Calculations of Hydrologic Design Peak Flows

Course Description

This course is designed to fulfill credit for the Professional Development Hours (PDH) of Civil Engineers. The objective of this course is to provide students with knowledge and experience using the National Streamflow Statistics (NSS) program which is developed by the United States Geological Survey. Students will learn how to use the NSS program to estimate flood-frequency statistics (e.g., 5-year or 100-year flood) for hydrologic basins in all states. The course will cover different procedures for NSS setup, input preparation and extracting results on flood peaks and other streamflow statistics. Automated procedure for input preparation using Geographical Information System (GIS) web-based tools is also covered.

Chapters

- Chapter 1: Introduction To Natural Streamflow Statistics (NSS)
- Chapter 2: Overview of the NSS program
- Chapter 3: Calculations and Estimations of Streamflow Statistics

Learning Objectives

Upon completion of the course, participants will be able to:
- Understand basic concepts of streamflow, river stage, return period and design flood
- Summarize the national streamflow gauging network operated by the U.S. Geological Survey (USGS)
- Learn how to calculate return periods for different flood exceedance probabilities, and vice versa
- Explain how to set up and run an NSS application scenario
- Identify which variables are required by NSS for different states/regions
- Create and produce graphical displays (hydrographs and frequency plots) based on NSS output
- Summarize the fundamental equations used to compute flow peaks in rural and urban basins
- Explain how to compute and interpret streamflow statistics for basins that cover multiple hydrologic regions
- Interpret the different uncertainty measures produced by NSS
Chapter One: Introduction to Natural Streamflow Statistics (NSS)

Overview

• Definitions
• How Floods are designated
• Natural Streamflow Statistics (NSS)
• Required Inputs for NSS Applications
• The Main Output of NSS
• Downloading and Installing the NSS Program

Learning Objectives

• Understand basic concepts of streamflow, river stage, return period and design flood
• Summarize the national streamflow gauging network operated by the U.S. Geological Survey (USGS)
• Learn how to calculate return periods for different flood exceedance probabilities, and vice versa

Definitions

The following are some definitions of basic concepts and terms that are necessary for understanding further material on estimation of flood peaks and streamflow statistics. (Source: The United States Geological Survey; USGS)

Discharge (or streamflow)
Discharge, or streamflow, is defined as the measured volume of water (usually expressed in cubic feet) that passes a certain point on the river or stream in a given amount of time (e.g., second, hour, or day). Discharge is usually expressed in cubic feet per second (cfs or ft³/s).

River Stage
Stage is the height of the water in a river, measured relative to a certain datum. Measurements of river stage and streamflow are collected over numerous sites in the United States (Figure 1) by the U.S. Geological Survey.

Hydrograph
A hydrograph is a plot that shows changes in discharge or river stage over a period of time. The period of time can be the duration of a storm given in days, months, year(s) or decade(s).

Flood
A flood is a high discharge or streamflow value that overtops the natural or artificial banks or levees of a river.
Design Flood
A design flood is the flood value that is chosen as the basis for the design of a hydraulic structure (e.g., a dam, a levee, a reservoir).

Design floods are usually specified for a certain design frequency (e.g., 5-year flood, 10-year flood, 100-year flood). The term “frequency” denotes the frequency of occurrence of a certain extreme event (e.g., a storm). The magnitude of an extreme event is inversely proportional to its frequency of occurrence. For example, extreme floods occur less frequently than moderate ones. The frequency of occurrence is closely related to the concept of “recurrence interval” or “return period”.

Recurrence interval or return period
The recurrence interval or return period ($T$) is defined as the average number of years between floods of a certain size. The actual number of years between floods of any given size varies significantly because of the naturally changing climate.

