WINDAM C EARTHEN EMBANKMENT

INTERNAL EROSION ANALYSIS SOFTWARE

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ABSTRACT Two primary causes of dam failure are overtopping and internal erosion. For the purpose of evaluating dam safety for existing earthen embankment dams and proposed earthen embankment dams, WinDAM C software will simulate either internal erosion or erosion resulting from an overtopping event. WinDAM C models erosion failure of a homogeneous embankment. Future expansion includes non-homogeneous embankments, and embankment protection analysis.

The four essential functions of the software are:

1. Hydraulically routes one input hydrograph through, around, and over a single earthen dam.
2. Estimates internal erosion and potential breaching of an earthen embankment dam.
3. Estimates erosion of the earthen embankment caused by overtopping of the dam embankment.
4. Estimates auxiliary spillway erosion in up to three earthen or vegetated auxiliary spillways.

The user imports an inflow hydrograph into WinDAM C and selects either internal erosion analysis or overtopping analysis.

Regarding internal erosion within the earthen embankment, the user sets the elevation and initial size of the internal erosion conduit. WinDAM C initially assumes a horizontal, rectangular conduit shape. The internal erosion conduit grows larger as flow erodes embankment material. The erosion may breach the embankment and drain the reservoir.

Since the research has been completed, USDA and KSU are currently verifying and validating a working version of WinDAM C, which should be released for external evaluation and testing in 2015.

INTRODUCTION

Windows Dam Analysis Modules (WinDAM) is a modular software application to analyze earthen embankments during internal erosion and overtopping. Recently released for testing and evaluation by the dam safety community, WinDAM B (USDA, et al. 2012) includes erosional failure of a homogeneous embankment through overtopping and release of stored water. The alpha version of WinDAM C, currently under development, includes analysis of internal erosion. Future planned development includes non-homogeneous embankments. 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 this software.

For nearly seventy years, the USDA-NRCS has partnered with landowners, municipalities, conservation districts and other sponsors to construct more than 11,000 rural flood control dams. These structures provide $1.5B in annual benefits by providing flood control, municipal and rural water supplies, irrigation water, wetland habitat, and recreation among others. Many of these aging dams were designed with a 50-year service life, and time takes a toll on these structures. Sediment pools fill and encroach upon the flood detention volume. Structure components deteriorate, and hazard creep occurs in urbanizing areas that were once rural cropland areas. As a result, the consequences of dam failure must be considered when evaluating and prioritizing these structures for rehabilitation since the structures may no longer meet NRCS design criteria (USDA, 2005).

Overtopping and internal erosion are the primary causes of dam failures, with each mode attributed to a roughly equal number of failures (Foster, Fell and Spannagle 1998). For a given dam, one (or neither) mode may be more likely. For example, many of the storage reservoirs in arid West have large volumes relative to inflow and are managed such that overtopping is very unlikely. The US Bureau of Reclamation (USBR, 2011) names internal erosion of embankments (or their foundations) as the number one cause of dam failures in the western US. WinDAM C, when completed, will estimate breach erosion of an earthen dam through one of two modes: internal erosion through the embankment or overtopping the embankment. This document describes the WinDAM model currently being developed to examine internal erosion. The model is currently at the alpha stage of development undergoing verification and validation testing by the developers. It is anticipated that additional testing by the dam safety user community will also be required.

WINDAM C CAPABILITIES

PURPOSE OF SOFTWARE The essential functions of WinDAM C software are threefold:

- Hydraulically route (level pool routing) one inflow 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 internal erosion or by overtopping of the dam embankment.

Since WinDAM C does not include any hydrology component, the user must create the reservoir inflow hydrograph in other software, such as WinTR-20 (USDA-NRCS, 2009) or SITES (USDA-NRCS, 2012). The user can import the hydrograph or paste the hydrograph points into the user interface. The user has the flexibility to choose the hydrologic software most suitable for analysis of site conditions.

