are complicated systems; operational decisions must consider fish behavior and environmental resources as well as engineering design. A bioengineering focus has led to new, innovative concepts for using hydraulic structures to manage regulated aquatic ecosystems in the West. A look at fishery and stream restoration issues in the West illustrates these new technological approaches.

RESERVOIR SELECTIVE WITHDRAWAL

The winter-run Chinook salmon population in the Sacramento River, California, has declined over the past two decades. A contributing cause of this decline is thought to be the mortality of eggs and fry caused by elevated water temperatures during the late summer and fall incubation and rearing season. Water temperatures exceeding 12.0 °C can cause significant egg mortality. Reclamation's hydraulic research in the late 1980's developed flexible curtain barriers to manage and control reservoir-release water temperatures for structures in the Trinity and Sacramento River drainages.

A sophisticated temperature stratified test facility (9-m by 9-m by 2.4-m deep) was built in Reclamation's WRRL to develop and test various temperature control device concepts for reservoir release. A refrigeration system was used to create temperature profiles in the range from 7 °C to 24 °C in the facility. Scaling laws allow research engineers to simulate releases from temperature-stratified reservoirs in the model facility. Flow in reservoirs approaching the outlets is significantly affected by water density which is directly related to temperature; therefore, it is important to properly simulate the water temperature in the laboratory test facility.

A model scale of 1:72 was used to simulate a 91-m-deep and 396-m-long, flexible curtain to control releases through the powerplant at Shasta Dam. The curtain could be lowered from the reservoir surface to permit withdrawal of warm surface water or could be raised off the bottom to access the cold bottom water. The 1.2-hectare curtain was to be made of 32-mil Hypalon reinforced with nylon. Lack of historic reference and field experience using underwater curtains of this size prompted the decision to use a "more traditional" steel structure. The steel structure to be installed on Shasta Dam in 1996 will extend 15.2 m out into the reservoir, run 122 m horizontally and plunge as deep as 107 m into the deeper part of the reservoir permitting access to near-bottom cold water. Field construction costs for the steel structure are estimated to be four times the cost of a flexible reservoir curtain.

The recent drought (1988-1992) in northern California resulted in limited volumes of stored cold water deep in reservoirs. Because of the urgent need to reduce reservoir outflow temperatures, Reclamation initiated an aggressive research program to study and install temperature control curtains in more shallow waters, such as those present at Lewiston Lake. Two curtains were designed and installed in Lewiston Lake in August 1992. The primary (reservoir) curtain, figure 6, was designed to hold back the warm water while colder water was released through Clear Creek Tunnel to the Sacramento River.

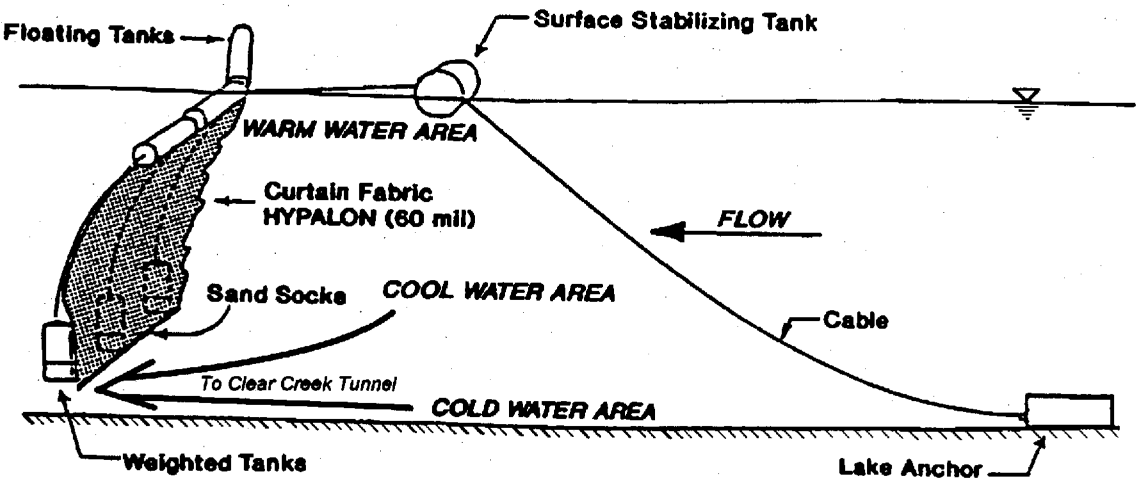

Figure 6. - Illustration of the Lewiston Lake temperature control curtain.