Probability of Exceedance
The return period (or recurrence interval), $T$, is related to another concept which is the probability of exceedance ($p$). In fact, $T$ and $p$ are reciprocals of each other:

$$T = \frac{1}{p} \quad \text{and} \quad p = \frac{1}{T} \quad (1.1)$$

The following table lists standard design return periods and frequencies:

**Table 1.1: Standard levels of design return period and probability of exceedance**

<table>
<thead>
<tr>
<th>Return Period (T)</th>
<th>Probability of exceedance ($p$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.5 (50%)</td>
</tr>
<tr>
<td>5</td>
<td>0.2 (20%)</td>
</tr>
<tr>
<td>10</td>
<td>0.1 (10%)</td>
</tr>
<tr>
<td>25</td>
<td>0.04 (4%)</td>
</tr>
<tr>
<td>50</td>
<td>0.02 (2%)</td>
</tr>
<tr>
<td>100</td>
<td>0.01 (1%)</td>
</tr>
</tbody>
</table>

For example, a flood that has a return period of 5 years (usually called 5-year flood) has a probability of exceedance of $1/5 = 0.2$, or exceedance frequency of 20%. Similarly, there is a 1% probability that a 100-year flood will be equaled or exceeded every year. It is noted that a 5-year flood is not the one that will necessarily be equaled or exceeded every five years. Instead, there is a 20 percent (20%) chance that this flood will be equaled or exceeded in any year. In fact, a 5-year flood could conceivably occur in several consecutive years, with a 20% probability of recurrence on every year.

How floods are designated
The term “100-year flood” is a statistical designation and is used to indicate the chance (1-in-100) or probability (1%) that a flood this size will occur during any given year. Scientists apply statistical techniques on long records of past floods to designate probability of exceedance of certain flood values.

Natural Streamflow Statistics (NSS)
These are basic flood-frequency statistics (e.g., 5-year or 100-year flood) for every State, for Puerto Rico, and for the island of Tutuila, American Samoa. Besides flood magnitudes of different return periods, streamflow statistics include other statistics, such as the mean annual and monthly flows, and low-flow frequencies. The low-flow frequencies represent lowest average flows that occur over a set number of consecutive days (e.g. 3, 7 days) at defined recurrence intervals (e.g. 2, 10 years), for example 7-day 10-year low flow or 7-day 2-year low flow.

Applications of Streamflow Statistics
Streamflow statistics are used in a variety of design, planning, and management and engineering applications:

a. Design of culvert and other roadway hydraulic structures
b. Flood control structures
c. Flood-plain management
d. Setting water allocations
e. Determining allowable waste discharges
f. Water quality regulation
Estimation of Streamflow Statistics
Streamflow statistics can be estimated directly from historical streamflow measurements. However, at ungaged sites (i.e., watersheds and river stations with no historical records of streamflow or stage data), it is not possible to directly calculate streamflow statistics. At such sites, streamflow statistics are estimated using techniques such as the USGS Natural Streamflow Statistics (NSS) computer program.

What is NSS?
The National Streamflow Statistics (NSS) Program is a computer program developed by the U.S. Geological Survey to provide a quick and easy way for estimating streamflow statistics (e.g., flood peaks) for ungaged sites across the United States. The program is equipped with an easily accessible graphical user interface. The program is based on a set of regression equations that relate watershed characteristics and climatic variables to streamflow statistics. The regression equations used in NSS are developed from data in gauged sites found within similar hydrologic regions and are used to estimate streamflow statistics for ungaged sites in the same region. The regression equations enable the transfer of streamflow statistics from gauging stations to ungaged sites simply by determining the watershed and climatic characteristics needed for the ungaged site and solving the regression equations based on these input values. The regression equations produce estimates of peak flows for the 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year return periods.

The NSS regression equations are regional equations created on a state-by-state basis, where each state is divided into hydrologically “similar” regions. These equations have been developed by the USGS, in cooperation with individual state Departments of Transportation, the Federal Highway Administration and the Federal Emergency Management.

How to Obtain the NSS Program
The NSS program is USGS hydrologic analysis software and is available for free through electronic retrieval from the World Wide Web at the following website: http://water.usgs.gov/software/nss.html. This webpage contains the software, a user manual, fact sheets, and links to state reports with detailed information on the applicable regression equations that are used by NSS for estimation of flow peak statistics.