INTERNAL EROSION OF HOMOGENOUS EARTHEN EMBANKMENT WinDAM C models the dam embankment as a homogenous earthen material. Many USDA-NRCS dams are homogenous earthfill, so the WinDAM C model applies. If applied to zoned embankments, the suggested approach is to consider material and geometry that will dominate the process. For computational purposes, the earthen embankment fits into a simplified, rectangular-shaped valley (Figure 1) with vertical abutments and level valley floor.

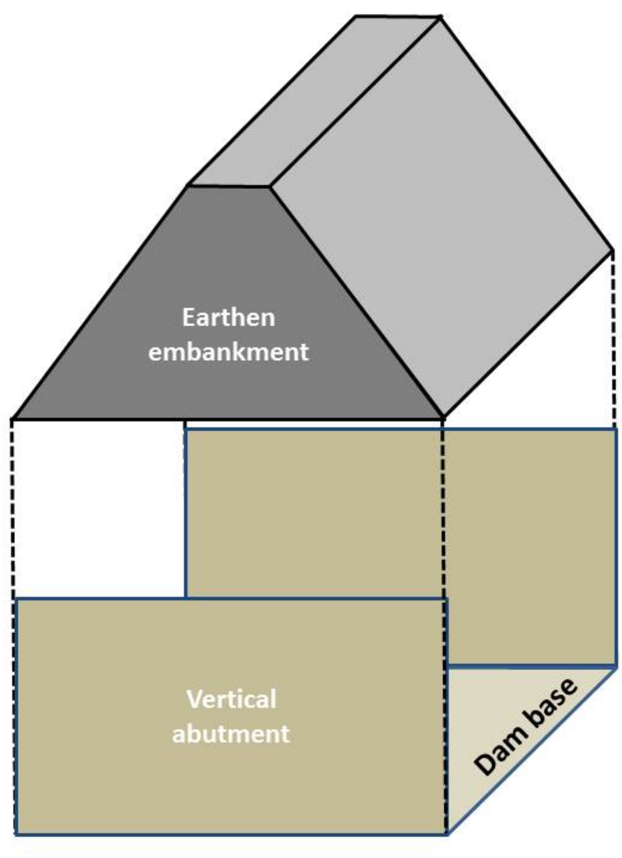

Figure 1 Homogenous earthen embankment in rectangular-shaped valley

INITIAL INTERNAL EROSION CONDUIT For a WinDAM C internal erosion analysis, the user specifies the initial size and location of the internal erosion conduit. To simplify the analysis, the conduit is horizontal—there is no slope in the upstream-downstream direction through the embankment, as shown in Figure 2. The conduit is assumed to be rectangular. The user must specify the initial conduit dimensions—width and height. The user must input the initial elevation of the conduit invert, as well as the lateral stationing between the left and right abutment.

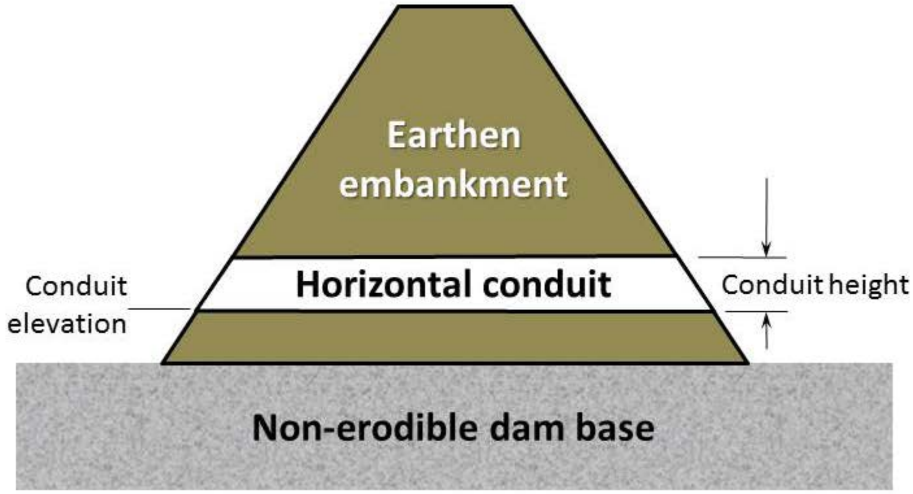

Figure 2 WinDAM C internal erosion horizontal conduit profile

In WinDAM C the left and right abutments are considered to be non-erodible and vertical, as shown in Figure 3. The embankment foundation, or dam base, is non-erodible and level. The dam crest profile is defined as a series of user-entered points (Figure 3).

