Room to Spare?

A Systematic Evaluation of Spillway Sizing for Existing High and Significant Hazard Dams in Oregon

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Introduction

According to one compilation of dam failures, approximately 34% of failures are caused by overtopping during floods, with spillway capacity playing a significant role in failure (ICOLD, 1995). In another compilation, the percent of failures related to overtopping is 66% (Salisbury, 1998). Even though inadequate spillway sizing can be a significant factor in dam failures, systematic evaluations of spillway sizes over large populations of dams are rare.

In Oregon, dams range in age from new to over 100 years old. The standards and methods for spillway sizing have evolved over this period. Dams built in certain time periods may not be up to current standards and practices.

To determine the extent to which dams in Oregon may have inadequate spillway discharge capacity, the Dam Safety Section of the Oregon Water Resources Department evaluated spillway capacity for 208 high and significant hazard embankment dams in Oregon with sizable watersheds upstream. As part of this study, spillway capacity was evaluated dam by dam and also by region and the time at which it was designed and built. For each dam, a ratio of the spillway capacity to the peak 100-year flow was computed. Reasons for differences in this ratio among dams were then examined by analyzing long-term hydrologic records for given streamflow gages near two case study dams with problematic spillway sizing.

Dams in Oregon are distinguished by both their size and "hazard rating." Dams smaller than 10 feet tall or less than 9.2 acre-feet in storage are not covered by Oregon's dam safety regulatory program. Hazard rating - low, significant, and high - refers to the damage a dam failure can inflict downstream. The hazard ratings given to dams do not imply anything about the condition of a dam. The breach of a high hazard dam would result in the direct loss of human life and widespread property damage (FEMA, 2004). Failure of a significant hazard dam would result in considerable property damage and could cause loss of life.

This study focused on high and significant hazard dams because of the consequences of their failure. Since concrete dams can generally withstand some overtopping without failure, they were excluded from this study. Furthermore, earth and rock embankment dams that have small watersheds and are filled by canals and pumping were also excluded because the 100-year peak flow analysis is not relevant in the design of the spillways for these structures. This left a data set of 208 dams to be evaluated. For each of these 208 dams, the ratio of the spillway capacity to the peak 100-year flow was computed.

Methods

Data on spillway capacity were gathered through a search of the data files in the Dam Safety Office. Spillway capacity was taken from as-built drawings, general plans, engineering calculations, or "Phase I" inspection reports when available. If capacity could not be found, it was calculated. Dimensions for the calculations were taken from as-built drawings or inspection reports to account for any changes during construction. Capacity calculations were done primarily with a single program "HydCalc" (Norris 1985). In regard to spillway capacity, Hydcalc has two subroutines: one for channel spillways and another for circular spillways, such as trickle tubes or drop inlets. The channel function uses specific energy and relationships at the critical point to determine capacity based on channel width, depth, and side slope. The circular spillway routine uses a sharp crested weir equation for head values up to the diameter of the spillway. At depths greater than the diameter, the program uses an orifice equation. These procedures are outlined in the *Design of Small Dams 2nd edition* (Bureau of Reclamation, 1973, p.388-391).

Dams with pipes for spillways were analyzed with a simple model, which used the energy equation with frictional losses computed using the Darcy-Weisbach formulation (Street, 1996, p.347). Local losses were also incorporated into the energy equation for entrances, bends, trash racks, and gates. An Excel spreadsheet was developed with Visual Basic for Applications (VBA) to help automate the calculations (Charpa, 2003). Dams with only pipes are very rare and only occur in the western half of the state.

Spillway for Barnes Butte Dam

Spillways with a weir for their control section were calculated with the sharp crested weir formula $Q = CLH^{(3/2)}$ (Bureau of Reclamation, 1987, p.365). Typically spillways with a weir for control had the capacity listed on the plans or accompanying calculations.

