HYDROLOGY TECHNICAL MEMO

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TEAM

Lead - Will Thomas	**wthomas@mbakercorp.com**	**703-334-4935**
Gary Guhl	gary.guhl@starr-team.com	301-2110-6800 x211
Art Miller	art.miller@aecom.com	
Michael Parrish	mparrish@g-and-o.com	
Mathini Sreetharan	msreetharan@dewberry.com	
Zhida Song-James	zsong-james@mbakercorp.com	
Matt Shultz	mshultz@dewberry.com	
Steve Eberbach	seberbach@mbakercorp.com	

MEMO

Recommended approaches will be: **cost effective, credible and easily understood, simple (can be performed by any qualified engineer), and repeatable.**

The new modeling approach for evaluating levees will require flood hydrographs for many situations in lieu of just peak discharges. A cost-effective approach is needed to estimate flood hydrographs for studies where only peak discharges are currently available or where funding is not sufficient to develop a rainfall-runoff model. The appropriate method for a given study will be a function of the data and models available. For riverine analyses, key factors are whether the watershed is gaged or ungaged and/or unregulated or regulated by flood control reservoirs. For coastal analyses, different approaches are applicable for tropical and extratropical storms.

A. Riverine Analyses - Methods for Developing Flood Hydrographs

1. Hydrographs for Gaged Watersheds

- Modify a major historic flood hydrograph by multiplying the ordinates by a factor to create the x-percent chance flood hydrograph - approach used by USACE for Upper Mississippi River (USACE, 2010)
    - Unit data available since the mid 1980s in the USGS Instantaneous Data Archive (IDA) at http://ida.water.usgs.gov/ida/. Flood hydrographs for major floods prior to the mid 1980s have been published in numerous flood reports by USGS and others.

- See example of using a historic flood in Figures 1 and 2. Several historic flood hydrographs should be evaluated to determine the typical hydrograph shape.
- Historic flood hydrographs can be transferred upstream or downstream on the gaged stream by multiplying the discharge ordinates by the drainage area ratio to a power less than 1.0 and the adjusting the time base of the hydrograph for the change in basin lag time (recommend plus or minus 50 percent of drainage area of gaging station)

- Develop a balanced synthetic flood hydrograph using peak discharge and n-day volumes
  - Daily data and peak discharges are available in the USGS National Water Information System at http://water.usgs.gov/nwis.sw
  - Process is to fit a single hydrograph to a peak discharge and volume data for different durations (1-, 3-, 7-, 15-days, etc.). Refer to the schematic in Figure 3 for example of developing a balanced hydrograph. Approach referenced in Bureau of Reclamation, *Flood Hydrology Manual* (Cudworth, 1989) and USACE EM 1110-2-1415, *Hydrologic Frequency Analysis* (USACE, 1993).
  - This approach may be appropriate if there are no major historic flood hydrographs available
  - If a historic flood(s) is available, evaluate and verify the shape of the balanced synthetic hydrograph

- Procedures for regulated gaged watersheds
  - Assumed that many studies for regulated watersheds will have a rainfall-runoff model for hydrograph estimation, if not the following approaches may be applicable
  - Utilize historic flood hydrographs where the gaging station is downstream of the reservoir(s) (note Roanoke River in Figure 1 is a regulated watershed)
  - Utilize an outflow flood hydrograph provided in the Reservoir Operation Manual
  - Route historic or synthetic flood hydrographs through the reservoir to obtain regulated outflow hydrograph (assume inflow frequency equals outflow frequency). Guidance on regulated flood frequency analysis is provided in USACE EM 1110-2-1415, *Hydrologic Frequency Analysis* (USACE, 1993).

- Discuss limitations and strengths of the various methods

2. Hydrographs for Ungaged Watersheds

- Utilize the USGS dimensionless hydrograph developed by Inman (1987) and implemented in the USGS National Streamflow Statistics (NSS) Program (Ries, 2007)
  - Requires a peak discharge and an estimate of basin lag time defined as the time from center of mass of rainfall excess to center of mass of the runoff hydrograph
  - Peak discharge can be estimated from USGS regional regression reports available at http://water.usgs.gov/osw/programs/nss/pubs.html
  - Basin lag time can be estimated by:

        - Equations summarized in Appendix B of Ries (2007)
        - Other published reports or equations available for the area of interest
        - Many county flood control districts have equations for estimation of basin lag time
    - Dimensionless hydrograph ordinates are ratio of discharge to peak discharge and ratio of time to basin lag time (see Figure 4). Multiply discharge ratio by 1-percent chance discharge and time ratio by basin lag time to get 1-percent chance flood hydrograph.
    - USGS dimensionless flood hydrograph is similar to the NRCS unit hydrograph (see Figure 4)
        - Lag time used by USGS is time from center of mass of rainfall excess to center of mass of runoff (comparable to time of concentration)
        - Lag time used by NRCS is time from center of mass of rainfall excess to peak of runoff hydrograph.
    - See Figure 5 for an example flood hydrograph estimated from the USGS NSS program
    - USGS dimensionless hydrograph applicable to unregulated watersheds with drainage areas less than 500 square miles (Inman, 1987)

- Utilize NRCS dimensionless hydrographs or state/regional dimensionless hydrographs
    - Utilize NRCS dimensionless unit hydrographs (DUHs) as documented in Part 630 Hydrology, National Engineering Handbook, *Chapter 16 Hydrographs*. DUHs are provided for peak rate factors ranging from 100 to 600.
        - Peak rate factor could be estimated by applying the DUH at nearby gaging stations similar to the ungaged stream
        - NRCS peak rate factors (other than 484) have been determined for Delmarva Peninsula (Welle and Woodward, 1989) and in Florida (Florida Water Management Districts)
    - Utilize state specific USGS dimensionless hydrographs that may be more appropriate than NSS dimensionless hydrograph. For example:
        - Dillow (1998) developed dimensionless hydrographs for three hydrologic regions in Maryland
        - Gamble (1989) developed dimensionless hydrographs for two regions in Tennessee including flat-sloped watersheds in West Tennessee.
    - Dimensionless hydrographs can be implemented in Excel to produce flood hydrographs. See example flood hydrograph in Figure 6 for Patuxent River in Maryland.