The internal conduit erodes laterally until it reaches an abutment, as shown in Figure 3. The conduit also erodes vertically between the dam crest profile and the dam base. As long as some portion of the conduit is flowing full and the shear stress is sufficient to erode the embankment material, the conduit expands in all four directions equally. Once conduit erosion reaches one of the embankment boundaries (abutment, dam base, or dam crest), expansion/erosion in that direction stops.

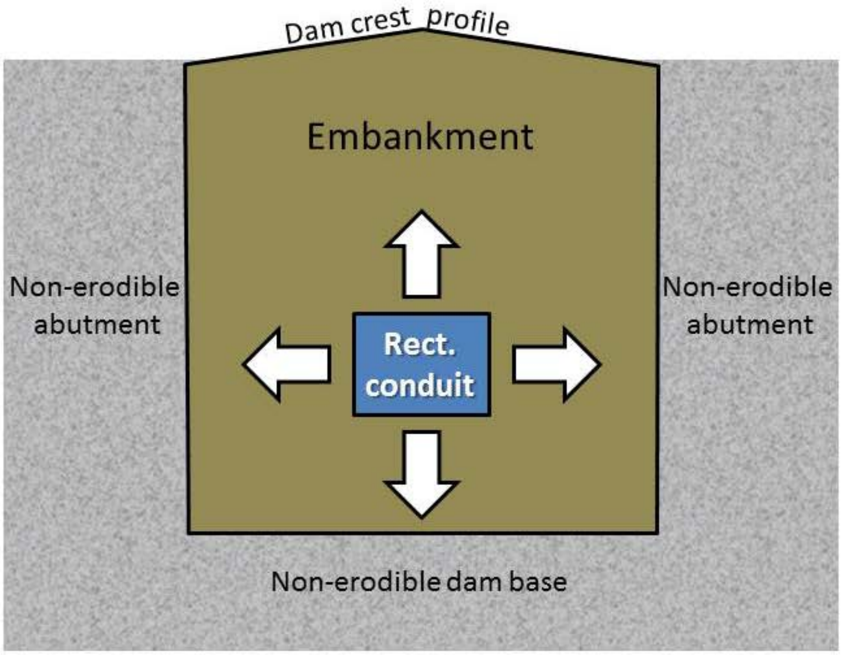

Figure 3 WinDAM C conduit cross-section looking upstream

EROSION PROCESSES Two erosion processes are simulated. The conduit enlarges concentrically due to shear detachment (laterally and vertically in a conduit simplified as having a rectangular cross section); classically this is the only process associated with internal erosion. However, development of a headcut at the outlet and subsequent advance of that headcut also play an important role in breach by internal erosion in some instances, so this process is also modeled.

At the beginning of each time step, the model computes the shear stress produced by flow passing through the rectangular internal erosion conduit. In instances where conduit is full for less than entire length, a backwater curve and resulting average shear stress along conduit length are computed. If the average shear stress is greater than the user-specified critical shear stress, then the amount of erosion is estimated and the conduit expanded accordingly for the next time step.

In addition to simply expanding the internal conduit laterally and vertically, WinDAM C also checks to see if a headcut will form at the downstream invert of the conduit (Figure 4). After this headcut has formed, headcut advance and deepening is computed for each time step using the user-prescribed erosion model (Table 3). This process is simulated much like that of a headcut formed in overtopping with important distinction that width is controlled by the conduit.

TRANSITION FROM INTERNAL CONDUIT EROSION TO BREACH EROSION Once this headcut reaches the upstream face of the embankment the internal conduit has become an open breach and flow transitions to breach flow. At this point, lateral expansion of the breach is the same as with overtopping flow conditions.

