HISTORY OF DRAINAGE IN THE BUREAU OF RECLAMATION

A History of Subsurface Drainage in the Bureau of Reclamation

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ABSTRACT

In the early days of the Reclamation Service, the criteria for irrigability of lands generally consisted of two elements: 1. Is water available? and 2. Can we get it to the land? Within a few years, many of the early projects were experiencing reduced agricultural productivity and reduced ability to repay construction loans because their soils were becoming waterlogged and saline. By 1915, construction of subsurface drainage facilities had been initiated on several projects. However, at the time, subsurface drainage was more of an art than a science. Much of the world's experience with agricultural drainage had been gained in humid areas which are quite different than arid areas. With no standards and limited knowledge of ground water movement, these early drainage efforts met with varying degrees of success.

Faced with large areas of nonproductive land, several irrigation districts requested and were granted deferments in their repayment contracts. Congress responded over a period of some 30 to 40 years by passing a series of laws that progressively attempted to correct the deficiencies in Reclamation's project formulation procedures. The Fact Finders' Act of 1924 initiated the economic land classification in which lands were charged according to their potential productivity. The Omnibus Adjustment Act of 1925 reduced the repayment obligations for several districts due to nonproductive lands. The Reclamation Act of 1939 provided for periodic reclassifications to adjust classifications based on current productivity. The Interior Department Appropriation Act of 1954 required the Secretary of the Interior to certify sustainable productivity of the lands by means of irrigation. This law provides that the Secretary of the Interior must certify to the Congress that lands to be developed for irrigation are suitable for sustained productivity under irrigation. This means that the lands must be drainable at a cost that is economically feasible within the limits of the repayment capacity of the lands.

To meet this challenge, Reclamation drainage engineers developed scientific methods for conducting soil and water investigations and mathematical procedures for the design of subsurface drainage facilities. Reclamation first adopted existing steady-state methods for drain design and later developed the more accurate transient-state procedures that are in use today. The methods and procedures developed by Reclamation have proven to be successful not only in correcting problems that develop on irrigated lands but also in predicting the drainage requirement before water is applied to the land.

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Reclamation drainage engineers were also involved in the development of modern construction practices and in the development of modern materials such as corrugated perforated plastic pipe which is used in drain construction today.

Even armed with the legal authority and the technical knowledge to develop sustainable irrigation projects, good drainage practices were not always followed. Political decisions that run counter to the best available technical knowledge have contributed to such actions as the Riverton Third-Division buy-back and subsequent resale, and the utilization of Kesterson Reservoir as a terminal storage facility for return flows. Agriculture in California's fertile Central Valley remains in jeopardy because the planned outlet drain has never been constructed. The curtailment of the Oahe and Garrison Diversion Projects were in part due to misconceptions regarding drainage. While these decisions did not make use of the best technical expertise, they are nonetheless an integral part of Reclamation's drainage history.

By the 1950s, Reclamation had gained recognition as a world leader in the field of subsurface drainage. Reclamation drainage engineers have been responsible for the construction of several thousand miles of subsurface drains that maintain the productivity of over a million acres of irrigated land in the western United States. They have also been actively engaged in successful drainage projects in many countries around the world.

This paper includes brief discussions of how the need for drainage helped to shape Reclamation law as we know it. It also summarizes the development of scientific methods to ensure success. Some of the early projects that suffered drainage problems, and the challenges and successes in providing drainage, are also discussed. Reclamation has introduced these methods to solve irrigated drainage problems at the international level. We will address the international experience, and how the same methods and procedures are now being used to design corrective drainage facilities for dams and other major structures and to support environmental enhancement programs.

INTRODUCTION

Drainage of irrigated lands by the Bureau of Reclamation began shortly after the passage of the Reclamation Act in 1902. However, not until the late 1940s and early 1950s did engineers in the Bureau of Reclamation begin pioneering efforts to develop the technology of drainage of irrigated lands into a modern engineering science. (USBR 1993)

In the early days of Reclamation, the criteria for bringing land under irrigation was quite simple. If water was available and if it was economically feasible to get it to the land, the land was irrigable. Within a few years of development, waterlogging and salinity became serious problems for some of the irrigation districts. Beginning in 1911, the Huntley Project on the Yellowstone River in Montana constructed subsurface drainage systems that were very successful in returning the lands to full productivity. However, subsurface drainage was more of

an art than a science at the time. Much of the world's experience with agricultural drainage had been gained in humid areas which are quite different than arid areas. A lack of standards and limited knowledge of ground water movement led to early drainage efforts which met with varying degrees of success. Huntley is located on coarse alluvial deposits that drained easily and were very forgiving if the drain was not placed in exactly the right location, orientation, and depth. For other projects, such as Belle Fourche in western South Dakota, the solutions were more difficult. Attempts at drainage met with limited success at best and in many cases they were completely unsuccessful.

Faced with large areas of nonproductive land, several Irrigation Districts requested and were granted deferments in their repayment contracts. Over the years, Congress passed various acts aimed at developing a sustainable irrigated agriculture in the western United States.

In order to ensure development of lands that could be kept in production within economic limits, Reclamation drainage engineers realized that they needed better methods of measuring soil permeability, a better understanding of soil salinity factors, and better drain spacing procedures. Working in cooperation with the U.S. Salinity Laboratory and other researchers who were struggling with the same issues, they adopted state-of-the-art standards for soil salinity, sodicity, and toxicity to various trace elements. Various in-situ permeability tests were developed and perfected. They adopted the steady-state drain spacing formula or ellipse equation as it is often called. Although several authors have published the same formula in different forms, Reclamation typically uses William Donnan's version which was published in 1935. While the Donnan formula is generally considered acceptable in the industry, it does not account for variations in irrigation practices nor does it account for specific yield, the natural water storage capacity of soils. To address these deficiencies, Reclamation engineers developed transient-state procedures that more accurately defined the required spacing and provided for risk analyses of drain systems. The first version of the transient-state procedure, published in 1953, underwent various modifications for about the next 15 years.

When the Chief Engineer's Office was established in 1948, it included the Drainage Engineering Section. This marked the first centralized effort to address drainage issues in Reclamation. Design standards were developed in order to achieve consistency of methods throughout Reclamation. The location, depth and orientation of pipe drains were designed to achieve the greatest system efficiency. Materials used and gradation and placement of envelope materials were controlled by standards, as were construction deviation tolerances. The standards were generally monitored and enforced by the Denver Office drainage staff.

Within the organizational framework of Reclamation, the drainage discipline has been unique in that it has been intimately involved in every phase of irrigation projects, from the preliminary planning through design and construction and, finally, operation and maintenance (O&M). The office originally designated Drainage Engineering Section later became the Drainage and Ground Water Division, and later still the Drainage and Ground Water Branch of the Engineering and

Research Center. From 1953 to 1994, the Reclamation Instructions required each Regional Director to have a Regional Drainage Engineer on staff. This person was to ensure that the Drainage and Ground Water organization in the Region was properly staffed and that Reclamation drainage policy was followed. On the organizational charts of that period, the Drainage and Ground Water Branch was located in the Planning Division in two of the seven Regions, in the Construction Division in one Region, and in the O&M Division in four Regions. The functional statements were nearly identical in all of the offices. There has never been a Drainage Office in Washington, D.C., but for many years there was a Drainage Liaison position in the Planning Division.

Construction techniques have evolved over the years, sometimes in response to Reclamation design standards. Contractors developed new and better ways to handle envelope materials and to maintain grade within the limits of specifications.

In the late 1960s, the plastic pipe industry developed corrugated polyethylene and polyvinyl chloride tubing for use in agricultural drains. Reclamation's Open and Closed Conduit Systems (OCCS) research program was deeply involved in writing corrugated flexible plastic pipe standards.

From the 1950s, through the 80s, Reclamation's drainage program was heavily involved in irrigation and drainage projects all around the world. The methods and procedures developed for use in the western United States proved to be useful wherever we went and the experience gained in other countries was used to modify and bolster the domestic program.

In 1978, the Drainage Manual containing "the engineering tools and concepts that have proven useful for planning, construction, and maintaining drainage systems for successful long term irrigation projects" was published as a Department of the Interior water resources technical publication.

In recent years, the methods and procedures that were developed for agricultural drains are gradually being accepted for use in control of seepage from dams, slope stabilization and other non-agricultural applications.

LEGISLATION

Fact Finder's Act (December 5, 1924)

The status of some Federal Reclamation projects of the western United States in the early 1920s was dire. Waterlogging and salinity problems were widespread and such conditions had not been anticipated. Lands were failing, farmers were failing, and costs for corrective measures were far greater than the costs originally anticipated. The U.S. Government decided to take action in the Fact Finder's Act of 1924, which charged the Secretary of the Interior, the cabinet official

responsible for federal irrigation development, that irrigable lands shall be classified with respect to their capacity to support a farm family and pay water charges. The Secretary was also empowered in that act to apportion equitably the total costs assessed against the irrigable lands so that they all would pay in accordance with their productivities. Thus, a federal irrigation development would be composed of lands having varying productivities and payment capacities, but all would have to be able to support a farm family and pay operation and maintenance costs.

Omnibus Adjustment Act (May 25, 1926)

This act adjusted water-right charges on specified projects (Belle Fourche, SD; Boise, ID; Carlsbad, NM; Grand Valley, CO; Huntley, MT; King Hill, ID; Klamath, OR; Lower Yellowstone, MT-ND; Milk River, MT; Minidoka, ID; Newlands, NV; North Platte, NB-WY; Okanogan, WA; Rio Grande, NM-TX; Shosone, WY-MT; Sun River, MT; Umatilla, OR; Uncompahgre, CO; and Yakima, WA.) The adjustments were deductions from the total repayment of projects costs because of unproductive lands determined by land classification. Lands that were found to be permanently unproductive, generally due to waterlogging and salinity, were excluded from the projects.

Reclamation Act of 1939 (August 4, 1939)

This act provides that the Secretary of the Interior is authorized to require provisions in Reclamation water contracts for proper accounting, to protect the condition of project works, and to protect project lands against deterioration "due to improper use of water." The contracts will also require advance payment of adequate operation and maintenance charges. This act requires the classification or reclassification of project lands from time to time but not more often than at 5-year intervals "as to irrigability and productivity those lands which have been, are, or may be included within any project." The reclassification is to be done only at the request of the water users association or other authorized representatives of the water users.

Interior Department Appropriation Act, 1953 (July 9,1952)

This was the first law that requires the Secretary of the Interior to certify to the Congress that an "adequate soil survey and land classification has been made and that the lands to be irrigated are susceptible to the production of agricultural crops * * *" before any appropriation for any of the construction items for a project is available. This requirement was repeated in the Interior Department Appropriation Act of 1954 and is generally cited under that law.

Interior Department Appropriation Act, 1954 (July 31, 1953)

This act provides that no appropriation for any of the construction items for a project is available until the Secretary certifies to the Congress that an adequate soil survey and land classification has been made and that the lands can be successfully irrigated.