- Utilize an existing rainfall-runoff model or develop one specifically for this study
    - Utilize rainfall-runoff model developed for the flood insurance study (FIS).
        - Models should be calibrated to gaging station data
        - Synthetic unit hydrographs normally used but could be based on derived unit hydrographs for that watershed for unusual watershed conditions
    - Utilize a rainfall-runoff model developed for other purposes (such as master drainage plan) and utilize the 1- and 0.2-percent chance peak discharges from the FIS

- Develop a simplified rainfall-runoff model for a single watershed with no subdivision or channel /reservoir routing or calibration
    - Applicable for unregulated watersheds less than about 100 square miles if watershed is reasonably homogeneous
    - NRCS procedures for the development of the temporal storm distribution, runoff curve number, unit hydrograph and lag time can be implemented in a cost-effective manner
    - Bureau of Reclamation (Cudworth, 1989) provides guidance for estimating parameters for the Snyder unit hydrograph in the western US
    - Many county flood control districts also have procedures for estimating the parameters of the rainfall-runoff model

- Procedures for regulated ungaged watersheds
  - Use a rainfall-runoff model that incorporates reservoir routing
  - Utilize an outflow flood hydrograph provided in the Reservoir Operation Manual

- Discuss the limitations and strengths of the various methods

3. Estimating Peak Discharges

- Peak discharge only may be sufficient for levees that do not meet CFR 65.10 and do not significantly impede landward conveyance (Scenario A), for levees that meet 65.10 (Scenario E) or levees that meet 0.2-percent chance flood protection (Scenario F)
- Procedures for estimating peak discharges described in Appendix C: *Guidance for Riverine Flooding Analyses and Mapping*, FEMA's Guidelines and Specifications. Procedures from Appendix C will be summarized for:
  - Gaged streams
  - Ungaged streams
    - Ungaged locations on gaged streams
    - Regression equations
    - Rainfall-runoff models

B. Coastal Analyses – Methods for Developing Flood Hydrographs

1. Tropical storms

    - Utilize approach documented in HEC-25, *Tidal Hydrology, Hydraulics, and Scour at Bridges*, developed by the Federal Highway Administration (FHWA, 2004) and referenced in FEMA's 2008 Technical Memorandum on Sheltered Waters – parameters needed:
      - Half storm duration (hr)
      - Radius to maximum wind speed (mi, km)
      - Forward speed of storm (knots, kph)

    - Peak surge elevation for selected **return period** (ft, m). The return period (percent chance exceedance) of the peak elevation determined from frequency analysis.
    - Time of peak surge or landfall (hr)
    - See Figure 7 for an example of applying HEC-25 methodology for estimating a 100-year (1-percent chance) storm surge hydrograph for the Chesapeake Bay at the mouth of the Patuxent River in Maryland
- Utilize Florida Department of Transportation (FDOT) storm surge hydrographs for the 100- and 500-year storms or storm surge hydrographs developed by other State DOTs
- Utilize data from an existing storm surge model to estimate a storm hydrograph that is indicative of the 1- or 0.2-percent chance storm hydrograph. Possible approaches include:
    - Use the median rank duration corresponding to the -1percent surge elevation
    - Use the median rank peak surge elevation corresponding to the 1-percent duration
    - Use several peaks and durations with their corresponding probabilities, determine associated floodplains, and map the median rank floodplain
    - Consider all combinations of peak surge and duration, compute the corresponding floodplain, apply probabilities of those combinations together with the breaching scenarios and map the median rank floodplain (a similar approach is required for Pacific Coast mapping)

2. Extratropical storms

    - Utilize a historic storm event that approximates a 1-percent chance hydrograph (utilize data available from NOAA at http://tidesandcurrents.noaa.gov)
    - Utilize a synthetic 1-percent chance hydrograph developed in previous studies

C. Combined Riverine-Coastal Analyses

1. Develop flood hydrographs for both riverine and coastal analyses
2. Evaluate the combined effects of the two flood hydrographs

D. Methods for Applying and Using the Flood Hydrographs

1. Flood hydrographs are indicative of the 1- or 0.2-percent chance inflow hydrograph to the riverine or coastal reach with a levee(s)
2. Breach discharges reaching landward or protected side of levee(s) will be determined by the unsteady hydraulic model using the inflow hydrograph (discharge capacity) and the geometry of the breach or overtopping reach
    - Discharge capacity is the volume of water reaching the leveed reach
    - Breach discharge is a function of the discharge capacity (volume and duration of flow), the breach formation time, breach development time and size of the breach – see Figure 8 for a schematic of this process (SERRI Report 70015-001)
3. Difference between the inflow flood hydrograph and the breach or overtopping flood hydrograph will determine the flood hydrograph downstream of the breach or breaches

4. For long levees with significant change in drainage area:
    - Flood hydrographs will be estimated at more than one location if flow can enter main channel
    - Flood hydrographs will be attenuated in unsteady HEC-RAS model if flow cannot enter main channel

E. Pilot Tests - Examples of Estimating Flood Hydrographs

The pilot tests will be selected from different existing flood insurance studies for which flood hydrographs need to be estimated.

- If flood hydrographs exist, we will assume they do not and estimate the flood hydrograph will alternative procedures described above
- If only peak discharges are available, the flood hydrographs will be estimated using the most appropriate alternative procedure

F. Summary of Findings and Recommendations from the Pilot Tests

Discuss the results from the pilot tests and application of the alternative methods. Discuss why alternative methods worked or did not work. There will be 3-5 pilot tests for riverine and coastal studies.

References

Bisese, J.A., 1994, *Methods for Estimating the Magnitude and Frequency of Peak Discharges of Rural, Unregulated Streams in Virginia*: U.S. Geological Survey Water-Resources Investigations Report 94-4148, 70 p.

Bullard, K.L., 1986, *Comparison of Estimated Probable Maximum Flood Peaks with Historic Floods*: a report of the Engineering and Research Center of the Bureau of Reclamation, U.S. Department of the Interior, 165 p.

Cudworth, A.G., Jr., 1989, *Flood Hydrology Manual*: A Water Resources Technical Publication, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado, 243 p.

Dillow, J.J.A., 1998, *Techniques for Simulating Peak-Flow Hydrographs in Maryland*: U.S. Geological Survey Water-Resources Investigations Report 97-4279, 39 p.

