MARYLAND DAM SAFETY

Dam Break Analysis
&
Hazard Classifications
Types of Dam Failures
Embankment Dam Schematic
Overtopping Failure

Overtopping Begins
Overtopping Breach of Earth Dam

Initial Breach

Final Breach
Overtopping Breach Stages for Earth Dam

Overtopping Begins
Overtopping Breach Stages for Earth Dam

Early Erosion Stage
Overtopping Breach Stages for Earth Dam

Horizontal Erosion Continues
Overtopping Breach Stages for Earth Dam

Vertical Erosion Begins
Overtopping Breach Stages for Earth Dam

Vertical Erosion Ends
Piping Failure for Earth Dam
Piping Failure at Loveton Dam (1989)
Loveton Dam Failure (1989)
Loveton Failure Viewed from Downstream
Medford Quarry Wash Pond Piping Failure
Piping Failure

Anti-seep collars do not prevent seepage failures!
Annap. Mall Piping Failure
Sinkhole in Dam Crest
Foundation Failure
Slope Failure

Saturated Slope Failure
Types of Dam Failures

- Overtopping: 38%
- Piping: 33%
- Foundation: 23%
- Other: 6%

Source: ASCE/USCOLD, 1975
Dam Hazard Classifications

• Low Hazard = Class “a”
• Significant Hazard = Class “b”
• High Hazard = Class “c”
MDE Dam Hazard Classifications

- **Low Hazard** - Potential loss of life is very unlikely due to low danger flood depths.

- **Significant Hazard** - Potential loss of life is possible with no more than 6 lives in jeopardy and flooding to no more than two isolated houses and downstream roads.

- **High Hazard** - Potential loss of life is very likely with more than 6 lives in jeopardy, and serious damage to residential, commercial, or industrial buildings, and downstream roads.
Failure Storms to Analyze

PMF

1/2 PMF

Brim-UP

100-Year

Sunny Day
Probable Maximum Flood (PMF)

PMF - the largest flood considered possible based on the most severe combination of meteorological and hydrologic conditions that are reasonably possible.
Figure 2-4
Probable Maximum Precipitation
6-HOUR, 10-SQUARE MILES (Inches)
Emergency Spillway and Freeboard Hydrographs

Source: Hydrometeorological Report 51
(All-Season PMF - 1978)

Note: If basin area is greater than 10 square miles see Hydromet, Reports 51 & 52.
Stippled areas are regions where detailed terrain effects have not been evaluated.

Aug. 1983
WORLD RECORD RAINFALL AMOUNTS

SOURCE: JENNINGS, A.H. WORLD'S GREATEST OBSERVED POINT RAINFALL
MONTHLY WEATHER REV., VOL 78, 1950
FIGURE 1 Maximum observed point rainfalls as a function of duration. (Courtesy of John Vogel, National Weather Service.), 1986.
Rainfall Greater than 50% PMP

Source: NWS, HMR 51, 1983 (?)
Increased Flood Risks

Before Downstream Development

After Downstream Development

Increased Flooding

100-YR

1/2 PMF

PMF

Sunny Day
Dam Break Models

- HEC-1 Computer Model
  - Develop & Route Hydrographs
  - Fail Dam with NWS Dam Break Method
  - Route Breach Hydrograph Downstream
  - Route Through & Over Downstream Roads or Dams
Breach Parameters for HEC-1 Model

- Breach Bottom Elevation
- Breach Top Elevation (Trigger Elevation)
- Bottom Breach Width
- Breach Side Slope
- Time of Failure

- HEC-HMS - New Windows Model
Breach Parameters

- H, Breach Height
- Breach Bottom Elevation
- Bottom Width, b

Trigger Elevation for Failure

Z = 0 to 1
## Suggested Breach Parameters for Earth Dams

<table>
<thead>
<tr>
<th>Source</th>
<th>Average Breach Width (ft)</th>
<th>Breach Side Slope (1V:ZH)</th>
<th>Breach Failure Time (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NWS (1988)</td>
<td>1H to 5H</td>
<td>Z = 0 to 1</td>
<td>0.1 to 2.0</td>
</tr>
<tr>
<td>COE (1980)</td>
<td>0.5H to 4H</td>
<td>Z = 0 to 1</td>
<td>0.5 to 4</td>
</tr>
<tr>
<td>FERC (1991)</td>
<td>1H to 5H</td>
<td>Z = 0 to 1</td>
<td>0.1 to 1.0</td>
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<tr>
<td>USBR (1982)</td>
<td>3H</td>
<td>N/A</td>
<td>0.003333b</td>
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<tr>
<td>Boss Dambrk (1988)</td>
<td>0.5 to 4H</td>
<td>Z= 0 to 1</td>
<td>0.5 to 4</td>
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<tr>
<td>Harrington (1999)</td>
<td>1H to 8H</td>
<td>Z= 0 to 1</td>
<td>H/120 to H/180</td>
</tr>
</tbody>
</table>
Froelich Breach Predictor Equations