The 100-year peak flow was determined using Cooper's method for peak discharges in western and eastern Oregon (Cooper, 2005 and 2006). The Oregon Water Resources Department (OWRD) has developed an interactive internet map and program that allows a user to pick a "pour point" and calculate peak flows at that point. The watershed attributes are then fed from a Geographic Information System (GIS) into Cooper's regression equations resulting in estimates of peak flow (Stahr and Harmon, 2006).

For some of the dams in eastern Oregon, the regression equations in Cooper's method did not produce an estimate that made sense (Cooper, 2006). Five dams in the study fell into this category. To estimate a peak discharge for these five dams, the basin ratio method was used with a similar gaged watershed (Robison, 1991a). The gage's 100-year flow came from Appendix D in Cooper (2005 and 2006).

Once the spillway capacity and 100-year peak flow discharge were calculated, a ratio between them was calculated, and this ratio was examined by time of construction, region and other factors to determine patterns in spillway capacity between factors. Dams with especially low capacities as compared to the 100-year peak flow were flagged for further investigation and for discussion in subsequent field inspections.

Two dams, Fishhawk Lake and Barnes Butte Reservoir, were chosen to be evaluated in greater detail. Fishhawk Lake is located in Clatsop County in northwest Oregon. Total storage volume for this dam is 980 acre-feet with a tributary area of eighteen square miles. Fishhawk's spillway is a 41-foot-diameter drop inlet structure. Fishhawk dam had a significant hazard rating (Oregon Water Resources Department, and U.S. Army Corps of Engineers, 1981), which was recently upgraded to high hazard. Barnes Butte Reservoir is a high hazard dam located near the town of Prineville in central Oregon. The dam has a maximum height of 32.5 feet and a crest length of 400 feet. Total storage volume in the reservoir is 611 acre-feet with an upstream watershed area of four square miles. The spillway is an unlined trapezoidal channel with a base width of seven feet, side slopes of 3:1, and a depth of 3.1 feet.

Each of these dams has a spillway capacity problem. In the winter of 2008-2009, Fishhawk Lake dam nearly overtopped during a large storm event. Barnes Butte shows evidence of down cutting in the spillway and erosion. For each of these dams, the long-term hydrologic record of nearby gages was examined to investigate wet and dry patterns in the record. The Log-Pearson III distribution (Interagency, 1982) was used to estimate the 100-year peak flow in increments and over the entire period, and these estimates were compared back to regional regression equations of Cooper (2005 and 2006).

Results and Discussion

Overall results for all dams

This data set of 208 dams throughout Oregon reflects a diversity in the ages of the dams (Figure 1). As can be seen from Figure 1, there was a period of heightened dam building in Oregon from 1950-1980, in which nearly 75% of the dams evaluated in this study were built. Even though most were built in this 30-year period, there has been steady activity before and after this time period.

As shown in Table 1, the average ratio of spillway capacity to the 100-year peak flow for high and significant hazard dams in Oregon is well above 1.0. However, there are dams with ratios near and below 1.0 that require more scrutiny. The minimum ratios of spillway capacity to 100-year peak flow were disturbing for both high and significant hazard dams (0.3 and 0.5 respectively). This indicates that these dams will likely overtop at flows that are one-third to one-half of the 100-year peak flow. Interestingly, the significant hazard dams (median value = 3.6) had higher ratios than the high hazard dams (median ratio = 2.6). One reason for this is that many of these significant hazard dams were built during a later time period.

Figure 1. Cumulative distribution of dam age for 208 high and significant dams in Oregon