Drainage and Minor Construction Act (D&MC) - Public Law 575 approved June 13, 1956

The so-called D&MC Act provides for funding up to $200,000 per year for irrigation districts to correct minor deficiencies that developed after the transfer of facilities to the District for operation and maintenance. The District enters into a contract with the United States to construct or repair minor facilities not to exceed $200,000 per year. One of the more common deficiencies is inadequate subsurface drainage. The law allows Districts to construct drainage facilities as the need develops over time. In some instances, it has been used in conjunction with a much larger rehabilitation and betterment (R&B) contract in order to get the most benefit from the dollars spent. The D&MC loan is repayable at the rate established by the District's primary repayment contract and usually is tacked on to the end to extend the time of repayment rather than increasing the amount of the payments.

Food Security Act of 1985

The Food Security Act of 1985, otherwise known as the Swampbuster Act, makes producers ineligible for certain U.S. Department of Agriculture farm program benefits if they convert wetland and use it to produce agricultural commodities after December 23, 1985. The problem then becomes determining what constitutes a "jurisdictional" wetland. The USDA Soil Conservation Service (renamed National Resources Conservation Service) was charged with making that determination on a case-by-case basis. Rules for making the determination were published in the Federal Register on September 17, 1987, and by October 1, 1987, wetland determinations had been made on about 750,000 acres on 34,000 farms. (Schnepf)

The Swampbuster Act did not have a profound impact on Reclamation's drainage program because our mission is to maintain agriculturally productive lands in a productive state, rather than draining jurisdictional wetlands. Nevertheless, it changed the process in that every proposed drainage project is now subject to Swampbuster rules and we must be vigilant in avoiding incidental drainage of wetlands.

Garrison Diversion Unit Reformulation Act of 1986.

This Act requires that Reclamation conduct investigations and provide an estimate of any trace elements or toxic substances which may be present in return flows from irrigation. In order to make this estimate, it is necessary to explore the entire soil profile through which the drainage water from the project will flow.

Federal Reports Elimination Act of 1998, P.L. 105-362, November 10, 1998.

This act eliminated the certification of land classification requirements by striking pertinent language of the 1953 and 1954 Appropriations Acts and Section 10 of the Garrison Diversion Unit Reformulation Act. Reclamation may seek to reestablish the certification through legislation.

DEVELOPMENT OF TRANSIENT STATE DRAIN SPACING PROCEDURES

The Bureau of Reclamation used a steady-state equation known as the ellipse equation to determine spacing between drains until the early 1950s. An adjustment to the equation is made to account for dissimilar flow conditions where drains are placed directly on an impermeable soil layer ("on barrier") rather than at some distance ("above-barrier"). The validity of the drain spacing obtained by use of the ellipse equation is dependent upon the assumed steady recharge of water to the water table. The steady-state assumptions seldom represent the conditions produced by intermittent irrigation applications nor do they account for water storage capacity of the soil profile.

Reclamation drainage engineers believed that more precise drain spacings could be computed using an equation that reflected the typical pattern of irrigation applications with alternate drain-out periods and would also account for storage capacity. Reclamation drainage staff embarked on an initiative to develop a drain spacing procedure which would be applicable to widely varying soil and ground-water conditions.

During the 1940s and 1950s, drainage field personnel were making many drainage investigations of soils across the western United States. The information collected during these investigations included the capacity of the soils to transmit water; the amount, source, movement, and chemical characteristics of the water to be transmitted; and the available hydraulic gradients. The data they were accumulating were sent to the Chief Engineer's Office and were used by Drainage Division staff to develop the transient-state spacing procedure.

Ray Winger initially conceived the transient state spacing theory and recruited Robert E. Glover to develop the mathematics. (Winger 2001) Glover had previously worked on the heat flow formulas that were used to cool the concrete at Hoover Dam. (Cunningham) Because the physics of heat flow is very similar to the physics of ground-water movement, Glover was able to adapt the heat transfer formulas for cooling a flat slab with initial uniform temperature distribution to the problem of ground-water movement to a drain.

In 1953, the transient-state procedure used an initial flat water table for drains above the barrier and second degree curve for drains on the barrier. (Dumm 1953) Winger and Glover worked together to adjust the shape of the curve based on field data from the Redfield Research Farm on the Oahe Unit in South Dakota. William Ryan installed and monitored wells on the drainage research plots at the Redfield farm to determine the water table response to various recharge and drawdown events. (Winger 2001)

In 1959, the Office of Drainage and Ground Water Engineering sent a memorandum to all Regional Directors presenting new formulas which redefined the initial shape of the water table between drains to more closely match conditions found on functioning drains in the field. (Maierhofer) This description of the initial water table condition for the drain spacing solution is

important because it more accurately predicts the height of the water table than the formula with a flat initial water table and relates the behavior of the water table to time, physical subsurface characteristics, and drain spacing. The validity of this new concept of water table shape over a subsurface drain was checked extensively using data from Australia, Canada, and the western United States. Good correlation was found between the computed and measured values. (Dumm 1962)

In 1966, W. T. Moody wrote a computer program that used a stable finite-difference formulation to solve the nonlinear differential equations for various depths to barrier from zero to infinity and a fourth degree parabola initial water table condition. This is the first time the fourth degree parabola initial water table shape was applied to the drain on barrier case. This is the basis for the drain-out curves that were published in the Drainage Manual. (Cunningham) The curves serve as a tool for designers, eliminating the need to slog through the rigorous mathematics for each new drain spacing effort. The intermediate curves have largely been underutilized by the drainage community although recent authors are discovering this important work.

The success of the development of the transient-state formula in design of drains is due to the flexibility of the drainage engineers at that time. They were willing to apply the theoretical to the practical and use the results to refine and redefine the theoretical. Glover, Maierhofer, Dumm, Winger, and Moody were also willing to look at field results and revamp the formulas for transient-state drain spacing.

DEVELOPMENT OF DESIGN STANDARDS

It has been said that drainage is as much an art as a science. As quaint as this sounds, as long as it was true, failure to achieve satisfactory results would always be a probable outcome of building complex drainage systems. On the Shoshone Irrigation Project, for instance, many drains were placed at 12 to 14 feet below ground, depending on how deep the contractor could bury them. This was done in the early 1950s in the belief that deeper was better without regard to scientific examination of the soil profile. The problem was that the shale barrier was at 8 to 10 feet - above the drain - in most locations. As a result, the drains are painfully inefficient. Although the drains do seem to work as well as they would at the barrier depth, the spacing is too wide, because it was based on the deeper depth.

Reclamation adopted the attitude that failure was unacceptable. The cost was just too great. With this motivation, Reclamation set out to establish design standards that would be as close to failsafe as good science and responsible economics would permit.

The Function Statement of the Drainage Section, Chief Engineer's Office in 1948 charged the Section with the task of developing Reclamation-wide standards for drainage. Design standards were needed to establish consistency and to protect the taxpayers and the water users from spending large sums of money for facilities that offered a low rate of success. Over the years,

Reclamation's policy toward ground water control has evolved to a stated policy that "...drainage construction is an integral part of all irrigation projects." Typically, projects must demonstrate favorable cost-benefit ratio before they are funded for construction. The cost/benefit factor includes costs for providing subsurface drainage.

The collector drains have always been considered a project cost, but the relief drains are not always so. In 1951, a general Reclamation Policy was established that "...construction of project drains on farm should be precluded or definitely restricted and that the land owner should assume responsibility for such construction the same as for other on farm development." (USBR 1954) This policy was reviewed and modified in 1963 to allow the cost of drains to "...be considered, depending upon the circumstances, as a project, or a farm cost." (USBR 1963) Since that time, on-farm drainage costs are decided during the planning stage of all projects. Since subsurface drainage problems tend to indiscriminately cross property lines and are usually contributed to by the distribution system, drainage is nearly always considered to be a project cost.

Among the original set of design standards was the placement of a graded sand-gravel envelope around all pipe drains. While gravel envelopes were used as early as 1911, their use was inconsistent and there was no specific gradation. Design criteria for envelope design which was based on hydraulic flow properties as well as filter properties was published in 1970. (Winger and Ryan) The resulting envelope enhances the flow of ground water into the drain while excluding soil particles which would clog the drain pipe. Along with the advent of plastic pipe came a plethora of synthetic envelopes that were cheaper and easier to install. Beginning in the 1970s, Reclamation tested many of these envelope materials. Every attempt to replace the sand-gravel envelope with synthetic geotextiles, fabrics, beads, or mats has resulted in inferior performance or complete failure of the drains. Each research effort concluded that the sand-gravel envelope, even with the greater cost compared to synthetics, is very inexpensive insurance.
The emergence of corrugated plastic pipe for use in subsurface drains represents the most significant change in design standards since the standards were developed. In 1968, the first test sections of 6-inch-diameter plastic pipe were installed in the Kansas River Projects and in the Columbia Basin Project in Washington. Within 4 years, plastic had become the most popular material for small diameter drains and, within 20 years, sizes up to 42-inch-diameter were available. Concrete pipe is still used in some instances, but clay tile has all but vanished and asbestos cement was eliminated when asbestos was classified as a hazardous substance.

The advent of plastic pipe allowed for curvilineal design of drains to better fit topographic features and eliminated the need for certain manholes. It also speeded the construction process as pipe is laid as a continuous unit rather than 3-to-5 foot segments. It also opened the door to high-speed trenchers, which at the time were not large enough to handle rigid pipe sections.

The Reclamation drainage community is concerned with protecting the resources that Reclamation develops. If we develop flourishing irrigation enterprises only to see them deteriorate into salt beds and low value marshes, we have failed in our mission. Reclamation's

design standards and procedures as described in 1977, (Frogge and Sanders) have remained nearly unchanged since that time.

EVOLUTION OF CONSTRUCTION PRACTICES

The construction of drains over the last century has taken as many forms as contractors and engineers could conceive. The following discussion is by no means a complete history of the evolution of construction techniques for drainage, but includes what the authors are familiar with or could find in the literature.

When the first drainage problems developed on Reclamation projects, the solution was to excavate open ditch drains using a horse-drawn earth-moving implement sometimes called a "tumblebug." The tumblebug was pulled by 4 or 6 horses or mules. As it was pulled along, it would scrape up about 1/3 of a cubic yard of earth. When it was full, the operator moved a lever to raise the blade for transport to the waste area, usually the drain bank. To unload, the operator pulled another lever and the implement tumbled to an upside down position, spreading its load over a short distance.

Some early subsurface tile drains were laid in an open trench and backfilled to make a subsurface drain. One such undertaking on the Huntley Project on the Yellowstone River just east of Billings, Montana, in 1912 lasted 4 months, from June 1 through September 30. The Contractor was paid $2,618.40 while his costs were $2,602.64 leaving a profit of $15.76. (USBR 1912) However, even in that time better methods were available. The ancestor of modern trenching machines was introduced on the Huntley Project in 1912. It was an Austin trenching machine that excavated a trench up to 8 feet in depth. It was joined a year later by a Parsons trenching machine with similar capability. Construction of 2500 feet of tile drain in one month's time was considered good progress. Neither machine carried a shield for laying the pipe, so where trench walls would not stand, shoring was constructed behind the machine. Where the grade line was deeper than 8 feet, laborers dug the last increment by hand, 2 to 4 feet in places. (USBR 1913)

In the summer of 1913, laborers were hard to find, so the wage rate was raised from $2.50 a day to $2.75 and rubber boots were furnished. The construction crew consisted of 30 to 40 men and from 2 to 8 teams of horses or mules. (USBR 1913)

Another early mode of excavation was the steam shovel, the precursor of modern backhoes. By the 1950s, most open drains were excavated by modern drag lines which are particularly well suited to ditch excavation.

