Turning Rainfall to Runoff: Estimating Flood Inflows

One of the most critical components of a safe dam is the adequacy of a spillway to safely pass the inflow design flood. Inflow design flood requirements are typically based on the potential hazard a dam poses to downstream floodplains and communities (hazard class) and are usually stipulated by the regulating agency for the structure. The inflow design flood itself is a function of rainfall, including distributions and patterns for a particular storm event frequency, and pertinent watershed characteristics. These pertinent watershed characteristics influence the rate and volume at which rainfall is "lost" and the conversion of the excess rainfall to a runoff hydrograph.

The purpose of this article is to present an overview of the processes and methodologies available for estimating the effects of watershed characteristics on runoff and the transformation of excess precipitation to an inflow design flood hydrograph. This overview is generally based on small dam watersheds throughout the western U.S. with a focus on Colorado, Montana, Utah and Wyoming. Pertinent reference documents are also presented.

Rainfall Event Characteristics

Before watershed runoff can be estimated, rainfall event characteristics must be defined. In the last issue of the Western Dam Engineering Technical Note we discussed the guidelines and estimation of precipitation depths and intensity-duration-frequency (IDF) relationships. In addition, each rainfall event must also be characterized by:

- Spatial patterns – The physical path of the rainfall event over the watershed.
- Temporal distribution – The variation of rainfall with time (i.e. intensity) during the rainfall event.
- Aerial reductions – A reduction in rainfall depth as a result of distributing point rainfall depth, as estimated for frequency and Probable Maximum Precipitation (PMP) events, over the watershed. Further reductions may also apply for watersheds located at sufficiently high elevations.
- Rainfall weighting – The process of developing incremental rainfall depths, based on equivalent blocks of time (i.e. hyetograph), for the duration of the rainfall event and arranging them such that the peak rainfall depth occurs at a specific percentage of the event duration.

These rainfall event characteristics can significantly influence the rate and volume of runoff; however, are outside the scope of this article. The reader is encouraged to further investigate these aspects of rainfall characterization. The primary focus of this article is runoff, so we will begin with basin losses.

Basin Loss Parameters and Excess Rainfall

Excess rainfall, or runoff, is the portion of rainfall that is not "lost" during the rainfall event. Rainfall losses are not actually "lost," but are defined as such because they represent the portion of rainfall that does not contribute to runoff and to the subsequent watershed outflow hydrograph (i.e. reservoir inflow hydrograph). The "losses" are instead recycled back to the system through various means. A visual representation of this rainfall-runoff process is presented in Figure 1.

Rainfall losses are generally defined by:

- Interception - The portion of rainfall that wets and adheres to above ground vegetation and is eventually evaporated.
- Depression storage - The portion of rainfall that collects and is retained in surface depressions, which are either impermeable or characterized by infiltration rates less than that of the event rainfall intensity (i.e. excess rainfall is produced, but does not contribute to the total runoff). The retained rainfall is eventually either evaporated or infiltrated.
- Evaporation – The portion of rainfall that is directly evaporated based on atmospheric conditions during a given rainfall event.
- Infiltration – The portion of rainfall that moves downward through surface soils and eventually recharges aquifers and supports baseflow of the stream.