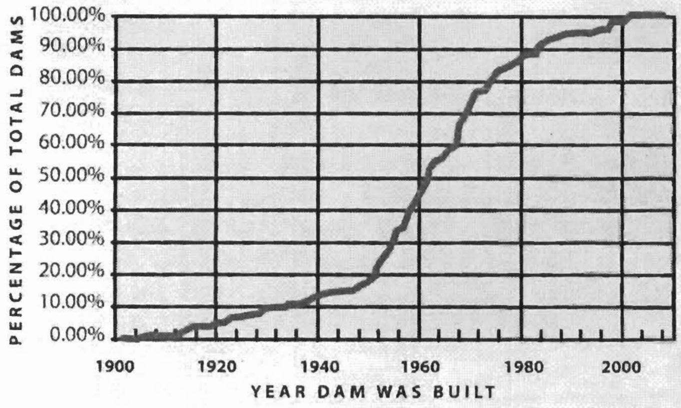


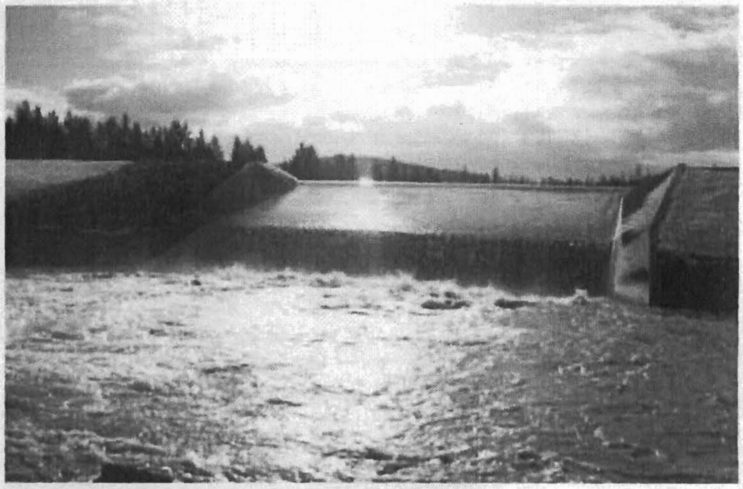
Table 1: Summary Statistics

	High and Significant Dams						
	Average	Median	Count	Standard Deviation	Standard Error	Max	Min
Ratio of Spillway Capacity to Q100 (High&Sig)	5.7	3.3	208	6.9	0.5	57.1	0.3
Ratio of Spillway Capacity to Q100 (High)	5.5	2.6	65	7.3	0.9	44.4	0.3
Ratio of Spillway Capacity to Q100 (Sig)	5.7	3.6	143	6.7	0.6	57.1	0.5

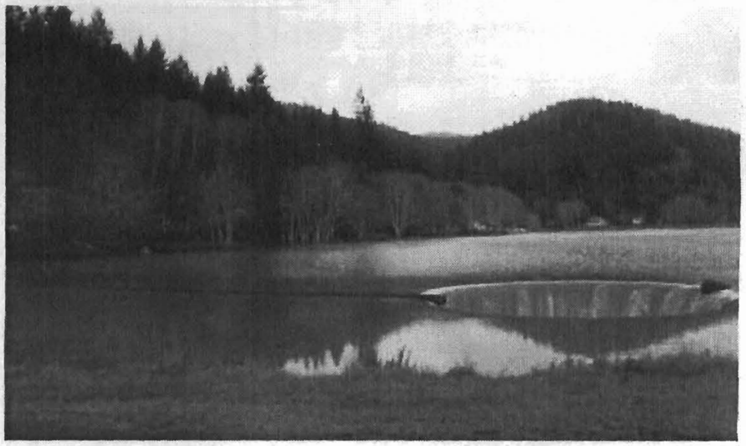
From Figure 2, it is apparent that the time period in which the dam was designed had some bearing on the ratio of the spillway capacity to the 100-year peak flow of the watershed. This ratio was noticeably smaller during the 1930's, a drought period in Oregon's history (Robison, 1991b) and a time of economic hardship. Dams built after this period have higher ratios, and no dams built since 1991 have a ratio of spillway capacity to 100-year peak flow less than 2.5. There are very low minimum ratios in each of the time periods except for those after 1991.

As shown in Table 2, there was little difference between major geographic regions in the ratio of spillway capacity to the 100-year peak flow. Ratios for dams in eastern Oregon were somewhat lower with a median value of 3.1 vs. 3.6 for western Oregon, Considering the variation in these ratios, these differences are not great.

