Washington State Department of Ecology
Water Resources Program / Dam Safety Office

Spreadsheets for Open Spillways and Riprap-Lined Channels

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Several spreadsheets are available to assist design engineers in performing the hydraulic computations related to open channel spillways. The calculations include the stage-discharge curve for the overall spillway, drawdown from critical flow to supercritical uniform flow in steep channels, and stability calculations for loose riprap. Key equations are summarized on the spreadsheets to facilitate their use for file documentation.

The spreadsheets and this paper presume the user is familiar with hydraulic calculations for open channels, including equations for geometry, energy, critical flow, uniform flow, and Froude number.

New developments

Compared to previous versions of these spreadsheets, the most significant change is that these stage-discharge calculations have an algorithm to estimate head losses in the overflow control section, especially for low flows where the depth of flow is relatively shallow compared to the length of the overflow section.

The algorithm was developed from analysis of data published in accepted hydraulic engineering references, so it seems to be conceptually correct; however, the algorithm has not been published in any peer-reviewed professional journals. The spreadsheets have a provision to turn off the head loss algorithm if the engineer does not wish to use this feature.

Spreadsheets

The spreadsheets are listed below, along with a brief description of the spreadsheet. These spreadsheets are compiled in Excel format (the current version in use at the Washington State Department of Ecology as of this writing). These versions of the spreadsheets include provisions for using either U.S. customary units or metric units, with a view toward making them more available to the international dam safety community.

ChanlCap calculates and compares critical vs. uniform flow for the given channel cross-section.

WeirBroad calculates the stage-discharge curve for the spillway based on critical flow (broad-crested weir) conditions.

WeirUnifm calculates the stage-discharge curve for the spillway based on subcritical uniform flow conditions (Manning equation).

Riprap-1 calculates the stability of loose riprap using uniform flow parameters.

Riprap-2 calculates the stability of loose riprap (same as Riprap-1), plus a recommended riprap gradation consistent with Dam Safety Guidelines.

Head Loss Hf vs Ls has the data and analysis used to develop the head loss algorithm. This spreadsheet is not used in the calculations for any specific project. This spreadsheet is included here to help spreadsheet users understand how the head loss algorithm was developed. Further discussion is provided below and in an appendix to this guidance following the list of references.

The general computation sequence and procedures are as follows:

1. Save a copy of the template spreadsheet to a new project-specific name before making any project-specific changes to that spreadsheet.

2. Use ChanlCap to compare critical vs. uniform flow in the spillway channel. In most cases, ChanlCap examines the drawdown from critical flow at the spillway overflow toward super-critical uniform flow down the spillway channel (Froude numbers > 1). If the computations indicate uniform flow is subcritical (i.e., Froude numbers < 1), then uniform flow will be the hydraulic control, not critical flow.

3. Use WeirBroad or WeirUnifm to calculate the stage-discharge curve for the spillway.

    a. Most spillways have a hydraulically steep channel, where spillway capacity is controlled by critical flow conditions at the spillway overflow crest. For this case, use WeirBroad to calculate the stage-discharge curve.

    b. If the calculations from ChanlCap indicate the flow in the spillway channel is subcritical (Froude number < 1), spillway capacity is controlled by uniform flow in the channel. For this case, use WeirUnifm to calculate the stage-discharge curve.

4. Enter the stage-discharge curve for the open spillway into the hydrology computer model for the watershed, along with the stage-discharge curves for any other spillways (any drop-inlet structures, for example) and other required input for watershed and precipitation parameters. Run the watershed model to determine the peak flow through the spillway and the peak water level in the reservoir.

    Reminder: For submittals to Dam Safety, all three storm scenarios (long, intermediate and short duration) need to be analyzed to determine which one causes the highest peak flow through the spillway and peak water level in the reservoir. The highest peak flow and water level become the Inflow Design Flood (IDF) for dam safety purposes.

5. [optional step] For file documentation purposes, I find it helpful to update the spillway and channel spreadsheets to explicitly show where the IDF occurs within the range of possible flows. A procedure to do this is discussed below.

6. If the designer wishes to consider a loose riprap lining for the spillway and channel, use Riprap-1 or Riprap-2 to verify the stability of the riprap. Make sure roughness (**n**) values are consistent between the riprap spreadsheet(s) and the spillway and channel spreadsheets.