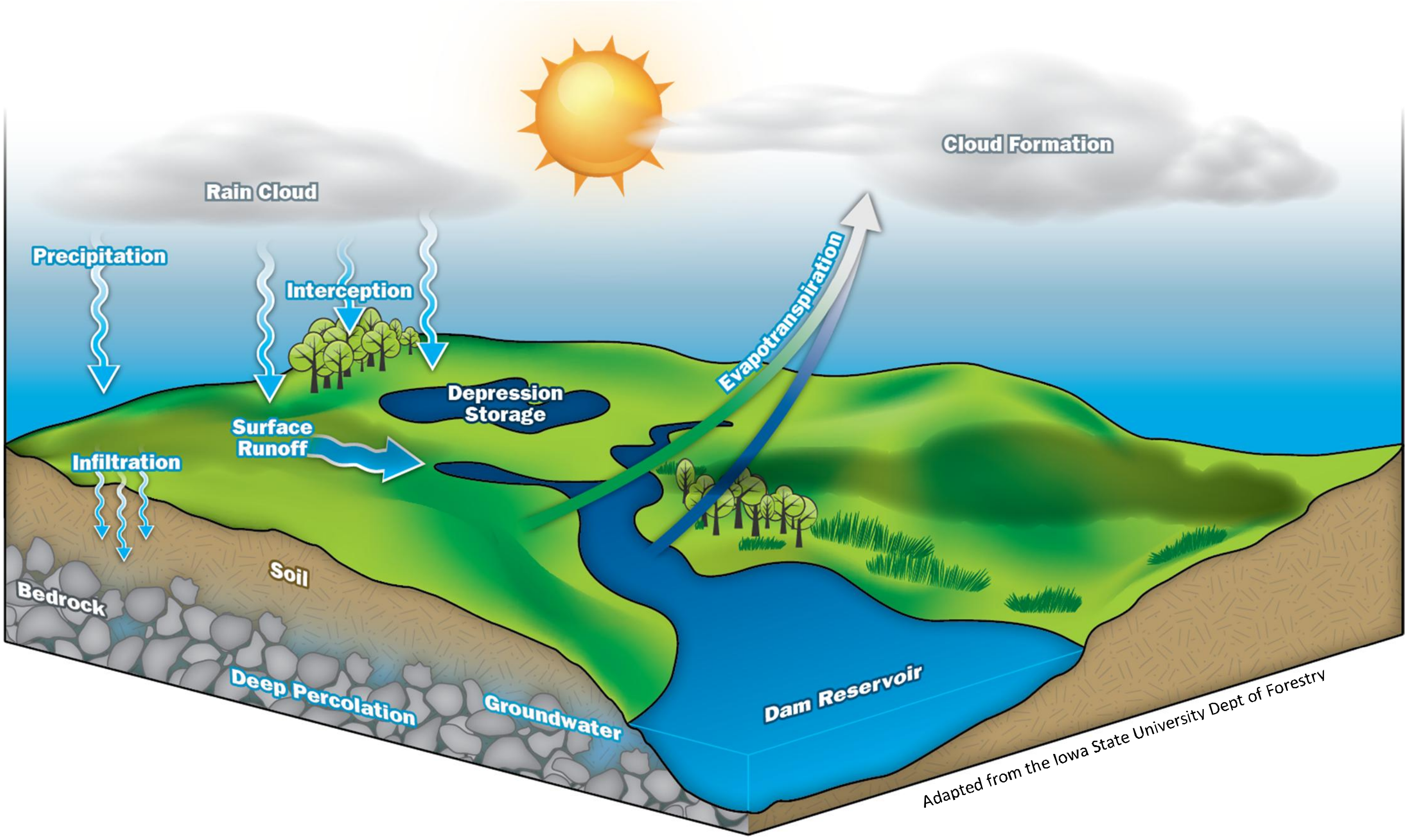

Figure 1: The rainfall-runoff process with losses.

The rate and volume of rainfall losses, and subsequently runoff, are influenced by a number of factors including:

- Rate of rainfall (i.e. intensity) as well as rainfall distribution and patterns
- Watershed pervious and impervious areas
- Soil infiltration rates
- Watershed properties like roughness, vegetative cover, soil properties and slope

Numerous rainfall loss estimation methodologies are available; however, with an interest in brevity and specific application to the western U.S., three of these methodologies will be presented in the following sections.

Green and Ampt Infiltration Loss Methodology

The Green and Ampt methodology is an approach based on the soil-water system where the inherent soil properties can be physically measured. It is particularly applicable for frequency event storms more frequent than and including the 100-year storm event, but can also be applied to less frequent storm events.

In general, the Green and Ampt methodology is based on the following factors:

- Surface Retention (Initial) Loss
  - Depression storage
  - Interception by vegetation
- Infiltration Loss
  - Hydraulic conductivity at natural saturation;
  - Wetting front capillary suction; and
  - Volumetric soil moisture deficit at the start of rainfall
- Imperviousness of the watershed

A simplified definition sketch of the Green and Ampt methodology is presented in Figure 2 and is representative of the aforementioned factors.

