Impact of Reclamation's Hydraulic Laboratory on Water Development

Philip H. Burgi [1]

ABSTRACT

The paper covers the history of Reclamation's hydraulic laboratory from its inception in 1930 at Colorado Agricultural Experiment Station, Fort Collins, Colorado to the present. Emphasis is placed on the laboratory's historical role in developing new design concepts for hydraulic structures to meet Reclamation's ever-increasing challenges over the past seventy years.

The paper presents the design challenges associated with specific structures such as: Hoover Dam side channel spillway, Grand Coulee Dam spillway bucket, Hungry Horse Dam tunnel spillway, and more recently the aeration slot design developed for Reclamation's tunnel spillways to prevent cavitation damage.

During the 1950's and 1960's Reclamation's hydraulic laboratory initiated an extensive research program to develop standard designs that eventually led to engineering monographs and manuals coauthored by hydraulic laboratory staff. The paper concludes with the hydraulic design challenges facing Reclamation in the next century. The water management issues associated with fish passage and water conservation as well as infrastructure security at numerous dams in the western U.S. are some of the hydraulic challenges in Reclamation's future.

BACKGROUND

The Bureau of Reclamation was established in 1902. In its first ten years eighteen dams were built. By 1930 fifty dams had been constructed. The first irrigation projects were fairly simple, consisting of a diversion dam, headworks, canals, and turnouts. These early projects involved no special challenges other than those peculiar to each site. To optimize water basin development, dams of increasing height were required and their design and construction created new problems and provided serious challenges for Reclamation's engineers.

The 1906 Congress introduced the function of hydropower when it authorized the sale of excess power generated at Reclamation projects. In 1928 Congress passed the Boulder Canyon Project Act (The name Boulder Dam was changed to Hoover Dam April 3, 1947 by joint congressional resolution). This act inaugurated a new era in the conservation and utilization of western water. Hoover Dam would be the principal structure of the Boulder Canyon Project and would introduce a new concept in western water development referred to as multi-purpose development. Other projects soon followed: the Central Valley Project, Columbia Basin Project, Colorado-Big Thompson Project, and the Missouri River Project. These multi-purpose projects optimized utilization of water and land resources in large areas of entire river basins. Rhone[1] states the quarter century between 1948 and 1973 was especially productive when more than half of Reclamation's dams were constructed.

THE EARLY YEARS

In the early years before 1930, many of Reclamation's design engineers were recruited from Reclamation's parent organization, the U.S. Geological Survey. The

[1] Founding Member EWRI of ASCE, Water Resources Consultant, Wheat Ridge, Colorado,

supervisory staff of the design units maintained extremely high engineering standards for their personnel. Typically, each design leader assembled and maintained a design manual based on their training and experience; these informal manuals were passed on to subordinates who, in turn, added to the standards and through their new knowledge and experience became even better qualified designers.

When Reclamation completed the construction of Shoshone Dam (100 m) in Wyoming in 1910, it was the highest dam in the world. In the next 25 years Reclamation held this record three more times with the construction of Arrowrock Dam (106 m) in Idaho in 1915, Owyhee Dam (127 m) built in eastern Oregon in 1933, and finally Hoover Dam (221 m) on the Colorado River in 1936.

RECLAMATION'S HYDRAULIC LABORATORY

Reclamation's hydraulic laboratory was established in the early 1930s expressly to solve the technical challenges presented in the design of these large structures. With the anticipation of designing Hoover Dam there came the recognition that this structure would impose design and construction challenges well beyond the textbooks and experience of the day. The tremendous construction costs associated with these large structures required careful attention to the preliminary design and required hydraulic model testing before one could finalize design and start construction.