The second curtain was designed to provide temperature control for water supplied to a nearby fish hatchery. Laboratory results indicated the reservoir curtain would reduce the water temperatures released from Lewiston Lake to the Clear Creek Tunnel by about 1.5 °C. Actual temperature measurements made at Clear Creek Tunnel intake after the August 1992 installation of the curtain showed a 1 to 1.5 °C temperature reduction, Vermeyen and Johnson (1993). Although this seems a small change in temperature, every degree reduction can significantly decrease the salmon egg mortality rate.

In a continuing multi-agency effort, two additional flexible curtains were laboratory tested, designed, and installed in Whiskeytown Lake in 1993. The use of this new temperature control technology, as well as the steel shutter structure at Shasta Dam, will increase the selective withdrawal capability within the Sacramento River basin and provide improved management by selective withdrawal of the limited cold water resource in the reservoirs. Table 1 summarizes retrofit selective withdrawal structure technologies used at five Reclamation power stations.

FISH PASSAGE

Considerable effort has been placed on improving fish passage technologies in recent years, including new designs for fishways, improved spawning facilities, fish barriers with associated bypass designs for canals and various screening and fish behavioral control concepts. Most recently, efforts have centered on returning the Sacramento River near Red Bluff Diversion Dam to a "run of the river" condition. Several alternatives are under study to improve the fishery. One alternative proposed by Liston and Johnson (1992) will evaluate the feasibility of replacing the diversion dam with a pumping station utilizing fish-friendly pumps. The plant will deliver 76.5 m^3/s, with a lift of 4.3 m to the Tehama Colusa Canal, while incurring minimal fish mortality. Every effort will be made to minimize fish entrainment at the pump intakes. A pilot pumping plant has been built that will initially pump up to 9.5 m^3/s. The pilot plant is designed to evaluate and monitor the mechanical performance of two fish-friendly pump concepts as well as evaluate fishery issues associated with pumping. An Archimedes screw pump and a screw-centrifugal (helical) pump will be evaluated, figures 7 and 8. Two 3.0-m-diameter, 8.0-m-long Archimedes pumps, placed on a 38° angle, will deliver a total of 4.5 m^3/s at a rotational speed of 28 r/min. One 1.2-m helical pump will deliver 5.0 m^3/s at 400 to 600 r/min. Construction of the pilot pumping plant will be completed in the spring of 1995. Fishery and mechanical issues will be evaluated over several years before construction of the larger, permanent pumping plant.