The Green and Ampt methodology is fairly comprehensive and accurate; however, as a consequence, the process of estimating the aforementioned parameters has been historically more cumbersome than other methodologies. However, modern GIS techniques can be applied to simplify the effort required to estimate pertinent parameters. See references [2] and [6] regarding application and use of the Green and Ampt methodology. Reference [6] also provides a spreadsheet solution to reduce the time required for parameter development.

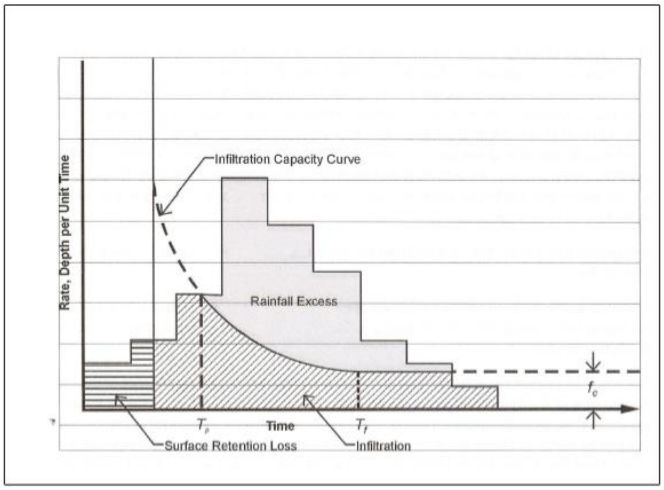

Figure 2: Green and Ampt methodology rainfall loss model (Source: DWR, 2008).

NRCS Curve Number Methodology

The curve number methodology represents a more simplified approach to estimating runoff as compared to the Green and Ampt methodology. The curve number methodology estimates the runoff using antecedent moisture conditions and empirical curves estimated from a series of field studies, which were conducted using numerous soil and vegetative cover combinations. As shown in Figure 3, high curve numbers indicate high potential for runoff with a maximum value of 100 representing a total conversion of rainfall to runoff. Conversely, progressively lower curve numbers represent more pervious soil conditions and subsequently lower potential for runoff.

The curve number is most easily applied to watersheds with relatively homogenous soil and vegetative cover properties; however, the methodology can also be applied to non-homogenous watersheds by estimating a composite curve number based on area weighted averages.

The curve number is among the most widely used methodologies due to its relative ease of application and extensive parameter database. See references [2], [4] and [5] for more information regarding the use and application of the curve number methodology, selection of curve numbers, and worked example problems.

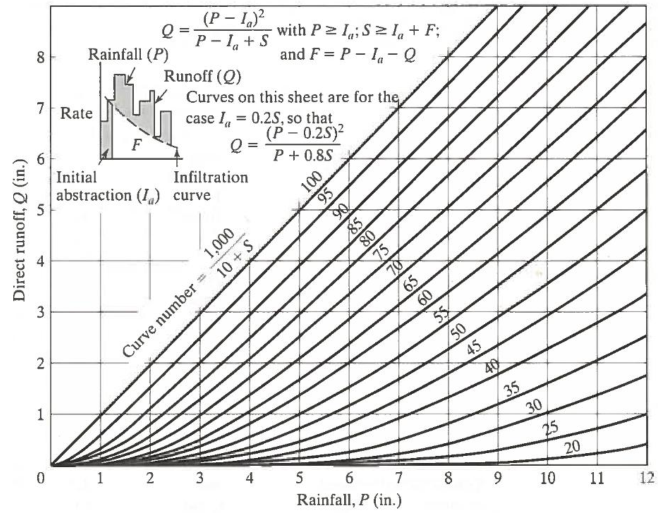

Figure 3: NRCS Curve Number methodology (Source: Viessman and Lewis, 2003).