Although the name "hydraulic laboratory" is relatively modern, the concept has been around for a long time. Scholars as early as Leonardo da Vinci recognized the importance of experimentation when dealing with the flow of water. He is quoted as saying, "Remember when discoursing on the flow of water to adduce first experience and then reason". [2] The purpose of the hydraulic model is to use the tool of similitude to demonstrate the behavior of flowing water at reduced scale. Typically, models are used to study rivers and waterways of hydraulic structures and equipment such as: spillways, outlet works, stilling basins, gates, valves, and pipes associated with large dams. Agreement between model and prototype has proven very satisfactory. [3, 4]

At the turn of the 20th century, some European universities and especially universities in Germany recognized the value of experimental model studies to solve hydraulic challenges such as those posed by dam spillways and outlet works, siphons, tunnel inlets, and bridge constrictions on rivers. John R. Freeman (1855-1932), a hydraulic engineer from the United States, felt very strongly that we should develop similar hydraulic laboratories to those being utilized in Europe. In 1924 he visited laboratories in Berlin, Dresden, Brunn and Karlsruhe. He had a significant influence on the development of hydraulic laboratories in the United States. Freeman writes in 1929, *"Nowhere, yet, in America has the writer found the acceptance and reliance upon the doctrines of similitude which he has found at substantially all of the great European engineering universities, and which have been developed there wholly during the past 30 years, and mainly during the past 10 years."* [5]

Beginning in the early thirties, laboratory activity in engineering schools in the United States greatly increased. Freeman describes some of the early work conducted in laboratories in the United States: Cornell University (1899), State University of Iowa (1919), Alden hydraulic laboratory of the Worcester Polytechnic Institute (1910), and several commercial laboratories conducting experimentation with hydraulic turbines. Eventually, hydraulic laboratories were established in government facilities such as the Miami Conservancy District in Ohio, the U.S. Bureau of Standards, U.S. Army Corps of Engineers, Soil Conservation Service, and the U.S. Bureau of Reclamation.

Figure 1. 1931 Photo of Reclamation Hydraulic Laboratory staff at Fort Collins

Investigations with hydraulic models had their start in the Bureau of Reclamation in August 1930 when thirteen engineers, technicians, and craftsmen from the Denver Reclamation Office began working in the hydraulic laboratory of the Colorado Agricultural Experiment Station in Fort Collins, Colorado. The 242 m^2 laboratory was built in 1912 under the direction of Ralph Parshall.

By 1935, the laboratory in Fort Collins had expanded to four times its original size to handle the ever-increasing Reclamation work load. One of the early studies was for the proposed shaft spillways for Hoover Dam. As a result of these studies a change was made from the original shaft spillway concept to two side-channel spillways to accommodate the design flow that had increased from 5,670 to 11,340 m^3/s.

In the summer of 1929, Emory Lane was appointed as engineer in charge of the Bureau of Reclamation's of hydraulic, sediment, and earth materials research studies. A graduate of Purdue and Cornell Universities, he worked for the Miami Conservancy District, Ohio before coming to Reclamation. During his 6-year period as administrator of the hydraulic laboratory, Lane initiated the comprehensive laboratory investigations undertaken for Hoover Dam, Grand Coulee Dam, Imperial Dam and de-silting works and the model studies of the All American Canal structures.

Jacob Warnock, another graduate of Purdue, came to Reclamation as an associate hydraulic engineer after working with the Corps of Engineers in their Chattanooga, Nashville, and Huntington offices. By 1934 Warnock, became head of the hydraulic laboratory in Fort Collins when Emory Lane moved to Denver to direct a small hydraulic laboratory that had been set up in the basement of the Old Custom House in Denver. Victor Streeter, who later became a renowned Professor of Hydraulics at the University of Michigan, was one of the staff members in Denver during this period.

Figure 2: Jacob Warnock (front right) with visiting engineers in the Custom House Laboratory

In a summary article written in 1936, Warnock stated, "*Models were first used extensively by the Bureau in 1930 in the design of the spillway for the Cle Elum Dam of the Yakima project in Washington. The design of the spillways for Boulder Dam, Madden Dam in the Panama Canal Zone, and Norris and Wheeler dams for the Tennessee Valley Authority, served as stepping stones in further developing the technique and improving the methods*."[6]

Warnock was a strong believer in the value of hydraulic model investigations. "*The procedure by which models of hydraulic structures are built and tested in the laboratory before the design is finally adopted and committed to construction is analogous to the manner in which a newly designed machine is thoroughly inspected for defects and imperfections at the factory. The models reveal undesirable features of the design and indicate the proper means for the correction.*" [7]

By 1935 Jacob Warnock became head of the laboratory in Denver and was instrumental in its move to the New Custom House in 1937 where there was approximately 475 m^2 available for studies.