Using the spreadsheets

The spreadsheets are intended to be very interactive. The user should be sure to understand the calculations and their physical significance. As always, the design engineer retains full responsibility for making sure these calculations are correctly applied to their specific project.

Green and blue shading is used to help identify the cells where key information needs to be entered by the user. Most of the green cells have "dummy" values in them just as a check to make sure the spreadsheet does the calculations correctly. Most of the parameters in the green cells need to be replaced with project-specific values. Blue cells identify parameters that the user may wish to update, or that can be left as-is without hurting the calculations. The specific item of data needed is usually listed nearby so that a print-out of the spreadsheet will serve as clear file documentation of the calculations performed.

When the correct value has been entered into a particular cell (including accepting any suggested values in the blue-tinted cells), my usual practice is to get rid of the green or blue shading for that cell as an indication that the data input for that cell has been completed, although for illustrative purposes I elected not to do this in the worked example spreadsheets.

You may also need to delete some lines and/or auto fill to add some lines (and adjust the data sources for the graphs) to make the spreadsheet fit your specific project. To some extent, each use of the spreadsheet has its own project-specific nuances and variations. Feel free to edit and revise these spreadsheets as appropriate for your own specific needs.

ChanlCap: Data for the dam, spillway overflow crest and spillway channel need to be entered in the appropriate cells on page 2. Possible blockage by debris is considered as % obstruction (obstr). The system of units, either U.S. or metric, are entered in the far right column on page 2, with U.S. customary units shown as the default values. If metric units are used, simply autofill or copy and paste the metric values in cells N48 thru N58 into the cells M48 thru M58; most of the units shown next to the input cells will update automatically, but many of the column headings in the various tabular presentations will need to be manually updated to list the metric units. The median rock diameter, D_{50}, for a riprap channel lining is entered in inches to correctly calculate the roughness coefficient (**n** value), although a conversion to metric units is shown nearby.

Uniform flow is computed based on the friction slope S_f computed between upstream and downstream water levels. In the absence of water surface elevation data to calculate a representative S_f, the friction slope is calculated to be the same as the bed slope S_o.

For use in conjunction with the riprap spreadsheets, the spreadsheet computes the roughness (**n**) value based on the median rock size for the riprap. Two calculations, for mild vs. steep slopes, are performed and compared (for more information about these equations, see: Haan *et al*, 1994, page 127; Abt *et al*, 1988). As written, the spreadsheet tentatively selects the larger of the two riprap **n**-values to use in the computations. If the spillway channel is lined with concrete, a grass cover, or other material, overwrite the dummy contents of the "Roughness **n** = " cell to insert the correct **n**-value. Space is also provided to cite the source for the **n**-value used in the calculations; for example: WSDOT Hydraulics Manual; Brater & King's Handbook of Hydraulics.

For file documentation purposes, space is provided to insert comments regarding the channel and its hydraulic regime. The spreadsheet was developed primarily for use with open channel spillways, but may be used for other open channels as well. Dummy notes are shown for the stereotypical case of an overflow spillway down the face of the dam. Correct information for your dam should be entered in these cells and the reminders to verify (shown in bold) should be deleted from these cells.

On page 3, select an increment for "y" that will cover about 2/3 to 3/4 of the range of spillway channel depths within 10 – 12 data points. As will be seen in the WeirBroad and WeirUnifm

spreadsheets, flow depths greater than that will probably give reservoir water levels higher than the dam crest and thus beyond the range of the stage-discharge curve for the spillway.

Froude numbers < 1 indicate subcritical flow; Froude numbers > 1 indicate supercritical flow. On the table on the bottom half of page 3, a column is provided to note whether the flow in the channel is sub- or super-critical.