Federal Emergency Management Agency, 2008, *Guidance for Coastal Flood Hazard Analyses and Mapping in Sheltered Waters*: Technical Memorandum, February 2008, 18 p.

Federal Highway Administration, 2004, *Tidal Hydrology, Hydraulics and Scour at Bridges*: Hydraulic Engineering Circular No, 25, Washington, DC.

Gamble, C.R., 1989, *Techniques for Simulating Flood Hydrographs and Estimating Flood Volumes for Ungaged Basins in East and West Tennessee*: U.S. Geological Survey Water-Resources Investigations Report 89-4076, 40 p.

Inman, E.J., 1987, *Simulation of Flood Hydrographs for Georgia Streams*: U.S. Geological Survey Water-Supply Paper 2317, 26 p.

Ries, K.G. III, 2007, *The National Streamflow Statistics Program: A Computer Program for Estimating Streamflow Statistics for Ungaged Sites*: U.S. Geological Survey Techniques and Methods 4-A6, 37 p.

Southeast Region Research Initiative, 2009, *Levee Breach Geometries and Algorithms to Simulate Breach Closure*: SERRI Report 70014-001, prepared by Mississippi State University and Oak Ridge National Laboratory for the U.S. Department of Homeland Security, 154 p.

Thomas, W.O., Jr., Monde, M.C., and Davis, S.R., 2000, *Estimation of Time of Concentration for Maryland Streams*: Transportation Research Record 1720, Transportation Research Board, National Research Council, National Academy Press, Washington, DC, pp. 95-99.

U.S. Army Corps of Engineers, 1993, *Hydrologic Frequency Analysis*: Engineering and Design EM 1110-2-1415, Washington, DC.

U.S. Army Corps of Engineers, 2010, *Saint Paul Flood Control Project, Levee Safety Risk Assessment Program, Issue Evaluation Report*: Saint Paul District (MVP), Saint paul , Minnesota, 20 p.

U.S. Department of Agriculture, 2007, *Chapter 16 Hydrographs*: Part 630 Hydrology, National Engineering Handbook, National Resources Conservation Service, Washington, DC, 39 p.

Welle, P.I. and Woodward, D.E., 1989, *Dimensionless Unit Hydrograph for the Delmarva Peninsula*: Transportation Research Record 1224, National Research Council, Transportation Research Board, Washington, DC, pp. 79-87.

ASSUMPTIONS / DEPENDENCIES

Assumptions and Dependencies

- Cost-effective methods are needed for estimating flood hydrographs for current studies with only peak discharges and future studies for which funding is not available to develop a rainfall-runoff model.
- Flood hydrographs for the 1- and 0.2-percent chance floods will be estimated as inflow to the riverine or coastal reach with levees. This is referred to as the discharge capacity in the SERRI Report 70015-001 and is a function of the volume and duration of the hydrograph. The duration of the inflow hydrograph will be critical in estimating the overtopping discharge.
- The hydraulics of the breach or overtopping sections will determine the flood hydrograph reaching the landward or protected side of the levee(s). Figure 8 illustrates the dependency of the breach discharge on the timing and development of the breach.

It is further assumed that procedures employed by Federal agencies, like the U.S. Army Corps of Engineers (USACE) and Federal Energy Regulatory Commission (FERC), for estimating flood hydrographs **for ungaged watersheds** involve the use of unit hydrograph procedures implemented in a rainfall-runoff model. This assumption is based on a **limited review** of the following documents. It is also assumed that estimation of flood hydrographs for ungaged watersheds from snowmelt will be based on some type of rainfall-runoff model.

USACE EM 1110-2-1420 (October 31, 1997), *Hydrologic Engineering Requirements for Reservoirs*: Chapter 7 on Flood Runoff Analysis indicates that "The standard Corps procedure for computing flood hydrographs from catchments is the unit hydrograph method". Recommends use of HEC-1 for estimating flood hydrographs. This EM also recommended that unit hydrographs and loss rate characteristics should be derived from observed storms and flood events.

USACE EM 1110-2-1417 (August 31, 1994), *Flood-Runoff Analysis*: Chapter 7 on Precipitation Excess-Runoff Transformation discusses two approaches for estimating flood runoff: Unit Hydrograph Approach (single-linear reservoir, Nash, Clark, Snyder and SCS) and the Kinematic Wave Approach. Both of these approaches are implemented through a rainfall-runoff model.

USACE EM 1110-2-1406 (March 31 1998), *Runoff from Snowmelt*: Chapter 10-2 on Hypothetical Floods summarizes way of estimating snowmelt hydrographs. The simple approach is to assume a fixed rate of melt that could be added to rainfall or to assume a variable rate of melt that could be estimated independently on the basis of a temperature-index approach. The second approach is to develop a 100-year event type model that uses 24-hours precipitation, maximum hourly precipitation, loss rate, initial snow depth, initial density, computed initial surface water equivalent and maximum air temperature. The third method was the detailed analysis and involved using energy budget equations.

Federal Energy Regulatory Commission, Chapter VIII, *Determination of the Probable Maximum Flood*: This document describes ways of developing unit hydrographs based on observed rainfall and runoff data, how to estimate loss rates, the PMP and implement the NRCS, Snyder or Clark synthetic unit hydrograph. These processes are to be implemented in HEC-1 or HEC-HMS.

MILESTONES

Milestone/Task	Dates	
	Start	End
Research complete and outline prepared	3/21/2011	4/8/2011
Feedback from FEMA	4/11/2011	4/22/2011
Draft memo	4/25/2011	4/29/2011
Final memo	5/2/2011	5/13/2011
Pilot Testing	4/25/2011	5/13/2011