Initial and Constant Loss Methodology

Another simplified methodology that is commonly used for estimating runoff is the initial and constant loss methodology. This methodology is similar to the Green and Ampt methodology and assumes that rainfall losses can be simulated as a two-step procedure where:

- Step 1: Rainfall is initially lost to a combination of infiltration and surface retention until the initial loss depth is exceeded.
- Step 2: Upon initial loss depth exceedance, a constant loss rate is applied to the rainfall that occurs during the remainder of the event duration.

Based on this methodology, if the rainfall intensity exceeds the constant loss rate, the rate difference is representative of runoff, as presented in Figure 4. Conversely, if the constant loss rate exceeds the rainfall intensity, no runoff is produced. Step 1 above is often set to zero when developing an inflow design flood hydrograph as a conservative approach.

The initial and constant loss methodology is particularly applicable to the modeling of very infrequent storm events characterized by significant precipitation. It can also be applied to more frequent storm events (no more frequent than the 100-yr storm event), particularly where watersheds are characterized by moderate to high infiltration rates.

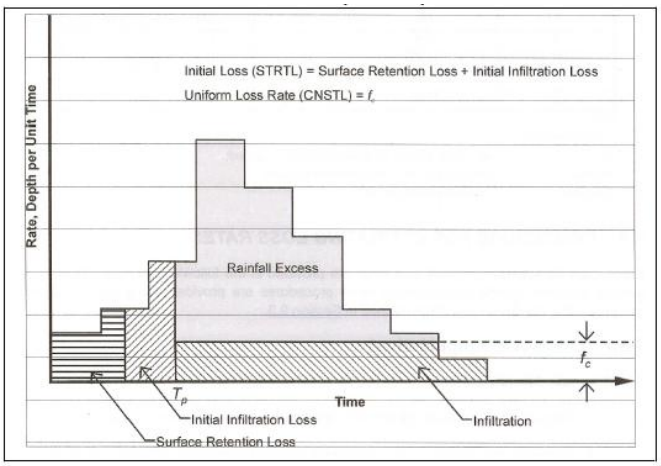

Figure 4: Initial and Constant Loss methodology rainfall loss model (Source: DWR, 2008).

Additional Watershed and Methodology Considerations

Watershed Characteristics

- Wild fires can significantly alter the pertinent watershed characteristics that affect runoff. For this reason, burned areas within study watersheds should be assessed with particular scrutiny.
- For some watershed studies, it could be prudent to consider not only present watershed characteristics, but also potential future watershed characteristics. Potential development and "urbanization" of watersheds can significantly increase runoff.

Green and Ampt Methodology

- Use of the Green and Ampt methodology is generally preferable for projects that warrant precision.
- Although perhaps more time consuming than other methodologies, it can be applied for any event frequency with a relatively high level of accuracy.

Curve Number Methodology

- Application of the curve number methodology is generally not recommended for soil and land cover combinations that yield curve numbers less than about 40.
- The curve number methodology is used successfully and extensively by the engineering community due to its ease of use and sufficient accuracy. Readers are cautioned, however, because the curve number has been shown to be less accurate than some physically-based infiltration methodologies due to its empirical nature. This aspect is presented not to discourage its use, but rather to highlight its applicability to a particular project. If a high level of accuracy is required for a particular project, use of the curve number methodology can be inadequate.
- It is recommended, particularly for projects where a high level of accuracy is required, to independently verify curve number methodology results with another runoff estimation methodology.

Transforming Excess Rainfall to Flow Hydrographs

Runoff rates are converted to flow hydrographs using a translation methodology. Numerous translation methodologies exist; however, the unit hydrograph methodology is used extensively and is generally the most preferred.

A unit hydrograph is defined as the time distribution of one inch of runoff from a storm event of a specified duration for a particular watershed, as presented in Figure 5. Unit hydrographs are reflective of the physiography, topography, land-use, and other unique characteristics of the individual watershed and assume that rainfall is uniformly distributed across the watershed. As such, different unit hydrographs are developed for the same watershed for different durations of rainfall excess.