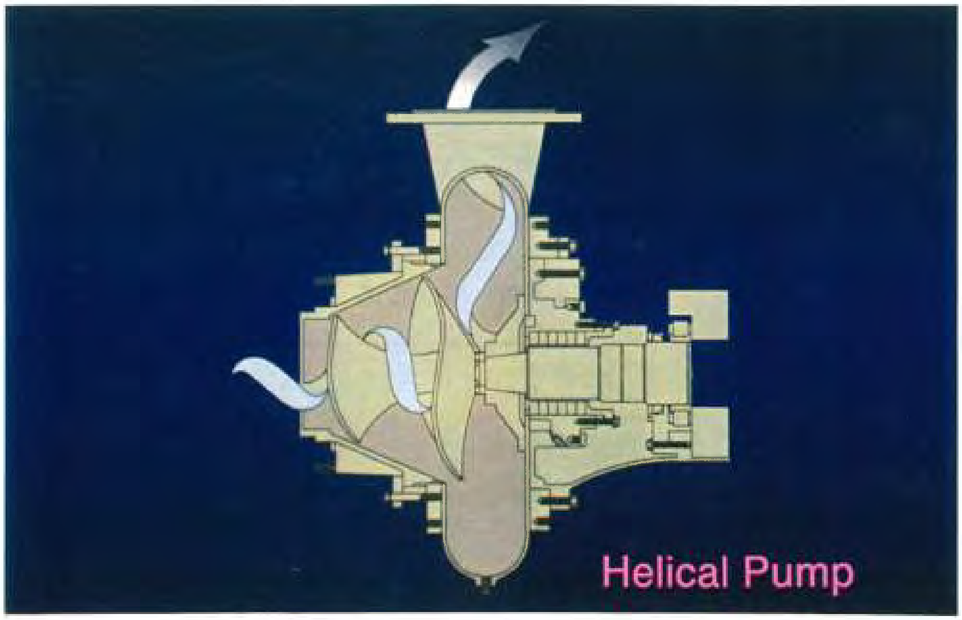

Figure 7. - Schematic views of helical pump.

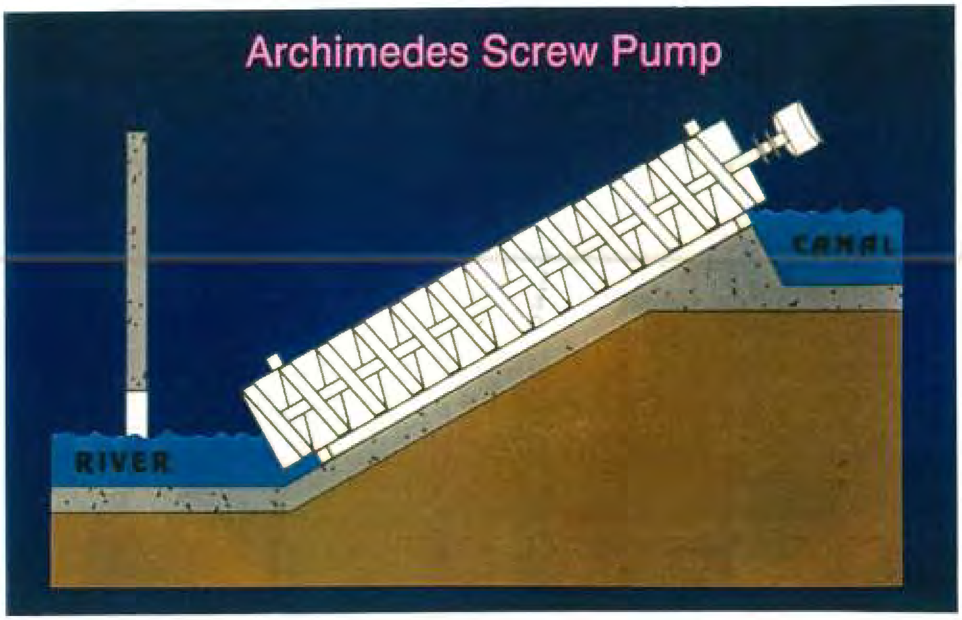

Figure 8. - Schematic view of Archimedes pump.

STREAM RESTORATION

Reclamation's water development projects have altered the charter of rivers and watersheds. We now refer to these systems as regulated aquatic ecosystems. Restoring a watershed or ecosystem damaged by physical alterations to the natural flow regime requires multidisciplinary research involving engineers, biologists, geomorphologists and others.

Muddy Creek, near Great Falls, Montana, is an example of Reclamation's stream restoration efforts. This creek has been drastically altered by irrigation return flows. Muddy Creek experienced flows of 12.3 million m^3/year before irrigation. The creek now sustains runoff of 98.7 million m^3/year. This has resulted in a 15-m incised channel in the glacially deposited silty soil since the early 1900's. Active measures to restore stream gradient and reduce erosion are underway in a cooperative project involving Reclamation, the Natural Resources Conservation Service and the local irrigation district. The erosion control demonstration project includes 19 rock ramps and 3 barbs placed along a 6.6-km reach of the creek in 1994 to control 8.2 m of stream gradient. The demonstration project will look at long term performance of the in-place technology with monitoring programs to track stream response in the short and long term.