After the hydrologic computer model has been run and the IDF determined, the table on the top half of page 3 may be updated as follows. Find the intervals within the table values for Q_{crit} and Q_{unif} where the IDF discharge will occur. In the typical case of supercritical flow in the channel, the row for uniform flow will be above (i.e., shallower depth than) the row for critical flow. For whichever flow has the smaller "y" value, usually Q_{unif}, manipulate the "y" value until the discharge in the Q_{unif} column equals the IDF discharge. Individual cells in the "y" column (far left) may be manipulated by the user to increase or decrease the nominal increment (i.e., multiply the increment by a number > 1 or < 1) to obtain the desired value in the Q_{unif} or Q_{crit} column. Since the next "y" value is incremented from the "y" value in the preceding row, the "y" value in the next row must be manipulated to increment from the row preceding the Q_{unif} row. This essentially isolates the Q_{unif} row from the regular intervals of the other rows in the table. Repeat the same procedure for the flow with the higher "y" value, usually Q_{crit}, to obtain Q_{crit} equal to the IDF discharge. Manipulate the "y" value in that row until the discharge in the Q_{crit} column equals the IDF discharge, then manipulate the "y" value in the next row to increment from the row preceding the Q_{crit} row.

As noted above, the spreadsheet was developed primarily for use with open spillways for dams, but may be used for other open channels as well. On pages 4 and 1, the heading on the graphs should be updated to identify which spillway or other open channel these computations are for. Page 1 serves primarily as an "executive summary" page for the computations, with most of the data input starting on page 2.

WeirBroad: Data for the dam, spillway overflow crest and spillway channel need to be entered in the appropriate cells on page 2. Possible blockage by debris is considered as % obstruction (obstr). The system of units, either U.S. or metric, are entered in the far right column on page 2, with U.S. customary units shown as the default values. If metric units are used, simply autofill or copy and paste the metric values in cells N49 thru N57 into the cells M49 thru M57; most of the units shown next to the input cells will update automatically, but many of the column headings in the various tabular presentations will need to be manually updated to list the metric units.

For riprap-lined spillways, the spreadsheet computes the roughness (**n**) value based on the median rock size for the riprap. Two calculations, for mild vs. steep slopes, are performed and compared (for more information about these equations, see: Haan *et al*, 1994, page 127; Abt *et al*, 1988). As written, the spreadsheet tentatively selects the riprap **n**-value for the mild slope at the spillway overflow to use in the computations. If the spillway channel is lined with concrete, a grass cover, or other material, overwrite the dummy contents of the "Roughness **n** = "

cells to insert the correct **n**-value. Space is provided to cite the source for the **n**-value used in the calculations; for example: WSDOT Hydraulics Manual; Brater & King's Handbook of Hydraulics.

As written, the spreadsheet provides approximately equal increments of flow depth ("y"). For trapezoidal channels, however, this does not translate into equal increments of driving head ("H") or reservoir water level ("WL"). Individual cells in the "y" column (far left) may be manipulated by the user to slightly increase or decrease the nominal increment (i.e., multiply the increment by a number slightly > 1 or slightly < 1) to obtain a more preferable increment in the H and WL columns. My experience has been that the range of multipliers to do this typically falls between 0.8 and 1.2.

The dummy increment for "y" gives H and WL increments of about 0.1 feet. If an increment of 0.2, 0.5, or 1.0 feet is preferred, multiply the y-increment input value by 2, 5 or 10, then further manipulate the individual cells in the "y" column as described above. I usually select an increment for "y" that will cover the entire range of spillway flows within 15 to 20 data points.

After the hydrologic computer model has been run and the IDF determined, the stage-discharge curve may be updated as follows. Find the interval within the table values for Q where the IDF discharge will occur. Manipulate the "y" value in that row until the discharge Q equals the IDF discharge. Since the next "y" value is incremented from the "y" value in the preceding row, the "y" value in the next row must be manipulated to increment from the row preceding the Q_{IDF} row. This essentially isolates the Q_{IDF} row from the regular intervals of the other rows in the table. To restore the other rows in the table to their previous regular intervals, the rows below the Q_{IDF} row will most likely need some minor manual updating.

Below the table on page 3 is a provision to explicitly identify the freeboard remaining on the dam compared to the peak water level in the reservoir during the inflow design flood. The reference to the cell in the WL column (dummy cell is L107) will need to be manually changed to refer to the correct WL value in the Q_{IDF} row.

The bottom of page 4 has some calculations for gabion-lined spillways that are intended to help the constructability of the gabion lining. These calculations compare the spillway cross-section geometry to the 6-foot lengths that are common for most gabions, with a view toward helping the designer select a spillway cross-section that may be constructed of integer numbers of gabions.

Page 1 serves primarily as an "executive summary" page for the computations, with most of the data input starting on page 2.