Ideally, a unit hydrograph would be developed based on gage and calibrated watershed data; however, engineers are frequently confronted with project watersheds that lack sufficient data to develop a unit hydrograph. As such, synthetic unit hydrographs are developed based on available watershed data at other locations that have hydrologic characteristics similar to those of the project watershed.

Numerous synthetic unit hydrograph methodologies exist; however, for the purposes of application to the western U.S., the following methodologies are most pertinent:

- U.S. Department of the Interior, Bureau of Reclamation (Reclamation) synthetic unit hydrograph as presented in the *Flood Hydrology Manual* (Cudworth, 1989)
- Clark synthetic unit hydrograph
- U.S. Geological Survey (USGS) synthetic unit hydrograph specific to Montana as presented in

Procedures for Estimating Unit Hydrographs for Large Floods at Ungaged Sites in Montana (Holnbeck and Parrett, 1996)

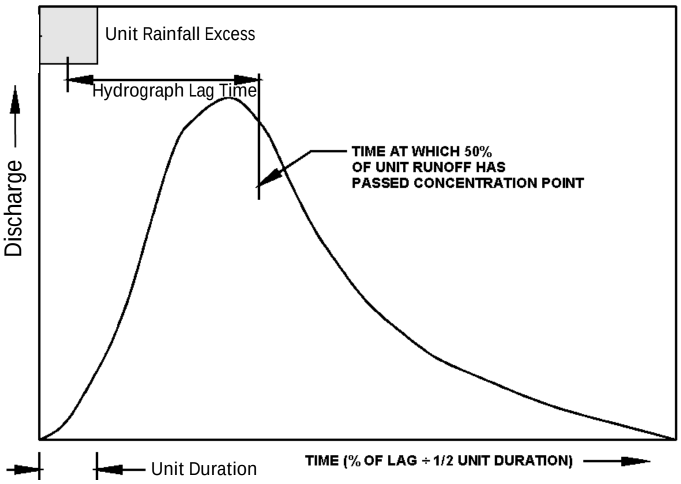

Figure 5: Unit hydrograph methodology (Source: Cudworth, 1989).

The development of a unit hydrograph, regardless of the methodology, is largely based on the watershed lag time, which is a measure of the watershed response time with regard to the translation of excess rainfall to a hydrograph. Estimation of the lag time varies according to methodology, but is generally a function of physical watershed characteristics. Different methodologies define and use parameters such as lag time and "time of concentration" differently and the reader should reference the specific use in each of the methodologies described below.

When developing a synthetic hydrograph, regardless of method, the unit duration used to develop the hydrograph should be appropriately small so as not to miss or underestimate the peak by averaging it over too large of a calculation interval. Different methodologies provide guidance for unit duration.

Reclamation Synthetic Unit Hydrograph

The lag time, as defined by Reclamation, is based on physical watershed measurements (i.e. watercourse length, slope, etc.) and the watershed average Manning's roughness value for the principal watercourses, "K_n". While the physical measurements can be easily estimated using topographic data, the watershed average Kn value is more subjective and difficult to estimate. Reclamation provides guidance on adopting the watershed average Kn values using a series of plots based on watersheds with appropriate gaged and watershed calibration data, which are sub-divided into the following hydrologic groups:

- Rocky Mountain
- Great Plains
- Colorado Plateau
- Agricultural Fields
- Urban

With an emphasis on dam safety, a conservative approach is recommended with regard to Kn value selection. As such, Kn values are often selected from the lower half of the proposed range of Kn values for a particular hydrologic group. Kn value selection from the upper half of a range is not recommended without appropriate justification.

Upon selection of a Kn value, the lag time can be estimated and applied to a set of time and flow ordinates, for the appropriate hydrologic group, to estimate the synthetic unit hydrograph.

See reference [1] and [6] for more detailed discussions regarding the use and application of the Reclamation synthetic unit hydrograph methodology, including guidance on Kn selection.