In the early stages of internal erosion, the conduit is usually stable regardless of support by hydrostatic water pressure. As the conduit enlarges, the support provided by water becomes critical. There are three cases when the roof of the conduit is considered to be stable:

1. The conduit is flowing full over the entire length of the conduit.

2. The conduit is flowing full over some part of the conduit length.

3. When flow transitions to free surface flow along the entire length of the conduit and the conduit width is less than twice the overburden height (vertical distance from the dam crest to conduit roof).

As the breach progresses and reservoir drains the roof of the internal erosion conduit will collapse. WinDAM C considers the conduit roof collapsed for these two cases:

1. Erosion of the roof reaches the dam crest profile

2. Free surface flow along the entire conduit length and the conduit width is more than twice the vertical distance from the dam crest to the roof.

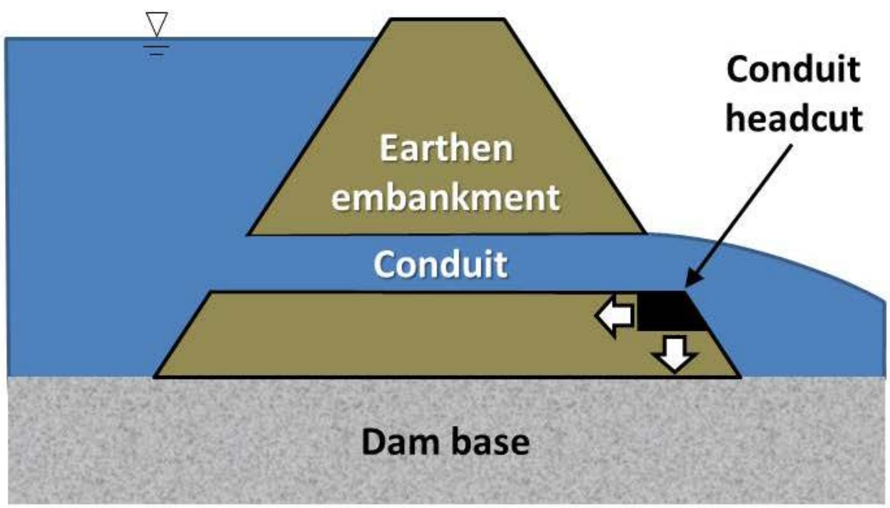

Figure 4 Conduit headcut

NEGLIGIBLE INTERNAL CONDUIT FLOW CASES There are cases where the resulting internal erosion is negligible. These possible cases include:

- Elevation of internal erosion conduit is above maximum water surface in the reservoir, which results in no flow in internal erosion conduit.
- Insufficient time or flow to produce meaningful erosion because the generated stress does not exceed the soil critical stress by sufficient time or amount.
- Highly erosion-resistant embankment materials may not generate shear stresses greater than the soil critical stress.

OVERTOPPING BREACH EROSION If the user selects overtopping erosion analysis in WinDAM C, flow through the breach depends on the eroded breach area and the driving head based on the reservoir water surface, breach elevation, and any downstream tailwater. The four stages of the overtopping breach are described in Table 1.

Table 1 Four stages of WinDAM overtopping breach

Stage 1	Surface protection on downstream embankment slope fails. Headcut forms on downstream face of dam at low point in the crest profile.
Stage 2	Headcut advances through the crest to upstream embankment slope. Breach is initiated when the headcut enters the upstream crest and begins to lower the hydraulic control.
Stage 3	Headcut continues to advance into the reservoir pool releasing stored water.
Stage 4	Headcut continues to widen as reservoir drains following local removal of the embankment in the breach area.

MODELING FLOW THROUGH EMBANKMENT CRACKS Earthen embankments are susceptible to cracking from seismic activity or from desiccation in arid regions. As an overtopping erosion event, the only way to evaluate a crack is to input the crack in the dam crest profile. WinDAM overtopping erosion analysis was not developed for such evaluation and is not appropriate for several reasons. First, crest width in WinDAM is a constant and WinDAM evaluates both stress and erosion strictly from a depth perspective rather than considering the extremely steep profile segments as walls. Second, overtopping is considered on a one-dimensional, unit-discharge basis.