The work of the laboratory became so prolific that Reclamation tested 80 models in the period from 1930-38 and had 50 engineers, technicians, and craftsmen working in three laboratories. "*The use of models has proved so advantageous in indicating opportunities for reducing costs and improving hydraulic properties that* *the work of the laboratories is now recognized as a regular part of hydraulic design. At the present time, the three laboratories are engaged in testing or constructing models of twenty different features relating to ten major projects*." [7]

In the fall of 1938, Reclamation discontinued its work in the Fort Collins laboratory. Warnock figured prominently in the design of the hydraulic features of Hoover, Grand Coulee, Shasta, Friant, and many other large dams and irrigation projects in the west. His untimely death in December 1949 at the age of 46 was a great shock to Reclamation's Denver Center.

The wartime westward shifting of population and industry created an impetus and need for a Reclamation construction program much larger after the war than it had been before. By 1943 Reclamation organized into seven regional areas based on large watersheds in the West and established a Chief Engineer's Office in Denver responsible for all design and construction. The small laboratory space in the New Custom House was inadequate for the enlarged program. Sufficient space was available at the former Denver Ordnance Plant (Remington Small Arms Plant) located on the west side of Denver and now referred to as the Denver Federal Center (DFC).

In the later part of 1946, the hydraulic laboratory was moved to its present home in the Denver Federal Center where it occupied some 4925 m^2 of laboratory space. At the time, Reclamation's staff at the Denver Federal Center totaled over 2240 employees. These facilities were unequaled in their specialized qualifications anywhere in the world. Design and construction engineers worked in tandem with experts in hydraulics, concrete, soils, chemical, and other laboratories to meet the new challenges of water development in the arid west.

A quote from the July 1950 edition of The Reclamation Era states, "*The combination of men and laboratory equipment is paying huge dividends to the public. Water and power users, who ultimately pay for Reclamation projects, pay for the work of the Branch of Design and Construction. They should be reassured to know that economies in construction discovered at the Center have more than paid for its total operating costs, as well as the entire cost of establishing and equipping it. Many of the money-saving techniques and materials conceived in connection with specific construction works will apply as well to later works, thus compounding the monetary economies*." [8]

There were other hydraulic laboratories developed and used by Reclamation. They were primarily field laboratories located at: Montrose, CO (1931-1936), Grand Coulee Dam (early 1940s), Hoover Dam (1939-1945), Estes Park Colorado Powerplant (late 60s and early 70s).

LABORATORY CONTRIBUTIONS

Spillways

Spillways at dams are used to pass the design flood and thus protect the dam from overtopping. Early in Reclamation history there were five general categories of spillways in use: "glory hole" or shaft-type (Gibson Dam), side-channel (Hoover Dam), overflow type (Grand Coulee), open chute type (Bartlett Dam), and enclosed tunnel chute (Seminole Dam).

The importance of adequate spillway design cannot be overemphasized.

Operating experience with spillways for dams has revealed problems of two types: (1. inadequate capacity, and (2. unsatisfactory performance for design or less-than-design discharges. Historically, Reclamation has taken a very serious position toward adequately studying spillway performance before going to final design.

One of the first major impacts resulting from hydraulic laboratory studies was the major improvement in spillway capacity resulting from the replacement of the planned glory-hole spillway design for Hoover Dam spillways with the side-channel spillway that ultimately provided the desired spillway capacity.

These early model studies were conducted at Ft Collins and Montrose as well as the Custom House in Denver. The large 1:20 scale outdoor model at Montrose was used to finalize the design of the drum gates on the side-channel spillways at Hoover Dam (total spillway capacity of 11,340 m^3/s) replacing the proposed Stony gates, which proved to be unsatisfactory during the model tests. A total of eight models were used in the hydraulic design of Hoover Dam with model scales of 1:20(2), 1:60(3), 1:64, 1:100, and 1:106.[9]

Four models were used in the design of Grand Coulee Dam ranging in scale from 1:30 to 1:184. A major improvement in the design for Grand Coulee Dam was the replacement of a proposed large hydraulic jump stilling basin with a roller bucket to dissipate the energy at the toe of the Grand Coulee spillway designed to pass 28,325 m^3/s. A construction savings of $4,750,000 (1941 costs) resulted from use of the roller bucket energy dissipator developed in Reclamation's hydraulic laboratory. [8]