ENVIRONMENTALLY ACCEPTABLE LUBRICANTS

Hydropower stations have historically used oil and grease for lubrication. Some of this grease inevitably enters the water, creating a source of contamination of potable water and aquatic habitat. Blum (1994) describes a test apparatus developed by the WRRL specifically to test the mechanical performance of environmentally safe greases for wicket gate bushing applications, figure 9. A 1:4 scale model of a prototype wicket gate at Mt. Elbert Powerplant, Colorado, is enclosed in a rectangular conduit with flow through the facility scaled to represent flow through one wicket gate passage. A computer-controlled, motor-driven operator is used to cycle the gate through a model test time of 20 hours. This involves 1,370 opening and closing cycles. As a result of these tests, we are able to identify several environmentally safe lubricants, which meet both water quality standards and mechanical performance requirements.

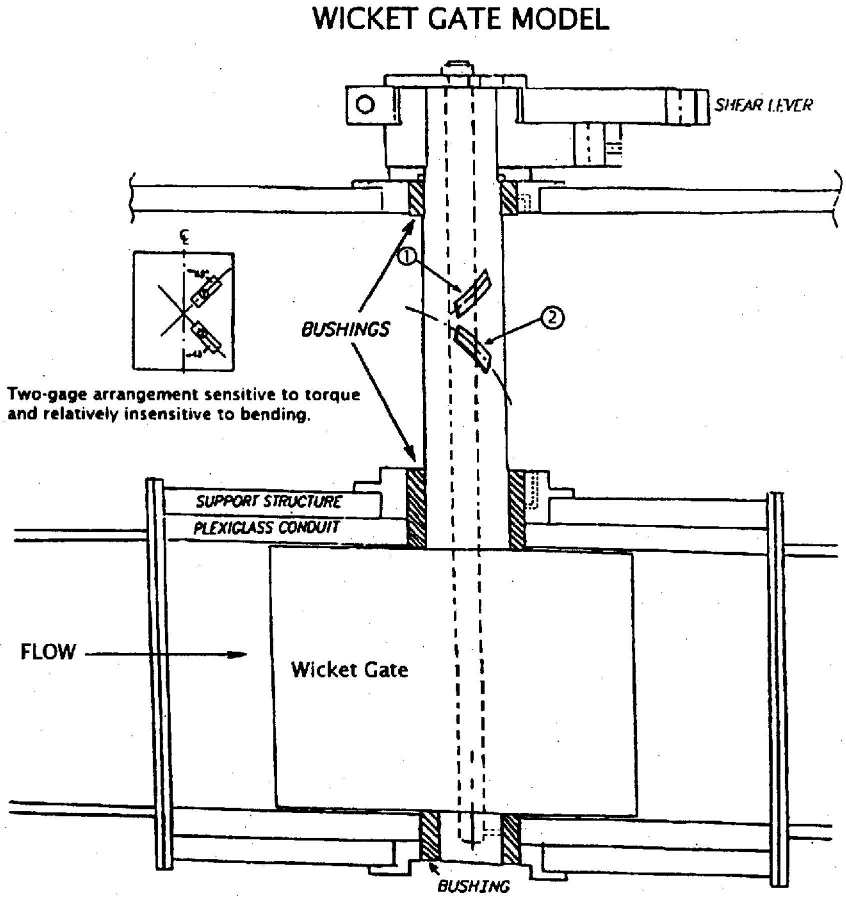

Figure 9. - Sectional view through the wicket gate lubricant test facility.

WATER QUALITY IMPROVEMENTS - DISSOLVED GASES

Hydraulic structures often dramatically affect water quality and aquatic life by changing the spatial and temporal distribution of dissolved gases within reservoirs and natural streams. Reclamation is using research to address problems of both nitrogen supersaturation and reduced dissolved oxygen concentrations downstream of energy dissipation structures and powerplants.

Spillways and outlet works associated with hydraulic structures affect the dissolved gas content of the released flow. Depending on the structure and conditions, there may be positive or negative impacts to the water quality. Releases may aerate flows depleted in dissolved gas, create supersaturated dissolved gas levels, or reduce supersaturated levels in the flow. Johnson (1975) presents an analysis to predict the effect of a wide variety of hydraulic structures on the dissolved gas content of the flow.

