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# A LOOK AT THE ENGINEERING CHALLENGES OF THE USDA SMALL WATERSHED PROGRAM



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**ABSTRACT.** *The Small Watershed Program, administered by the USDA Natural Resources Conservation Service (formerly the Soil Conservation Service), originated in the 1940s and 1950s through the following statutes: the Flood Control Act of 1944, the pilot watershed program (1953–1954), and the Watershed Protection and Flood Prevention Act of 1954. The Small Watershed Program has been recognized by ASABE as one of the outstanding achievements of agricultural engineering in the 20th century in soil and water. With a \$15 billion infrastructure investment, more than 11,000 flood-control dams were constructed, and thousands of acres of farms and ranches are protected by conservation practices. The objectives of the majority of the projects were flood control and watershed protection. Other purposes included water management, municipal and industrial water supply, recreation, fish and wildlife habitat improvement, water quality improvement, and water conservation. Throughout the history of this program, there have been several engineering challenges in the fields of geotechnical engineering, hydrology, and hydraulics. The challenges included designing structures with limited information in unfamiliar conditions in a wide variety of settings. Challenges now include management of an aging infrastructure along with changes in national policy, laws, and needs. This article describes the history and impact of the Small Watershed Program, the engineering challenges surrounding this program, and how these challenges were and are being addressed. This article also takes a look at future challenges for the Small Watershed Program and what this means for engineers.*

**Keywords.** *Dams, Dispersive clays, Erosion, Rehabilitation, Spillways, Vegetation.*

The USDA Small Watershed Program was recognized by ASABE as one of the outstanding achievements of agricultural engineering in the 20th century (Cuello and Huggins, 2000). During the past 60 years, more than 11,000 dams and associated conservation practices were constructed in 2,000 watershed projects in 47 states. These projects provide \$1.5 billion annual benefits by reducing flooding and erosion damages, providing recreation and water supply, and improving wetlands and wildlife habitat. The Small Watershed Program has improved the quality of life and the environment in rural communities across the nation.

The USDA Small Watershed Program actually includes three separate federal authorizations, the Flood Control Act of 1944 (Public Law 78-534), the 1952 Appropriation Act that authorized 62 pilot watershed projects in 36 states, and

the Watershed Protection and Flood Prevention Act of 1954 (Public Law 83-566). Watershed projects are unique, federally funded water resource projects as they are federally assisted, not federally owned. The Small Watershed Program statutes authorized the USDA Natural Resources Conservation Service (NRCS), formerly named the Soil Conservation Service (SCS), to provide technical and financial assistance to local sponsors, who are local units of government, including conservation districts and other special-use districts, counties, states, and other municipal entities. Project sponsors are responsible for implementing the projects, including acquiring land rights. Sponsors are also responsible for operation and maintenance of the structures in the projects.

Since 1948, more than \$15 billion of federal and local funds have been invested in watershed projects (2007 dollars). More than half of the watershed dams are located in Oklahoma, Texas, and Iowa. The rest are located in 44 other states (fig. 1).

Typical watershed dams are earth embankments with principal and auxiliary spillways. Embankments normally range between 6 and 12 m in height, with several dozen over 30 m. The dams have drainage areas ordinarily from one to ten square miles and are usually located in the upper reaches of watershed tributaries. The principal spillway is most often reinforced concrete pipe ranging from 0.30 to 1.22 m in diameter, with the purpose of slowly releasing temporarily stored runoff waters. Dams are designed to provide storage for the total amount of sediment that is anticipated to be deposited in the reservoir during its design life. An auxiliary spillway (generally a vegetated channel) conveys extreme flood flow events safely around the dam to the valley downstream.

Dams are classified according to their potential for adverse consequences that may result from an uncontrolled re-

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# Watershed Project Locations