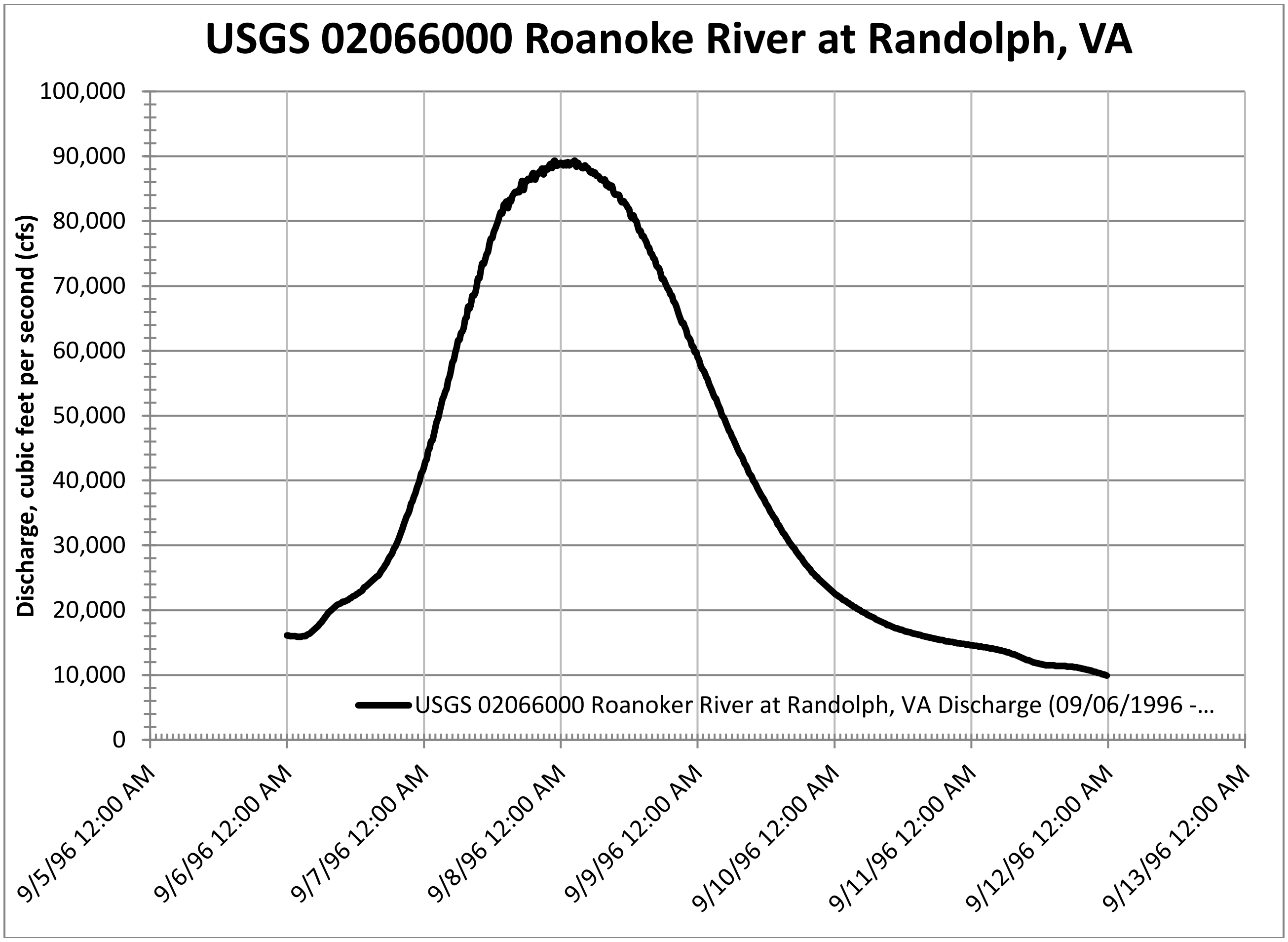

Figure 1. Observed flood hydrograph for the Roanoke River at Randolph, VA (02066000), drainage area of 2,966 square miles, for the September 1996 flood (data from http://ida.water.usgs.gov/ida/.) The peak discharge of the September 1996 flood was 89,300 cfs. The Roanoke River is regulated by upstream reservoirs but there is significant unregulated drainage area upstream of the gaging station at Randolph, VA.