Reclamation's high dam tunnel spillways proved to be a very economical means to pass large flood discharges in lieu of building large capacity surface spillways and stilling basins on the dam abutments. However, as early as the winter of 1941 when the Arizona tunnel spillway at Hoover Dam operated for 116 days there was suspicion of the vulnerability of concrete to damage caused by high velocity flow in tunnel spillways.[10] This spillway operation resulted in a large hole in the tunnel spillway elbow 14 m deep, 9 m wide and 35 m long. The damage was thought to initiate at a "misalignment" of the tunnel invert just above the elbow. The damage was caused by high velocity flow passing over the roughness and leading to bubble formation (similar to boiling water) in the flow. When the bubbles collapsed, high energy shock waves were generated damaging the concrete. This phenomena is referred to as cavitation formation and damage. In the 1940's the damage was repaired by backfilling with river rock and then covering with a thick layer of high quality concrete. The concrete surface had a very fine finish, almost terrazzo, to prevent reoccurrence of the cavitation. Tunnel spillways were later constructed at Yellowtail, Flaming Gorge, Blue Mesa, and Glen Canyon Dams.

The cavitation damage problem surfaced again in June and July 1967 when the tunnel spillway at Yellowtail Dam discharged for 20 days at 425 m^3/s. By July 14 it was evident that there was a problem in the tunnel spillway. When drained and inspected a hole 2 m deep, 6 m wide and 14 m long was discovered. In earlier laboratory investigations, the introduction of as little as 7.5% air into the water flow eliminated damage associated with cavitation on concrete surfaces.[11] In 1967, Hydraulic laboratory studies on a 1: 49.5 scale model of the Yellowtail Dam tunnel spillway resulted in design of an aerator located some distance upstream of the elbow consisting of a 760 mm high ramp that extended above the springline of the tunnel and provided air to the underside of the high velocity jet traveling through the tunnel.

The first installation of an aerator in a tunnel spillway was at Reclamation's Yellowtail Dam.[12]

In 1983, high runoff in the Colorado River basin created the need to pass flood flows through tunnel spillways at Blue Mesa, Flaming Gorge, Glen Canyon, and Hoover Dams. The resulting damage was so extensive at Glen Canyon Dam's two tunnel spillways that $42,000,000 (1985 costs) and a year of reconstruction was required to repair the spillways and install an aerator in each tunnel.[13] Reclamation conducted extensive laboratory model tests to determine hydraulic performance of the aerators at these tunnel spillways.

Figure 4. Damage to Glen Canyon Dam left spillway in 1983.
The "big hole" was 11 meters deep.

By 1985 aerators were installed in all five of these high head tunnel spillways in the western United States. The left tunnel spillway (Arizona side) at Hoover Dam experienced cavitation damage in 1983 and had to be repaired with an aerator added despite the smooth surface placed in 1943. Henry Falvey wrote a comprehensive engineering monograph summarizing Reclamation's experiences and developments in cavitation damage control entitled, *Cavitation in Chutes and Spillways*.[14] This publication was yet another of the numerous documents produced by the hydraulic laboratory staff to assist in the design of water projects.

Sediment Control Structures at Diversion Dams

In the period from 1950-1965 numerous model studies were used to develop sediment control measures at diversion dams.[15] To develop the most satisfactory solution of a sediment control problem at a diversion usually requires a "movable bed" hydraulic model study. Structures and techniques such as curved guide vanes, short tunnel under sluices, and vortex tubes were developed in the laboratory to exclude sediments. On large projects such as the All-American Canal, large settling basins were developed and built. However, the cost of these large structures was prohibitive for many of the diversion dams across the Plains States. More economical solutions were often developed which included a simple gated sluiceway and using some of the water as a means to bypass the sediments around the diversion intake structure.