\[ b = 9.5 \cdot K_0 \left( V_s H \right)^{0.25} \]
\[ \tau = 0.59 \left( V_s^{0.47} \right) H^{0.91} \]

- \( b \) = Average Breach Width (ft),
- \( \tau \) = Time of Failure (hrs)
- \( K_0 \) = 0.7 for Piping & 1.0 for Overtopping Failure
- \( V_s \) = Storage Volume (ac-ft)
- \( H \) = Selected Failure Depth (ft) above Breach Bottom
- \( \tau \) = Time of Failure (hrs, \( \sim H/120 \) or Minimum of 10 Min)
Dam Break Models

NWS Simple Dam Break Equation

\[ Q_b = Q_0 + 3.1B_r\left(\frac{C}{T_f + C/\sqrt{H}}\right)^3 \]

\( Q_b \) = Breach + Non-Breach Flow (cfs)
\( Q_o \) = Non-Breach Flow (cfs)
\( B_r \) = Final Average Breach Width (ft, ~ 1H to 5H)
\( C \) = 23.4 As/Br
\( A_s \) = Reservoir Surface Area (ac) at Failure Elevation
\( H \) = Selected Failure Depth (ft) above Final Breach Elevation
\( T_f \) = Time of Failure (hrs, ~H/120 or Minimum of 10 Min)
NWS Simple DAMBRK Equation

100-Year Failure for Your Dam

BREACH FLOW EQUATION:

\[ Q_b = Q_o + 3.1 \cdot Br \left( \frac{C}{T_f} + \frac{C}{H^{1/2}} \right)^3, \]

WHERE,

- \( Q_b = \) BREACH FLOW + NON-BREACH FLOW (cfs)
- \( Q_o = \) NON-BREACH FLOW (cfs)
- \( Br = \) FINAL AVERAGE BREACH WIDTH (ft, APPROX. 1H TO 5H)
- \( C = 23.4 \cdot \frac{As}{Br} \)
- \( As = \) RESERVOIR SURFACE AREA (ac) AT MAXIMUM POOL LEVEL
- \( H = \) SELECTED FAILURE DEPTH (ft) ABOVE FINAL BREACH ELEVATION
- \( T_f = \) TIME TO FAILURE (hrs, USE H/120 OR A MINIMUM OF 10 MIN)

**INPUT VARIABLES:**

<table>
<thead>
<tr>
<th>Qo</th>
<th>0 cfs</th>
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<tbody>
<tr>
<td>As</td>
<td>5.00 ac</td>
</tr>
<tr>
<td>H</td>
<td>20.0 ft</td>
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</table>

**OUTPUT VARIABLES:**

<table>
<thead>
<tr>
<th>Br, [ft]</th>
<th>Tf, [hrs]</th>
<th>C VALUE</th>
<th>Qb, [cfs]</th>
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<tbody>
<tr>
<td>20.0 [H]</td>
<td>0.17</td>
<td>5.85</td>
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<tr>
<td>30.0 [1.5H]</td>
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<td>3.90</td>
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<td>40.0 [2H]</td>
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<td>50.0 [2.5H]</td>
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<td>60.0 [3H]</td>
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<td>70.0 [3.5H]</td>
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<td>80.0 [4.0H]</td>
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<td>100.0 [5.0H]</td>
<td>0.17</td>
<td>1.17</td>
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</table>

35.4 Froelich 0.22 3.31 4508
35.4 Froelich 0.17 ---- 2847

\(<\text{SELECTED FLOW} = \frac{Vs}{T_f}>\)

