WINDAM B EARTHEN EMBANKMENT OVERTOPPING ANALYSIS SOFTWARE

Karl Visser, Hydraulic Engineer, USDA-NRCS, Fort Worth, TX, karl.visser@ftw.usda.gov; Gregory Hanson, Research Leader, ARS, Stillwater, OK, greg.hanson@ars.usda.gov; Darrell Temple, Research Engineer Retired, ARS; Stillwater, OK, darrel.temple@ars.usda.gov; Morris Lobrecht, Design Engineer Retired, USDA-NRCS, Fort Worth, TX, morris.lobrecht@ftw.usda.gov; Mitchell Neilsen, Professor of Computing and Information Sciences, Kansas State University, neilsen@k-state.edu; Tony Funderburk, Hydraulic Engineer, USDA-NRCS, Fort Worth, TX, USDA-NRCS, tony.funderburk@ftw.usda.gov; Helen Moody, Hydraulic Engineer, USDA-NRCS, Beltsville, MD, helen.moody@wdc.usda.gov

INTRODUCTION AND HISTORY

Windows Dam Analysis Modules (WinDAM) is a modular software application being developed for the analysis of overtopped earth embankments and internal erosion. The development is being carried out in stages. The initial computational model development addressed routing of the flood through the reservoir with dam overtopping and evaluation of the potential for vegetation or riprap to delay or prevent failure of the embankment. That model, WinDAM A+, has now been developed which includes auxiliary spillway erosion technology. The next computational model development is WinDAM B, which is presently underway and is described in this paper, includes erosional failure of a homogeneous embankment through overtopping and drainage of stored water. Later planned expansion of the model is anticipated to include analysis of internal erosion, non-homogeneous embankments, and embankment protection analysis.

Participating Agencies WinDAM B Earthen Embankment Overtopping Analysis Software is designed to address the dam safety concerns facing the national legacy infrastructure of over 11,000 small watershed dams constructed with Federal involvement over a seventy-year period. The US Department of Agriculture – Agricultural Research Service (USDA-ARS), US Department of Agriculture – Natural Resources Conservation Service (USDA-NRCS), and Kansas State University (KSU) are working jointly to develop and refine this software.

Federal Involvement Of Small Watershed Dams History Design and construction of small watershed dams on private lands with Federal involvement began with the Civilian Conservation Corps during the 1930's. The Coon Creek Watershed District in Wisconsin was formed in 1933 under the Soil Erosion Service.

Initially the Civilian Conservation Corps began constructing dams on private lands in the 1930's. Wisconsin formed the Coon Creek Watershed in 1933 with the Soil Erosion Service (Later the Soil Conservation Service – USDA-SCS). The first small watershed project was Cloud Creek Site 1 near Cordell, OK which was dedicated in 1948 (USDA-NRCS, 2009). The experience of the USDA-SCS in designing and building farm ponds was transferred to the design of the small watershed structures in the late 1940's.

The USDA Small Watershed Program includes three separate Federal authorizations (Caldwell, 1999), 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).

Public Law 78-534 – Flood Control Act of 1944 enacted the first 11 USDA-SCS watersheds covering thirty million acres:

Buffalo Creek – NY
Coosa River – GA & TN
Little Sioux River – IA & MN
Little Tallahatchie River – MS
Los Angeles River – CA
Middle Colorado River – TX
Potomac River – VA, W. VA, MD, & PA
Santa Ynez River – CA
Trinity River - TX
Washita River – OK & TX
Yazoo River - MS

Public Law 83-566 – Watershed Protection and Flood Prevention Act of 1954 started the small watershed program. The map of watersheds and number of dams constructed by year are shown in figures 1 and 2. This map shows the impact on the nation of Public Law 566 and 534. Starting in 1958, an average of one dam per day was constructed over a period of twenty years. The USDA-SCS and watershed sponsors obtained landrights, designed, and constructed over 7,000 dams during this period. More than 11,000 dams and associated conservation practices were constructed in 2,000 watershed projects in 47 states during the last 60 years. More than $15 billion dollars (2007 dollars) of Federal and local funds have been invested in watershed projects (Hanson et al. 2007).