All of the data input and results of the computations are shown on the worksheet for the **Computations** tab. The worksheet for the **Head Loss** tab is included primarily to show where the equation for head loss $\mathbf{h_f}$ came from, but does not need any input or manipulation by the user.

WeirUnifm: Data for the dam, spillway overflow crest and spillway channel need to be entered in the appropriate cells on page 2. Possible blockage by debris is considered as % obstruction (obstr). The system of units, either U.S. or metric, are entered in the far right column on page 2, with U.S. customary units shown as the default values. If metric units are used, simply autofill or copy and paste the metric values in cells N49 thru N59 into the cells M49 thru M59; most of the units shown next to the input cells will update automatically, but many of the column headings in the various tabular presentations will need to be manually updated to list the metric units. The median rock diameter, D_{50}, for a riprap channel lining is entered in inches to correctly calculate the roughness coefficient (**n** value), although a conversion to metric units is shown nearby.

Uniform flow is computed based on the friction slope S_f computed between upstream and downstream water levels. In the absence of water surface elevation data to calculate a representative S_f, the friction slope is calculated to be the same as the bed slope S_o.

For riprap-lined spillways, the spreadsheet computes the roughness (**n**) value based on the median rock size for the riprap. Two calculations, for mild vs. steep slopes, are performed and compared (for more information about these equations, see: Haan *et al*, 1994, page 127; Abt *et al*, 1988). As written, the spreadsheet tentatively selects the riprap **n**-value for the mild slope at the spillway overflow to use in the computations. If the spillway channel is lined with concrete, a grass cover, or other material, overwrite the dummy contents of the "Roughness **n** = " cells to insert the correct **n**-value. Space is provided to cite the source for the **n**-value used in the calculations; for example: WSDOT Hydraulics Manual; Brater & King's Handbook of Hydraulics.

As written, the spreadsheet provides approximately equal increments of flow depth ("y"). For trapezoidal channels, however, this does not translate into equal increments of driving head ("H") or reservoir water level ("WL"). Individual cells in the "y" column (far left) may be manipulated by the user to slightly increase or decrease the nominal increment (i.e., multiply the increment by a number slightly > 1 or slightly < 1) to obtain a more preferable increment in the H and WL columns. My experience has been that the range of multipliers to do this typically falls between 0.8 and 1.2.

The dummy increment for "y" gives H and WL increments of about 0.1 feet. If an increment of 0.2, 0.5, or 1.0 feet is preferred, multiply the y-increment input value by 2, 5 or 10, then further manipulate the individual cells in the "y" column as described above. I usually select an increment for "y" that will cover the entire range of spillway flows within 15 to 20 data points.

After the hydrologic computer model has been run and the IDF determined, the stage-discharge curve may be updated as follows. Find the interval within the table values for Q where the IDF discharge will occur. Manipulate the "y" value in that row until the discharge Q equals the IDF discharge. Since the next "y" value is incremented from the "y" value in the preceding row, the "y" value in the next row must be manipulated to increment from the row preceding the Q_{IDF} row. This essentially isolates the Q_{IDF} row from the regular intervals of the other rows in the

table. To restore the other rows in the table to their previous regular intervals, the rows below the Q_{IDF} row will most likely need some minor manual updating.

Below the table on page 3 is a provision to explicitly identify the freeboard remaining on the dam compared to the peak water level in the reservoir during the inflow design flood. The reference to the cell in the WL column (dummy cell is L107) will need to be manually changed to refer to the correct WL value in the Q_{IDF} row.

The bottom of page 4 has some calculations for gabion-lined spillways that are intended to help the constructability of the gabion lining. These calculations compare the spillway cross-section geometry to the 6-foot lengths that are common for most gabions, with a view toward helping the designer select a spillway cross-section that may be constructed of integer numbers of gabions.

Page 1 serves primarily as an "executive summary" page for the computations, with most of the data input starting on page 2.

This spreadsheet was developed primarily for use with open spillways for dams, but may be used for other open channels as well. On pages 4 and 1, the heading on the graphs should be updated to identify which spillway or other open channel these computations are for.