DEVELOPED BY BRUCE HARRINGTON, 9/92
Recently some statistically derived predictors for average breach width (b) and time of failure (Tf) have been developed by MacDonald and Langridge-Monopolis (1984) and Froelich (1987, 1995). From Froelich’s work in which he used the properties of 63 breaches of dams ranging in height from 12 to 285 feet, with 6 dams greater than 100 feet, the following predictor equations were obtained:

\[ b = 9.5Ko(VsH)^{0.25} \]

\[ Tf = 0.59(Vs^{0.47})/(H^{0.91}) \]

where,

- \( b \) = average breach width (ft),
- \( Tf \) = time of failure (hrs),
- \( Ko \) = 0.7 for piping and 1.0 for overtopping failure
- \( Vs \) = storage volume (ac-ft), and
- \( H \) = height (ft) of water over breach bottom

**BREACH WIDTH & TIME OF FAILURE FOR**  
NWS Simple DAMBRK Equation  
100-Year Failure for Your Dam

**INPUT VARIABLES:**

- \( H = 20.0 \text{ ft} \)
- \( Vs = 40.0 \text{ ac-ft} \)
- \( Ko = 0.7 \)

**OUTPUT PARAMETERS:**

- \( b = 35.4 \text{ ft} \)
- \( Tf = 0.22 \text{ hrs} \)
Dam Break Models

- SCS (NRCS) Breach Formula

\[ Q_b = 3.2H^{5/2} \]

- Usually Conservative Estimate of Breach Flow but not Always
- Storage Volume not included in Formula
- Similar to a V-Notch Weir Formula
COMPARISON OF DAM BREACH EQUATIONS
NWS SIMPLE DAMBRK vs NRCS BREACH EQUATIONS

NWS SIMPLE DAMBRK EQUATION:  
\[ Q_{NWS} = 3.1B_r \left( \frac{C}{T_f} + \frac{C}{\sqrt{H}} \right)^3 \]

NRCS MD-378 EQUATION:  
\[ Q_{NRCS} = 3.2H^{2.5} \]

Br = 3H (Breach Width, ft)
H = Height of Water at failure, ft
C = 23.4As/Br = 7.8As/H
As = Surface Area at Failure (acres)
T_f = H/120 (Failure Time, hrs)
= Minimum Time of 10 min = 0.17 hrs

<table>
<thead>
<tr>
<th>H [ft]</th>
<th>As [ac]</th>
<th>T_f [hrs]</th>
<th>C</th>
<th>Q_{NWS} [cfs]</th>
<th>Q_{NRCS} [cfs]</th>
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<td>1996</td>
<td>1012</td>
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<td>1.95</td>
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<td>0.33</td>
<td>7.80</td>
<td>46207</td>
<td>32382</td>
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</table>
Dam Break Models

- **NWS Simple Dam Break Equation**
  - Developed from NWS Full Dam Break Model
  - Based on Falling Head Weir Flow
  - Input Non-Breach Flow, Surface Area, Selected Failure Depth, & Time of Failure
Dam Break Models

• NWS Simple Dam Break Model
  – Easy to Use
  – Uses NWS Simple Dam Break Equation for Breach Flow
  – Uses Dynamic Routing of Flood Wave
  – Input Downstream Cross Sections
  – Will Not Route through Downstream Structures
Dam Break Models

- NWS Full Dam Break Model (DAMBRK)
  - Very Difficult to Learn & Temperamental
  - Uses Unsteady State Dynamic Routing by a Finite Difference Technique
  - Includes Pressure & Acceleration Effects
  - A Hydrograph must be Inputted
  - Has Been Replaced by NWS Flood Wave Model (FLDWAV), Free Download at:
    http://hsp.nws.noaa.gov/oh/hrl/rvrmech/rvrmain.htm
## PRETTYBOY DAM DANGER REACH

### A COMPARISON OF NWS DAMBRK & HEC-1 MODELS

#### Template Cross Sections

<table>
<thead>
<tr>
<th>Miles Below Dam</th>
<th>**** Discharge ****</th>
<th>Elev. Change</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>NWS [cfs]</td>
<td>Elevation</td>
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<tr>
<td></td>
<td>HEC-1 [cfs]</td>
<td>NWS [NGVD]</td>
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<tr>
<td></td>
<td></td>
<td>HEC-1 [NGVD]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Elev. Change [feet]</td>
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<tr>
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<td>18.18</td>
<td>335059</td>
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</tr>
</tbody>
</table>

**Note:** Table entries for discharge and elevation are in cubic feet per second (cfs) and National Geodetic Vertical Datum (NGVD), respectively.
Recommended Dam Failure Methods for Small Dams < 15 feet High