Subsurface pipe drains were first installed by digging an open ditch, laying a bedding for the pipe, placing the pipe by hand, covering it with a gravel envelope, and finally backfilling the ditch. Often the bedding consisted of wooden cribbing placed in the trench to support the pipe. The wooden cribbing was later replaced by coarse gravel material which will stabilize a trench

that displays quicksand conditions. Surprisingly, open ditch methods of construction are still used in many cases, although the excavation equipment has generally changed to large backhoes.

In 1951, a trenching machine appeared on the Delta-Mendota Canal in the Central Valley Project. This machine towed a sled-mounted shield for laying pipe and gravel envelope. The forward movement of the trencher was assisted by a cable winch with a block and tackle arrangement hooked to a deadman dozer. This avoided slippage of the tracks which would quickly dig into the boggy ground and the trencher would become stuck. Similar arrangements were used to assist trenchers to move over boggy ground as late as the mid-970s. In 1955, trenching machines were working in the Gila Project in Arizona and the Heart Mountain Division in Wyoming. Both machines were ladder-type excavators and had shields for placing the gravel envelope and pipe. The Cook and Butler machine on the Gila Project was mounted on a halftrack with large steel wheels on the front. The wheels made traversing boggy ground nearly impossible. Another design problem was that the shield was rigidly attached to the machine, which prevented separate control of the shield and the trencher. The machine was still in use as late as 1969. The Heart Mountain machine was a Parsons model 310. It was track-mounted and the shield was completely separate from the trencher, having its own set of tracks and being towed rather than carried.

The Jetco wheel trencher was developed specifically for conditions on the Columbia Basin project where rock-like caliche layers must be excavated. The wheel was 16 feet in diameter and could excavate a trench to a depth of 12 feet. In the Republican Valley of Nebraska and in California's Imperial Valley, quicksand conditions presented the most difficult conditions. There, Buckeye trenchers with ladder excavators and wide floatation tracks were developed. The Buckeye machine with its trench shield attached was 50 feet long and weighed 50 tons. It could place drains in fairly boggy conditions at a depth of 10 feet. It carried two large diesel engines, one to move the machine forward and run the digging mechanism and one to run the hydraulic pumps to adjust the depth of the digger and the shield.

Both the Jetco and the Buckeye carried a trench shield in which the concrete or clay tile sections were placed by hand. A hydraulic lift was used to lower 2.5-foot lengths or "joints" of pipe into the shield where a man placed it in position on a set of steel rails. A hydraulic ram pushed the pipe tight against the preceding joint and held it there as the machine moved forward. When the machine had traveled the length of the pipe joint, the man in the shield sounded a horn and the operator stopped the machine to allow another joint of pipe to be lowered into place. The machine move at a pace of about 50 feet per hour, including the stops. Later a dual ram apparatus was introduced which allowed continuous forward movement as the joints were handled. The pace accelerated to a dizzying 300 feet per hour.

Besides the rails, the hydraulic ram and cramped quarters for a man to work in, the shield contained a chute for placing the gravel bed for pipe to lay on and another chute to place gravel around and over the pipe before it left the shield and was subject to trench wall caving. Often there was a spool mounted on the back of the shield to dispense a continuous sheet of plastic or

asphalt saturated felt along the top of the pipe. This so-called blinding was thought to prevent soil from being washed into the pipe along with the drain water. That practice was discontinued when the hydraulics of the system became better understood. Most shields also carried a hopper for gravel material so that a continuous feed of gravel was made as the pipe was laid. With the advent of plastic drain pipe, there was no longer a need for a laborer to ride inside the shield. The man and machinery inside the shield were replaced by a chute through which the continuous pipe is fed so that the pipe and gravel envelope emerge from the rear of the shield as a single unit. The machines were not manufactured for placement of a gravel envelope around the pipe as Reclamation standards require. Contractors typically found it necessary to modify their new machines by attaching shields, strengthening bearings and shafts, and adding special controls before the new machine ever went to the field. This procedure is still common in the industry.

In 1970, a German-made Hoess Machine was introduced in the Republican Valley. The Hoess was a smaller, lighter weight machine with a high-speed chain digger. Although the machine could not lay solid pipe joints, it could lay continuous 4-, 6- and 8-inch plastic tubing at 7 feet deep at a pace of 1200 feet per hour. Several more years would pass before larger-diameter plastic pipe was approved for use. Many contractors preferred to stay with their old machines rather than have two large machines on the job. By the end of the 1970s, plastic pipe was approved in diameters up to 18 inches. The need for greater depth and larger shields to accommodate the larger pipe meant that many contractors simply converted their old machines rather than investing in the new smaller ones. During this time, several European companies introduced the larger high-speed trenchers that are now in use. Forward speeds of 2,000 feet per hour are now common.

In addition to the accelerated rate of construction, field drainage engineers found that trenching machines provided a superior product when working in unstable soil conditions. (Frogge and Sanders) In 1974, the first drains for which a trenching machine was required by the construction specifications were constructed down the center of a primary street in Loup City, Nebraska. The purpose of this requirement was to ensure that the gravel envelope was placed in direct contact with undisturbed soil to form a strong hydraulic connection between the soil profile and the drain. Construction specifications requiring the use of trenching machines that excavate the trench, lay the pipe and the gravel envelope are becoming a common practice where construction costs are high and the consequences of failure unacceptable.

A longstanding problem for contractors building subsurface drains is operating heavy equipment on wet ground. In many cases, the drains are designed to remove excess water from land that has become perpetually marshy. A drain contractor in the Kansas River Projects solved this problem by constructing through such areas in midwinter when there was a foot or more of frost. Using a concrete saw, two cuts were made through the frost layer, one foot on each side of centerline. The blocks of frozen soil were removed with a backhoe making a slot for the trenching machine to work through. This operation required great caution to avoid placing frozen chunks in the backfill, which is forbidden by the specifications. Another solution was the use of flotation

tracks. In the early 1980s, a Hollanddrain trencher having tracks that were 4 feet wide was used on the Riverton Project. It could easily trench through ground so soft that walking was difficult.

With the early trenching machines, grade control was done one pipe joint at a time and the digger was adjusted as needed. As speed increased, contractors began using a string line which the operator tried to follow (with varying degrees of success) to maintain grade. Another approach to grade control was a line of targets. This line of targets was set up in the field at an exact elevation above the grade line. The operator sighted on these targets and lined up two targets attached to the digging apparatus with the line of targets in the field. The targets were more reliable than the string lines, but still required a skilled operator to maintain an acceptable grade on the drainpipe. Along with the high-speed trenchers came laser-controlled grade where the operator adjusted the machine according to a red laser dot that was aimed at the control panel. Often the laser beam would be warped by the heat of the trenching machine's engine, making the dot much larger than the permissible deviation from grade. Sometimes the dot would disappear entirely. That system was quickly replaced by laser planes that project a plane of laser light on the correct slope over the entire field by a revolving laser sending unit. The plane is intercepted by sensors on the trenching machine; the sensors signal the hydraulic controls several times per minute to adjust the digger and the shield up or down as needed. Interference from engine heat has been overcome by placing the sensors on masts, several feet above the machine.

The September 1955 issue of Intermountain Industry Magazine featured a machine developed by Sumner G. Margetts & Company of Salt Lake City, Utah claiming it was "The only machine of its type in the world (government approved)." The manufacturer was not identified and photos appear to be different from any of the machines discussed earlier in this writing, indicating that at that time there were at least 4 such machines in existence. However, as revolutionary as these giant machines were they never became common construction industry equipment. A total of 12 machines were reported to be in operation in 1977, (Frogge and Sanders) and in the United States, there are currently less than 10 operable machines with a depth capability greater than 8 feet.

OPERATION AND MAINTENANCE

As noted earlier, the Drainage and Ground Water function organizationally resided in the Operation and Maintenance (O&M) Division in four of the seven Regions for nearly 50 years. This was due in part to the reality that drainage problems usually arose after the projects had been transferred to the O&M Division. However, regardless of their position on the organizational chart, the maintenance of drains after construction was the responsibility of the Regional Drainage Engineer with the support of the Projects Office Drainage Branches.

The same observation well network that is used for planning and design is used to monitor the effectiveness of drain systems after they are built. Usually, the records of ground water fluctuation are maintained by the same drainage personnel who installed the wells. Most

drainage offices in the 1950s, 1960s and 1970s maintained hand-written or typed records of all the well readings within their project area. The wells were measured 2 to 12 times a year, depending on the relative need for detail. Hand-drawn hydrographs of the measurements were updated annually and kept in three-ring binders for ready access. In more recent times, the records are usually kept electronically and, thanks to modern software, hydrographs are printed as needed. The hydrographs are used to forecast emerging drainage needs in time to plan and execute corrective measures before they became a serious economic burden on the landowners or the irrigation district. The hydrographs are also useful in diagnosing deficiencies in existing drainage works.

In projects where drainage was a major factor, drainage personnel typically participated in scheduled reviews of maintenance along with the distribution system O&M experts. When problems developed in drainage systems, the drainage staff advised O&M forces on methods of repair and, in many cases, actively participated in the repair, as they still do. Through the years, these kinds of activities have aided in verification of design criteria and methods.

EARLY EXPERIENCE

Many of the first wave of Reclamation projects experienced severe drainage problems within a few years. Efforts to correct drainage deficiencies met with varying degrees of success. The experiences of some of these early projects are recounted here.

Belle Fourche Project

The Belle Fourche Project was among the first Reclamation projects to be developed. The project was initiated in 1903. By 1910, many of the facilities were in place and water was being delivered. However, by 1912, seeped areas totaling 1420 acres were scattered over most of the project. By 1914, the seeped areas had grown to 2,500 acres and, by 1917, they were estimated to be 35,000 acres. Small drainage districts were formed and managed to get several thousand acres relieved of water charges. Notes from a landowners meeting in 1920 state, “It begins to look like the only way to accomplish drainage of the project would be to have an order from the Secretary of the Interior with provision that the costs be charged to Operation and Maintenance of the Project.”(USBR 1920) The district requested and was granted a delay in the repayment contract. The 1926 Omnibus bill provided an adjustment to water charges due to drainage deficiencies.