Main Capabilities of NSS
The main capabilities and utility applications of the NSS program can be summarized as follows:

a. Provide estimates of flood-frequency discharges (i.e., flow peaks for different return periods) for both rural and urban streams, watersheds and drainage basins that lack historical streamflow measurements (i.e., ungaged sites). The estimates are based on regression equations fitted to streamflow data from gauged sites.
b. Provide estimates for low-flow duration and frequency discharges for ungaged sites.
c. Estimate discharges for natural streams. The program does not account for the effects of water diversions, dams, flood-detention structures, and other manmade works.
d. Incorporate existing information from observed records of streamflow, or information on flow per unit area, at gauged sites, with estimates obtained using the regression equations at ungaged sites.
e. Produce plots of flow hydrographs.
f. Generate flow-frequency plots summarizing the flow-frequency analysis.

Required Inputs for NSS Applications

For drainage basins and watersheds located in rural areas the NSS user needs to provide some hydrologic and climatic characteristics about the basin. The number and type of input variables required for NSS applications vary from a site to another and from a state to another. Examples of the input variables that are commonly required include:

1. **Drainage area or contributing drainage area:** This input variable appears in nearly all of the statewide rural regression equations given in NSS.
2. **Slope of the main channel in the basin:** This is the other most frequently used basin characteristic used required by NSS. It is defined as the slope between two points on the main channel located at distances 85% and 10% of the channel length upstream from the watershed outlet.
3. **Mean annual precipitation over the basin:** This is the most frequently required climatic characteristic. It is usually expressed as the average amount of precipitation that occurs during 24 hours, with a return period of 2 years. Other climatic character-
4. Mean basin elevation
5. Estimates of basin coverage (e.g., percentage of basin area covered by lakes, ponds, forests, etc.)

6. The following is an example of the NSS user interface used to enter the specific values of the input variables for a certain basin. Note that the number and type of input variables is a site and state-specific.

The user needs to come up with estimates for the input variables, most of which can be derived from topographic maps, aerial photographs, and rainfall reports and atlases. Most of such information is available as digital data and can be derived using Geographical Information System (GIS). The USGS has developed an automated procedure for estimating basin characteristics and preparing input variables for NSS applications. More detailed information about this automated system is provided later in the course.

For drainage basins and watersheds located in urban areas, there are typically seven input variables that the user needs to specify. These variables provide information on basin area, channel slope, average precipitation, basin’s storage capacity represented by percentage of area occupied by lakes and ponds, degree of basin development and urban drainage improvements, and the percentage of area occupied by impervious surfaces in the basin.

The Main Output of NSS

The most typical output provided by the NSS program includes streamflow statistics (flood peaks) estimated for different return periods that range from 2 years up to 500 years. By default, the NSS output window displays the following streamflow statistics information:

Where PK2, PK5, …, PK500 denote the estimated flood peaks for return periods of 2, 5, …, 500 years. The next two columns (Standard Error and Equivalent Years) provide some measures of the accuracy associated with these estimates.

Besides the default tabular output, the user can produce two types of plots: (a) a frequency plot, which shows the estimated flow peaks on the y-axis plotted against the corresponding return periods on the x-axis, and (b) a hydrograph plot, which shows a temporal distribution of the streamflow for any desired return period. For the hydrograph plots, the user also needs to provide an estimate of the basin’s time lag.
Finally, the NSS program generates a comprehensive report including detailed information about the performed analysis. Such information includes a summary of the basin characteristics and the specific values of the input variables provided by the user, a list of the actual regression equations used to estimate the flood peaks, and other relevant information.