Initially each USDA-SCS region developed design criteria for dams. USDA-SCS Engineering Memo 3 (USDA-SCS, 1956) standardized criteria based on risk for the entire US. This hazard classification system was pioneered by the Small Watershed Program with the release of Engineering Memo 3 and further refined with Engineering Memo 27 (Rev) (USDA-SCS, 1965). The first edition of TR-60 (USDA-SCS, 1976) replaced Engineering Memo 27. The current version of TR-60 (USDA-NRCS, 2005) covers many aspects of earth embankment and reservoir design.

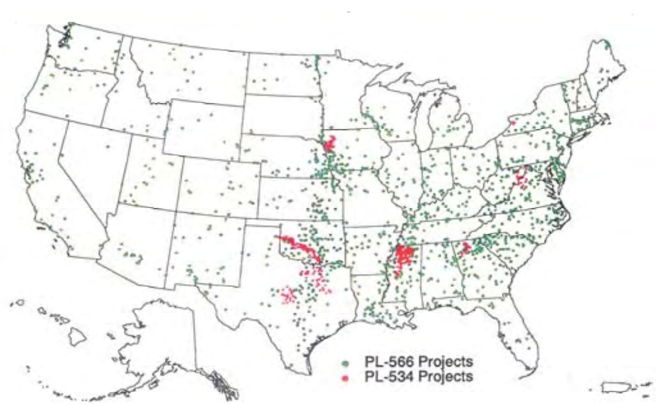

Figure 1 Map of Small Watershed Projects across the U.S.

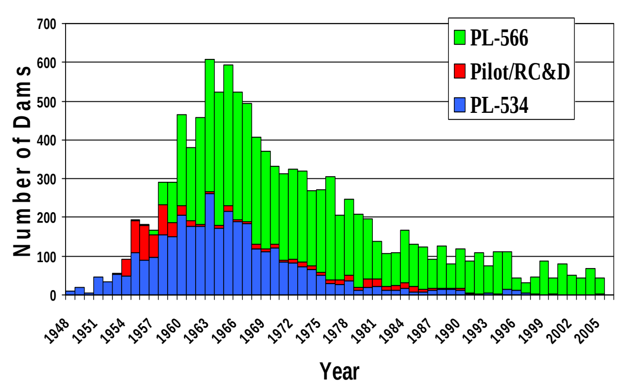

Figure 2 Number of Dams constructed per year per Federal authorization.

A breach analysis, flood routing, and flood inundation areas were determined to classify the structure's hazard. Hydrologic criteria for determining spillway discharges and floodwater storage were an important aspect of the engineering design involved in proportioning components of these structures. Detailed procedures for developing principal spillways, auxiliary spillways, and freeboard hydrographs were developed and included in USDA-NRCS National Engineering Handbook (NEH) 4 Chapter 21 (USDA-SCS, 1971) (which will be revised to 210-VI-NEH-Part 630-Chapter 21), and spillway systems are contained in NEH 4 Chapter 17 (USDA-SCS, 1972) (which will be revised to 210-VI-NEH-Part 630-Chapter 17). Hydraulic routing relative to dams in series provided additional computational complexity.

Most flood routing of dams before the middle 1960's were done manually. Then, mainframe computer routing began to replace manual methods. In the 1960's a mainframe routing would require several weeks since the data had to be mailed to a central location where data cards were punched and computations completed. The output was then printed and mailed back to the user. The turnaround time was at least two weeks on each separate run.