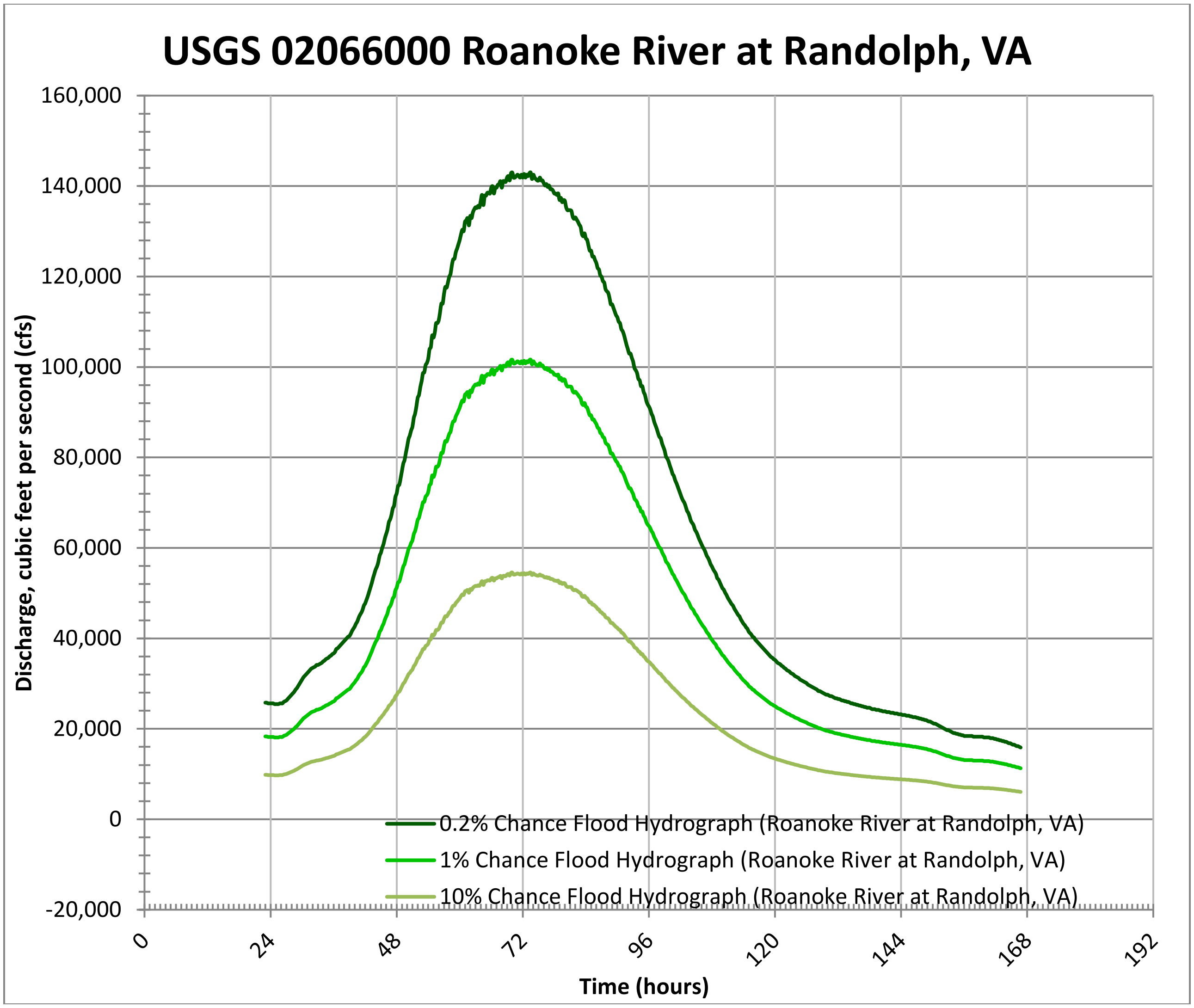

Figure 2. Estimated 0.2-, 1- and 10-percent chance flood hydrographs for the Roanoke River at Randolph, VA. The ordinates of the September 1996 hydrograph were multiplied by a factor to give the appropriate peak discharge for the x-percent chance flood hydrograph. Note that the peak discharge of the 1-percent chance peak discharge is 102,000 cfs so the September 1996 flood hydrograph ordinates were multiplied by 1.142 (102,000/89,300) to give the 1-percent chance flood hydrograph.

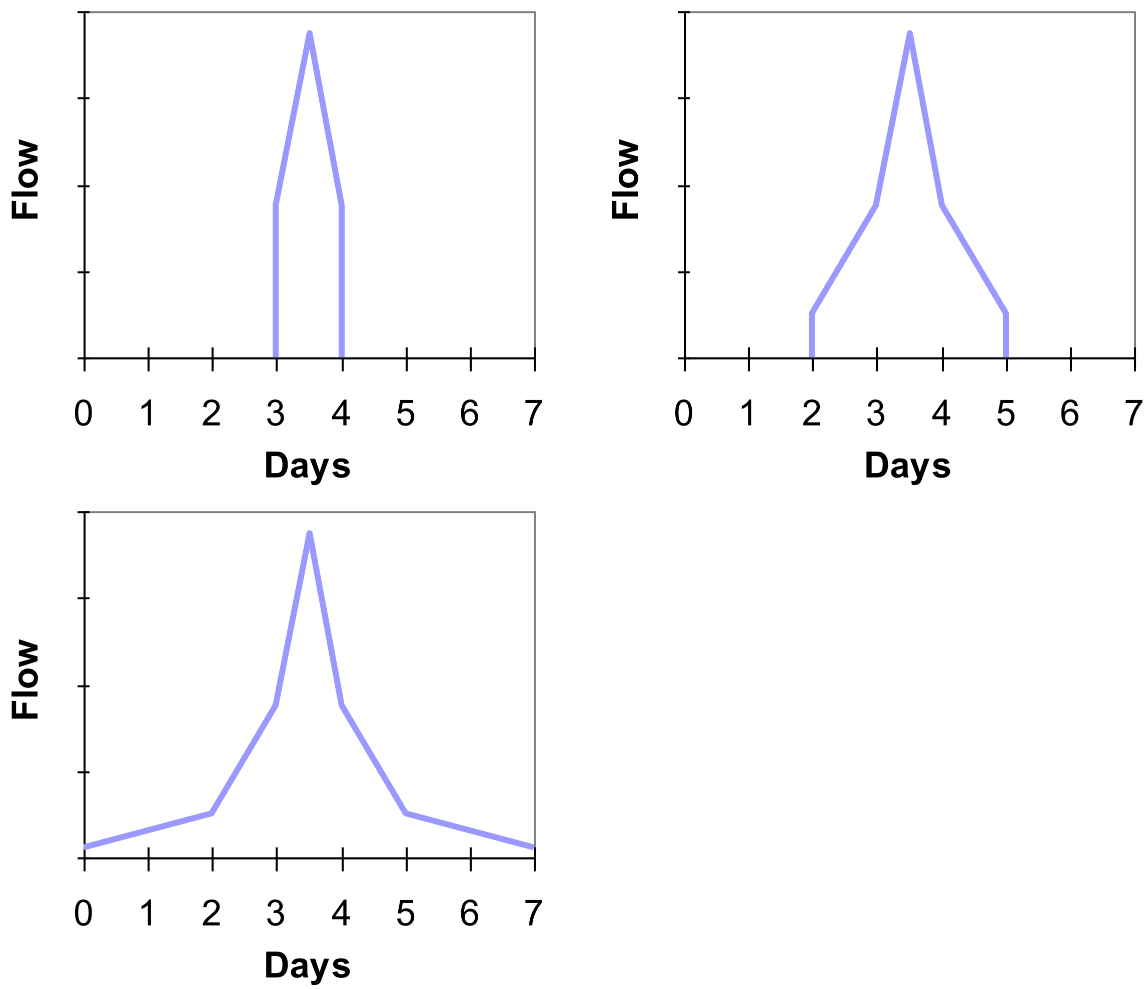

Figure 3. Schematic of estimating a balanced synthetic flood hydrograph: upper left figure uses peak discharge and 1-day volume to shape hydrograph, upper right figure uses the 3-day volume to shape hydrograph, and lower left figure uses the 7-day volume to shape the flood hydrograph. (Approach used in the Lewis County, WA flood insurance study.)