Fishhawk dam's ratio of spillway capacity to 100-year flow of 1.3 was chosen as a threshold of concern because of its recent near overtopping problems. There were 13 dams with a ratio of spillway capacity to 100-year peak flow at or below 1.3, and nine were below a ratio of 1.0. Each of these dams has been flagged for further review.

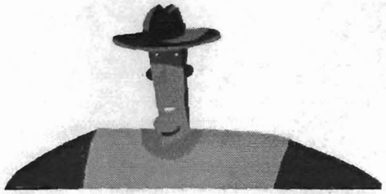


Spillway at Mompano Dam
(a properly functioning spillway during a flood)



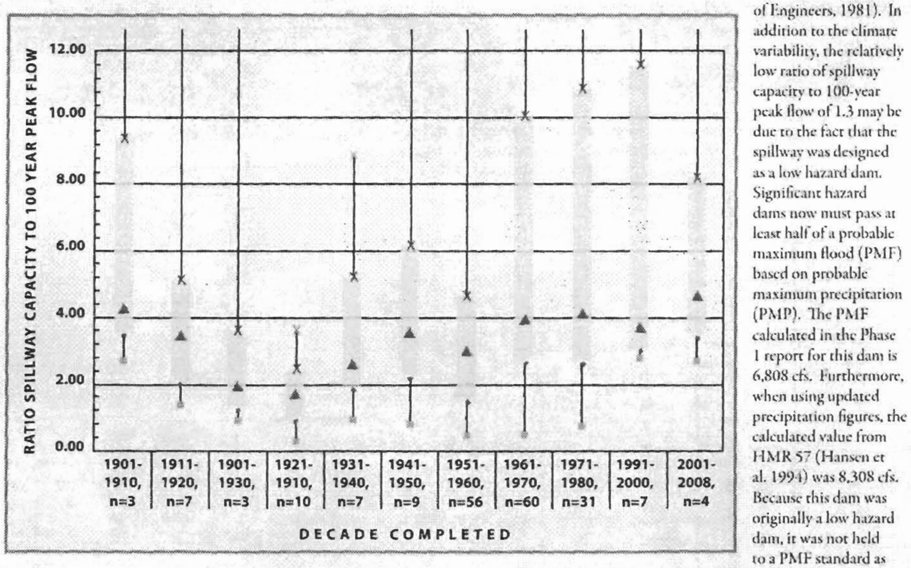
Drop Inlet Spillway for Fishhawk dam

Focused analysis for two dams with known spillway capacity issues



Two dams, Fishhawk Lake Dam and Barnes Butte Dam, were chosen for further analysis. Since the evaluation of the set of 208 dams demonstrated that there were differences in the ratio of spillway capacity to 100-year peak flow depending on when the dam was built, streamflow records from gages on streams near these two dams were evaluated to determine how estimates of the 100-year peak flow could vary using frequency analysis based on time period chosen (Figures 3 and 4).

Figure 2. Box and whisker plots, by decade in which the dam was constructed, of the ratio of spillway capacity to 100-year peak flow. The triangle represents the median value and the box represents the standard deviation about the mean with the lines being the range. The black square represents the minimum value.



As shown in Figure 3, the time period can have a sizeable effect on the estimate of 100-year peak flows, with values at Nehalem River at Foss varying from under 47,000 cfs, using annual peak flow data from the period 1939-1959, to over 66,000 cfs, using annual peak flow data from the period 1980-1999. For the Middle Fork John Day River, the estimates could vary from near 4,200 cfs to 5,700 cfs depending on the time period used for the flood frequency analysis. If dams were designed in the 1930's and 1940's with limited records during a drought period, it is understandable how spillway capacity could be under-designed compared to today's standards.