Gates and Valves

It was clear in the 40's that as the size of dams and reservoirs increased, for economic reasons it became necessary to design projects for multiple use, such as flood control, irrigation, power development, and river regulation for navigation. The rigorous demands imposed by such multiple use of a storage dam required that the outlets be designed to give close regulation of the rate at which stored waters were released. The increase in dam height lead to higher pressures and velocities and in many cases the need for larger capacity outlets. Many improvements in the mechanical design of gates and valves were made to meet the challenge of these new conditions. However, most gates and valves were designed for simple open or closed operations. Regulation in some cases was made by providing numerous outlets controlled by gates such as those used at Grand Coulee Dam where increase or decreases could be made in finite increments equal in value to the capacity of a single outlet. Most valves developed prior to the 1930's were designed for pressure heads up to 130 m, totally inadequate for the new dams proposed.

The Hoover Dam tunnel-plug outlets provided the most outstanding challenges. Each tunnel had six – 1830 mm needle valves under pressure heads up to 171 m which discharge up to 623 m^3/s into a 15 m diameter concrete tunnel. The laboratory model studies included tests at scales of 1:106, 1:60, and 1:20 to assure the validity of the design against any scale effects. The final configuration selected represented a distinct improvement over those originally proposed. The laboratory tests also showed that large air vent tunnels originally proposed were not necessary resulting in construction savings of $30,000 (1932 costs).[16] There were several occasions in the 1980's where the old internal differential needle valves failed during uncontrolled closure. In some cases, these uncontrolled closures resulted in loss of life. In the early 1990's Reclamation undertook additional studies to replace all of their needle valves across the West. The needle valves were soon replaced with large jet flow gates developed by Reclamation in the late 40's for Shasta Dam.

The preferred large valves for Reclamation dams were the needle valves (1909-1942) and the hollow jet valves (1950-1967). Over the years, Reclamation has upgraded outlet gates and valves from the early Ensign valves (1905-1915), to needle valves (1909-1942), to tube valves (1941-1945), to hollow-jet valves (1950-1967) and jet-flow gates (1945-67). James Ball, Donald Colgate and Donald Hebert were three key hydraulic laboratory contributors to Reclamation's work in the development of high-head outlet gates.[17] A 1973 American Society of Civil Engineering article gives a summary of some of these gates and valves and their installations across the United States.[18]

Hydraulic Laboratory Techniques

In 1955 hydraulic laboratory personnel published Engineering Monograph No.18 entitled *Hydraulic Laboratory Practice*. It was prepared as an aid in applying engineering knowledge and experience to hydraulic laboratory studies. Emphasis was placed on the basic principles of similitude; techniques of model design, construction, and operation; equipment; and field studies. The volume which has been used in hydraulic laboratories world-wide was updated in 1980 on the golden anniversary of the Bureau of Reclamation's first hydraulic model tests.[19]

Stilling Basins and Energy Dissipators

Although hundreds of stilling basin and energy dissipating devices have been designed and built for spillways, outlet works, and canal structures, it is often necessary to make model studies of individual structures to be certain that these will operate as anticipated. In the early 1950's a ten-year laboratory research effort was undertaken to develop general design criteria for stilling basins and energy dissipators. Existing information was gathered from laboratory and field tests collected from Reclamation records and experiences over a 23-year period. Hundreds of additional tests were conducted using six laboratory test flumes. The largest flume was 102 mm wide, 24 m long with an available height of 5.5 m and a discharge capacity of 800 l^3/s. Tests included hydraulic jump stilling basins, short stilling basins for canal structures and small spillways, wave suppressors for canal structures, sloping apron stilling basins, slotted and solid bucket energy dissipators, baffled apron drops, tunnel spillway flip buckets, and test to size riprap downstream of stilling basins. This effort conducted solely in Reclamation's hydraulic laboratory and supervised by Alvin Peterka, resulted in the world renowned Engineering Monograph No. 25 entitled, *Hydraulic Design of Stilling Basins and Energy Dissipators* [20], which has been used for many years as a standard for such hydraulic structures world-wide.

By the 1970s the trend for spillway terminal structures had returned to the flip bucket - the principle used was to direct the flow away from the structure and downstream a sufficient distance where the water could erode its own plunge pool or discharge into a pre-excavated plunge pool. Devices such as a combined hydraulic jump/flip bucket were used for the tunnel spillway at Yellowtail Dam and the surface spillway at McPhee Dam. The energy is dissipated within the basin at the end of the tunnel spillway up to a predetermined discharge where the jump flips out and the structure acts as a flip bucket for larger discharges. Most of the tunnel spillways previously mentioned terminate with flip buckets designed based on various hydraulic model studies in the 50's and 60's.