All of the data input and results of the computations are shown on the worksheet for the **Uniform** tab. The worksheet for the **Critical** tab is used to perform the head loss $\mathbf{h_f}$ computations (which are then copied to the **Uniform** tab), but does not need any input or manipulation by the user. The worksheet for the **Head Loss** tab is included primarily to show where the equation for head loss $\mathbf{h_f}$ came from, but also does not need any input or manipulation by the user.

<u>Velocity coefficient</u>. The most reputable authors in hydraulic engineering note that these types of calculations should properly consider use of a velocity correction factor (called by various similar names in the literature, identified as $\boldsymbol{\alpha}$ (alpha)). They also note that $\boldsymbol{\alpha}$ for most prismatic channels is slightly more than 1.0. As a practical matter for most engineering applications, given the range of uncertainty in the other parameters in the calculations, $\boldsymbol{\alpha}$ may be taken as 1.0 and omitted from the computations without introducing significant error into the computations. See: Chow, 1959, pages 28 - 29; Brater and King, 1976, page 3-8; Henderson, 1966, pages 20 - 21; Zipparro and Hasen, 1993, pg. 2.3. This convention ($\boldsymbol{\alpha}$ = 1.0) was implicitly adopted in previous versions of these spreadsheets.

In the current version of these spreadsheets, I have elected to include a provision for $\boldsymbol{\alpha} > 1.0$. Consistent with Chow, 1959, page 2-8, the default value is $\boldsymbol{\alpha} = 1.15$. This has the effect of increasing the driving head (water level in the reservoir) required to pass a particular discharge through the spillway. In the spreadsheet calculation, $\boldsymbol{\alpha} > 1.0$ applies only to the computation of velocity head, after the flow velocity has been calculated. For critical flow, the flow velocity is calculated from the hydraulic mean depth as $V^2 = g\ y_m$, where $y_m = A / T$, without explicit consideration of the velocity coefficient $\boldsymbol{\alpha}$. For uniform flow, the flow velocity is calculated

using the Manning equation, without explicit consideration of the velocity coefficient ***α***. Only the velocity head calculation uses ***α*** > 1.0.

Head loss and weir coefficient. The computations for head losses and back-calculating the weir coefficient are new features in these spreadsheets, an explicit attempt to account for energy losses at the spillway entrance and control section, especially for very shallow flows over relatively long control section and entrance channel lengths (long compared to depth of flow). The computations for these parameters are discussed in more detail in a later section.

Riprap-1; Riprap-2: Data for the spillway channel, design discharge and median rock size, D_{50}, need to be entered into the appropriate cells on page 1. The values shown for riprap properties seem to be typical values, but may be updated by the user if you have more accurate data for your specific rock. For comparison with the spillway and channel spreadsheets, these spreadsheets compute roughness **n**-values (on page 1) for the riprap lining based on median rock size. Two calculations, for mild vs. steep slopes, are performed and compared (for more information about these equations, see: Haan *et al*, 1994, page 127; Abt *et al*, 1988).

The desired factor of safety is a matter of the professional judgment of the designer. The Corps of Engineers (USACE, 1991, Section 3-7.C.) recommends a minimum safety factor of 1.1 for sizing riprap, although they use a different design procedure than is used in the spreadsheets. It should also be noted that the downstream hazard potential and population at risk is already factored into the design storm as the rainfall depth. I am open to suggestions from readers and users on this. In the meantime, my suggestion would be to use a desired factor of safety of at least 1.2 as shown in the blue cell on the spreadsheets.

Riprap-1 focuses on the factor of safety computations to verify the stability of the riprap lining. Riprap-2 adds a third page to calculate design features such as a recommended gradation, riprap layer thickness, and other key features needed for the riprap lining to perform as intended.

Each spreadsheet has two worksheets (tabs) to allow the use of either U.S. units or metric units. The worksheet for metric units accepts the input values in metric units, converts them to U.S. units to perform the calculations, then converts the results back into metric units.

Erosion protection for spillway channels. In many cases, the stability calculations will confirm the difficulties of using loose riprap in steep channels as noted in Dam Safety Guidelines Part IV, Section 4.3.5.2. For short spillways, using gabions to hold the rocks in place, or an alternative lining material (such as grouted riprap, or concrete), may be necessary.