Original design documents for Fishhawk dam, dated 1964, included several peak flow calculations with comparisons to nearby gages and empirical equations. The year of calculation was just before one of the larger floods of record and during a period with far fewer significant flood events than have occurred in the last 20 years. Using the methods described in this study, a 100-year peak flow of approximately 2,540 cfs was determined for this dam. The capacity of Fishhawk's drop inlet spillway is 3,300 cfs with a water level at the crest of the dam (Oregon Water Resources Department, and U.S. Army Corps of Engineers, 1981). In addition to the climate variability, the relatively low ratio of spillway capacity to 100-year peak flow of 1.3 may be due to the fact that the spillway was designed as a low hazard dam. Significant hazard dams now must pass at least half of a probable maximum flood (PMF) based on probable maximum precipitation (PMP). The PMF calculated in the Phase 1 report for this dam is 6,808 cfs. Furthermore, when using updated precipitation figures, the calculated value from HMR 57 (Hansen et al. 1994) was 8,308 cfs. Because this dam was originally a low hazard dam, it was not held to a PMF standard as it would be if designed today. Recently the hazard classification of this dam has been changed from significant to high hazard. High hazard dams require a full PMF, which at Fishhawk Dam is a flood of over 8,000 cfs. Changes in hazard rating due to downstream development are hard to anticipate, but dams such as Fishhawk, which have had upgraded hazard ratings, are likely to have substandard spillway capacities.

Design documents for Barnes Butte Dam, dated 1955, included comparative calculations of needed spillway capacity of 652 cfs, but for some unexplained reason its spillway capacity prior to the dam being overtopped was only 160 cfs (Oregon Water Resources Department, and U.S. Army Corps of Engineers, 1980). Empirical estimates of streamflow are much smaller (only around 40 cfs) for a 100-year peak flow event, giving this dam a respectable capacity to peak flow ratio. However, empirical formulas are difficult to use in this particular area due to the effects of volcano pumice and variable groundwater in the vicinity of this dam. From the severe erosion observed in the spillway during numerous field inspections, the spillway is undersized.

Table 2: Summary statistics of ratios of spillway capacity to 100-year peak flow for high and significant hazard dams compared by geographic region - Western and Eastern Oregon.

Western and Eastern Oregon High and Significant Dams							
	Average	Median	Count	Standard Deviation	Standard Error	Max	Min
	Western Oregon						
Ratio of Spillway Capacity to Q100	5.7	3.3	208	6.9	0.5	57.1	0.3
	Eastern Oregon						
Spillway Capacity to Q100	5.5	2.6	65	7.3	0.9	44.4	0.3

Figure 3. Frequency analysis for different time periods and for full period of record for Nehalem River at Foss (downstream from Fishhawk Lake Dam) compared with regression equation number for the watershed from Cooper (2006).

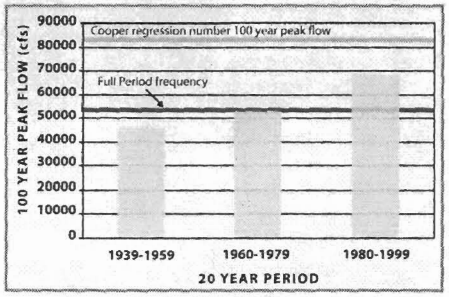
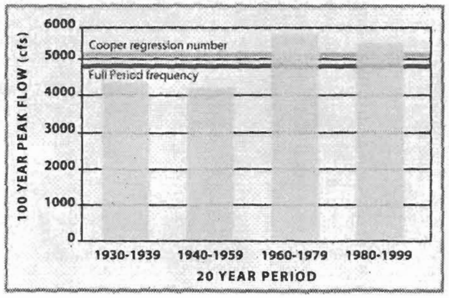


Figure 4. Frequency analysis for different time periods and for full period of record for Middle Fork John Day River near Ritter (near Barnes Butte Dam) compared with regression equation number for the watershed from Cooper (2006).



Like Fishhawk Dam, Barnes Butte Dam, when originally constructed, was considered a low hazard dam. Since then, however, considerable downstream development has occurred. The city of Prineville Oregon has encroached into the area with a housing development slated to be built immediately downstream from the dam. This has caused the hazard classification of this dam to be changed to a high hazard, which, for new dams, requires a spillway with the capacity to pass a full PMF. For a localized thunderstorm event, the PMF is estimated at nearly 5,000 cfs in the Phase 1 report and nearly 4,000 cfs in a recalculation using the most recent PMP data. This means the current spillway capacity is at least an order of magnitude less than what would be required of a new dam built at the same location.