From 1917 to 1930, a drainage construction program was carried out to correct the problems. Some 230 miles of drains, mostly open ditch, were constructed. Over the years, the Soil Conservation Service constructed buried pipe drains on many of the fields. Even that effort was not fully successful in relieving the drainage problems. Improved irrigation practices have helped. In 1984, the District entered into a Rehabilitation and Betterment (R&B) contract with Reclamation. Work done under the R&B put most smaller irrigation laterals in pipe, and lined

many of the larger ditches, thus eliminating many sources of seepage. In the1990s, a land reclassification placed some of the more unproductive lands into class 6 (nonirrigable). All of these actions have improved the overall situation, but parts of the district suffer from unresolved drainage problems to this day.

Huntley Project

Huntley Project was authorized in 1905 and many of the facilities were completed by 1908. As was the case on the Belle Fourche Project, within a few years serious waterlogging problems developed, but with a much happier outcome. In 1911, there were 160 acres of waterlogged land and "another 40 farms where seepage has shown up." (USBR 1911) Even as drains were being constructed and successfully relieved seepage problems, the problems continued to grow. In 1914, there were 1,426 acres "waterlogged" and 8,000 acres "threatened" (USBR 1914), but by 1920, construction had caught up with demand and the problem was well under control.

From 1911 to 1920, some 65 miles of drains were constructed, most of which were clay tile. Eventually, the total drainage on the project reached 186 miles. (USBR 1981) The manholes or "trap boxes" as they were called, were 3 feet square, made of creosote-treated wood, with 6-inch by 6-inch vertical timber corners and sides consisting of 2-inch planks. Some of these manholes have been replaced by corrugated metal pipe, but many of them are still in use. As to the effectiveness of the drains, they were nearly 100 percent successful and continue to function with minimal maintenance.

Newlands Project

The USBR dataweb provides the early project history:

"The United States Geological Survey (USGS) began investigations into possible irrigation projects in the Truckee and Carson River Basins in the late 1880s. In 1902, the newly organized United States Reclamation Service took over investigations. On March 14, 1903, the Secretary of the Interior authorized the Truckee-Carson Project, making it one of the first projects authorized for construction by the Reclamation Service.

"Work on the Truckee-Carson Project began in mid-1903. The original plan proposed reclamation of over 300,000 acres of land in western Nevada. *(Eventually the service area included about 73,000 acres. (USBR 1981))* * * * The first water deliveries to project settlers began in February 1906.

* * * * *

"As early as 1908 it had been recognized that there were serious problems throughout the project. In spite [of] the Reclamation Service's belief that soils would support a wide variety of crops, that sufficient water would be available to farms, and that markets existed for produce, many entrymen soon discovered that a forty-acre farm was too small to produce an adequate income, that irrigation water did not drain properly, and that little water was available during the later part of the irrigation season. By 1912, large areas on the project were saturated and unusable, and
farm prices were much lower than expected. Drainage ditches excavated in 1906 did not sufficiently drain irrigated fields, and the water table was very near the surface, saturating the root zone.

"Lack of adequate drainage was a significant impediment to successful farming in the region. Area water users formed an informal organization and began to demand that the Reclamation Service provide a solution to the drainage problem. Conflicts over who was responsible delayed resolution of the situation. The water users claimed that the Reclamation Service had promised adequate drainage, while the Reclamation Service contended that the problem was due to over-irrigation and that the farmers should assume the cost of constructing a drainage system. Offers by the Reclamation Service to correct the drainage problems with the costs paid by the water users were overwhelmingly rejected.

"In 1916, after several years of resisting the formation of a formal water users organization, the Reclamation Service proposed to begin work on a drainage system as soon as an irrigation district could be formed that could contract for payment of the costs of the drainage system. In March 1917, the Nevada Legislature passed a bill approving formation of the irrigation district, and on November 16, the Truckee-Carson Irrigation District (TCID) was created by a vote of nine-to-one in favor of organization.

"A contract for construction of a drainage system was not approved until 1921, and a second contract had to be approved in 1924. By 1928, when work under the contracts was complete, more than 230 miles of drains had been excavated. * * * *

"Following World War I, conditions on many Reclamation projects had become so bad with many farmers unable to fulfill their payment obligations that the Secretary of the Interior appointed a fact finding commission to investigate the situation and make recommendations. The commission determined that by 1926, $7,899,479 had been spent on the Newlands Project. Of that amount, the commission determined that $4,437,820 had been spent without proper cause and that the water users should not be responsible for repayment of that amount. The Omnibus Adjustment Act of 1926 relieved the water users of that amount and gave them forty years to repay the remaining $3,281,999." (USBR Dataweb)

Although the drainage system was considered complete upon completion of the contracts in 1928, drainage work continued at a slower pace. In a trip report dated October 28, 1964, Ray J. Winger, Jr. reported " ... a total of about 335 miles of open drains." Winger also noted that they

observed several small areas of 100 acres or so that needed additional drainage for good production. He was told that the farmers do not want drainage because they believed they were benefitting from subirrigation. He noted that, "Under these circumstances, the lands are becoming salinized. Without drainage they will eventually become sufficiently saline to limit or preclude crop production." (Winger 1964) His conclusion was apparently acted on because a 1985 land classification report by Reclamation says, "A maze of nearly 400 miles [additional 65 miles] of open drains and 4 miles of closed drains presently serve the Newlands Project." (USBR 1985)

A unique feature of the Newlands Project is the concept of so-called "bench and bottom lands" based primarily on subsurface drainage characteristics which were not clearly defined until some 60 years after the concept was initiated. In 1925, following a series of legal actions and hearings that began in 1913, a temporary restraining order was issued. Under the restraining order farmers on the project were to receive, after transportation losses, 3.5 acre-feet of water per acre for bottom lands and 4.5 acre-feet of water per acre for bench lands. The restraining order neither defined nor identified project bench and bottom lands. In 1944, a final decree simply restated the restraining order. Legal actions continued through the years and a 1986 Court Order directed the Secretary of the Interior to prepare and submit a "revised initial designation of Bench and Bottom lands in the Newlands Project." The new map was to be based on two criteria, including waterholding capacity of the soils and the "seasonal high water table." In 1990, Reclamation drainage personnel produced a "final draft" report which included detailed maps and legal descriptions of the designations.

CHALLENGES MET

Examples of early Reclamation drainage history are too numerous and varied to include them all in this paper. A few of the more outstanding experiences are presented here.

Riverton

The Riverton Project consists of three divisions. Construction began on the first and second divisions in 1921 and first water was delivered in 1925. Drainage problems developed on some of the lands almost immediately. In the 1930s and 40s, a few open drains were constructed along farm boundaries but were largely ineffective in controlling the seepage because the spacing was too wide. In the 1950s, additional open drains were constructed midway between the original drains, but still the spacing was too wide because the open drains were constructed to keep crop producing areas at an optimum. All of this was done prior to the development of the transient-state drain spacing procedures. Meanwhile, construction began on Third Division in 1947 and public notice number 26 opened 55 farm units for homestead. An additional 50 farm units were opened in 1950, and 54 units were opened in 1951. Since certification of irrigability was not yet law, no drainage studies were conducted prior to settlement.

As newcomers, mostly returning veterans from World War II, colonized the First and Second Divisions in greater numbers, Reclamation heard some bad news about the Third Division. The Third Division, a foundation of promise for post-war homesteaders, had a false bottom. A 1951 soil survey reclassified large areas of shallow soil in the Third Division as Class 6-nonirrigable. This acreage drained poorly and was susceptible to waterlogging and salinity severe enough to prevent cultivation. Congress passed Public Law 258 in 1953 permitting homesteaders on inadequate farms to amend their existing properties with vacant lands on the same project. Public Law 258 also allowed farmers to exchange their units for land on other Reclamation projects. Every landowner on a Reclamation project in the West could file a claim under Public Law 258, but the law specifically helped farmers working unproductive acreage on the Riverton Project. (USBR dataweb) Within a few years, all or parts of every farm unit in Third Division were suffering from waterlogging and salinity problems. The problem was attributed to poor irrigation practices as well as natural drainage deficiencies of the land. Many of the farms were located downslope from other farm units, so they had to deal with return flows from neighbors as well as their own irrigation applications.

Another problem faced by Riverton farmers and by drainage engineers trying to correct problems was sodium in the soils. Some of the lands contained high levels of sodium, which can cause the soil structure to break down leaving the land impossible to drain adequately. Although the problem may develop on any project in semiarid climates, the Riverton Project seemed to be particularly susceptible.

Enactment of Public Law 258 resulted in many farmers leaving Wyoming. Those who relocated under the provisions of Public Law 258 settled the Columbia Basin Project in Washington, the Minidoka Project in Idaho, and the Gila Project in Arizona. Those staying in Riverton added vacated land to their existing acreage. Public Law 258 stabilized the Riverton Project as remaining homesteaders increased the size of their units and subsequently improved themselves financially. Those determined to farm the Third Division formed an irrigation district in August 1957. By the dawn of the 1960s, a Bureau Project History lamented their decision: "The ratio of operating expenses to prices received for crops and livestock continued unfavorable." (USBR dataweb)

By the early 1960s, the situation on the Third Division required the Government to make a hard decision. Reclamation proposed to buy out the homesteaders and write off most of the $20.5 million on the Federal books. A congressional delegation came to Riverton in October 1961 to hear local grievances. The testimonials the delegation heard "were adverse and favored abolishing the project." Reclamation responded by threatening to shut off water to the Third Division if growers refused to sign a repayment contract. One farmer, Marvin H. West, stated to a Denver newspaper in 1962, "10 to 12 years should prove the feasibility of these places. We have not made a living or showed any repayment ability in that time." (USBR dataweb)

The growers' anger was enough to persuade the government in 1964 to pass Public Law 88-278 authorizing Federal purchase of Third Division lands. The Bureau bought back 78 units totaling

about 22,000 acres. Farmers from the Midvale Irrigation District leased certain sections of the land over the next 6 years. In September 1970, Public Law 91-409 consolidated the three divisions of the Riverton Project. Besides employing power sales to pay rehabilitation costs on project works, the bill restored 8,900 irrigable acres of the Third Division to private ownership, with provision that no further Federal funds would be provided for drainage works. In January 1971, the Third Division Irrigation District ceased operations. The following month, the Government auctioned 43 units to farmers of the Midvale Irrigation District. By spring, the farmers petitioned the 43 units into Midvale. In December, the Government executed a new amendatory repayment contract with Midvale. (USBR dataweb)

In 1976, the Midvale Irrigation District entered into a Rehabilitation and Betterment (R&B) contract with Reclamation to upgrade certain facilities and to provide adequate subsurface drainage for the First and Second Division lands. Over the next 10 years, some 200 miles of subsurface drains were constructed. Many of the original open drain ditches, which had eroded to several times their design width, were replaced with more effective subsurface drains and backfilled, reducing maintenance costs and increasing the tillable acreage. In an odd twist, a provision of the law authorizing the R&B contract precluded expenditures of any of the funds for drainage works on Third Division lands.

A reclassification of the Midvale Irrigation District in 1999 confirmed that for the most part, the entire project was experiencing good productivity. Although small scattered parcels of land were placed in a non-irrigable class due to the sodium content of the soil being too high to permit economical drainage, waterlogging and salinization are under control within the project lands.