For longer spillways, the designer may wish to use the concept of *Survivability* to design the spillway lining (see Guidelines Part IV, text page 3). For example, the riprap lining might be sized to be stable during a smaller storm (Step 1, perhaps), with other features such as buried erosion cutoff walls to prevent any erosion that does occur during larger storms (such as the IDF) from propagating upstream through the dam crest and into the reservoir. The concept is that the spillway might be damaged during the IDF, but the damage would be limited within the

spillway and would not lead to a catastrophic failure of the dam. Damage to the spillway lining would be repaired after the storm has subsided, to be prepared for the next one.

For spillways lined with loose riprap and/or designed for survivability, be sure to include in the engineering report an explanation of the design intent and criteria, with supporting calculations.

In some cases, spillways may be designed for subcritical slopes in order to stay below allowable velocity criteria for a grass or compacted-earth channel lining. Such spillways may also be designed to be stable during a smaller storm and survivable during a larger IDF. Grass- or earth-lined channels should be sure to include in the engineering report an explanation of the design intent and criteria, with supporting calculations.

Examples

Three open spillways from previous projects illustrate how these spreadsheets may be used. Example 1 is a rectangular gabion-lined spillway for a stormwater pond. The spillway is located on the downstream face of the dam on a 2 H:1V slope. Example 2 is a trapezoidal grass-lined spillway for an irrigation reservoir. The spillway goes around the left abutment on a subcritical slope, and has a steeper side slope on the left side of the channel than on the right side.

Example 3 is a trapezoidal riprap-lined lined spillway for a dam on a lake that provides outdoor recreation and wildlife habitat. To be stable during IDF conditions, a riprap lining of WSDOT heavy loose riprap (D_{50} = 2.2 feet) would be required. The example spreadsheets also show the stability (or lack thereof) for quarry spalls (D_{50} = 0.5 feet) during IDF conditions and also during a smaller design storm used in conjunction with the *Survivability* concept.

At this time, only examples using calculations in U.S. units are available. I would be interested in feedback from anyone using these spreadsheets with calculations in metric units.

Example 1 spreadsheets:
- Ex1-Chan. Critical vs. uniform flow for the steep, rectangular channel.
- Ex1-Weir. Stage-discharge curve for this spillway based on critical flow.

Example 2 spreadsheets:
- Ex2-Chan. Critical vs. uniform flow for the trapezoidal channel, confirms subcritical slope.
- Ex2-Weir. Stage-discharge curve for this spillway based on uniform flow.

Example 3 spreadsheets:
- Ex3-Chan1. Critical vs. uniform flow for the steep, trapezoidal channel. Channel lined with WSDOT heavy loose riprap. IDF conditions.

- Ex3-Rip1. Verifies stability of heavy loose riprap during IDF conditions.
- Ex3-Weir. Stage-discharge curve for this spillway based on critical flow at the spillway overflow crest.

- Ex3-Chan2. Critical vs. uniform flow for the steep, trapezoidal channel. Channel lined with WSDOT quarry spalls. IDF conditions.
- Ex3-Rip2. Verifies lack of stability of quarry spalls during IDF conditions.

- Ex3-Rip3. Used to find flow depth for which quarry spalls would be stable.
- Ex3-Chan3. Used to find the allowable discharge for a smaller design storm (to be used in conjunction with the *Survivability* concept) for which quarry spalls would be stable. Critical vs. uniform flow for the steep, trapezoidal channel for that range of flows.

Head loss and weir coefficient

The computations for head losses and back-calculating the weir coefficient are new features in these spreadsheets, an explicit attempt to account for energy losses at the spillway entrance and control section, especially for very shallow flows over relatively long control section and entrance channel lengths (long compared to depth of flow).

My general logic is as follows. For a broad-crested weir spillway, critical flow conditions will control, and most of the driving head is critical head. Additional energy losses would be reflected in a reservoir water level higher than critical head, or a weir coefficient smaller than 3.09. (At critical flow, the equivalent broad-crested weir coefficient is 3.09 in U.S. units; see Brater and King, 1976, page 5-24). The length of the control section (length parallel to the direction of flow) should be a relevant parameter, with more head loss expected for shallow flows over longer flow lengths, and relatively less head loss expected during deeper flows over shorter flow lengths.