However, analyzing a crack, even one that extends to the dam crest, as an internal erosion event may be appropriate if the user develops a thorough understanding of the computational model and interprets inputs and results accordingly. Cracks have been associated with internal erosion (Bonelli, et al. 2006) (Fell, et al. 2003). The geometry of a crack can be more correctly approximated in an internal erosion simulation in WinDAM C. However, the research program and software were not undertaken to address the early stages of breach development represented by narrow cracks. Users should recognize model constraints and interpret results accordingly, e.g.

- WinDAM C assumes turbulent flow through the internal conduit, whereas flow through narrow cracks may be laminar flow.

- WinDAM C embankment materials properties do not change during the analysis. Over a sufficiently long period of time, flow within small cracks may saturate portions of the embankment and alter its resistance to erosion.

INTERACTION OF EROSION AND HYDRAULICS The hydraulics and erosion are coupled for the embankment breach analysis. In other words, a larger breach in the embankment lets more flow pass through the embankment breach during the next time step. Erosion prediction is relatively straightforward in the homogeneous earth embankment.

Erosion prediction in the auxiliary spillway, however, is much more complex than in the homogenous earth embankment. Hydraulics and erosion are not coupled in the auxiliary spillway because the erosion model only includes information on the weakest unit width subsurface materials in the auxiliary spillway. As a result, WinDAM C does not have the data to estimate the lateral expansion in the auxiliary spillway. Erosion computations in the auxiliary spillway stop when the headcut reaches the upstream edge of the level crest of the auxiliary spillway.

WINDAM VERSIONING

Research is ongoing for future enhancements to WinDAM software, as shown in Table 2. USDA and KSU are currently verifying and validating a working version of WinDAM C, which should be released for evaluation and testing in 2015.

Table 2 WinDAM Versioning

Version	Existing Capabilities or Future Enhancements
WinDAM A+ (2008)	Embankment overtopping analysis (Slope protection evaluation: no embankment erosion analysis)
WinDAM B (2011)	Homogenous fill embankment overtopping and erosion analysis
WinDAM C (2015)	Internal erosion 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

The auxiliary spillway materials in WinDAM C are described with the same data inputs as in SITES (USDA-NRCS, 2012).

WinDAM C requires the user to input one flow hydrograph. This hydrograph input is similar to the SITES input procedure. SITES gives the user the option to input hydrology through a watershed model, but WinDAM C only allows hydrology input through a single hydrograph. Various design hydrographs will require a different WinDAM C run for each hydrograph.

WinDAM C may be run with or without embankment breach evaluation. When breach evaluation is desired, the earthen embankment must be described so WinDAM C can model either internal erosion or overtopping erosion. The user specifies the embankment slope protection: vegetation, rock riprap, or no cover. The dam embankment crest and slope dimensions are also input.

For the breach analysis option, the user selects one of two headcut models: Temple/Hanson Energy model or Hanson/Robinson Stress Model (Hanson, et al. 2011). The WinDAM C erosion prediction models are designed for estimating erosion of typical NRCS earthen embankments composed of fine-grained, cohesive materials, where the dominant erosion process is the formation, advance, and deepening of a headcut. The soil parameter inputs for each model are listed in Table 3.

Table 3 WinDAM C Erosion Model Soil Inputs

Model	Hanson/Robinson Stress Model	Temple/Hanson Energy Model
Input Parameter *(Units)*	Erodibility $(ft/hr)/(lb/ft^2)$	Erodibility - $(ft/hr)/(lb/ft^2)$
	Critical Shear Stress (lb/ft^2)	Critical Shear Stress – (lb/ft^2)
	Undrained Shear Strength (lb/ft^2)	Advance coefficient - $(ft/hr)/(ft/s^3)$
	Total Unit Weight (lb/ft^3)	

All four input parameters in the Hanson/Robinson stress model can be measured. In addition this model is recommended for tall dams (> 50 ft high). Since the advance coefficient parameter in the Temple/Hanson cannot be measured directly, most users select the Hanson/Robinson stress model.

A WinDAM C internal erosion analysis covers a few hours or days. The WinDAM model does not account for wetting or drainage of embankment soils during the erosion analysis. Therefore, the material properties of the embankment soil do not change over the period of the breach analysis.