Summary and Conclusions

This study represents a systematic review of spillway sizing using an objective measure of 100-year peak flow as a standard by which to compare spillway capacity. The study allowed us to quickly distinguish some of the most problematic under-designed spillways in our inventory of high and significant hazard dams. This information has been cataloged dam by dam in a database that we use to advise dam owners of possible safety deficiencies moving forward.

A more focused analysis of two problematic dams confirmed that a low ratio of spillway capacity to 100-year peak flow (for instance 1.3 for Fishhawk Dam) is a good indicator of spillway capacity issues. However, in studying the other dams, it was apparent that the ratio can also be misleading at those dams where the empirical equation for 100-year peak flows can over- or under-estimate.

Based on our analysis of the two dams with known spillway problems, it is also apparent that dams originally designed as rural low hazard dams but later reclassified as high hazard, have spillway capacity problems because design criteria has changed over the years.

Follow-up correspondence is planned for all dams that have ratios of spillway capacity to 100-year peak flow less than or equal to 1.3. Review of these ratios indicates that procedures in place since 1991 have consistently yielded sufficient spillway capacity. However, for older dams, especially those designed in the 1930's, there may be some issues. Overall this systematic study has aided and complemented our regular inspection program and allowed us to prioritize activities and guide us to possible spillway capacity issues for dams.

Acknowledgement

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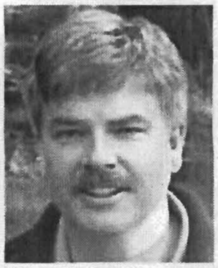

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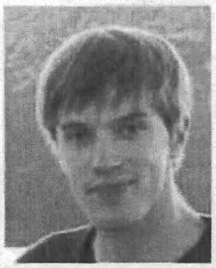

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References

Bureau of Reclamation. 1987. *Design of Small Dams* (3rd ed). Washington, DC: United States Government Printing Office.

Bureau of Reclamation. 1973. *Design of Small Dams* (2nd ed). Washington, DC: United States Government Printing Office.

Chapra S. 2003. *Power Programming with VBA/Excel.* Upper Saddle River, NJ: Pearson Education.

Cooper R. 2005. *Estimation of Peak Discharges for Rural, Unregulated Streams in Western Oregon.*: Scientific Investigations Report 2005-5116. Reston, VA: U.S. Geological Survey.

Cooper R. 2006. *Estimation of Peak Discharges for Rural, Unregulated Streams in Eastern Oregon.* Open File Report SW 06-001. Salem, OR: Oregon Water Resources Department.

Federal Emergency Management Agency. 2004. *Federal Guidelines for Dam Safety:* Hazard Potential Classification System for Dams. Washington, DC: U.S. Department of Homeland Security, Federal Emergency Management Agency.

Hansen, E., Fenn, D., Corrigan, P., Vogel, J., Schreiner L., & Stodt R. 1994. *Hydrometeorological Report No. 57: Probable Maximum Precipitation- Pacific Northwest States.* Silver Springs, MD: U.S. National Oceanic and Atmospheric Administration, National Weather Service.

Interagency Advisory Committee on Water Data. 1982. *Guidelines for Determining Flood Flow Frequency.* Reston, VA: USGS. Office of Water Data Coordination.

International Commission on Large Dams. 1995. *Dam Failures: Statistical Analysis. Bulletin 99.* Paris, France: ICOLD.

Norris B. 1985. *HydCalc.* [Computer Program]. Salem, OR: Oregon Water Resources Department.

Oregon Water Resources Department and U.S. Army Corps of Engineers. 1980. *Phase I Inspection Report: Barnes Butte Dam.* Salem, OR: Oregon Water Resources Department, Dam Safety Office.