A device called a baffled apron drop was developed in the laboratory primarily for use on canals as a drop structure at wasteways. In the late 1970's laboratory staff started looking at the baffled apron drop as a spillway structure for dams. In the 80's many baffled apron drops were used as spillways on several Reclamation dams as well as for the States of Washington, New Mexico and Nevada (Conconully Dam, Truth or Consequences Dam, Marble Bluff Dam).

THE HYDRAULIC LABORATORY IN THE 21st CENTURY

At the beginning of the 21st century, Reclamation continues to use the laboratory facilities at the DFC, however there have been many changes over the past 70 years. There are new and improved microprocessor laboratory controls. An ozonator system has been installed to improve water quality and provide for longer use of recirculated water. There have been giant strides in electronic control and measurement as well as increased use of hybrid modeling where numerical and physical modeling techniques are brought together to better understand fluid mechanics. Skilled craftsmen who build the intricate models have always been part of the laboratory staff and continue to play a key role in laboratory studies.

Reclamation's hydraulic structures and equipment investigations and development in the period from 1930 through the 1970's resulted in world class technological advancements in water-resource development. However by the latter quarter of the 20th century, a major paradigm shift had occurred with water development in the United Sates. As public values shifted toward more environmental sensitivity, water agencies changed their focus from an emphasis on *water development* to *water management*. Reclamation's hydraulic laboratory program maintained a contemporary focus throughout these changes over time. The new focus led to an emphasis on developing improved technologies for **(1.** *protecting the public and existing water infrastructure*, **(2.** *encouraging water-use efficiency*, and **(3.** *emphasizing environmental enhancement on regulated river systems*. [21]

In the area of <u>water infrastructure protection</u>, Reclamation's hydraulic laboratory has played a key role in the development of cost-effective spillway designs focused on dam safety issues. Alternative spillway designs, fuse plug concepts, and overtopping protection concepts have been tested and developed. Laboratory research on the labyrinth spillway concept produced design criteria that were applied to the 14 cycle labyrinth spillway for Ute Dam in New Mexico.[22] The labyrinth spillway resulted in construction savings of over $24,000,000 (1982 costs) compared to a traditional gated structure at Ute Dam.[21]

Another alternative spillway design gaining acceptance in the engineering community is the fuse plug concept. Reclamation's hydraulic laboratory advanced the science and acceptance of fuse plugs now used at several Reclamation dams.[23] The construction savings realized by using fuse plugs for additional spillway capacity for Horseshoe and Bartlett Dams on the Verde River in Arizona were in the range of $150-300 million (1984 costs).[21]

Stepped spillway design criteria developed in Reclamation's hydraulic laboratory played a pivotal role in its world-wide acceptance in the 1990's. Stepped spillways are very compatible with Roller Compacted Concrete (RCC) construction and provide an economical spillway when constructed as an integral part of the dam. Hydraulic model studies of stepped spillways for McClure, Milltown Hill, Stagecoach, and Upper Stillwater Dams in the late 1980's were critical in defining energy dissipation characteristics and hydraulic performance of this new concept.[24]

Another recent advancement has been the protection of embankment dams during overtopping occurrences. Studies performed in Reclamation's hydraulic laboratory as well as tests performed in a large-scale outdoor overtopping facility at Colorado Sate University have proven the viability of 305 mm wide, 51 mm high, and 610 mm long concrete blocks to protect the surface of an embankment**.** [25]

<u>*Water-use Efficiency*</u> continues to play an important role in Reclamation's program. The Western United States depends on a water storage and delivery system built over the past 150 years to provide water for irrigated agriculture, municipal and industrial use, power generation, and recreation. Population growth and environmental water requirements place additional demands on a limited supply and require managers to look for water-use efficiencies. In response to this reality, the

hydraulic laboratory has placed increased emphasis on conservation technologies. The ability to measure discharge in open channels on Reclamation projects has been dramatically improved in the last twenty-five years by the development, in cooperation with Agricultural Research Service, of the long-throated flume and broad-crested weir measurement methods as well as other technologies that are robust, low cost and accurate.