The USDA-SCS TR-52 (USDA-SCS, 1973) design procedure from 1973 to the mid 1990's utilized the bulk length concept to determine the auxiliary spillway length and geometry. In 1983 the USDA-SCS - ARS Emergency Spillway Flow Study Task Group (ESFSTG) was formed to develop better earth spillway technology. The ESFSTG collected data on dams that experienced either emergency spillway flow at least three feet deep or significant damage during a storm event. The ESFSTG visited several hundred sites over the following 10 years. Approximately 100 sites were selected for more in-depth evaluation and data collection. Task group members tried to understand the processes being observed, identify appropriate data for collection, and order the data in a systematic fashion. Data analysis began in 1990 from the field spillway data initially collected. Tests were conducted in the USDA-ARS outdoor laboratory during this time to further understand spillway performance processes such as flow concentration, vegetal cover failure, surface detachment, and headcut migration.

These findings were incorporated in DAMS2 software, and then in <u>S</u>tability and <u>I</u>ntegrity <u>T</u>echnology for <u>E</u>arth <u>S</u>pillways (SITES) software in 1994, (Temple, 1993; SITES, 2005; Lobrecht, 2006). The bulk length concept was replaced by SITES spillway erosional modeling technology in other USDA-NRCS references including NEH 628 Chapter 50 (USDA-NRCS, 1997a), 51 (USDA-NRCS, 1997b), and 52 (USDA-NRCS, 1997c).

Although the SITES program may be used for analyses of dams and spillways, it was developed primarily for design and was developed over a period in which computational capability was much more limited than today. The legacy infrastructure of aging structures means a transition from design of new structures to the analysis of existing structures. For example, existing structures may overtop as a result of watershed changes or sediment deposition within the flood pool leading to inadequate spillway capacity. The WinDAM software builds on and extends the technology in SITES to provide the needed capability for these types of analyses.

The evolution of USDA-NRCS dam design methods are summarized in Figure 3.

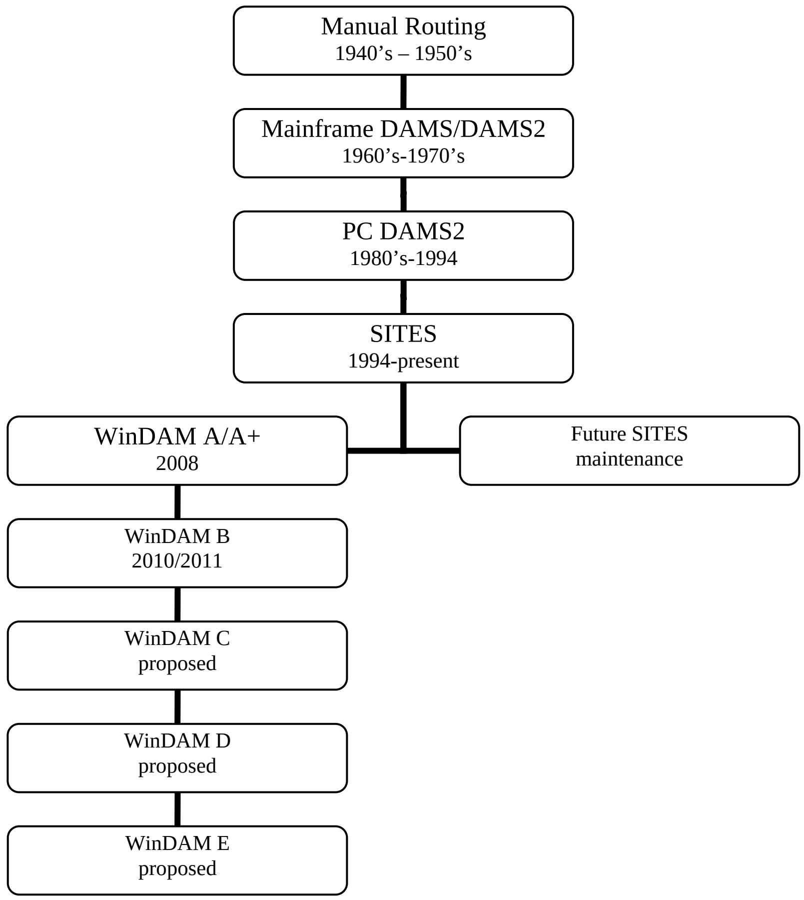

Figure 3 Evolution of USDA-NRCS Dam Design Methods (Dates are approximate)

WINDAM B CAPABILITIES

Primary Purpose of Software The primary functions of WinDAM B software are threefold:

- Hydraulically route one input hydrograph through, around, and over a single earthen dam.
- Estimate auxiliary spillway erosion in up to three earthen or vegetated auxiliary spillways.
- Estimate erosion of the earthen embankment caused by overtopping of the dam embankment.