Kansas River Projects

A series of irrigation projects in the Republican River Valley from Trenton in southwest Nebraska to south of Courtland, Kansas, were completed around 1960. By 1965, waterlogging was becoming prevalent in many areas along this 200-mile reach of the river. Drain construction began in 1966 and more than 200 miles of drains had been constructed in the Republican River Valley by 1975.

The Bostwick Division, Kansas, is a 40,000-acre project located mostly on uplands around the town of Courtland. On July 3, 1967, a field review of drainage needs was conducted by representatives of the Chief Engineer's Office, the Region 7 Office and the Kansas River Projects Office. During that review, Mr. Lee Dumm of the Chief Engineer's Office noted that the water table was in a delicate state of dynamic equilibrium and that sooner or later a spell of unusually wet weather would probably upset the balance, creating serious problems. His prediction came true sooner rather than later. The fall of 1968 brought heavy precipitation that continued through the winter and into the summer of 1969. By August 1969, fully 90 percent of the 27,500 acres under irrigation were seriously affected by high water tables and about 2,000 acres were not farmed. In 1970, a 12-person office consisting of an investigations crew, a survey crew, an engineer, and a construction inspection crew, was opened in Superior, Nebraska, with

the specific purpose of constructing drains on the Kansas-Bostwick Unit and the lower half of the Nebraska-Bostwick Unit. By 1981, when the Superior Field Engineering Office closed, more than 250 miles of pipe drains and 50 miles of open ditch drains had been constructed on the Kansas-Bostwick Unit.

In order for this small group to accomplish this effort in a span of 10 years required some innovative measures. Ground water depth probes were made from 1/4-inch iron pipe lined with 1/8-inch plastic tubing. Water level was read by hooking an ohmmeter to the pipe and inserting a wire connected to the other terminal into the plastic tubing. When the wire reached the water surface, it completed the circuit. The probes were easily inserted to a depth of about 5 feet wherever the water table was less than 2 or 3 feet below land surface, which was almost everywhere. The probes allowed a 2-man crew to create ground water surface maps in about one-third the time needed to do it with augers.

Soil profiles were logged using a variation of split tube sampler that was developed by the Superior Office. It was driven directly into the ground without benefit of the hollow stem augers that are usually used. While the tube increased production of the soil logging operation by four to five times, it was specific to the Kansas upland soils and was never successful in other areas of the country or even other areas of the Kansas River Projects.

Another first for the Superior Field Engineering Branch Office was the hiring of Reclamation's first women as field technicians, whose duties included operating small drill rigs. In 1973, Naomi Fritson, a Nebraska farm girl, and Mary Torpin, daughter of a Hollywood film director, were Engineering Tech students at Curtis Community College in Curtis, Nebraska. They were hired as summer employees. Their 4-month employment with Reclamation constituted one semester of their required curriculum. At the time, it was a significant enough event to rate a spot on the evening news of the Nebraska Television Network.

Columbia Basin Project

The Columbia Basin Project in eastern Washington is the most extensive drainage construction that Reclamation has undertaken in our first century of existence. About 540,000 acres has been developed of what was initially envisioned as a 1-million acre project. The first water was delivered in 1948 and water tables began to rise almost immediately. By the early 1950s, the need for artificial drainage was becoming evident. Water table levels rose steadily until they reached a point where drainage was needed on large areas of land to maintain productivity. By 1968, the water table had risen an average of 150 feet over the entire project. (Monteith and Myers)

The extensive need for drainage had not been recognized in the original project formulation and it was not until 1960 that a large-scale construction program was initiated. (Christopher and Campbell) The Columbia Basin Drainage staff was established in 1954 and, during the peak drain construction period of 1971 to 1976, the staff numbered around 60 full-time drainage

personnel. Innovative approaches to field investigations were initiated in an attempt to increase productivity without increasing staff. In the geologic setting of the Columbia Basin, 20 feet was the depth of most drainage borings. The need to increase productivity and lower engineering costs led to the modification of the drill rigs used in field investigations. The small rigs were fitted with a mast and a 20-foot long continuous auger so that 20 foot holes could be drilled without stopping to insert and remove the standard 5-foot auger sections. Seismic equipment was used to locate caliche layers so that borings could be farther apart.

The first drains to be constructed were open ditches to be used as outlets for the pipe drains. In 1961, construction of pipe drains began with a 3-mile segment. This would increase fairly steadily until the peak in 1974 when 195 miles of drains were constructed. By 1979, more than 2,200 miles of drain had been constructed and, by 1995, the total was 2,845 miles. (Hubbs)

Drainage of the lands was complicated by the existence of caliche layers underlying most of the project lands. Caliche is a form of solidified calcium deposit which occurs at depths shallower than the design depth of the drains. Construction equipment was often unable to excavate the caliche until it was blasted with dynamite. The large wheel trenching machines were designed for this type of construction and were quite successful in reducing or eliminating the need to blast.

Drain depths on the Columbia Basin Project are typically 8 to 9 feet, which is 1 to 2 feet deeper than on most Reclamation projects. This decision was based largely on the capability of the local contractors' equipment, although the depth of the outlet drain and the depth to a favorable drain zone in the soil profile may control the depth locally. (Brohl)

Central Valley Project

The Central Valley Project was authorized by Congress in 1937. First water was delivered from the Contra Costa Canal on August 16, 1940. Water deliveries began on the Delta-Mendota service area in 1950 and the first tile drains were constructed on the Grasslands area in the early 1950s. The drains discharged into wetlands. (Most of the following was paraphrased from written communications provided by Michael Delamore, South-Central California Area Office, USBR, and Joel Zander of the Mid Pacific Regional Office, USBR)

In 1956, the California State Department of Water Resources recommended the state study a "comprehensive master drainage works system" indicating that drainage problems were beginning to develop on a significant scale. Also, Reclamation submitted a feasibility report on the San Luis Unit to Congress. The report included a 300 cubic feet per second earth-lined interceptor drain as part of the "distribution system and drains." On-farm drainage on the San Luis Unit was the responsibility of the landowner, but Reclamation was to provide an outlet drain that could be accessed by irrigators through irrigation district facilities. Construction of the San Luis Drain began in 1968, and Reclamation acquired 5,900 acres of land for Kesterson Reregulating Reservoir. The reservoir was to be operated according to a cooperative agreement

with US Fish and Wildlife Service for the conservation and management of wildlife, subject to the primary use of the lands for regulation of drain flows. Water was to be held in the reservoir until final discharge permits were acquired for the drainage water.

On July 1, 1969, U.S. Fish and Wildlife Service (FWS) began managing the lands acquired for Kesterson Reservoir under terms of the agreement. Construction of the reservoir began a year later. In 1972, construction of the first phase of the reservoir and the adjacent drain were completed. However, by February 1975, funds had run out, and construction was stopped with about 40 percent (85 miles) of the drain and the first stage of Kesterson Reservoir complete. Four months later, the first contract for collector drains on Westlands Water District was awarded and construction began on a collector system, encompassing about 42,000 acres of irrigated lands.

In 1977, Public Law 95-46, the 1978 appropriation, increased the ceiling for distribution and drainage systems on the San Luis Unit. Construction was not reinitiated at least in part because discharge criteria had not been established. Attempts to address this critical issue were unsuccessful as the State Water Resources Control Board (SWRCB) had the authority to set discharge requirements but was " not in a position to do so at this time." A March 20, 1978, letter from Reclamation's Regional Director to SWRCB explained Reclamation's position and hinted at the urgency of having discharge criteria established.

In 1978, use of Kesterson Reservoir as interim evaporation ponds for subsurface agricultural drainage flows from Westlands Water District began. The proportion of subsurface drainage flows to surface flows increased yearly until inflows to Kesterson were principally subsurface drainage water in 1981.

In May 1979, FWS began expressing reservations about the quality of the drainage water from San Luis Drain and the possible effects of toxic constituents on receiving waters. A year later, they would notify Reclamation that such effects would need to be evaluated in a Fish and Wildlife Coordination Report and there were concerns over completion of the San Luis Drain.

In 1981, Reclamation began studies to identify any potential toxic constituents in the drain water. The studies found high concentrations of selenium in San Luis Drain and Kesterson Reservoir. Reclamation imposed a moratorium on additional farm drainage connections to San Luis Drain because Kesterson Reservoir was reaching capacity and the outlet had not yet been constructed. Existing farm drains continued discharging through local wetlands to the San Joaquin River. Meanwhile, Reclamation was developing detailed plans for completion of San Luis Drain and, at the same time, reevaluating possible alternatives such as in-valley evaporation, desalinization, discharge to San Francisco Bay rather than Suisun Bay, and no action. Through the early 1980s, Reclamation and several cooperating state and federal agencies and universities spent about $4 million gathering information needed to obtain the discharge permit.

In 1982, FWS found high selenium concentrations in fish at Kesterson Reservoir and discovered higher-than-normal waterfowl mortalities and deformities a year later. Reclamation took action to minimize waterfowl attraction at Kesterson Reservoir by reducing the number of ponds and providing additional water to neighboring wetland areas. In September 1984, a hazing program was started to keep the birds off Kesterson Reservoir. A number of techniques were tried, including periodic shotgun blasts and chasing birds with ATVs. At the same time, 15,000 acre-feet of clean water was provided to alternate habitat sites.

In February 1983, because of high rainfall, Reclamation filed an application with the Central Valley Regional Water Quality Control Board (CVRWQCB) for a discharge permit from Kesterson to the San Joaquin River. CVRWQCB responded by acknowledging the need to discharge excess water from San Luis Drain and Kesterson Reservoir and requiring Reclamation to immediately begin a sampling program and submit reports. On January 13, 1984, Reclamation notified CVRWQCB that high rainfall amounts combined with drainage water were threatening the dikes and warning that failure would mean uncontrolled flooding. On February 2, the application was approved for limited discharge to prevent failure of the dikes, but large discharges were not allowed.

On April 8, 1983, Reclamation requested SWRCB approve a schedule for preparation of a technical report to accompany the application for the discharge permit to Suisun Bay and for the board to act on the application by November 1984. The Board responded on May 4 saying the schedule could not be met but that December 1984 was workable only if the report met acceptance by the scientific community, the SWQCB, and National Pollution Discharge Elimination System (NPDES) permit conditions.

In March 1985, the Department of the Interior announced plans to close Kesterson Reservoir and San Luis Drain and to terminate deliveries to 42,000 acres in Westlands Water District because of concern of violation of the Migratory Bird Treaty Act. A month later, the Department reached an agreement with Westlands to continue delivering water to all of the lands in the district, but the drain remained closed. This was followed quickly by landowners filing law suits against the United States for taking of their property by seepage of drainage water from Kesterson Reservoir. In November, Westlands Water District filed a draft EIR on plans for on-farm management, water recycling and plugging of the farm drains if necessary. By May 1986, Westlands completed plugging of the drains to prevent drainage water from entering San Luis Drain.