In 1953 Reclamation's hydraulic laboratory produced the first edition of the *Water Measurement Manual*. It was compiled from Reclamation's Manual for Measurement of Irrigation Water published in 1946. A second edition was published in 1967. The most recent edition published in 1997 still emphasizes the basics of water measurement but is updated to include the latest measurement technologies.[26] It is also available at: **http://www.usbr.gov/pmts/hydraulics_lab/.**

In addition to water measurement, the laboratory staff has worked for over thirty years in development of water system automation technologies. Reduced cost and increased capabilities of sensors, computer hardware, software, and data telemetry systems have brought practical canal automation capabilities within reach of the majority of water and irrigation districts in the western United States, including many smaller and older districts that still operate their systems using the same methods used decades ago**.**

Future water development will be closely linked with *environmental enhancement* as Reclamation continues to play a role in providing a high standard of living while protecting environmental resources. Historically, Reclamation has had a concern for the natural environment especially as it may impact fish and wildlife resources. In the late 1950's Reclamation's hydraulic laboratory staff assisted with the development and field and laboratory testing of a pilot fish screen structure constructed in the headworks of the Tracy Pumping Plant.[27]

More recently, several fishery and stream restoration projects have built on this earlier experience and illustrate this new enhancement approach. To improve the winter-run Chinook salmon population in the Sacramento River, the laboratory initiated an aggressive research study to develop temperature-control curtains in reservoirs such as Lewiston and Whiskeytown Lakes.[28] The use of this new temperature-control technology, as well as the steel shutter structure at Shasta Dam, has increased the selective withdrawal capability within the Sacramento River basin and improved the management of the river temperature by several degrees and greatly improving the habitat for anadromous fish species. The laboratory has also been involved in retrofitting several Reclamation dams to provide selective withdrawal capability: Shasta, Lewiston, Whiskeytown, Hungry Horse, and Flaming Gorge Dams.

Within Reclamation a bioengineering focus (biological science and engineering) has led to new, innovative concepts for using hydraulic structures to manage regulated water systems in the West. This cooperation of hydraulic engineering and biological sciences in recent years has produced innovative technologies for fish screening, fish separation and handling, and fish passage upstream and downstream at dams and diversion works. These research efforts and experiences will soon be published as a Reclamation fisheries manual. On many Reclamation projects these advancements have been crucial to maintaining water deliveries while also providing new environmental benefits.

SUMMARY

The history of Reclamation's hydraulic laboratory is a story of engineers, technicians and craftsmen who have had an attitude and work ethic best characterized by their persistent high quality work used to tackle the challenges of water development in the West. To some degree, they were exceptional individuals but for the most part their greatest achievements resulted from their ability to work as a team. Although some individuals have been mentioned in this paper, one needs to recognize that the greater gains were almost always the effort of a team. There are many excellent engineers on the present staff who no doubt will become part of the great legacy of Reclamation's hydraulic laboratory. Future generations will make those judgments. Suffice to say, that Reclamation and the nation have benefited greatly by the productivity of the hydraulic laboratory staff over the past seventy years. There are new challenges facing today's laboratory engineers and scientists and their responses to these challenges will define the future legacy of the laboratory.

REFERENCES

1. Thomas J. Rhone, 50th Anniversary of the Hydraulics Division 1938-1988, ed. Adnan M. Alsaffar (ASCE, 1990), 132-147.

2. Gunther Garbrecht, ed., Hydraulics and Hydraulic Research A Historical Review- International Association for Hydraulic Research 1935-1985, A.A.Balkema/Rotterdam/Boston/1987.

3. "Conformity Between Model and Prototype in Hydraulic Structures", Transactions, American Society of Civil Engineers, Vol 109, pg 3-193.

4. Philip H. Burgi, ed, Model-Prototype Correlation of Hydraulic Structures, Proceedings of the International Symposium, American Society of Civil Engineers, August 9-11, 1988. Pp 1- 480.

5. John R. Freeman, ed., Hydraulic Laboratory Practice, The American Society of Mechanical Engineers, 1929, 1-4, 17, 28-32, 697-742.