- Use NWS SMPDBK and SCS Breach Equation to determine Breach Flows
- Use HECRAS Model to determine Downstream Flood Depths
- Stop Danger Reach when roads flood < 1.5 feet, and Flooding to Houses & Buildings < 6 inches
Recommended Dam Failure Methods
for Dams > 15 & < 75 feet high

• Use Hec-1 Model for Breach Flows
• Use HECRAS Model to determine Downstream Flood Depths & USBR Hazard Charts to determine Flood Dangers
• Stop Danger Reach when Increased Flooding < 1 foot or no structures flooded
Recommended Dam Failure Methods for Dams ≥ 75 feet high

- Use HMR-52 & HEC-1 Model for Hydrology
- Use DAMBRK or FLDWAV Model for Breach Flow
- Suggest Checking DAMBRK and FLDWAV Results with HECRAS Model
Flood Danger for Houses

Source: USBR Hazard Charts, 1988
Flood Danger for Adults

Source: USBR Hazard Charts, 1988
Rainfall from Hurricane Floyd, Sept 99

Rainfall Totals from Floyd
Sept. 15-16, 1999
Nagel Mill Dam before Floyd
Nagel Mill Dam after Floyd
Nagel Mill Dam after Floyd
Nagel Mill Dam after Repair
Nagels Breach Statistics

Piping Failure
Breach Width = 60 ft = 4H
Side Slope Z = 0.4
Time of Failure <20 min
Foreman Branch Dam after Floyd
Foreman Branch Dam after Floyd
Foreman Branch Dam after Repair
Foreman Dam Breach Statistics

Overtopping Failure
Breach Width = 85 ft = 8H
Side Slope Z = 0.5
Time of Failure <30 min
Frazer Mill Dam before Floyd
Frazer Mill Dam after Floyd
Frazer Mill Dam after Floyd
Frazer Dam Breach Statistics

Overtopping Failure
Breach Width = 120 ft = 6H
Side Slope Z = 0.6
Time of Failure Unknown
Jones Lake Dam before Floyd
Jones Lake Dam after Floyd
Jones Lake Dam Breach Statistics

Piping Failure
Breach Width = 103 ft = 6H
Side Slope Z = 0.6
Failure Time Unknown
Sassafras Dam before Floyd
Sassafras Dam after Floyd
Sassafras Dam During Floyd
Sassafras Dam after Repair
Sassafras Dam During Repair
Sassafras Dam Breach Statistics

Overtopping Failure
Breach Width = 47 ft = 4H
Side Slope Z = 0.2
Failure Time = 15 Min
Stubbs Dam after Floyd
Stubbs Dam after Floyd
Stubbs Dam after Repair
Stubbs Dam Breach Statistics

Piping Failure

Breach Width = 30 ft = 2.5H

Side Slope $Z = 0.2$

Failure Time Unknown
Tuckahoe Dam after Floyd
St Pauls Emergency Spillway during Floyd
Boundary Dam Near Seattle Washington
Hoover Dam
One of the “Seven Modern Civil Engineering Wonders”

Location:
Black Canyon
Arizona & Nevada

Owner:
U.S. Bureau of Reclamation

Built:
1931-1935

Height:
726.4 ft.

Length:
1244 ft.

Max. Depth:
500 ft.

Storage:
28,537,000 ac.-ft.
Emergency Action Plan

Introduction

1) Purpose. The purpose of the Emergency Action Plan (EAP) is to safeguard lives and secondarily to reduce property damage in the event that (your dam) would fail. To carry out this mission, the EAP contains: 1) procedures to monitor (your dam) periodically and during flood warnings issued by the National Weather Service; 2) notify (County) Emergency Operation Center of a potential dam failure; and 3) warn and evacuate the isolated residences at risk. These procedures are to supplement and be used in conjunction with (your County's Emergency Operation Plan).

2) Flood Description. Failure of the dam could cause significant damage to (all roads and isolated residences downstream of your dam within the danger reach) located ___ miles downstream of (your dam).

OPERATING PROCEDURE

I. The dam will be inspected periodically each year for maintenance and distress signals.

II. The dam observer will inspect the dam when the National Weather Service issues a Flood Warning for the area and complete the following tasks.