**Summary**

This chapter introduced some basic concepts about streamflow statistics and their applications in design of engineering projects. The concepts on design floods, return period, frequency and probability of exceedance were introduced. The National Streamflow Statistics (NSS) program was introduced. The most common applications of the NSS program were discussed such as: design of roadway hydraulic structures, design of flood control structures, and determining allowable waste discharges. The Chapter also covered the main input information and variables required for an NSS, the most common of which is the area of the drainage basin or watershed under study. The main NSS output are estimates of peak flows and their corresponding hydrographs. A detailed procedure on how to obtain and install the NSS program from the USGS website was given.
Chapter Two: Overview of the NSS Program

Overview

- Main Components of the NSS Program
- Main Windows and Functionality of the NSS Program
- Graphical Display of NSS Output
- Combining Statistics from Different Regions
- Sensitivity Analysis on the NSS Output

Learning Objectives

- Explain how to setup and run an NSS application scenario
- Identify which variables are required by NSS for different states/regions
- Create and produce graphical displays (hydrographs and frequency plots) based on NSS output

Main Components of the NSS Program

The NSS Program has four main components:

1. **A user interface** is the main interface of NSS, which allows the user to interact with the program by entering input information and receiving and visualizing output results.

2. **A calculation routine** is the main engine of the program which includes regression equations used by NSS to compute the streamflow statistics based on basin and climatic characteristics specified by the user through the user interface.

3. **A database** is where NSS stores all information it needs to perform the streamflow statistics, such as format and parameters of the regression equations and their error bounds.

4. **A help facility:** The NSS program provides online and offline help features such as user manual, help menu, access to web pages, etc.

Main Windows and Functionality of the NSS Program

The main user interface of NSS contains three pull-down menus: **File:** used to open projects and save analysis output and graphs; **Graph:** used to create graphical output such as flow hydrographs and frequency plots; and **Help:** used to provide access to help features. Below the pull-down menus are two boxes that allow the user to select the state in which the drainage basin is located and to give a name for the project.

The main NSS window is divided into two parts: the left frame is for rural analysis and the right frame is for urban analysis. Each of these two frames is equipped with a set of three buttons (Edit, New, and Delete) allowing the user to modify an existing NSS scenario, create a new one or delete the current scenario.

The top part of each frame displays the input information specified by the user on the site of interest. The lower part displays the output results, which mainly include the estimated flood peaks at different return periods with some information on the degree of uncertainty associated with such estimates.
By clicking on the New or Edit scenario buttons, a new window will open, which allows the user to enter the basin characteristics and other relevant information. The user needs to select a hydrologic region (or multiple regions) where the basin of interest is located, and specify the values of the input variables (reflecting hydrologic and climatic characteristics of the basin) that are required for analysis in each selected hydrologic region. The program provides guidelines on the recommended ranges of such variables, within which the regression equations used to estimate streamflow statistics are most applicable.

This procedure can be used to create rural or urban scenarios; however, a rural analysis is required prior to performing an urban analysis.

After performing the streamflow estimation, the user has the option to produce text reports (by selecting File → Report from the main pull-down menu) and graphical presentations of the results (by clicking on Frequency Plot and Hydrograph at the bottom of the main window).

Finally, the Weight button can be used to incorporate information from gauged sites into the estimation of streamflow statistics at ungauged sites. This is done via statistical weighting either with actual observed data, or with values at other gauged sites.

An Example Application of NSS

In this section we will go through a tour session on how to setup and implement an example analysis of streamflow statistics estimation using the NSS program:

Start the NSS program from the Start menu (under USGS) or by double-clicking on the desktop shortcut icon. A new small window will open where the users can provide their name (optional) and specify a path and a name for their project. The user is also prompted to select which unit system (Metric or English) to be used in the project. Click Run to continue the session.

The main window of NSS will open. In this menu, select a state where the project is located. In this example, select the state of Florida. Enter an optional name for the Project site. The window contains two sides, one for rural estimates and the other for urban estimates. Let us create two scenarios (rural and urban).

Click on “New” next to Rural to start a new scenario (by default it will have the name Rural 1). A new window will open where you can specify input parameters for this scenario. First, we need to decide on which region in the state the project is located.
Calculations of streamflow statistics in the NSS program are based on dividing each state into various regions. For information on which region your project is located in, go to http://water.usgs.gov/osw/programs/nss/pubs.html. Click on the US national, and then click on the state of Florida.

Select the appropriate web link (in this case, select the link that points to “Estimating the Magnitude and Frequency of Floods for Streams in West-Central Florida, 2001”). On the left side of the page, click on the link “Figure 1 with links to individual stations”. This map helps the user identify which state region the project is located in. Let us assume that our project site is located in the domain of Region 1.