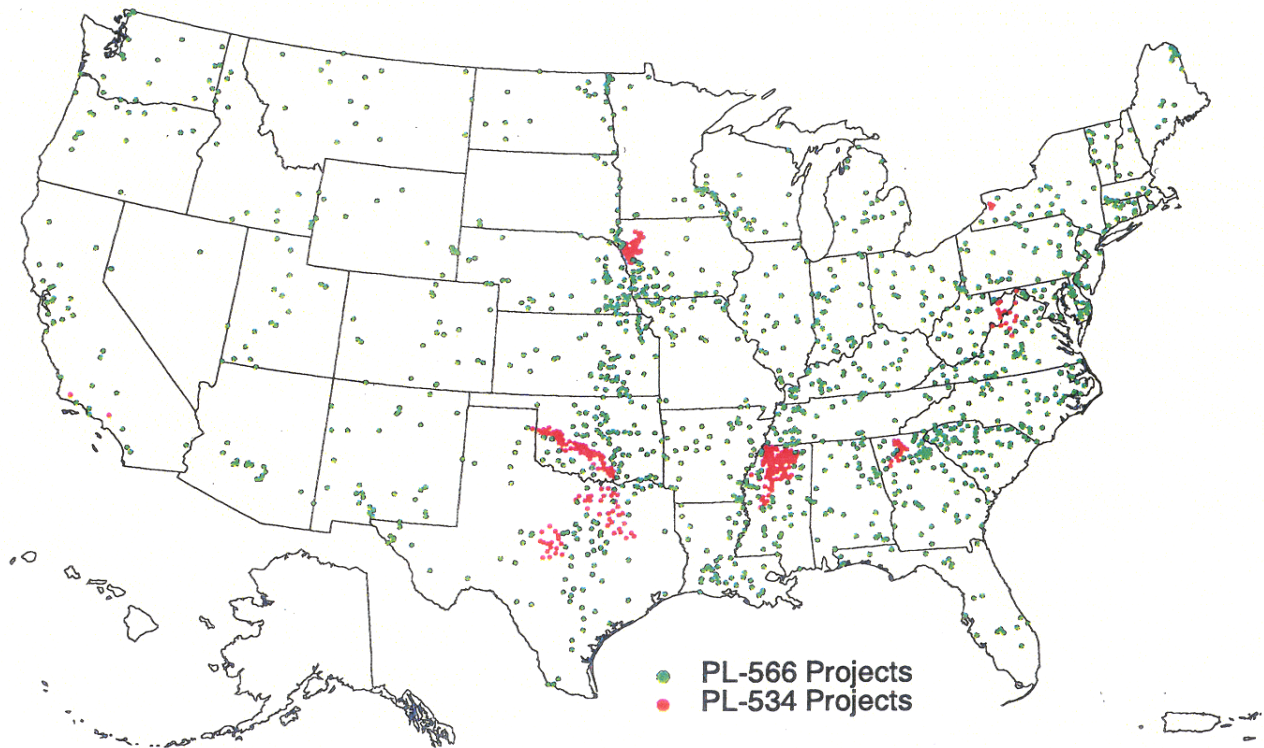


Figure 1. Watershed project locations.

lease of water due to a failure of the dam. This hazard classification system was pioneered by the Small Watershed Program with the release of SCS Engineering Memo 3 (USDA-SCS, 1956). This document introduced the concept that the design criteria become more stringent as the potential downstream risks increase. The design criteria involve requirements for hydrologic return period for spillway design storms, slope stability safety factors, and design of components of the dam.

Watershed plans require an economic analysis comparing the long-term benefits to the cost of the project to ensure that it is economically feasible. The period of time considered in the economic analysis is called the evaluated life. The majority of the earlier projects assumed an evaluated life of 50 years. Projects planned after the mid-1960s were generally planned with

an evaluated life of 100 years. Approximately 75% of the watershed dams were designed with a 50-year life.

Cloud Creek watershed dam number 1, located near Cordell, Oklahoma, in Washita County, was the first watershed dam constructed in the U.S. It was dedicated on July 8, 1948. From the mid-1950s to the mid-1970s, an average of one watershed dam was constructed each day. The peak construction period was during the 1960s (fig. 2). Federal funding for the watershed program has been reduced significantly since the mid-1990s, resulting in less than 50 watershed dams constructed each year.

Engineers on these projects faced several challenges in the fields of geotechnical engineering, hydrology, and hydraulics, including designing structures with limited information in unfamiliar conditions from desert to tropical climates on

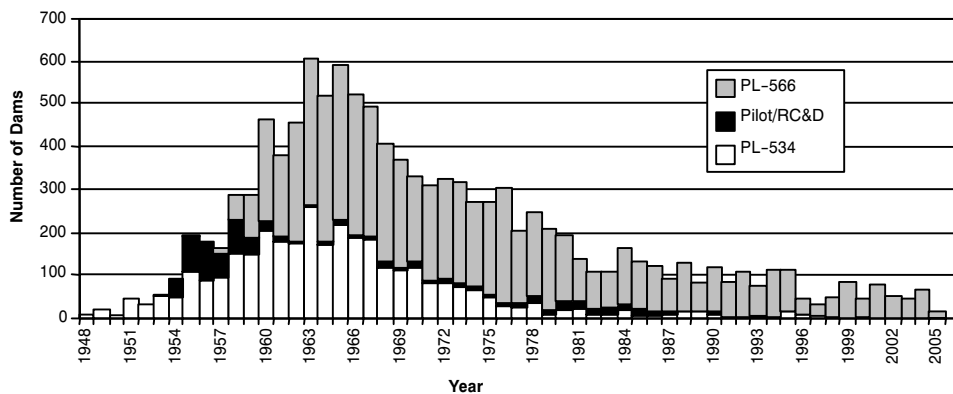


Figure 2. Watershed dams constructed by year.