The Tennessee Valley Authority (TVA) has led efforts in recent years to improve dissolved oxygen conditions in reservoirs and downstream of powerplants, Bohac and Ruane (1990). Reclamation is now assisting TVA, the U.S. Army Corps of Engineers, the Iowa Institute of Hydraulic Research, and CSU with efforts to develop auto-venting turbine technologies that use aeration of powerplant flows to improve dissolved oxygen (DO) concentrations of powerplant releases. Reclamation has also retrofitted turbines at Deer Creek Powerplant on the Provo River, Utah, to improved DO concentrations through turbine aeration, Wahl (1995).

FUTURE NEEDS

There are numerous practical problems associated with hydraulic structures on water resource projects that will serve to motivate applied hydraulic research into the next century. Water use in the future will, of necessity, require continued use of hydraulic structures to effectively manage the water resource. Crucial topics for future research include:

- Improved understanding of dam breach phenomena - Research is needed to provide better data and methods for selection of breach parameters and/or algorithms typically used in programs, such as BREACH and DAMBRK.
- Removal of sediment deposition in reservoirs - Development of sediment transport bypass methods are needed for extension of reservoir life and environmental benefits.
- Development of criteria for flushing flows - Flushing flows are now used to clean silts from gravel and substrate to provide improved spawning gravels. Development of a numerical model is needed to evaluate water routing schemes and provide management options for protection and restoration of riverine habitats.
- Improved fish passage alternatives - Synergistic effort of hydraulic engineers and fishery biologists is needed to develop and evaluate new technologies for fish passage at dams. This is particularly important for the hundreds of small dams that are barriers to native species habitat.
- Improved management of regulated aquatic ecosystems - Studies are needed to improve the application of computer and communication technologies to better regulate systems in real time and thus provide for demand management.

Some of our past successes in water resource development have produced new problems in water management as societal values have changed. The challenge is to keep our hydraulic research contemporary by clearly identifying the problems and identifying those social and scientific disciplines needed as partners in developing holistic solutions.

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Table 1. - Summary table - retrofit structure selective withdrawal technologies at Reclamation's power stations.

Power Station (year constructed)	Fish species	Problem	Retrofit	Approximate cost	Actual temperature improvement	Model scale	Maximum discharge (m^3/s)	Power (MW)
Shasta Dam (1945)	Four species Chinook salmon	Winter - too cold Summer - too warm (high and low-level withdrawal needed)	Steel shutter structure attached to dam (76 m x 91 m x 15 m) (1995)	$64 M	1-5 °C (Projected)	1:72	498	540
Lewiston Dam (1963)	Four species Chinook salmon							0.35
	Steelhead trout	Winter - too cold Summer - too warm (high and low-level withdrawal needed)	**Hatchery Intake** Curtain 91 m x 11 m (1992)	$150 K	3-4 °C	No physical model	1.5	
		Too warm (low-level withdrawal needed)	**Carr Powerplant** Curtain 253 m x 9 m (1992)	$600 K	1-1.5 °C	1:120	100	
Whiskeytown Dam (1963)	Four species Chinook salmon							
		Too warm (low-level withdrawal needed)	**Spring Creek Powerplant** Intake Curtain 731 m x 30 m (1993)	$1.8 M	1-2 °C	No physical model	100	150
		Too warm (low-level withdrawal needed)	**Carr Powerplant** Curtain 243 m x 9 m (1993)	$500 K	1-2 °C	1:72	100	140
Hungry Horse Dam (1953)	Bull trout	Too cold (high-level withdrawal needed)	Semi-cylindrical bulkhead inside trashrack structure (13-m R, 61-m high) (1996)	$6.3 M	5 °C (Projected)	1:18	350	428
Flaming Gorge Dam (1962)	Trout	Too cold (high-level withdrawal needed)	Steel selective withdrawal structure on face of dam (10 m x 10 m x 67 m) (1978)	$4.6 M	8 °C	No physical model	120	108