WinDAM B does not include any hydrology component—in other words the user must create the input hydrograph in other software. The WinDAM B user can then import the hydrograph or paste the hydrograph points into the user interface. This allows the user the flexibility to choose the hydrologic software most suitable for analysis of site conditions.

Overtopping Homogenous Earthen Embankment WinDAM B assumes the embankment of the dam is a homogenous earthen material. Many USDA-NRCS dams are homogenous earthfill, so the WinDAM B model applies. Future versions of WinDAM software will address zoned-fill dams where each zone exhibits markedly different erosion resistance from other zones.

Types Of Embankment Slope Protection The overtopping/breach analysis component of WinDAM B begins with an evaluation of the failure of the surface of the downstream slope of the embankment. Erosion is conservatively assumed to begin at the point on the downstream slope surface closest to the reservoir. Points of concentrated attack such as the groin and toe areas are assumed to be protected, submerged, or evaluated external to the software. Initial slope conditions included for evaluation are vegetal (grass) protection, riprap protection, and no protection (bare soil). Vegetation is described with the same parameters as in SITES—vegetal cover factor, maintenance code and retardance curve index. The riprap is described using the D_{50} diameter, uniformity, porosity, and thickness of the riprap layer. The case where “no cover” exists on the embankment is described solely by the Manning’s n value.

Principal Spillway Types WinDAM B principal spillways can be single stage risers, two-stage risers, or hood inlet risers. The principal spillway conduit for the single-stage or two-stage riser can be circular or rectangular. In addition, the user may also specify that the dam has no principal spillway or a principal spillway rating may be entered directly in the form of elevation-discharge pairs. When the principal spillway elevation-discharge rating is entered directly, the effects of tailwater on the rating cannot be included in run-time calculations.

Three Auxiliary Spillways Most new USDA-NRCS dams are built with a single earthen auxiliary spillway. In rehabilitation of old USDA-NRCS-designed dams, it is more common to utilize additional auxiliary spillways. As a result, WinDAM B allows the user to input a maximum of three auxiliary spillways, each auxiliary spillway with different physical characteristics. The auxiliary spillway can be described with a surface profile, or as a rating table with elevation-discharge points. The auxiliary spillway erosion analysis is optional. The user may also specify no auxiliary spillway.

Material Parameter Statistical Analysis – Auxiliary Spillway Auxiliary spillway integrity analysis applies the same technology utilized by the SITES program. The technology is implemented through linking to the SITES Spillway Erosion Analysis (SSEA) routines described by Temple et al. (2003). Reservoir releases associated with earth auxiliary spillway breach are not evaluated. An extensive geotechnical investigation provides the information necessary to model the erosion in the weakest material in the auxiliary spillway. To analyze the sensitivity of the results relative to the input geotechnical parameters, WinDAM B can make multiple runs with different values. The parameters that can be varied are:

Plasticity Index
Dry Density
Head Cut Index
Percent Clay or Detachment Rate
Representative Diameter

The user inputs the number of values to check, a seed value, a sampling method (random or Latin hypercube), pairing method with other parameter variables (random or restricted), and selects a distribution. The available distributions are shown in Table 1.

Table 1 WinDAM B Distributions for Material Parameter Statistical Analysis.

Normal	Truncated Lognormal	Geometric	Gamma
Truncated Normal	Truncated Lognormal-N	Binomial	Maximum Entropy
Bounded Normal	Uniform	Negative Binomial	Lognormal-B
Lognormal	Loguniform	Hypergeometric	Normal-B
Lognormal-N	Triangular	Exponential	
Bounded Lognormal	Beta	Weibull	
Bounded Lognormal-N	Poisson	Pareto	

SITES Vs Windam B Comparison SITES is the predecessor to WinDAM, so it is helpful to understand how these two differ. Table 2 summarizes key points for each.