On December 30, 1986, the United States and Westlands Water District reached a compromise settlement known as the “Barcellos Judgment” filed in United States District Court as a court judgment. The judgment, among other things, required the Federal Government to develop a plan for drainage service facilities by December 31, 1991. The Judgment stipulates that the drainage facilities shall have “sufficient capacity and capability to transport, treat as necessary, and dispose of the annual quantity of subsurface agricultural drainage water from the District (not less than 60,000 acre feet and not more than 100,000 acre feet) required to be disposed of by December 31 2007 ...” To help finance construction of the drainage service facilities, the District

was required to make annual contributions to a trust fund established under the judgment. These funds were released to the District in June 1992 when the court ruled that the Government had failed to meet the terms of the Barcellos Judgment.

In January 1988, after considerable controversy, Reclamation began dewatering Kesterson Reservoir in preparation for cleanup. The dewatering was completed on April 12 and by November low-lying areas of Kesterson Reservoir had been filled with dirt. This did not end the life of the San Luis Drain.

In 1996, the San Luis Drain was reactivated as part of the Grassland Bypass Project. Drainage water from 97,000 acres of agricultural land in the Grasslands Basin that historically drained to the San Joaquin River is transported through the lower 28 mile segment of the drain. The drain water contains lower concentrations of selenium than did the original drain water that flowed to Kesterson reservoir. The drain carries the water around the Grassland Conservation District to the terminal structure of San Luis Drain and returns to the San Joaquin River through Mud Slough. The selenium load is monitored for compliance with agreed-upon monthly and annual load limits. Fees of $25,000 to $250,000 are levied against the participating irrigation districts when the limits are not met. (Quinn etal)

One of the many entities involved in the drainage problems surrounding the fertile Central Valley lands was the San Joaquin Valley Drainage Program (SJVDP). Public Law 96-375 passed in 1980 authorized San Joaquin Valley Drainage Investigation feasibility study. In August 1984, Governor Deukmejian and Secretary of the Interior William Clark established the SJVDP as a cooperative effort of the U. S. Bureau of Reclamation, U. S. Fish and Wildlife Service, U. S. Geological Survey, California Department of Fish and Game, and California Department of Water Resources. The purpose of SJVDP was to conduct comprehensive studies to identify the magnitude and sources of the drainage problem, the toxic effect of selenium on wildlife, and what actions needed to be taken to resolve these issues. By the end of 1990, funds totaling $50 million had been appropriated to support the Program.

In April 1987, SJVDP issued a draft report which discussed ocean disposal possibilities. Public reaction was so strongly adverse that the SJVDP Management Committee narrowed the focus of the program to exclude any disposal of agricultural drainage water or brine outside the San Joaquin Valley. In September 1990, SJVDP issued its final report titled "A Management Plan for Agricultural Subsurface Drainage and Related Problems on the West Side San Joaquin Valley." In December 1991, four federal agencies, including Reclamation, and four state agencies signed a Memorandum of Understanding for Implementation of the San Joaquin Valley Drainage Program's Recommended Plan. The major components of the plan are to (1) reduce the amount of irrigation water applied to the field, (2) reuse drainage water, (3) store drainage water in evaporation ponds, (4) cease irrigating lands that have high selenium levels in the subsurface, (5) pump ground water to lower the water table, (6) discharge to the San Joaquin River, and (7) protection, restoration, and provision of substitute water supplies for fish and wildlife habitat.

The controversy over the trace element selenium and how to handle drainage waters containing elevated concentrations has sparked numerous research efforts and other spinoff activities. In September 1986, the Westlands Water District Board approved a $6.6 million drainage treatment plant and a prototype deep well injection unit. After 18 months, the research project was indefinitely postponed because it did not appear to be economically feasible on a large scale. However, in October 1989, the District entered into an agreement with state and federal agencies and universities to begin work on a treatment research center to be located in the district. At about the same time, Panoche Drainage District began construction of a prototype facility to remove selenium from water using an iron absorption process. In June 1989, Westlands began drilling on an 8,100-foot-deep prototype injection well to be used for disposal of drainage water.

Several treatment methods were employed in an effort to reduce selenium in the soil, including field testing of a biological cleanup plan using selenium eating fungi.

The problems associated with high concentrations of selenium in the drainage water at Kesterson Reservoir were the primary reason why the Department of the Interior launched the Irrigation Drainage Program in 1985 with an inventory of more than 600 irrigation projects in the western United States to discover the extent of toxic trace elements in drainage water from the projects. (Department of the Interior, NIWQP website)

In 1992, Reclamation announced that it would award Challenge Grants for demonstration projects of innovative approaches to advance water conservation and address agricultural drainage problems in the Mid-Pacific Region. Challenge Grants addressing drainage problems would be accepted only for the SJVDP study area. Six Challenge Grants investigating various methods of treatment or management of selenium rich drainage water were executed in 1994.

Central Utah Project

In the middle to late 1960s, the Central Utah Project (CUP) was one center of activity for Reclamation's drainage forces. Detailed drainage investigations covering nearly 250,000 acres were completed in anticipation of development of the project, which would provide a full water supply to about 33,000 acres and supplemental water to the remainder. The bulk of these lands lie in the Uintah Basin, which is tributary to the Green River, in Emery County in east Central Utah, and in the Sevier Basin, a closed dry lake bed in southwestern Utah. The CUP was one of the primary proving grounds for the auger hole permeability test, which has become a standard test for permeability of saturated soils. Several thousand auger hole tests were conducted, some as deep as 25 feet, and a number of minor modifications to the test procedure were initiated. Observation well networks were installed on about a 1-mile grid and monitored weekly. The wells generally consisted of a galvanized downspout with holes punched by a geologist's pick and an endcap for a lid.

For the most part, drainage field crews across Reclamation at the time were mobile. The CUP crews would make a brief visit to the Provo Office each Monday morning to get their assignment

for the week, turn in time sheets and conduct any necessary personnel business. They would make the 2- to 4-hour drive back to Provo on Friday evening, on their own time. A CUP field crew generally consisted of 10 to 20 people, including a lead engineer, several subordinate engineers and technicians, and a group of 90-day temporary laborers. The lead engineer's office was a pickup truck containing all the tools and equipment needed for the investigations and brief-cases containing reference materials, test forms, and personnel files for the engineer and his crew.

The summer and fall of 1965 found enough Reclamation drainage personnel in the small town of Delta, Utah, to fill all 7 rooms in the only motel and a good part of the only apartment building for a period of about 6 months. In October, a football game was played between the Feds and the town in which the Feds scored a narrow victory. On the last day in Delta - before Christmas break - the local restaurant closed to the public and the owner prepared a special Japanese meal for the Reclamation employees in appreciation of their patronage. By 1990, about 50 miles of subsurface drains had been constructed in the Uintah Basin and in Emery County. As of this writing, the Sevier Unit has not been developed.

Oahe

The Pick-Sloan Missouri Basin Plan envisioned two irrigation developments in the Dakotas to compensate the states for the loss of prime agricultural land to the Main Stem Reservoirs, which now form a nearly continuous lake from Yankton, South Dakota, to Williston, North Dakota. The 5 dams, built for flood control and power generation, flooded thousands of acres of rich river bottom lands in the Dakotas. Originally, the Garrison Diversion Project and the Oahe Project were each to be more than a half million acres. Construction was begun on both projects in the mid-970s but, to date, neither of them has been completed.

Although the Oahe Unit was never completed, it was an important milepost in the history of drainage in the Bureau of Reclamation. Investigations began on the Oahe Unit in 1950 with the exploration of glacial till soils in eastern South Dakota. Water for the project would be pumped from Oahe Reservoir on the Missouri River.

Extensive investigations were carried out in an effort to determine the ability of glacial till soils to support sustained irrigation. The techniques for some of the in-place permeability tests that are standard Reclamation procedure were developed and proven on the Oahe Unit. At the same time, Reclamation was developing the transient-state drain spacing procedures and data from the Oahe Unit was being used to help establish the relationships that are used in the calculations.

An exhaustive study of prairie potholes was conducted to understand the connection between the surface water in the potholes and the ground water under and around them. At one point, in an attempt to understand the movement of water in till soils, men were placed in a cage and lowered into large-diameter drill holes in order to log the sidewalls of the hole.

The studies of glacial till soils was in concert with similar studies on the Garrison Diversion Unit in North Dakota and in Alberta, Canada. Each study that was done concluded that the permeability of glacial till soils was inadequate to provide economical subsurface drainage for irrigation. In 1957, based on all available knowledge, the decision was made to bypass the till soils and develop the Oahe Unit on the lake plain soils in the James River Valley some 100 miles east of the Missouri River.

A detailed drainage investigation was carried out on the lake plain soils in an effort to forecast drainage needs for the authorized 190,000-acre project. Soil sampling tubes adapted specifically to the Oahe soils investigations and other specialized tools were handmade by Oahe drainage engineers because no commercial supplier existed. (Burnett and TeKrony)

Because soils at drain depth in the Dakota Lake Plain are very unstable when saturated and construction would be very costly, the plan was to construct drainage facilities along with the water distribution facilities "in the dry". (Burnett and TeKrony) This procedure would also avoid the lag time between the need for drainage and the construction of facilities. Historically, the lag time on most projects was long enough to cause economic hardship for the farmers and the irrigation districts.

Construction of the drainage system before the delivery of water would have been a first for Reclamation. Since drainage construction was to take place prior to the development of high water tables from irrigation, the drainage investigations during the planning stage of the project were completed to design data standards, a much greater level of detail than normal for projects in the planning stage. As it turned out, project opponents gained control of the Conservancy District Board in 1977 and requested Congress to deauthorize the project. The takeover of the Board was bolstered by the fact that thousands of acres of glacial till lands were being impacted by the 100-mile-long canal, but were not allowed to share in the benefits because of their inherent drainage deficiency. Deauthorization never was formalized, but the action nevertheless sounded the death knell for the Oahe Unit. Even though the pumping plant and parts of the Oahe canal were constructed, no further construction funding was provided.

Eastern South Dakota Basins Study

The Eastern South Dakota Basins Study (ESDB) was the most far-reaching drainage study ever conducted by Reclamation. This study was unique in that drainability was the first controlling element in the assessment of potential for irrigation development. The entire area east of the Missouri River in South Dakota was covered by a subreconnaissance-level investigation aimed at locating lands that would sustain irrigation. Soils were logged on a 3-mile grid covering the entire area and about 6000 in-place permeability tests were conducted. Based on these data and visual observations, the land was divided into four categories according to estimated drainage costs if the land were irrigated. Category I was the least expensive and category IV included lakes, rock outcrops and other areas considered to be nondrainable. The soils logs, permeability results and category delineations were recorded on aerial photos at a 1,000-foot-per-inch scale

and a narrative report explaining the process. The results were published in 1972. The original report and the photos are on file in the Great Plains Regional Office in Billings, Montana.