Go back to the NSS Edit Scenario Window and specify West-Central Region 1 as the region of this Rural 1 scenario. Based on this selection, a list of variables will be displayed. In this example case, the user is required to specify two variables: Contributing Drainage Area; and Percent of area occupied by Lakes and Ponds.

The window contains suggestions on ranges of these variables that are typically applicable in the selected region. The user is supposed to provide input values of these variables. These input values can be computed from available maps or from other information available about the study site. Automated procedures to calculate these variables are available through the use of Geographical Information System (GIS) or other USGS program (StreamStat; see Chapter 3). For our example, let us assume that the project drainage area is 1500 mi² and that 3% of this area is occupied by ponds and lakes.
It is advised to save a copy of your NSS project file by clicking on File / Save As in the main window. Saving is recommended after each change is made to the project scenarios.

Optionally, the user can also get probable maximum flood estimates based on the Crippen and Bue (1977) method (C&B method), which is available for 17 flood regions in the U.S. We first need to specify the flood region in which our project is located. Click on the Map button and a new figure will open. As you can see in this figure, our Florida example project is located in flood region #3. Select “3” in the flood region box and click Ok.

The program will take you back to the main window where the output results of this scenario are displayed. The upper frame in the displayed window shows a summary of input variables and information provided earlier by the user. The lower frame displays the output statistics in terms of peak flow for different return periods (2, 5, 10, ..., 100, 200, 500 years). It also displays an estimate of the uncertainty associated with the estimation of these peak flow statistics. Various measures of errors can be displayed based on the particular method of estimation used by the NSS program over the specific site of the study. In this example, the uncertainty is described by two measures: the average standard error of prediction, expressed percent (%), and the equivalent years of record. More details on different measures of uncertainty available in the NSS program will be provided later. The last line in the results shows the probable maximum flood value computed based on the selected C&B region.

It is possible that the project site and its drainage area span (or cross) more than one region in the state. In this case, the user can select multiple regions. (Note: this is possible for computations of rural scenarios only.) The user needs to specify the drainage area associated with each region in the appropriate boxes in the NSS window. The NSS window will display the entire drainage area (sum of sub-areas from different regions). For each region, the user will specify entries for the appropriate variables (each region may require a different set of variables).

Note that the results are being displayed based on combining the drainage areas in the two regions.
If desired, the same procedure can be repeated for an urban site. However, unlike the rural scenario, if an urban scenario is developed, only one region can be selected. Note that some urban calculations may depend on results from rural scenarios; in such cases, the rural scenarios need to be computed first.

The results will now be displayed in the left frame of the window (rural scenario) and the right frame of the window (urban scenario).

The second type of graphical display of the results is a hydrograph plot. Click on the Hydrograph box and a new window will open. The user can generate hydrographs for a certain return period (recurrence interval) and for different scenarios. For each scenario, the lag time of the basin under consideration needs to be specified. In our example, let us specify the lag time as 6 hours for the rural scenario and 1 hour for the urban scenario and let us produce hydrographs for two return periods of 5 and 100 years. The hydrograph plot can be edited, saved and printed through a pull-down menu.
The ordinates of the plotted hydrograph can also be obtained as numerical values by clicking on the List button. A time series of the generated hydrographs will be displayed and can be copied and pasted into an outside program (e.g. EXCEL) for further analysis.

You can also generate a text report containing the results of your analysis. The report can be generated by selecting File/Report from the NSS main window and specifying a name for it. The report will contain detailed information about your project, input information about the study site, the equations that were used to calculate the streamflow statistics, the resulting peak flow estimates, the uncertainty measures, and other relevant information.

Combining Statistics from Different Regions

In the displayed report, one can see that the equations used for rural calculations in West-Central Region 1 were of the following form:

\[
PK2 = 132 \times (CONTDA)^{0.528} \times (LAKEAREA + 0.6)^{-0.542}
\]

Where PK2 is the 2-year peak flow, CONTDA is the contributing drainage area, and LAKEAREA is the percentage of area occupied by lakes and ponds.