Clark Synthetic Unit Hydrograph

The Clark synthetic unit hydrograph approach is similar to that of the Reclamation methodology; however, the Clark approach uses a synthetic runoff time-area relation, which is similar to the time and flow ordinates of the Reclamation synthetic unit hydrograph, but is based on ratios of contributing area to total area. The Clark approach also considers the effect of runoff storage on the unit hydrograph shape using a storage coefficient. See reference [6] for more information.

USGS Synthetic Unit Hydrograph (for Montana)

The USGS also developed a synthetic unit hydrograph specifically for application within Montana. The USGS unit hydrograph for Montana was developed by compiling the predicted unit hydrograph results using the Reclamation and Clark methodologies for 26 watersheds throughout Montana. These results were further analyzed and averaged to produce a unit hydrograph that is representative of the watershed conditions specific to Montana.

For more information regarding the use and application of the USGS synthetic unit hydrograph within Montana and also worked examples, see reference [3]and [4].

Baseflow Separation

Although not usually critical for infrequent and very infrequent rainfall events, the natural stream baseflow can influence the total watershed outflow hydrograph (i.e. reservoir inflow hydrograph). The unit hydrograph methodology does not account for baseflow; therefore, in some instances the baseflow could have an appreciable effect on inflow design flood hydrographs and subsequent spillway adequacy.

Summary

Inflow design flood hydrographs are a key component of dam safety and are estimated based on the translation of excess rainfall, or runoff, to a watershed outflow hydrograph (i.e. reservoir inflow hydrograph). Runoff is representative of the portion of rainfall that is not lost during a rainfall event. Rainfall losses are comprised of several factors and can be estimated using numerous methodologies.

Once the total volume of runoff is known, it can be transformed into a hydrograph which models the variation of runoff discharge from the flood over time. There are also several methodologies used to transform runoff to a flow hydrograph, however, the most widely used and preferred methodology is that of the unit hydrograph. Reclamation and Clark synthetic unit hydrographs are the most common approaches where gaged and watershed calibration data are not available; however, the USGS approach is also used throughout Montana.

The purpose of the information presented herein is to inform the reader of general procedures and methodologies applicable to the western U.S. and provide them with references to attain more in-depth procedure guidance and examples. The information presented is not comprehensive and readers are encouraged to further investigate the requirements, shortcomings, and procedures specific to each methodology. Readers should also be familiar with particular methodology preferences specific to the guidelines and requirements for the state or other regulating agency with jurisdiction of the dam.

Several state agencies prefer some methodologies over others, but most do not have specific requirements with regard to methodology selection. In general, any one of the numerous methodologies presented could be applied to aid in the estimation of inflow design floods provided that the engineer uses appropriate judgment and justification in methodology selection.

References (links provided where applicable)

[1] Cudworth, A, 1989. *Flood Hydrology Manual.* U.S. Bureau of Reclamation, Water Resources Publication, 1989.

[2] Feldman, A., 2000. *Hydrologic Modeling System HEC-HMS - Technical Reference Manual.* U.S. Army Corps of Engineers, Hydrologic Engineering Center, March, 2000.

[3] Holnbeck, S.R. and Parrett, C., 1996. *Procedures for estimating unit hydrographs for large floods at ungaged sites in Montana.* U.S. Geological Survey (USGS), Water Supply Paper 2420, 1996.

[4] Montana Department of Natural Resources and Conservation (DNRC), 2008. *Analysis of Spillway Capacity in Montana.* Dam Safety Program, Technical Note 1. Prepared by Hydrometrics, Inc. on behalf of the DNRC, October, 2008.

[5] Moody, H., 2004. *National Engineering Handbook, Part 630 – Hydrology, Chapter 9: Hydrologic Soil-Cover Complexes.* U.S. Department of Agriculture, Natural Resources Conservation Service, July, 2004.

[6] State of Colorado, Division of Water Resources, Office of the State Engineer (DWR), 2008. *Hydrologic Basin Response Parameter Estimation Guidelines.* Prepared by Tierra Grande International, Inc. on behalf of the DWR, May, 2008.

[7] Viessman, W. and Lewis, G., 2003. *Introduction to Hydrology.* 5th Ed., Pearson Education, Inc., 2003.