6. Jacob E. Warnock, "Experiments Aid in Design at Grand Coulee", Civil Engineering, November 1936, pp.737-741.

7. U.S. Department of the Interior, Bureau of Reclamation, Dams and Control Works, February 1938, 205-212.

8. U.S. Department of the Interior, Bureau of Reclamation, The Reclamation Era, February, 1941, 29-32 and July 1950,127-128.

9. Boulder Canyon Project Final Reports, U.S. Department of the Interior, Bureau of Reclamation, Part VI- Hydraulic Investigations, Bulletins 1-3, 1938.

10. Keener, "A Challenge to Hydraulic Designers", Engineering News Record, November 18, 1943.

11. A. J. Peterka, “The Effect of Entrained Air on Cavitation Pitting”, Proceedings of the Joint Meeting of the International Association for Hydraulic Research, ASCE, Minneapolis, MN, August 1953.

12. D. Colgate, “Hydraulic Model Studies of Aeration Devices for Yellowtail Dam Spillway Tunnel”, U.S. Department of the Interior, Bureau of Reclamation, REC-ERC-71-47, 1971, 13.

13. P.H. Burgi and M.S. Eckley, “Repairs at Glen Canyon Dam,” Concrete International: Design and Construction of the American Concrete Institute, March, 1987, pp. 24-31.

14. H.T. Falvey, Engineering Monograph No. 42 Cavitation in Chutes and Spillways, U.S. Department of the Interior, Bureau of Reclamation, 1990, 145.

15. Enos J. Carlson, “Laboratory and Field Investigations of Sediment Control Structures at Diversion Dams”, Ninth Congress on Irrigation and Drainage, International Commission on Irrigation and Drainage, Moscow, 1975.

16. Engineering News Record, “Hoover Dam Number”, December 13, 1932.

17. D.J. Hebert and J. W. Ball, “The Development of High-Head Outlet Valves”, Report on Second Meeting, Appendix 14, International Association for Hydraulic Structures Research, Stockholm, Sweden, June 6-7, 1948.

18. Cortland C. Lanning, “High Head Gates and Valves in the United States”, Journal of the Hydraulics Division, ASCE, Vol. 99, No Hy 10, October, 1973, pp. 1727-1775.

19. J.C. Schuster, ed., “Hydraulic Laboratory Techniques”, U.S. Department of the Interior, Bureau of Reclamation, 1980, 208.

20. A. J. Peterka, Engineering Monograph No.25 Hydraulic Design of Stilling Basins and Energy Dissipators, U.S. Department of the Interior, Bureau of Reclamation, 1964, 217.

21. Philip Burgi, Issues and Directions in Hydraulics , eds. Tatsuaki Nakato and Robert Ettema A.A.Balkema/Rotterdam/Brookfield/1996,187-198.

22. K.L. Houston, “Hydraulic Model Study of Ute Dam labyrinth Spillway”, U.S. Department of the Interior, Bureau of Reclamation, GR-82-7, August, 1982, pp 41.

23. C.A. Pugh, “Hydraulic Model Studies of Fuse Plug Embankments”, REC-ERC-85-7, December, 1985.

24. Kathleen L. Houston and Alan T. Richardson, “Energy Dissipation Characteristics of a Stepped Spillway for an RCC Dam”, International Symposium on Hydraulics for High Dams, Beijing, China, November 15-18, 1988.

25. Kathleen H. Frizell and Brent W. Mefford, “Designing Spillways to Prevent Cavitation Damage”, Concrete International: Design and Construction of the American Concrete Institute, May, 1991, pp. 58-64.

26. Water Measurement Manual,3rd ed., U.S. Department of the Interior, Bureau of Reclamation, 1997, pp.400.

27. Thomas J. Rhone and Daniel W. Bates, “Fish Protective Facilities at the Tracy pumping Plant-Central Valley Project California”, 9th Hydraulics Division Conference, American Society of Civil Engineers, Seattle, WA, Aug 17-19, 1960.

28. Tracy B. Vermeyen and Perry L. Johnson, “Hydraulic performance of a flexible curtain used for selective withdrawal- a physical model and prototype comparison”, Proceedings, ASCE National Hydraulic Engineering Conference, 1993.