Similar equations were used for West-Central Region 2 but with one more variable (CSL10_85) which represents the stream slope:

\[
PK2 = 2.03 \times (CONTDA)^{1.065} \times (CSL10_85)^{-0.017} \times (LAKEAREA + 3)^{-0.259}
\]

The calculations are done for each region separately and then merged together according to the specified area-weight assigned for each region; for example, PK2 for region 1 (1500 mi²) and region 2 (1000 mi²) were found to be 4100 cfs and 5240 cfs, respectively. The area-weighted average PK2 value is then calculated as:

\[
PK2 = \frac{4100 \times 1500 + 5240 \times 1000}{2500 + 2500} = 4556 \text{ (cfs)}
\]
The rest of the calculations are done in a similar way as shown in the following table and figure (note that this kind of analysis is only possible for rural basins):

<table>
<thead>
<tr>
<th>Recurrence Interval (year)</th>
<th>Computed peak Q in Region 1 (ft³/s)</th>
<th>Computed peak Q in Region 2 (ft³/s)</th>
<th>Area-weighted estimates (ft³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4100</td>
<td>5240</td>
<td>4556</td>
</tr>
<tr>
<td>5</td>
<td>7280</td>
<td>10500</td>
<td>8568</td>
</tr>
<tr>
<td>10</td>
<td>9800</td>
<td>14700</td>
<td>11760</td>
</tr>
<tr>
<td>25</td>
<td>13400</td>
<td>20600</td>
<td>16280</td>
</tr>
<tr>
<td>50</td>
<td>16300</td>
<td>25200</td>
<td>19860</td>
</tr>
<tr>
<td>100</td>
<td>19500</td>
<td>30100</td>
<td>23740</td>
</tr>
<tr>
<td>200</td>
<td>22700</td>
<td>35100</td>
<td>27660</td>
</tr>
<tr>
<td>500</td>
<td>27700</td>
<td>42000</td>
<td>33420</td>
</tr>
</tbody>
</table>

### Sensitivity Analysis on the NSS Output

Let us try to perform some analysis on the sensitivity of the computed streamflow statistics to the basin characteristics. For rural areas, we can examine the effect of percentage of the total area occupied by lakes and ponds. For this test, let us assume that our drainage area is entirely located in West-Central Region 1. We will run the NSS program using two different values of the variable that represents the percentage of total area occupied by lakes and ponds: 3% and 8%. This represents a situation where a reservoir, or a detention pond, was introduced in the drainage basin to increase the area occupied by such coverage from 3% to 8%. As expected, the effect of increasing the “storage” capacity of the drainage basin will lead to a reduction in the peak flows as shown in the following table and figure:

<table>
<thead>
<tr>
<th>Recurrence interval (year)</th>
<th>Computed peak Q with 3% lakes/pond area (ft³/s)</th>
<th>Computed peak Q with 8% lakes/pond area (ft³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3130</td>
<td>1950</td>
</tr>
<tr>
<td>5</td>
<td>5610</td>
<td>3530</td>
</tr>
<tr>
<td>10</td>
<td>7590</td>
<td>4760</td>
</tr>
<tr>
<td>25</td>
<td>10400</td>
<td>6520</td>
</tr>
<tr>
<td>50</td>
<td>12700</td>
<td>7930</td>
</tr>
<tr>
<td>100</td>
<td>15300</td>
<td>9460</td>
</tr>
<tr>
<td>200</td>
<td>17900</td>
<td>11000</td>
</tr>
<tr>
<td>500</td>
<td>21900</td>
<td>13400</td>
</tr>
</tbody>
</table>

Another sensitivity test can be performed on the urban basin. We can test the effect of increased urbanization by changing the percentage of area occupied by impervious surfaces (variable Area-of-Impervious-Surfaces) from 25% to 50%. After running the NSS program with these two scenarios, the peak flows at different return periods can be compared. As expected, increased urbanization in the basin leads to an increase in the peak flows at every return period as shown in the following table and figure:

<table>
<thead>
<tr>
<th>Recurrence interval (year)</th>
<th>Computed peak Q with 25% impervious surface (ft³/s)</th>
<th>Computed peak Q with 50% impervious surface (ft³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>426</td>
<td>895</td>
</tr>
<tr>
<td>5</td>
<td>755</td>
<td>1450</td>
</tr>
<tr>
<td>10</td>
<td>1060</td>
<td>1940</td>
</tr>
<tr>
<td>25</td>
<td>1570</td>
<td>2720</td>
</tr>
<tr>
<td>50</td>
<td>2040</td>
<td>3410</td>
</tr>
<tr>
<td>100</td>
<td>2640</td>
<td>4250</td>
</tr>
<tr>
<td>500</td>
<td>4570</td>
<td>6870</td>
</tr>
</tbody>
</table>
Summary

In this chapter, an overview of the four main components (user interface, calculation routine, database, and help interface) of the NSS program was provided. The main windows and functionality of the program were described. A full example of the NSS application including various scenarios was presented. The NSS can be applied for rural as well as urban drainage basins (a rural analysis is required prior to performing an urban analysis). Different number and types of input variables are needed by NSS depending on the drainage basin type (urban versus rural) and the hydrologic region and state in which the basin is located. The NSS program provides an automated way for specifying the required input variables. While a typical NSS scenario includes a drainage basin that is entirely located within a single hydrologic region, the program also allows for analyzing basins that cross boundaries of more than one region (possible for rural basins only). In such cases, an average based on area weighting is applied. The chapter also covered the main output of NSS, which includes tables of flow peaks for different return periods as well as graphical displays of frequency plots and streamflow hydrographs. To display a streamflow hydrograph plot, the user needs to specify the lag time of the basin. Finally, we also learned how to study the sensitivity of streamflow statistics (e.g. peak flows) to the characteristics of the drainage basin (e.g. effect of increased urbanization; effect of increased basin’s detention capacity).
Chapter Three:
Calculations and Estimations of Streamflow Statistics

Overview

• Regression Equations in NSS
• Equations for Rural Basins
• Hydrologic Regions in NSS
• If the Drainage Basin Crosses Two (or more) Hydrologic Regions
• Measures of Uncertainty in NSS Peak Flow Estimates
• Estimation of Flood Hydrographs in NSS
• Preparation of NSS Input
• Using StreamStat Web-Application for Preparation of NSS Input
• Feeding StreamStats Output into NSS
• Using StreamStats to Generate Streamflow Statistics

Learning Objectives

Upon completion of the course, participants will be able to:

• Summarize the fundamental equations used to compute flow peaks in rural and urban basins
• Explain how to compute and interpret streamflow statistics for basins that cover multiple hydrologic regions
• Interpret the different uncertainty measures produced by NSS

Regression Equations in NSS

The National Streamflow Statistics (NSS) Program provides a methodology for estimation of streamflow statistics (peak flows; low flows for different return periods or recurrence intervals) in ungauged sites that lack records of historical flows. The program is based on a set of regression equations that were developed for gauged sites with long historical records of streamflow measurements. Hydrologic regions that represent areas of relatively homogeneous streamflow characteristics are identified and regression equations are developed from data of gauged sites within each region. These equations are found by fitting peak flows from gauged sites to watershed and climatic characteristics of these sites. Then, for an ungauged site in a certain region, the regression equations of that region are used to estimate streamflow statistics using watershed and climatic characteristics of the site.

A typical regression equation will have the following form:

\[ Q_T = aX_1^{e_1}X_2^{e_2}X_3^{e_3} \ldots X_n^{e_n} \]  

(1.1)

Where \( Q_T \) is the peak flow for a certain return period \( T \) (\( T \) is in years), \( X_1, X_2, X_3 \ldots, X_n \) are watershed and climatic characteristics (e.g., drainage area, main channel slope, mean precipitation, etc.), and \( a, e_1, e_2, e_3, \ldots, e_n \) are regression coefficients.