coastal to mountainous landscapes in rural to urban areas. Recent challenges include management of an aging infrastructure along with changes in national policy, laws, and needs.

## GEOTECHNICAL CHALLENGES

Because the Small Watershed Program was spread across a wide variety of geologic conditions and covered much of the continental U.S., many geotechnical engineering problems were encountered, including collapsible foundation soils, soft compressible low shear strength foundations, permeable foundations, and high shrink swell embankment soils. In addition to these more common problems, engineers encountered some less common geotechnical problems, and contributed to a new understanding of them. These included: dispersive clays, broadly graded embankment soils, desiccated embankments with transverse cracks, and foundations with stress-relief fractures.

The three most important contributions made to advance the science of embankment design and construction that resulted directly from the Small Watershed Program relate to dispersive clays, filter design, and the use of filter diaphragms. Each of these contributions is discussed in more detail in the following sections.

### DISPERSIVE CLAYS

Forty percent of the total dams built under the Small Watershed Program have been constructed in Oklahoma, Texas, and Mississippi. These states have the greatest concentration of geologic formations containing the special class of soils known as dispersive clays. Dispersive clays are predominated by single-charged sodium cations rather than double-charged cations. The result of this unusual chemical makeup is clays with net negative charges on their particles, which causes a repulsion rather than an attraction to neighboring particles. This phenomenon causes the soils to become highly erodible, and embankment dams constructed with this material are vulnerable to failure.

In the early years of the Small Watershed Program, little was known or understood about dispersive clays and the problems they could cause. An extensive bibliography of early articles by Perry (1975) includes some of the early work on dispersive clays. After a rash of small embankment failures like those shown in figure 3, NRCS engineers began intensive investigations to determine a physical understanding of these embankment failures. Sherard et al. (1972a, 1972b) evaluated a number of the embankment failures that occurred in Oklahoma and Mississippi as a result of dispersive soils. Several tests, including the laboratory pinhole test and crumb test, were developed to help identify dispersive clays, and are now American Society for Testing and Materials (ASTM) standards (D 4221, D 4647, and D 6572).

### FILTER STUDIES

Besides dispersive soils, Sherard worked extensively on filter design. Beginning in about 1981, Sherard worked closely with the NRCS soil mechanics laboratory in Lincoln, Nebraska, in running tests to determine filter criterion. A series of articles published from this research laid the foundation for modern filter design (Sherard et al., 1984a, 1984b; Sherard, 1986). Most government agencies, including the U.S. Army Corp of Engineers (USACE) and U.S. Bureau of Reclamation (USBR), use this filter design.



Figure 3. Typical small embankment failure resulting from hydraulic fracture of an embankment constructed of highly dispersive clays.

### FILTER DIAPHRAGMS AS A DESIGN ELEMENT

As failure mechanisms became better understood, particularly the importance of hydraulic fracturing, the NRCS and other federal agencies abandoned the incorporation of anti-seep collar designs (Talbot and Ralston, 1985; USDA-NRCS, 1994). Since the mid-1980s, all NRCS watershed dams have been designed with a filter diaphragm rather than anti-seep collars. Currently, most modern embankments are not designed with anti-seep collars, and engineering experience with watershed dams was instrumental in this change in design practice.

## HYDRAULIC AND HYDROLOGY CHALLENGES

A wide variety of landscapes and hydrologic conditions were encountered across the U.S. in the Small Watershed Program. Designers were not only challenged by these conditions but by the lack of design guidance for new hydraulic applications. New hydraulic and hydrology challenges included:

- Hydraulics related to spillway ratings and energy dissipation.
- Hydraulic design of vegetated channels and rip-rap protection.
- Hydrologic policy and criteria for estimating runoff.

The most important hydraulic and hydrologic contributions as a result of the Small Watershed Program were in the area of closed-conduit spillways, vegetated auxiliary spillways, and hydrologic studies for determining watershed runoff.