Table 2 SITES vs WinDAM B Comparison

Item	SITES	WinDAM B
Hydrology	Full-featured hydrologic model capable of modeling multiple sites, watershed areas, and stream reaches.	No hydrologic modeling. User must input hydrograph
Hydraulics	Routes up to three separate design hydrographs through dam	Routes one input hydrograph through the dam
Downstream tailwater	Fixed	Variable
Auxiliary spillway erosion prediction	Single auxiliary spillway	1-3 auxiliary spillways
Embankment erosion prediction	None	Single homogenous earth embankment.
TR-60 Policy	Many TR-60 policy requirements are hard-coded into the software. Future policy changes will require changes to software.	User must know and understand TR-60 criteria. Future policy changes are less likely to require software changes.
“What if” alternatives analysis	Reservoir routing computation ceases when auxiliary spillway crest is breached by predicted erosion.	Computation continues during predicted erosion and downcutting of earthen embankment. (Auxiliary Spillway erosion computation ceases when the crest is breached)
Complexity	More input screens and multiple sites available for input.	Single site analysis. Fewer input screens to populate. Hydrographs imported from hydrologic software and exported to stream routing software.

SITES replaced the DAMS2 software, but the transition from SITES to WinDAM B is different. SITES will likely be maintained, but no new features are being planned for SITES. WinDAM B will be the recipient of any new software features.

After WinDAM B is released, SITES will continue to be an acceptable design tool. Many designs for new dams will probably utilize SITES software. However, there will be specific cases where WinDAM B is clearly the preferred software over SITES. For example, if there is significant downstream tailwater, then WinDAM B would be the best design tool. The user will need to determine the best design tool for the situation.

Windam Versioning WinDAM software already has two versions – A and B. Research is ongoing for future enhancements to the software, as shown below.

Table 3 WinDAM Versioning.

Version	Existing Capabilities or Future Enhancements
WinDAM A+ (released)	Embankment overtopping analysis (Slope protection evaluation: no embankment erosion analysis)
WinDAM B (beta)	Homogenous fill embankment overtopping and erosion analysis
WinDAM C (proposed)	Internal erosion (piping) prediction through homogenous fill embankment
WinDAM D (proposed)	Potential failure initiation at toe, berms, and groins. Alternative embankment slope protection materials (i.e. blocks, reinforced vegetation)
WinDAM E (proposed)	Zoned fill embankment overtopping erosion prediction

INPUT DATA

For a SITES user, the inputs required to describe the principal spillway and the auxiliary spillway look familiar in WinDAM B. One new piece of data required in WinDAM B to describe the principal spillway is a tab labeled, “Coefficients” where the user enters data describing the orifice inlet of the conduit. SITES assumes that the design utilizes a standard USDA-NRCS riser of sufficient height so that flow control passes from riser weir flow, then riser crest orifice flow to full pipe flow in the conduit. WinDAM B checks to see if flow control is governed by orifice control at the conduit-riser interface.

The auxiliary spillway in WinDAM B is described with essentially the same data as in SITES. WinDAM B requires the user to input one flow hydrograph. This hydrograph input is similar to the SITES input procedure. SITES has the option to input hydrology through a watershed model, but WinDAM B only allows hydrology input through a single hydrograph. Various design hydrographs will require a different WinDAM B run for each hydrograph.

WinDAM B may be run with or without embankment breach evaluation. When breach evaluation is desired, the earthen embankment must be described so WinDAM B can model overtopping erosion. The user specifies the type of slope protection for all runs: the options are vegetation, rock riprap, or no cover. For the breach analysis option, the user selects one of two headcut models: Temple/Hanson Energy model or Hanson/Robinson Stress Model. Then the user enters the required geotechnical parameters for use in the selected model. The dam embankment crest and slope dimensions are also input.