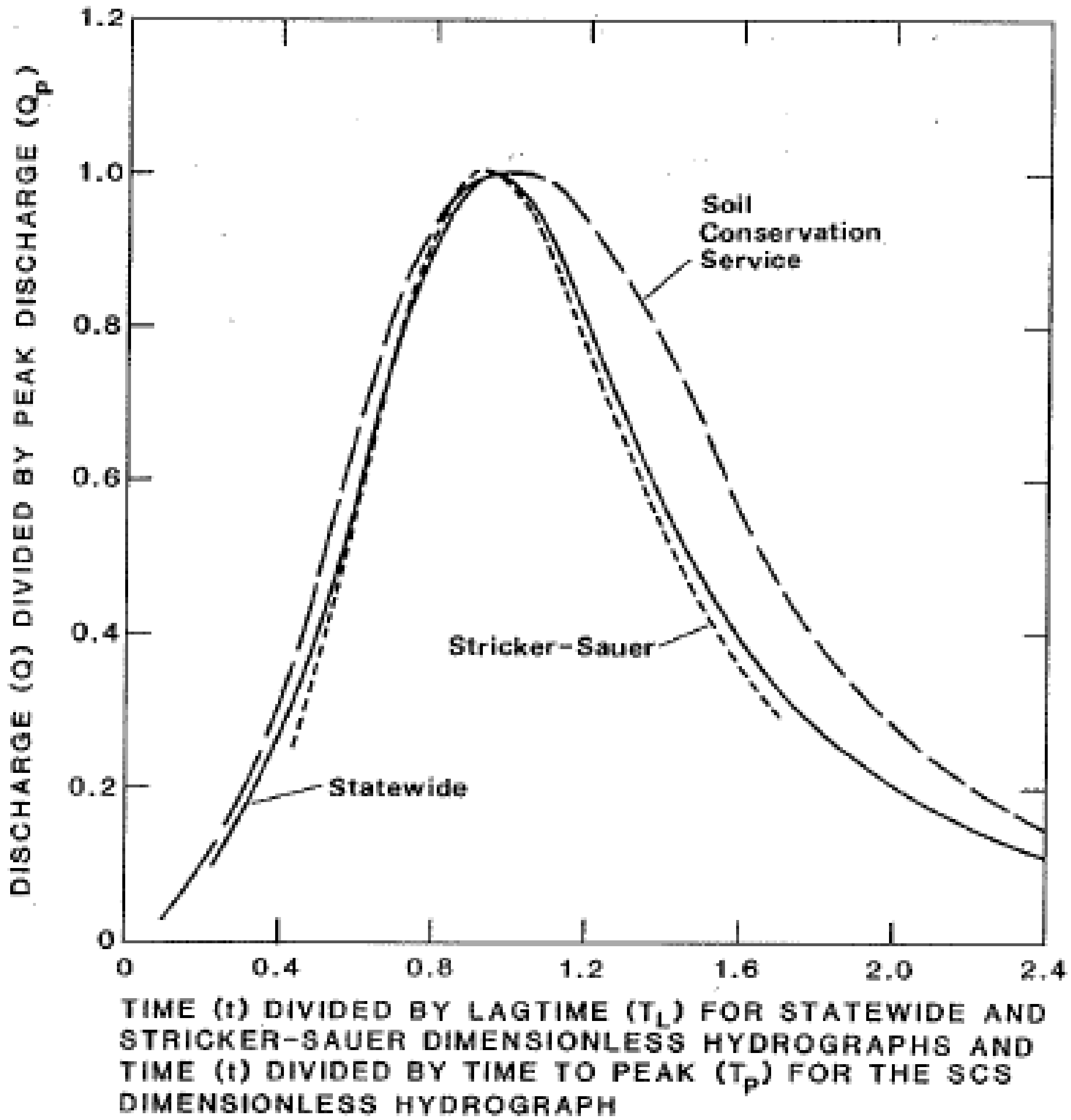

Figure 4. Comparison of the Georgia statewide dimensionless hydrograph (used in the USGS NSS program) to the Natural Resources Conservation Service (formerly Soil Conservation Service) unit hydrograph and a Clark unit hydrograph developed by Stricker-Sauer (USGS Open-File Report 82-365). Note that the Georgia statewide hydrograph is plotted versus time divided by lag time and the NRCS hydrograph is plotted versus time to peak to consistent with the hydrograph development.