### CLOSED-CONDUIT SPILLWAYS

The closed-conduit spillway was implemented on the majority of the watershed dams to serve as the principle spillway. The typical closed-conduit spillway has three primary components: the drop inlet (usually with a trash rack on top), the closed conduit through the dam, and an outlet that may

consist of an energy dissipation basin and/or a stilling pool. Each component of the closed-conduit spillway has presented technical challenges that were addressed by both research and experience.

Flood control reservoirs not only store water, but also trap sediment and debris (i.e., branches, grass, leaves, and man-made products). Debris becomes a problem when it accumulates around points of discharge because it restricts the flow capacity of the principal spillway. Trash racks implemented on risers were researched by Hebaus and Gwinn (1975). The best design tested was the step-baffled trash rack, an idea conceived by M. M. Culp (Gwinn, 1976). The step-baffled trash rack is now a standard NRCS design (USDA-NRCS, 2005).

The drop inlet (fig. 4a) was common practice from the start of flood control work. Most early risers were square or round with an anti-vortex baffle. By 1963, a rectangular standard riser with a length of 3 times the diameter of the pipe ( $D \times 3D$  dimensions) was used. These design changes were incorporated due to research conducted by ARS from the late 1940s through the 1970s. Standard methods and drawings were developed for drop inlet spillways and are documented in NRCS Technical Release (TR) 29 (USDA-SCS, 1965a), TR-30 (USDA-SCS, 1965b), and Engineering Standard (ES) 169 (USDA-SCS, 1965c).

The closed-conduit spillway outlet (fig. 4b) typically consists of a cantilevered pipe and plunge pool or an impact energy dissipation basin. The purpose of the cantilevered pipe outlet and plunge pool is to ensure that the flow energy is dissipated far enough downstream to prevent scour damage to the dam, and the scouring energy is dissipated in the plunge pool and not passed into the downstream channel. Initially, information was limited for the design of preshaped, armored, plunge pool energy dissipators, but after extensive research, procedures for the design of plunge pool energy dissipators were developed, which include criteria for scour

hole shape and the size of the riprap lining material (Blaisdell and Anderson, 1989).

#### VEGETATED AUXILIARY SPILLWAYS

Vegetated auxiliary spillways were used on the majority of the dams due to their economical ability to convey infrequent flood flows around the dam to the valley below with little or no damage. These spillways are designed so that (1) the flows are infrequent and of short duration, (2) the flow depths may be greater than a meter, (3) the spillway exit channel may be relatively steep, and (4) erosion of the spillway is permissible if the spillway does not breach during passage of the flood flow. Vegetated channel design was originally published in SCS-TP-61, the *Handbook of Channel Design for Soil and Water Conservation*, a document that has been used worldwide for the design of vegetated channels for more than 50 years (USDA-SCS, 1947). This handbook provides permissible velocity criteria and n-VR curves, both of which are valuable tools for the design of vegetated waterways (Cox and Palmer, 1948; Ree, 1949). This work, along with further research conducted by Ree et al. (1977) and Temple et al. (1987), set the groundwork for auxiliary spillway design. The vegetated channel design criterion is used to prevent erosion in the spillway exit channel for flows up to those of a stability design hydrograph.

Despite the widespread successful use of the design procedures, the complex processes by which earth spillways erode have not been well understood. An Emergency Spillway Flow Study Task Group was formed jointly by the NRCS and ARS in 1983. NRCS was responsible for observing and gathering data from field spillways that had experienced greater than 0.9 m of head or had sustained major damage from flood flows; ARS was responsible for research focused on the development of a stress-based rather than the velocity-based grass-lined channel design method (Temple et al., 1987). This effort included additional study of the failure of grass channel linings and an improved procedure for the design of grass-lined channels, including grassed waterways (Temple et al., 1987). As a result of this combined effort, a new partnership between the NRCS and ARS, known as the Design and Analysis of Earth Spillways team, formed. Through the analysis of field and laboratory studies, computational algorithms were developed for the use in design and analysis of earth spillways (Temple et al., 1993; Temple and Hanson, 1994; Moore et al., 1994). This computational algorithm was incorporated into the Water Resources Site Analysis computer program (SITES) used by NRCS and private design firms for use in determining the potential for spillway breach when the spillway is subjected to the freeboard hydrograph (USDA-NRCS, 1997).