Oakes 5,000-Acre Test Area

One of the obstacles faced by North Dakota's Garrison Diversion Project was that the project overlapped the continental divide into Hudson Bay drainage rivers. The Canadian Government raised concerns over the possibility of biota transfer from Missouri River waters to the Hudson Bay drainage, where it was feared that the fishing industry might be adversely affected. Among the solutions that were proposed was a closed system concept in which no surface return flows from irrigation would be allowed. In order to test this concept, the Oakes 5,000-Acre Test Area was constructed on the James River south of the city of Oakes, North Dakota. Missouri River water was to be carried through canals to the James River where it would be pumped to irrigate the test area. In the early 1980s, the Oakes Office drainage staff installed monitoring wells on a 1/4-mile grid so that the water table could be closely monitored. In 1985, 42 miles of pipe drains were constructed to provide adequate subsurface drainage and a terminal seepage pit was constructed to handle all surface return flows. This was followed by construction of the pumping plant and distribution facilities. No water would be allowed to leave the project until it had passed through the aquifer.

As of this writing, the canal system has not been completed and there has never been a full water supply for the test area. However, the drains have provided the opportunity to study various irrigation management schemes and iron ocher problems. The drains have also been effectively used to distribute artificial recharge waters through the aquifer. Spring flood flows on the James River are pumped to the main canal where it is discharged to closed depressions around the project. The pipe drains help to convey water from the depressions to other parts of the aquifer. During the irrigation season, the water is pumped by individual farmers for irrigation.

Wellton-Mohawk

Early history of agricultural development in the Wellton-Mohawk area, in southwestern Arizona, dates back to 1538 when the Pima Indians irrigated some of the bottom land adjacent to the Gila River. In the late 1800s, settlers developed irrigation in the area by diverting water from the Gila River, but alternating floods and drought encouraged them to turn to pumping the abundant supply of ground water. This worked well for a time, but by 1934, Wellton-Mohawk farms were facing another hazard. Excessive salt appeared in many wells and the water table had declined alarmingly. One after another, farms were abandoned as water and soil became too saline for successful farming.

In 1937, the Welton-Mohawk Division was authorized as a Reclamation project. Construction of the irrigation features was started in August 1949. On May 1, 1952, water from the Colorado River was turned onto the Wellton-Mohawk fields for the first time. However, importation of

water from the Colorado River caused the water table to rise and threatened crops. (USBR Dataweb)

Conventional drainage was contemplated, but investigations revealed that conventional drains would not be effective due to artesian pressures in the aquifer. (Tapp) The solution was to lower the water table by pumping the aquifer. Drainage wells were constructed to remove the excess ground water and the drainage water was discharged into the Gila River. The drainage water was highly saline, initially averaging about 6,000 parts per million. Late in 1961, the Wellton-Mohawk Main Conveyance Channel was constructed for the entire length of the Wellton-Mohawk Division to carry drainage water from about 67 wells. Additional wells were installed in 1963 to allow for selective pumping to reduce the salinity of the effluent during the winter months and to provide drainage to other areas with high ground water. (USBR Dataweb)

The Welton-Mohawk Division is unique in Reclamation as it is the only major drainage project that relies on pumping wells rather than horizontal drains to control ground water levels. The concept works well with the single drawback that operation, maintenance and replacement costs are very high compared to conventional drain systems.

National Irrigation Water Quality Program

Subsurface drainage from Reclamation irrigation projects was generally considered to be a beneficial side effect of irrigation as long as salinity levels in the water were not excessive. Even the high salinity waters were often welcomed by the managers of wildlife refuges. When unusually high numbers of waterfowl deaths and deformities were found at California's Kesterson Reservoir National Wildlife Refuge in 1982, FWS began an investigation which continued through 1985. The problem was attributed to high levels of the element selenium in the water and sediments of the reservoir. At very low concentrations selenium is benign or even beneficial, but at high concentrations it can be toxic to biological communities. The source of selenium in Kesterson reservoir was determined to be drainage water from irrigation, which was the primary water supply for the reservoir. This revelation was to have far reaching impacts to Reclamation's drainage program. A more detailed discussion of Kesterson Reservoir and reasons for the buildup of selenium is included in the Central Valley Project section of this paper.

Congressional interest and widespread media attention, including several television programs and more than 100 newspaper and magazine articles, prompted the Secretary of the Interior to open an investigation of the possible toxic effects of irrigation drainage water in the western United States. The investigation resulted in the National Irrigation Water Quality Program (NIWQP). NIWQP focused on areas important to migratory birds and endangered species and public water supplies receiving water from DOI irrigation projects. NIWQP, which is ongoing, is a 5-phase program. The studies are conducted by a core team of DOI agencies including FWS, Geological Survey, and either Reclamation or the Bureau of Indian Affairs (BIA), depending on which agency sponsored the project involved.

Phase 1, Site Identification, was essentially complete by 1989 (more sites could possibly be identified in the future). Based on existing information, sites likely to have irrigation-induced toxicity problems advanced to Phase 2, Reconnaissance Investigations. If selenium levels found posed a possible threat to fish and wildlife resources, the site moved on to Phase 3. Phase 3, Detailed Studies, consists of field studies to measure the extent of any adverse biological impacts. Where adverse impacts are found, the site advances to Phase 4, Remediation Planning, and then to Phase 5, Remediation Implementation. FWS was the lead agency in phases 1, 2, and 3 with Reclamation or BIA having the lead role in phases 4 and 5.

A survey of about 600 irrigation projects and wildlife areas was completed in phase 1. Thirty-one sites moved to phase 2, eight sites to Phase 3, five sites to Phase 4 and two sites are currently in Phase 5. All of the sites involved in Phases 4 and 5 are Reclamation projects. The two Phase 5 sites are Middle Green and Kendrick. The Middle Green centers around Stewart Lake State Wildlife Area, which receives a large part of its inflow from subsurface drains on the Jensen Unit of the Central Utah Project. Drainage water containing high concentrations of selenium are believed to be the source of selenium found in the lake sediments. In 1999, facilities were constructed to route the pipe drains around the lake so they discharge directly to the Green River, where the water is quickly diluted to naturally occurring concentrations. A number of "cleanup" techniques are being tested to remove selenium from the lake sediments. The Kendrick site is being addressed by eliminating return flows to two small closed basins and providing flow through water to flush two others. In addition, Reclamation will construct replacement wetlands at locations away from selenium sources.

RESEARCH

Since the Chief Engineer's Office was established, Reclamation Drainage and Ground Water personnel have been involved in applied research into every aspect of subsurface drainage. Some of the subjects are:

- water movement through soils
- field permeability testing
- salt balance in the root zone
- quality of return flows
- drain spacing, location, and depth
- orientation of drains with respect to natural hydraulic gradient
- influence of irrigation practices on drainage
- how water enters drain pipes
- envelope design
- biological and mineral clogging of drains
- construction methods
- construction costs
- materials used in pipe drains

- drain cleaning techniques
- well construction and rehabilitation

The purpose of the research was to check scientific theories, improve constructability and maintenance techniques, and validate current practices. Analog, physical, and digital models were used extensively in the various research studies.

The complicated processes by which water moves through soils has been a focal point of research efforts since Reclamation first viewed subsurface drainage as a science. In many cases cooperating with other agencies or universities, researchers studied flow through saturated and unsaturated soils, between different soil textures, and through preferential flow paths. Sand tanks were constructed where water movement could be observed and 16-mm movie films were made of the processes for training purposes.

In 1978, a 16-mm movie titled “Subsurface Drainage” was produced in cooperation with Washington State University. The film used sand tanks with manometers to show how water moves through soil profiles to buried drains, and how a shallow saline water table can harm or even kill growing plants. This film has since been copied to video tape for use in standard VCR units.

The Oahe Project in the early 1950s was the impetus for some of the most important research in the drainage discipline. The drainage requirements for Oahe were known to be extensive and the plan was to construct drainage facilities in conjunction with the distribution facilities. In that way, the financial burden on the farmers and the irrigation districts resulting from the normal lag time between the need for and the provision of drainage could be avoided. Mathematical theories for the transient-state drain spacing equations were developed in response to this need. Analog models were used first to verify the theories and later field measurements would validate the procedures.

Field tests for hydraulic conductivity, or permeability, that had been developed in the 1940s were adopted, tested and, in some cases, modified to meet specific needs of Reclamation projects. These tests were also subjected to analog model verification as well as field testing.

Many analog models and digital models have been constructed in an attempt to predict return flow quantity and quality from various projects. Reclamation has worked closely with the U. S. Department of Agriculture Salinity Laboratory to establish safe root zone salinity levels and leaching requirements needed to maintain acceptable salinity levels.

Drainage on sloping land was investigated in the early 1970s by constructing a sand tank in the Hydraulics Laboratory. The tank was 60 feet long, 2.5 feet deep and 2 feet wide and was mounted on a platform that could be tilted at slopes between zero and twelve percent. The wood frame tank was fitted with plexiglass panels so that observers could see what was occurring

outside the drains. The tank was later used to study sediment accumulation in drains with sags built into the grade.

Analog models were used during the 1960s and 1970s to predict the effects of placing interceptor drains on an angle to the natural hydraulic gradient on sloping land. Field verification was done in the Columbia Basin and on the Kansas-Bostwick Unit in Kansas.

Drainage staff participated in the Irrigation Management Service (IMS) studies that were done beginning in the 1960s. IMS studies were conducted on several projects and in every region to determine the fate of irrigation water that was applied to fields. All water entering the field through irrigation or precipitation was measured, consumptive use was estimated using state-of-the-art consumptive use formulae, root zone moisture levels were measured, and tail waters leaving the field were measured. Cooperating irrigators were assisted in management of their irrigation water to the benefit of production and reduction in water usage. Reclamation phased out the program in the late 1970s, but the practice is carried on by private industry for the benefit of private irrigators as well as those on federal projects.

Analog and sand tank models were used to study the way water enters clay tile and concrete drain pipe that had open joints for water to enter and how it enters perforated plastic pipe. Standards were set for the length of the clay tile and concrete pipe between open joints for various diameters of pipe. The larger the diameter of a pipe, the longer the pipe section can be. This research included establishing gradations and thicknesses for gravel envelopes around drain pipes. Sand tank models to study envelope and pipe perforation design are still in progress.

In the 1970s, clogging by iron ocher caused by bacteria growth was noted at several locations. Reclamation initiated a cooperative program with Dr. Harry Ford, a renowned expert in ocher-forming bacteria, of Florida State University. The result was early identification of problem soils and various means of treating the problems that develop.

In the 1970s, the “Open and Closed Conduit Systems” research program was used extensively to study various methods of construction, including the introduction of high-speed trenchers and trenchless drain construction or “plow drains”. The program was also used in the development of standards for plastic pipe drain materials. Video inspections of installed drains were used to determine deflection and other problems associated with pipe strength. Working closely with the corrugated plastic pipe industry and the Soil Conservation Service, U. S. Department of Agriculture, who were also developing a progressive drainage program, standards were developed for pipe strength and other properties. Mr. Ray J. Winger Jr., Chief of the Drainage and Ground Water Branch in the Engineering and Research Center from 1972 to 1981, was inducted into the Drainage Hall of Fame for his contribution to the advancement of plastic pipe for use in agricultural drains.