Data were obtained from the following sources:

- SCS, Hydraulics of Broad-Crested Spillways, TR-39, 1968; especially Drawing ES-171 (Sheet 1 for Case 1), ES-176 (Sheet 1 for Case 1). Graphs relating driving head, critical head, weir length, roughness **n**-value.
  (Also in: Haan, Barfield and Hayes, Design Hydrology and Sedimentology for Small Catchments, 1994; pp. 167 - 173, App. 5D and 5E; especially Figure 5D.1 in App. 5D on page 512, Figure 5E.1 in App. 5E on page 522.)

- Brater and King, Handbook of Hydraulics, 1976; pp. 5-23 to 5-26, Table 5-9 on page 5-43. Tabular data for weir coefficient, driving head, weir length in direction of flow.

Data were also considered from Brater and King, Table 5-3 on page 5-40, and from FHWA, HDS-5, 1985 (in: Haan, Barfield and Hayes, 1994; pp. 156 – 157), but were ultimately not very influential in developing the final algorithm.

Some further comments describing my logic are offered here. Critical head is function of spillway geometry and depth of flow, and the control section length is easily measured from the drawings or in the field, so head loss is the only unknown to be calculated by the empirical equation once the other parameters are known.

Values range from $H_{cr}/L_s = 0.001$ to $h_f/H_{cr} = 0.001$. At the low end, H_{cr} is negligible relative to L_s. The typical case here is the first few increments for the stage-discharge curve, when water just begins to overflow through the spillway. L_s is the dam width at spillway overflow elevation, plus the length of any shallow entrance channel with a width and depth similar to the control section. For $H_{cr} = 0.1$ ft (a common first increment for the stage-discharge curve), the range of h_f calculations will encompass any $L_s < 100$ feet. $L_s < 100$ feet has been the case for most of the dams and spillways I have had experience with in my decade here with Dam Safety.

Aside: For upstream and downstream face slopes on the order of 3 H:1V, L_s will be longer than the dam crest width by about 6 feet for every foot of spillway depth. For example, for a dam with spillway 2 feet deep and crest 12 feet wide, spillway length L_s will be roughly 24 feet. For a dam with spillway 5 feet deep and crest 20 feet wide, spillway length L_s will be roughly 50 feet.

At the high end, h_f becomes negligible relative to H_{cr}. When this situation occurs, H_{cr} exceeds L_s. For spillways through earth embankments, this is physically not possible. As noted above, L_s increases faster than H_{cr} with increasing spillway depth. The conclusion here is that the range of h_f calculations will encompass any $L_s > H_{cr}$.

For the stereotypical case of a hydraulically steep spillway channel such that the spillway discharge is controlled by critical flow at the spillway crest, the WeirBroad spreadsheet will calculate head loss h_f directly, then add h_f to critical head H_{cr} to get total reservoir head H_p.

For a spillway channel with a hydraulically mild slope such that the spillway discharge is controlled by uniform flow in the spillway channel, the spreadsheet cannot calculate head loss h_f directly. The procedure in the WeirUnifm spreadsheet is to estimate head loss h_f as being approximately equal to the head loss for critical flow, then add h_f to flow depth **y** and velocity head H_v to get total reservoir head H_p. To do this, the WeirUnifm spreadsheet has an extra worksheet (**Critical** tab) to perform the critical flow and head loss calculations, then the computed values for h_f are copied to the **Uniform** worksheet to perform the actual uniform flow stage-discharge calculations.

My interpretation of Haan *et al*, Figure 5E.1 (from SCS, 1968), is that to a rough approximation, head loss in the spillway control section is directly proportional to the roughness **n**-value of the spillway relative to a reference **n**-value of 0.04. Both the WeirBroad and WeirUnifm spreadsheets use this approximation in the head loss calculations.

Summary comments

The spreadsheets presented here were developed and refined over a number of years, and have been used extensively in engineering reviews of proposals for new dams and in conjunction with periodic inspections of existing dams. These spreadsheets are intended to be public domain, so please feel free to edit and revise them as appropriate for your own specific needs. As always, the engineer retains full responsibility for making sure these hydraulic calculations are correctly applied to their specific project.

Engineers from the Dam Safety Office are available to provide technical assistance regarding dam design and construction and related engineering analyses, so please feel free to contact us early in the planning stages for your project.