1. The dam observer will note & record water levels in reservoir and the rate at which the pool is rising.

2. If the dam shows signs of internal piping (muddy seepage exiting the downstream embankment), erosion, slope failures, blocked spillways, or other ominous distress signs, the dam observer will call the County Emergency Operation Center to send out police to roadblock downstream roads and warn any isolated residences in the danger reach. The dam observer may contact the Md Dam Safety Division or his designated engineer to provide assistance.

3. If the pool level rises too within one foot (or other levels accepted by MDE) of the dam crest, the dam observer will contact the County Emergency Operations Center to dispatch police to roadblock downstream roads and warn any isolated residences in the danger reach.
# Emergency Action Plan

**DAM NAME**

**Signatures of Persons Involved in Emergency Action Plan**

<table>
<thead>
<tr>
<th>Role</th>
<th>Typed Name</th>
<th>Title</th>
<th>Phone (day)</th>
<th>Phone (night)</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dam Owner</td>
<td>By __________________</td>
<td>Date</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>County Department of Emergency Operations</td>
<td>By __________________</td>
<td>Date</td>
<td></td>
<td></td>
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<tr>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Local or State Police</td>
<td>By __________________</td>
<td>Date</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<tr>
<td>Department of the Environment</td>
<td>By __________________</td>
<td>Date</td>
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<tr>
<td>Dam Safety Division</td>
<td>By Brad Iarossi</td>
<td>Chief</td>
<td>410-631-3538</td>
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<tr>
<td>Owner's Engineer</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**PREVENTATIVE ACTIONS**

If time allows, contact your engineer (__________________) and the Maryland Dam Safety Division for advice on preventative actions. Listed below are potential emergency actions which may prevent or delay the failure of the dam. They should be considered based on site-specific conditions, as well as the risk of failure and risk to employees.

**Possible Actions To Be Taken In The Event Of:**

**Imminent Overtopping by Flood Waters:**

1) Open drain or flood gates to maximum capacity.
2) Place sand bags along the dam crest to increase freeboard.
3) Place riprap or sandbags in damaged areas of dam.
4) Provide erosion protection on downstream slope by placing riprap or other appropriate materials.
5) Divert flood waters around dam if possible (such as emergency spillway)

**Erosion of Dam by Seepage Through the Embankment, Foundation, or Abutments:**

1) Plug the seepage with appropriate material such as (riprap, hay bales, bentonite, sandbags, soil, or plastic sheeting if the leak is on upstream face of dam).
2) Lower the reservoir level until the flow decreases to a non-erosive velocity or stops leaking.
3) Place a sand and gravel filter over the seepage exit area to minimize loss of embankment soils.
4) Continue lowering the reservoir level until the seepage stops or is controlled. Refill reservoir to normal levels only after seepage is repaired.

**Slide or Slope Failure on Upstream or Downstream Slope of Embankment:**

1) Lower the reservoir water level at a rate, and to an elevation that is considered safe. Contact your engineer or the Dam Safety
Emergency Action Plan

SUPPLIES AND RESOURCES

In an emergency situation, equipment and supplies may be needed on short notice. The following supplies and resources may be needed during an emergency: earthmoving equipment, sand and gravel, sandbags, riprap, pumps, pipe, laborers.

List of Contractors

It will be the responsibility of the owner to maintain the list of contractors that may be contacted during an emergency condition for equipment, materials, and repairs.

For each contractor on the list, the following information is needed:

- Contractor name
- Contact person.
- Address.
- Phone number.
- Equipment & repair supplies available.
- Arrival time to dam

1. Contractor: ________________________________
   Contact person: _____________ Phone No: _____________
   Address: ________________________________
   Services contracted for: ________________________________
   ________________________________

2. Contractor: ________________________________
   Contact person: _____________ Phone No: _____________
   Address: ________________________________
Emergency Action Plan

DANGER REACH MAP

EVACUATION ROUTES

RESERVOIR
DAM
DANGER REACH ZONE

EVACUATION ROUTES
MDE Dam Break Web Site
ftp://ftp.mde.state.md.us/outgoing/Dam_Safety/

**Microsoft Word Documents**
- Hazard Guidelines
- Model Emergency Action Plans

**Microsoft Excel Spreadsheets**
- NWS Dam Break Equation
- USBR Hazard Graphs
- Hydrology Spreadsheets
- Hydraulic Spreadsheets

**Executable Programs**
- HEC-1 Program
- NWS Simple Dam Break Program
- Sample Data for HEC-1 & NWS Simple Dam Break
Any Questions?

Bruce Harrington, MD Dam Safety, 410-334-3411