#### WATERSHED RUNOFF METHODS

Before 1957, each SCS region used different hydrologic policy and criteria for designing flood control structures. Design was based on experience in designing farm ponds. Sites were designed to provide the most economical design while at the same time providing the required flood reduction benefits. Hamilton and Jepson (1940) developed early methods for determination of peak runoff rates from the watershed. These methods were limited to drainage areas less than 800 ha. The unit hydrograph method was used for drainage areas larger than 800 ha. Design storms related to the 100-year storm were used to size the structure.



Figure 4. Components of the closed-conduit spillway: (a) trash rack and drop inlet tower, and (b) cantilevered outlet and plunge basin.

By the mid-1950s, a direct method for estimating runoff from storm rainfall, known more commonly as the curve number method, was developed (USDA-NRCS, 2004). The curve number is related to the hydrologic soil type, cover type, and hydrologic conditions. The average antecedent moisture condition and a standard dimensionless unit hydrograph were developed concurrently for design purposes. Hydrology of the watershed was developed using computer techniques in TR-20 (USDA-SCS, 1964). In 1963, USDA-SCS Engineering Memo (EM) 27 standardized hydrologic policy for the design of flood control structures (USDA-SCS, 1963). A standardized theory for determining hydrology (Snyder, 1964) and a method for estimating volume and rate of runoff in small watersheds (USDA-SCS, 1968) were developed.

## ON-GOING CHALLENGES AND LOOKING AHEAD

Many of the watershed projects are now in far different settings than when they were originally constructed. Hazard classifications for dams and land use have changed as a result of population and infrastructure growth. Additionally, sediment pools have filled, and structural components have deteriorated. Consequently, many dams do not meet current dam safety regulations. Public safety, environmental and social concerns, funding (for operation, maintenance, and rehabilitation), and liability are some of the increasing challenges project sponsors are now facing. In 2007, many watershed dams have already exceeded their evaluated life. More than half of the watershed dams are now more than 40 years old. Many of these aging dams are in critical need of rehabilitation to keep them safe.

In 2000, Congress passed the Watershed Rehabilitation Amendments, which authorized NRCS to assist local sponsors to rehabilitate their aging watershed dams. Congress is struggling for continual funding of the \$1.5 billion backlog of watershed projects that have been authorized in the Small Watershed Program. Appropriations for the Small Watershed Program have been reduced from more than \$200 million per year in the early 1990s to \$75 million in 2006. The local-federal partnership that has been the basis for the success of this program will be tested in the future. Many present and future challenges, both social and technical, exist with the Small Watershed Program.

Social challenges include:

- Aging structures, more stringent dam safety laws, changing demographics, and changing hydrology.
- Funding for rehabilitation of the Small Watershed Program infrastructure.
- Priority ranking for rehabilitation.
- Maintaining local interest and understanding of the watershed projects.
- Acquiring land rights.
- Local financial and legal burdens.
- Dam safety, risk assessment, hazard classification, and development of evacuation plans.
- Maintenance of technical expertise within NRCS.

Technical challenges include:

- Dam safety, risk assessment, hazard classification, and development of evacuation plans.
- Methods for safely conveying larger design floods for dams that were originally designed as low hazard structures.
- Methods for rehabilitating dams in the arid southwest that have developed extensive desiccation cracks and pose a hazard of failure should they store a design storm.
- Methods for rehabilitating dams with shallow surficial slides caused by highly plastic clay structures developing over the years.
- Methods for evaluating the erodibility of auxiliary spillways constructed in earth and rock materials.
- Networking with other design agencies and experts to improve earth dam design.
- Methods to allow overtopping of dams for a limited amount of time in certain situations.
- Methods for estimating the likelihood of embankment failure caused by overtopping, internal erosion, foundation seepage, earthquakes, and sliding.

## CLOSING

The Small Watershed Program accomplished much during the past 60 years, and tremendous technical and administrative challenges were overcome to create the water resources infrastructure that now exists across the nation. Many challenges were met, from the establishment of a unique local-federal partnership, to the development of technical criteria and procedures to design and construct hundreds of dams each year in a variety of landscapes. The success of the Small Watershed Program is demonstrated by the on-going benefits these dams continue to provide to rural America, even well beyond the original evaluated life of the structures.

Our predecessors met the challenges needed to build the successful Small Watershed Program. Now, our generation must meet the challenges of continuing with the original watershed program, as well as rehabilitating the resulting \$15 billion water resource infrastructure so that it will continue to provide the original economic and environmental benefits across the nation, as well as provide for the public health and safety for generations to come.

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