Generally, the outflow from dams is controlled primarily by the hydraulic features of the dam—principal spillway and auxiliary spillway. For these dams where backwater effects are not significant, a single downstream tailwater elevation is sufficient. However, some dams have downstream hydraulic features such as levee or road embankments that impose significant and dynamic backwater effects. WinDAM B incorporates a tailwater rating table to simulate how the outflow from the dam varies with downstream capacity. This backwater is used when analyzing the auxiliary spillway flow, but is not yet utilized when computing the auxiliary spillway erosion.

OUTPUT RESULTS

Just like SITES, WinDAM B has three forms of output; the initial summary screen the user sees upon completion of a valid run, the ASCII text output file, and numerous graphical plots. The summary table has a few more output items than SITES does due to the overtopping analysis. The new summary items in WinDAM B are listed in Table 4.

Table 4 New Summary Table Items in WinDAM B.

AS (1-3) Crest Elevation And Peak Outflow	Overtopping Flow Duration	Percent Allowable Erosion Effective Stress On Dam Face	Dam Fill Advance Rate Coefficient
Length Of Dam	Time Of Slope Protection Failure	Percent Allowable Unit Discharge On Dam Face	Dam Fill Total Unit Weight
Maximum Overtopping Depth	Time Of Breach Initiation	Maximum Gross Stress On Dam Face	Dam Fill Erodibility
Peak Overtopping - Breach Flow	Time Of Breach Formation	Dam Breach Model	Dam Fill Undrained Shear Strength
Maximum Overtopping-Breach Unit Discharge	Percent Allowable Gross Stress On Dam Face	Dam Fill Critical Shear Stress	Final Breach Width

The text output file has more parts than a SITES text output file. The WinDAM B text file includes output that shows the performance of the embankment of the dam. There are other text files detailing the performance of each auxiliary spillway, if there are multiple auxiliary spillways.

The WinDAM B graphic output plots are listed in Table 5.

Table 5 WinDAM B Graphic Output Plots.

Category	Specific Plot
Breach and Dam	Breach Width Dam Cross-section Dam Crest Profile
Embankment Headcut	Headcut Advance Headcut Position
Hydrographs & Reservoir	Hydrographs Reservoir Storage Volume Reservoir Water Surface Area
Overtopping	Maximum Overtopping &Breach Discharge Maximum Overtopping Head Overtopping Stress
Tailwater & Ratings	All Discharge Ratings Principal Spillway Rating Auxiliary Spillway Ratings Tailwater Rating Tailwater Elevation

POLICY AND APPROPRIATE USE

Currently, the most commonly used USDA-NRCS method to estimate breach outflow from dams are the envelope equations listed in the Peak breach discharge criteria section of TR-60. However, TR-60 also mentions that “The peak discharge value determined by using principles of erosion, hydraulics, and sediment transport may be used in lieu of the peak discharge computed using the above equations.” Since the WinDAM B model, once fully tested and accepted for use, estimates a discharge hydrograph using the principles of erosion, hydraulics, and sediment transport, it meets TR-60 criteria.

Some USDA-NRCS design engineers have wondered if WinDAM B software will usher in the possibility of rehabilitating dams subject to higher regulatory design storms with flows overtopping the dam embankment as an acceptable design. Currently, USDA-NRCS does not regard overtopping as an acceptable design practice.

However, there are design scenarios where overtopping is a much-needed design tool. For example, for dams in series, TR-60 criteria requires that the design of the lower structure include an analysis of the upstream dam. If the upstream dam is overtopped, it is considered breached, and the breach outflow is routed downstream to the lower dam. WinDAM B maybe an appropriate design tool to estimate the breach outflow from the upper dam in designing the lower dam. If the upper dam overtopping depth is very minor and the upper dam embankment is erosion resistant, the resulting upper dam breach outflow may be much smaller than the predicted discharge from TR-60 breach outflow equations. Also, local dam safety officials and emergency planners may want to utilize the results of a downstream breach wave resulting from a WinDAM B model of a particular dam. State dam safety officials should be consulted prior to such use.

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