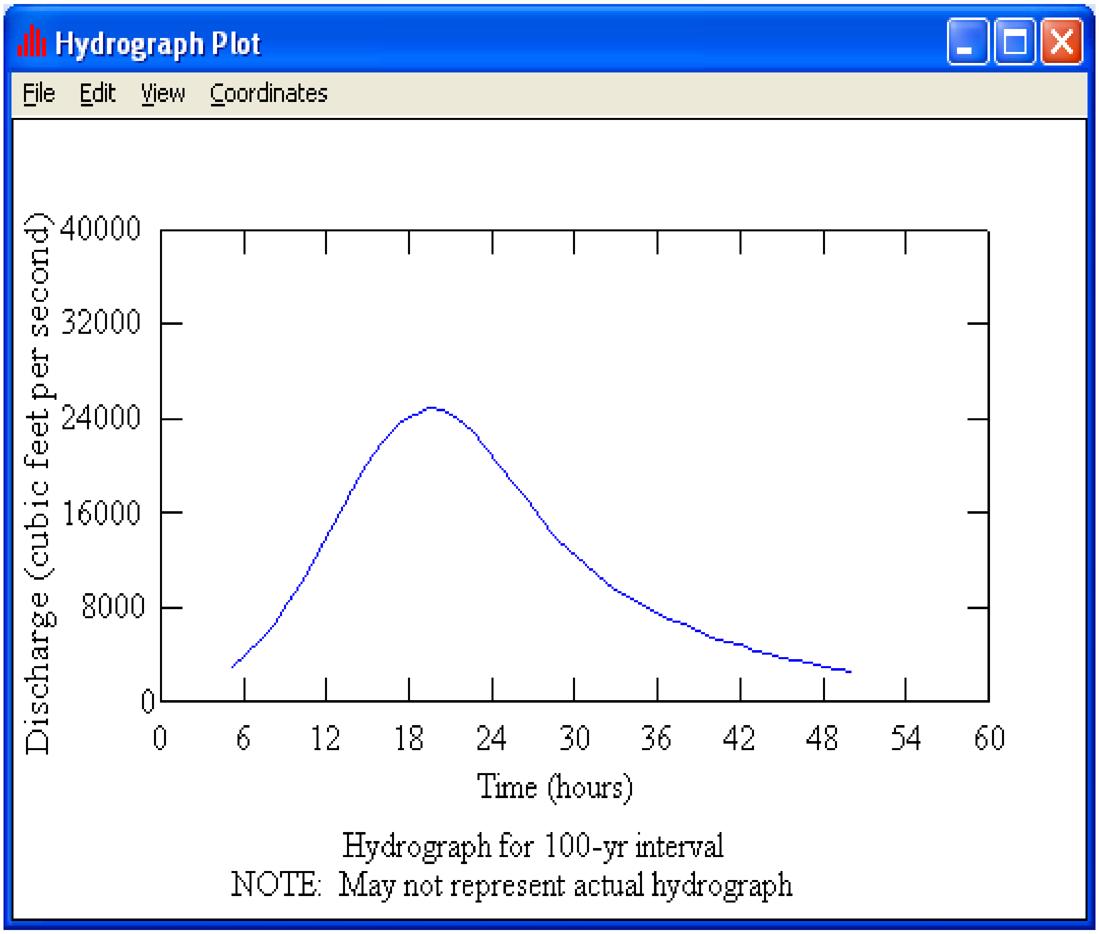

Figure 5. Example of a 1-percent chance flood hydrograph from the USGS NSS Program for the Banister River in the Southern Piedmont Region of Virginia. The peak discharge was estimated from regression equations in Bisese (1994) and the basin lag time was estimated from basin lag times available for similar watersheds in the Piedmont Region of Maryland.

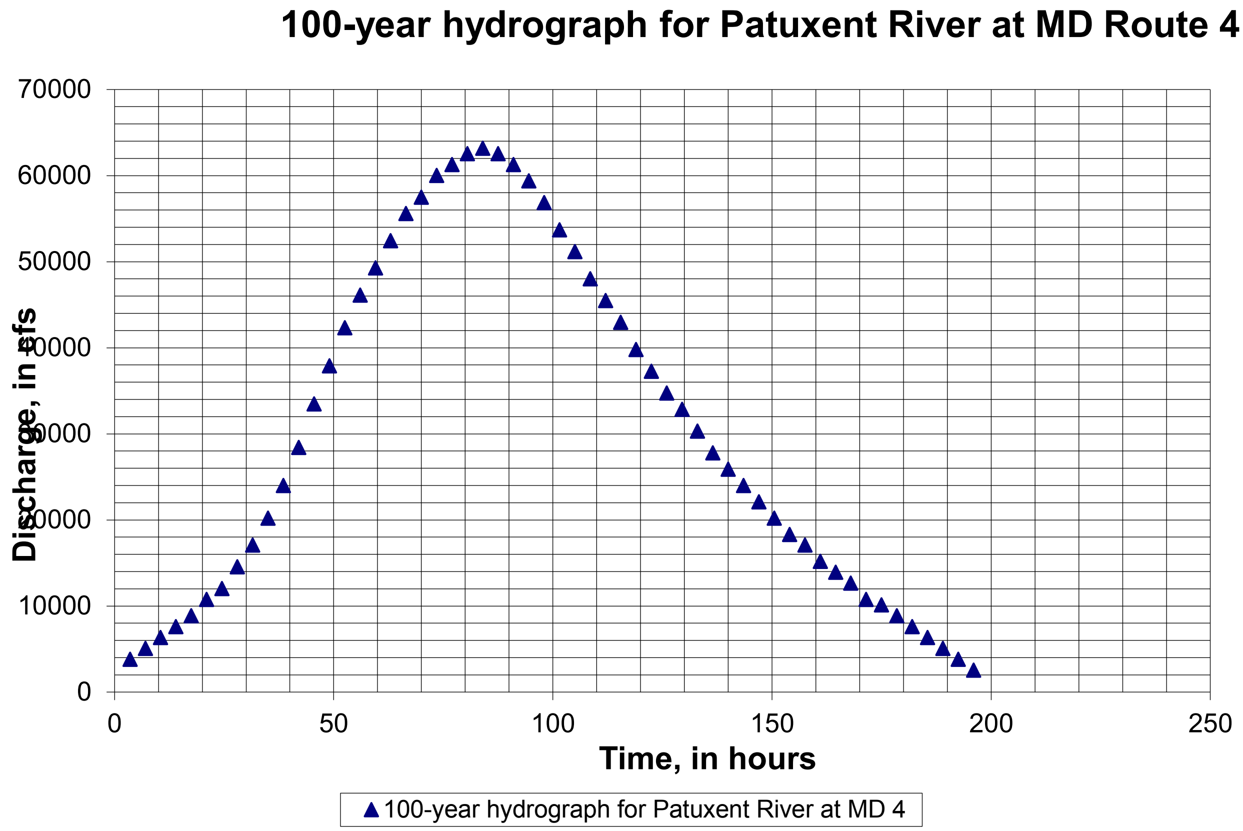

Figure 6. Example of developing a flood hydrograph for the Patuxent River in Maryland at MD Route 4 near the mouth. The flood hydrograph was developed using a dimensionless hydrograph in Dillow (1998) and multiplying the discharge ordinate by the 100-year or 1-percent chance peak discharge and the time ordinate by basin lag time estimated from equations developed by Thomas and others (2000).