In the 1980s, a 12-inch-diameter hemispheric demonstration well was constructed in the Hydraulics Laboratory. The well was completed as an actual well except that it was fitted with a

plexiglass plate across the flat side so that observers could see what occurred in the aquifer and gravel pack outside the well during various rehabilitation treatments.

Not every research venture ended in new methods or products being adopted. Through the 1970s, Reclamation tested "no envelope" and thin synthetic envelopes under various conditions in California, Kansas, Wyoming, Washington and Montana. In every case, the drains either failed completely or performed poorly compared to a sand/gravel envelope. In 1976 and 1978, ABS plastic pipe was installed at two locations in the Republican River Valley. ABS was a lightweight, thick-walled pipe formed in 5-foot long sections with bell and spigot joints. In both cases, the pipe failed to retain its shape after being in place for less than 1 year. In 1974, a "trenchless" plow was used to install drains near Courtland, Kansas. The drains failed to control the water table and had to be replaced by conventional drains. In 1989, a thick or "voluminous" synthetic envelope consisting of styrofoam beads held in place by a nylon net was installed on a drain in central Nebraska. Hydrostatic pressure forced the beads into the pipe perforations and thoroughly plugged them, preventing any water from entering the pipe. These learning experiences have not deterred the Reclamation drainage staff from being receptive to new products and ideas.

INTERNATIONAL INFLUENCE

Since the Chief Engineers Office was established in 1948, Reclamation Drainage and Ground Water staff have been involved in assisting other countries in developing responsible drainage programs. The first foreign assignments for drainage staff were in Pakistan, India, Thailand, Peru, Egypt, Taiwan, Sri Lanka (formerly known as Ceylon), Afghanistan and the Philippines. Much of the data used to develop root zone moisture and salinity concepts was collected on assignments to Spain, Turkey, Australia, and other countries. Assignments to the African continent began when African nations gained independence from colonial rule: Senegal, Sudan, Somalia, Kenya, Tanzania. Our largest foreign involvement occurred during the 1970s, when we were involved in drainage and ground water activities throughout the developing world - South America, Africa, and Asia.

The foreign assistance focus has been to educate foreign nationals on the importance of understanding agricultural irrigation and the need to minimize land salinization or waterlogging of the soils. An economic land classification which considers drainage costs is central to protecting the land resources from permanent degradation and ensuring that the lands being developed are productive enough to provide the farmer with a living wage. Another area of emphasis is the importance of operation and maintenance of all facilities, including drains.

The individual assignments of a few weeks up to several years in length were typically financed by World Bank, Asian Development Bank, or the U.S. Department of State under the Aid to Developing Countries Program.

In the 1970s, Ray J. Winger Jr. of the Engineering and Research Center participated in technical meetings of the U.S. and U.S.S.R. Specialists Working group on Cooperation in the Field of Water Resources. The topic "Plastics in Hydrotechnical Construction" and subtopic "Investigating the Effectiveness of Utilizing Plastic Pipe in Irrigation and Drainage" were part of the U.S. - U.S.S.R. Agreement on Science and Technology of May 24, 1972. Materials and specifications were exchanged, field experiments were conducted in each country and meetings and field reviews were held in each country. The results of these experiments are incorporated into Reclamation's technical drainage policy.

Reclamation drainage staff served as consultants to the Prairie Farm Rehabilitation Administration, Department of Agriculture, Canada in the 1950s. A field review and comment on the drainage and related salinity and waterlogging problems in Alberta and Saskatchewan Provinces were requested by the Canadian government.

Through the 1980's and early 1990's Reclamation drainage engineers participated in an informal discussion group known as the Northern Plains Water Management Workshop. The workshop was made up of engineers and soil scientists from various universities and government agencies from the Dakotas, Montana, Alberta and Saskatchewan. The workshop had no formal structure, no officers, and no budget, but they would gather once a year at some facility and spend 2 to 3 days discussing the problems, research needs, and breakthroughs in irrigation of glacial till soils. The place and time of the gathering depended on someone volunteering to be the host.

PUBLICATIONS

Drainage Manual

Drainage engineering was in its infancy during the 1940s through 1960s and standard procedures for investigation and design had not been adopted. The purpose of the Drainage Manual was to present engineering tools and concepts that had proven useful in planning, constructing and maintaining drainage systems for successful long-term irrigation projects. The first drafts of the manual were in limited circulation within Reclamation in the early 1960s, but new procedures were being developed so rapidly that it was very difficult to arrive at a final draft. It was not until the deluge of new concepts began to subside that the manual was published as a hard cover book. The first edition was published in 1978. The manual was then quickly accepted as an authoritative publication by many in the world drainage community, and is used now as a textbook by several universities. A revised reprint in 1993 contains only a few substantive changes.

The Drainage Manual is used throughout Reclamation as a guide to performing drainage investigations, and the design, construction, and operation and maintenance of drainage systems for irrigated lands. The manual is gradually gaining acceptance as a guide to other drainage applications such as dam toe drains and slope stability

Ground Water Manual

The Ground Water Manual was developed as a guide to field personnel in the more practical aspects and commonly encountered problems of ground-water investigations, development, and management. It standardized Reclamation's procedures for ground water. The manual was developed over a period of years. Its contributors included personnel from the Bureau of Reclamation, other agencies, foreign governments, and many individual scientists and engineers.

Comprehensive Construction Training Program

In 1987, Reclamation's drainage and ground water personnel from several projects and regional offices contributed to the Comprehensive Construction Training Program by producing two modules titled Buried Pipe Drains and Well Construction.

Plastic Pipe Specification

With the introduction of plastic pipe for subsurface drains in the late 1960s came a need to ensure reliability of the new product. Research and testing conducted by Reclamation led to the need to develop standards for the strength and performance of the pipe. As larger diameters of pipe became available, new specifications were written to accommodate these sizes. By the early 1990s, American Society of Testing and Materials (ASTM) and American Association of State Highway and Transportation Officials (AASHTO) had developed parallel standards for the same product. In 1995, Reclamation produced a new document titled M-20 which combines all of the former specification documents and relies heavily on ASTM and AASHTO while retaining certain standards that are more stringent than ASTM or AASHTO.

SPINOFF APPLICATIONS

Not all of the drainage and ground water work is in the agricultural arena. Often dams, pumping plants, large canals, and other structures require subsurface drainage facilities to stabilize foundations and prevent damage from sloughing earthen slopes or seepage water.

Safety of Dams

It has long been recognized that most earth dams and some concrete dams need adequate toe drains to maintain a stable foundation. It was not until the 1980s that agricultural drainage experts began to have involvement in the design and construction of drains where the cost of failure could be measured in human lives. Replacement of the toe drains at Sherman Dam in Nebraska was the first such venture for the agricultural drainage staff. Then slowly came Canyon Ferry Dam in Montana, Diamond Creek Dike at Buffalo Bill Dam in Wyoming, Bonny Dam in Colorado and Glendo Dikes in Wyoming. Success in these projects has demonstrated that the science of ground water engineering is not limited to agricultural applications. While adaptations

need to be made to deal with the greater hydraulic gradients and the greater risk in the case of failure, the same basic concepts, materials and construction techniques are applicable.

Canal and Structure Stabilization

Toe drains are constructed along major canals for a variety of reasons. Slope stability, waterlogging of agricultural lands, and salinity control have all been accomplished by use of subsurface drains. McClusky Canal on the Garrison Diversion Unit in North Dakota experienced slope stability problems through cut sections 100 feet or more in depth. The canal was constructed in the 1970s and suffered chronic sloughing of the banks into the canal prism. Attempts to solve the problems using horizontal wells placed with an "Aardvark" horizontal drilling machine proved futile. After 10 to 15 years of severe maintenance problems, drainage personnel in the Garrison Diversion Office provided solutions to these problems by applying their knowledge of agricultural drainage in till lands.

The New Rockford Canal in North Dakota was constructed in the mid-1980s and marked the first example of canal toe drains being constructed as part of the canal contract specifically to protect agricultural lands from seepage from the canal.

The Courtland Canal along the Nebraska-Kansas border is perched atop the steep river bluffs and causes serious waterlogging problems in the irrigated fields below. Most of these problems have been relieved by use of interceptor drains at the base of the bluffs. However, the volume of water coming from the canal overwhelmed the first attempts at interception in the mid-1960s. Additional drainage works were constructed periodically for the next 20 years. A field review in the summer of 2000 concluded that the problems have finally been essentially solved.

Agricultural drainage techniques were used in 1980 to prevent the Yellowstone River from washing out the Terry Pumping Plant. As the slope progressively sloughed, the river threatened to cut a new channel behind the 60-cubic-foot-per-second pumping plant. Field investigations and transient-state computations revealed the source of the problem and it was solved by constructing a simple agricultural drain.

Again in 1990, concepts that were developed for agricultural drainage came to the rescue of a 50-foot-wide, 22-foot-high drop structure that carries 2,300 cubic feet per second at full capacity. The East Drain Terminal Drop structure below Palmetto Bend Dam on the gulf coast of Texas is subjected to extreme variations in hydrostatic pressure as tides move in and out. Perforated plastic pipe drains at the sides of the structure and a graded gravel bed at the bottom successfully relieved the stresses on the structure.

Wetlands Applications

As the focus of Reclamation activities has shifted from construction to water management, drainage and ground water personnel have used the knowledge gained over the past 50 years to incorporate wetland construction and management into their realm of expertise. In the Bay

Delta, programs associated with the Central Valley Project in California, the Platte River Recovery Program in central Nebraska, and the National Irrigation Water Quality Program, the same concepts that were developed for drainage are being used by drainage personnel to create and enhance wetlands.

CONCLUSIONS

In our first century, Reclamation has constructed over 13,000 miles of surface and subsurface drains to protect an estimated 1 million acres of irrigated land from damage due to waterlogging and salinity. This does not include the miles of drains or acres protected on projects that treat drainage as a farm development cost.

The first 50 years were typified by struggles to cope with technical unknowns as scientists, engineers, farmers, irrigation managers and politicians attempted to develop water projects to attract settlers to the American West. During the last 50 years, we have seen the uncertain art of drainage evolve into a science which removes most of the technical unknowns from the drainage of irrigated lands and allows development of sustainable agriculture to occur in a controlled manner.

Changing social values in the last quarter century have preempted some very promising irrigation developments. We have seen our focus change from developing new agricultural lands to maintaining existing water resources and environmental assets for the good of all society. We want to take note of a common thread that repeatedly appeared in the references used for this paper. It was the concern that Reclamation employees have always had for the environment. Well before the time of U.S. Environmental Protection Agency and most environmental groups, Reclamation drainage engineers were concerned about the quality of water that flowed from the drains and the effect that it would have on wildlife and other downstream users. Drainage engineering also has provided the agricultural community with the comprehension and capability to keep irrigated farm land in productivity and avoid exploitation. The 20th century has been the first time in history that large-scale irrigation has not been marked by a majority of lands that became waterlogged, salinized, and abandoned.

The lessons learned and the science that was developed around Reclamation's experience in drainage and ground water will be useful to future developments in the United States and around the world as developing countries endeavor to feed and clothe their people.

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