Feedback and questions regarding these spreadsheets are welcome, and should be directed to Marty Walther at phone 360-407-6420, fax 360-407-7162, e-mail martin.walther@ecy.wa.gov, or regular mail to Washington State Department of Ecology, Dam Safety Office, PO Box 47600, Olympia, WA 98504. In particular, I would be interested in feedback from anyone using these spreadsheets with calculations in metric units.

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Section 4.2.4.1, Principal Spillways, Channel Freeboard on page 4-16.
Section 4.3.5, Experience/Practice for Various Spillway Features on pages 4-24 to 4-25.
Section 3.5.4.1, Wave Protection, Riprap Blankets on pages 3-38 to 3-40.

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Appendix

Head loss algorithm

Data used to develop my head loss algorithm were obtained from the following sources:

- SCS, Hydraulics of Broad-Crested Spillways, TR-39, 1968; especially Drawing ES-171 (Sheet 1 for Case 1), ES-176 (Sheet 1 for Case 1). Graphs relating driving head, critical head, weir length, roughness **n**-value.
  (Also in: Haan, Barfield and Hayes, Design Hydrology and Sedimentology for Small Catchments, 1994; pp. 167 - 173, App. 5D and 5E; especially Figure 5D.1 in App. 5D on page 512, Figure 5E.1 in App. 5E on page 522.)

- Brater and King, Handbook of Hydraulics, 1976; pp. 5-23 to 5-26, Table 5-9 on page 5-43. Tabular data for weir coefficient, driving head, weir length in direction of flow.

Data were also considered from Brater and King, Table 5-3 on page 5-40, and from FHWA, HDS-5, 1985 (in: Haan, Barfield and Hayes, 1994; pp. 156 – 157), but were ultimately not very influential in developing the final algorithm.

The data were analyzed in spreadsheet ***Head loss Hf vs Ls*** as follows. For the data from Brater and King and from FHWA HDS-5, an estimate for critical head was calculated based on the weir coefficient and the reservoir head. Values for critical head were available directly from the SCS data. Head loss was calculated as the difference between the values for reservoir head and critical head. The following values were compiled for each data set: weir length (in direction of flow) L_s, reservoir head (driving head) H_p, critical head H_{cr}, head loss h_f, and ratios for H_{cr}/L_s and h_f/H_{cr}. The ratios H_{cr}/L_s and h_f/H_{cr} are intended to put things on a dimensionless, relative basis. The analysis then selected one composite set of values for H_{cr}/L_s and h_f/H_{cr} considered to be most representative of the range of values, then found an empirical equation to estimate h_f/H_{cr} as a function of H_{cr}/L_s. The composite data and the equation were copied to the **Head loss** tab of the WeirBroad and WeirUnifm spreadsheets to use in the actual computations.

In ***Head loss Hf vs Ls*** , the data from Brater and King are shown on pages 1, 2 and 3. The data from FWHA HDS-5 are shown on pages 4 thru 9. The data from SCS TR-39 are listed on pages 10, 13 and 16, with graphical analyses shown on pages 11 and 14. Page 12 shows a comparison of the Brater and King, FWHA HDS-5 and SCS TR-39 data. Page 15 shows two data sets that represent the full range of the data; one is a composite of just the SCS data, and one is a composite developed from all three data sources. Page 17 shows my initial attempt to find some empirical equations to approximate the relationship between H_{cr}/L_s and h_f/H_{cr}, which was superseded by the analyses on pages 19, 20, 22 and 23. Pages 19 and 20 show my analysis of the composite data (taken from all three sources) and the resulting equation to relate h_f/H_{cr} to H_{cr}/L_s. Pages 22 and 23 show my analysis of the composite SCS data and the resulting equation to relate h_f/H_{cr} to H_{cr}/L_s for the SCS data. For use in the spillway computations, I elected to use the data set and corresponding equation for the composite data (shown on pages 19 and 20). Pages 18, 21 and 24 are part of the 3 x 8 matrix of pages for the spreadsheet, but were not used in the analysis so those pages are blank.

As mentioned previously, the head loss algorithm was developed from analysis of data published in accepted hydraulic engineering references, so it seems to be conceptually correct. However, the algorithm has not been published in any peer-reviewed journals. The spreadsheets have a provision to turn off the head loss algorithm if the engineer does not wish to use this feature.

[end]