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 C 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

WinDAM C has three forms of output; the initial summary screen the user sees upon completion of a valid run, ASCII text output files, and numerous graphical plots. WinDAM C has multiple text output files to describe the expected performance of the embankment and multiple auxiliary spillways. The current list of available output plots in WinDAM C are listed below.

- Conduit/Breach Width
- Dam Cross-section
- Dam Crest Profile
- Conduit Width/Height
- Headcut Advance
- Headcut Position
- Hydrographs
- Reservoir Surface Area
- Reservoir Storage Volume
- Reservoir Water Surface
- Maximum Overtopping / Breach Discharge
- Maximum Overtopping Head
- Overtopping Stress
- All Discharge Ratings
- Auxiliary Spillway Ratings
- Principal Spillway Rating
- Tailwater Elevation
- Tailwater Rating

A sample of the Headcut Advance plot is shown in Figure 5.

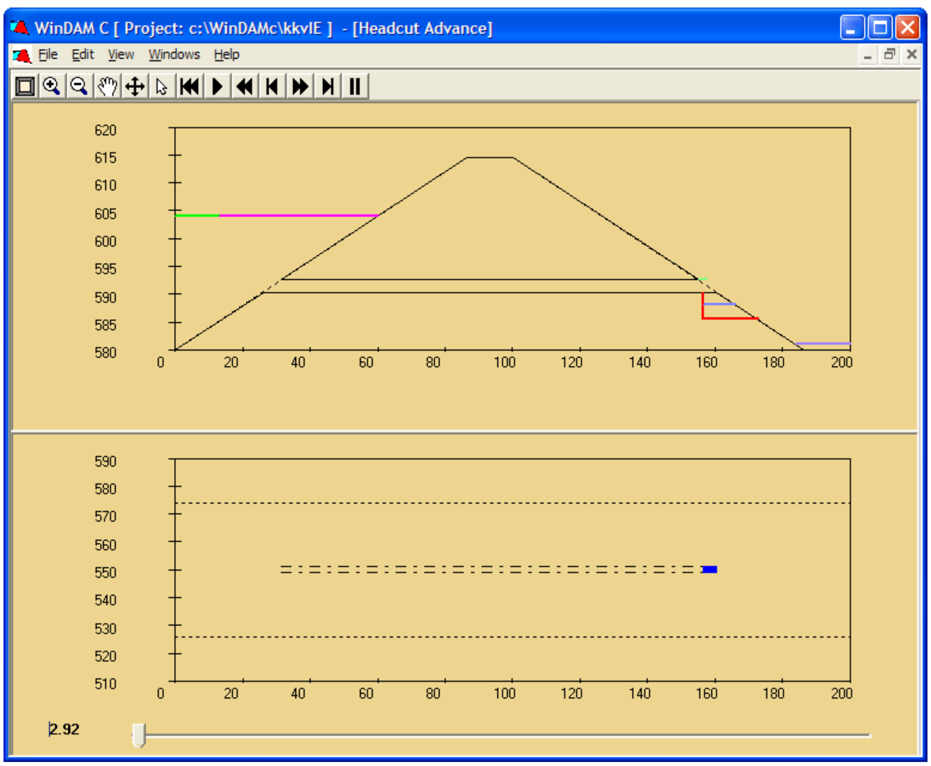

Figure 5 Sample WinDAM C headcut advance plot. Top half is dam cross-section. Bottom half is plan view.

INITIAL MODEL VALIDATION

Four different internal erosion tests on earthen embankments have been conducted at the ARS Hydraulic Engineering Research Unit in Stillwater, OK. Qualitatively, the WinDAM C predicted erosion matches the prototype erosion. The tests indicate that critical shear stress is a key parameter for initiation of erosion and particle detachment, especially for low-head dams. (Tejral, 2014)

CONCLUDING REMARKS

This report contains a preview of the internal erosion modeling capability being developed for WinDAM C. In addition, attention was given to capabilities already available to WinDAM B users—analysis of auxiliary spillways and overtopping breach. WinDAM software download and answers to frequently asked questions can be found at http://go.usa.gov/8Oq.

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