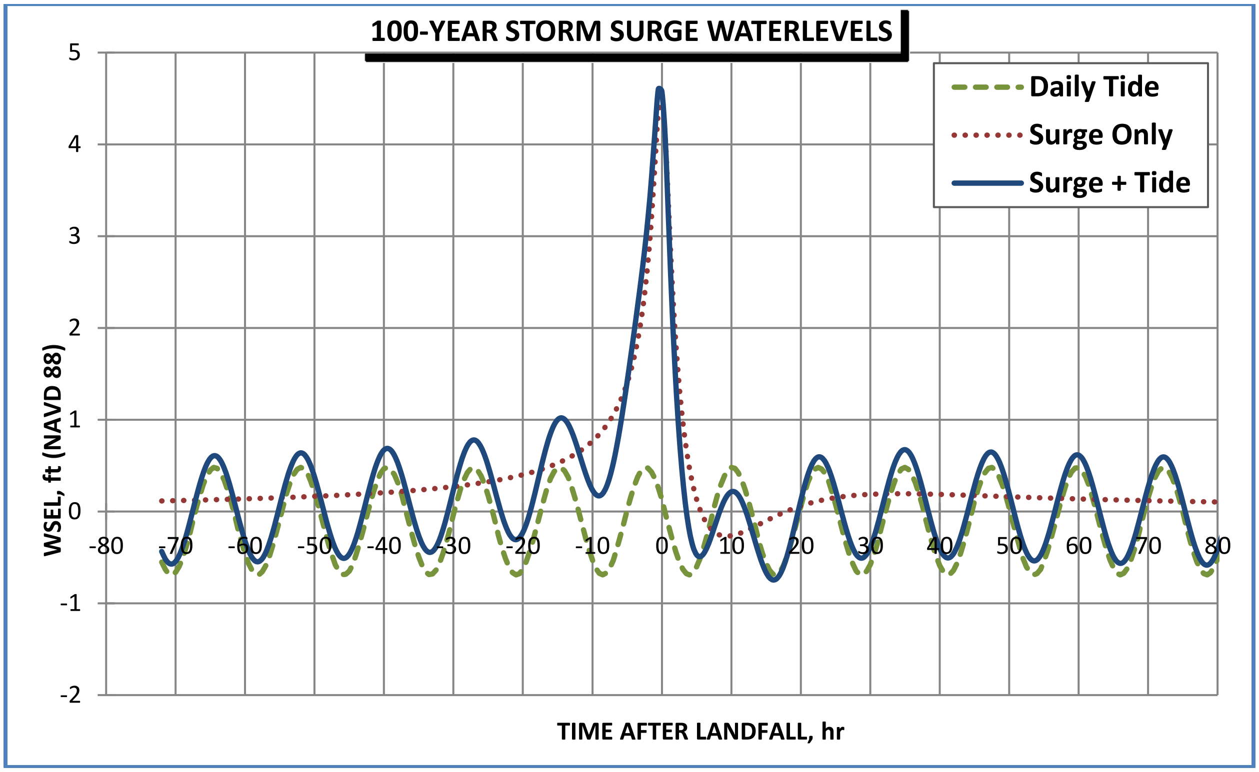

Figure 7. Plot of coastal surge components and combined curve for the 100-year (1-percent annual chance) event for Chesapeake Bay at the mouth of the Patuxent River in Maryland. From a report to the Maryland State Highway on evaluating riverine and coastal flood flow conditions for the MD Route 4 bridge at the confluence of the Patuxent River with the Chesapeake Bay.

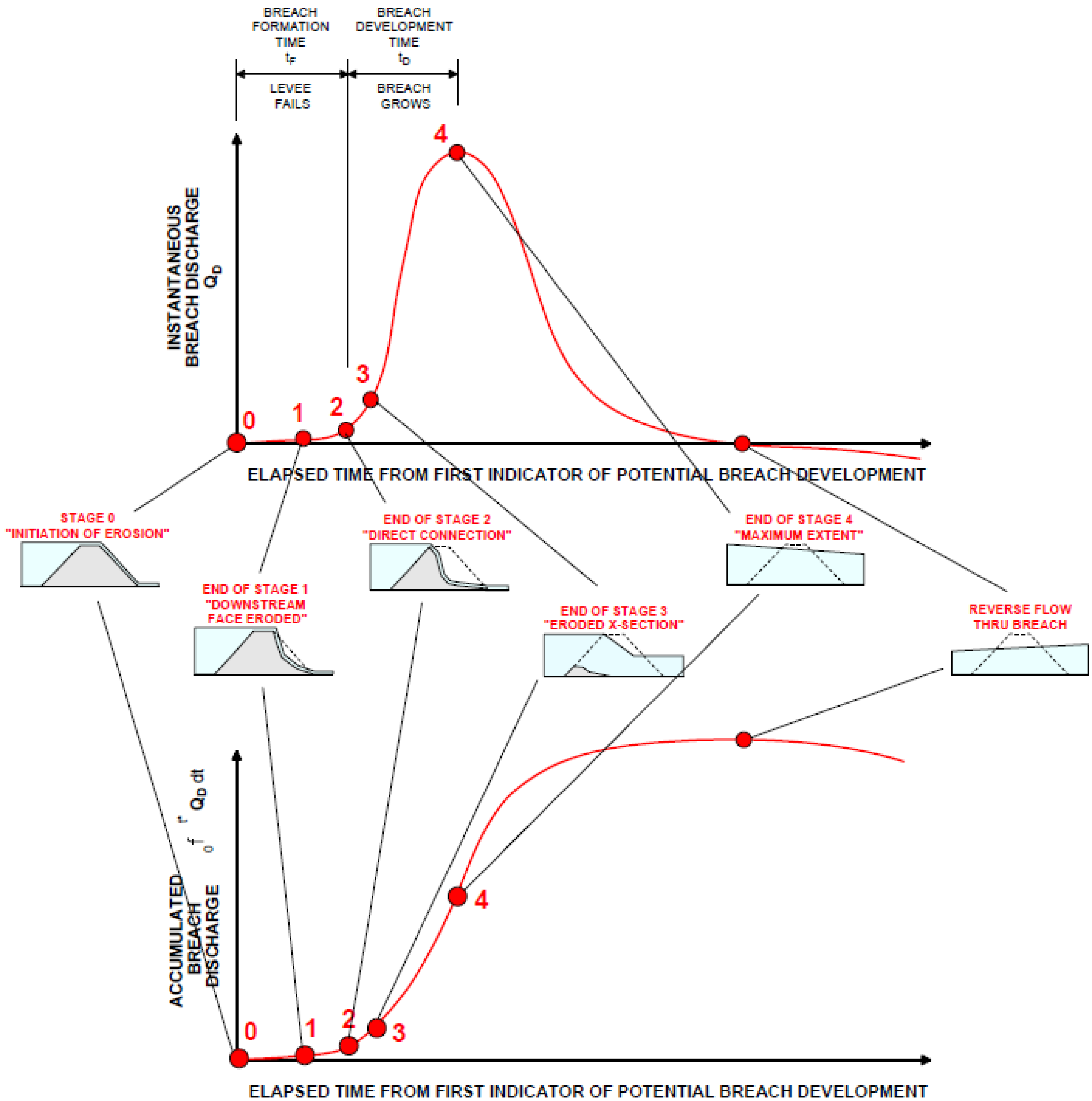

Figure 8. Typical breach discharge curves that develop as a function of the breach development and geometry. Taken from SERRI Report 70015-001, dated October 2009.