The NSS equations depend on the type of watershed under examination (rural or urban). For rural areas, the number and type of input variables \( (X_1, X_2, X_3, \ldots X_n) \) and the number of regression coefficients \( (e_1, e_2, e_3, \ldots, e_n) \) vary from a state to another and within different hydrologic regions in the same state. For urban watersheds, a nationwide set of equations is used with the option of using a site-specific or local equation if available.

Equations for Urban Basins

In the case of urban basins, the NSS program uses nationwide equations with seven parameters (exponents) to calculate urban peak discharges, \( UQ \), for different return periods, \( T \). A typical form of such equations is as follows:
Calculations of Hydrologic Design Peak Flows

Where $UQ$ is the urban peak discharge (ft$^3$/sec), $A$ is the contributing drainage area (mi$^2$), $SL$ is the slope of the main channel (ft/mi), $RI$ is the rainfall depth (inch) for a 2-hour, 2-year return storm, $ST$ is a measure of the storage in the basin (estimated as the percentage of the basin area occupied by lakes, reservoirs, swamps, and wetlands), $BDF$ is a factor that accounts for urban drainage improvements in the basin, $IA$ is measure of the degree of urbanization in the basin and is represented by the percentage of the drainage basin occupied by impervious surfaces (e.g., houses, parking lots, streets, etc.), and $RQT$ is the equivalent discharge (ft$^3$/sec) for a rural basin having the same area and estimated for the same return period as that of the urban basin.

Similar equations are available for other return periods between 2 and 100 years. The values of parameters in such equations vary according to the specified return period.

The above seven-parameter urban flood-frequency equations can be used in urban drainage nationwide; however, the user can also use local or state-specific equations that have been included in the NSS program. These additional equations are site-specific and should not be used for urban areas other than those that they were developed for.

It is noted that these seven-parameter equations should not be used to calculate flood-frequency values in basins where flow is modified or controlled by reservoirs or detention basins.

**Equations for Rural Basins**

For basins located in rural areas, the number and type of input variables ($X_1, X_2, X_3, ..., X_n$) and the number of regression coefficients ($e_1, e_2, e_3, ..., e_n$) vary from one state to another and within different hydrologic regions in the same state. For example, in hydrologic region # 2 in Central Florida, the contributing drainage area (DA), the main channel slope (SL), and the percent of the total drainage area covered by lakes (LK), provided the best regression models for this region. An example of such equations for a 5-year return period peak flow is as follows:

$$Q_5(\text{cfs}) = 5.82(DA)^{1.023}(LK + 3.0) - 0.339(SL)^{0.149}$$

Another example is in hydrologic region # 4 in the state of Utah where the 100-year flood is predicted using information on drainage area (DRNAREA mile$^2$), basin mean elevation (ELEV, ft), and average basin slope (BSLDEM10M, percent):

$$Q_{100}(\text{cfs}) = 4.18 \times DRNAREA^{0.792}$$

The following Table shows a list of different watershed and climatic variables that are used by the various regression equations within the NSS program. It should be noted that not all of these variables are used in every regression equation or every hydrologic region.

**Hydrologic Regions in NSS**

The regression equations used by the NSS program to estimate streamflow statistics in ungauged sites are developed for distinct regions that represent areas of rela-
tively homogeneous streamflow characteristics. These are known as hydrologic regions. On average, there are about four hydrologic regions per state (see figures below for two examples in Texas and California). These regions were determined by using major watershed boundaries and information on the mean elevation of the watershed. It is noted that some states have inadequate data to define streamflow relations in some regions (e.g., Florida, Georgia, and South Carolina).

If the Drainage Basin Crosses Two (or more) Hydrologic Regions

It is possible that the drainage basin under consideration lies within an area that crosses two hydrologic regions. There are two possible cases:

a. The basin boundary crosses more than one hydrologic region in the same state.

b. The basin boundary crosses more than one hydrologic region that spans neighboring states.

In the first case, NSS has an automatic way for estimating the streamflow statistics for a basin that crosses two hydrologic regions within the same state. Let us assume that total area of the drainage basin is $A_t$, part of it, $A_1$, lies in a certain hydrologic region, and the other part, $A_2$, is located in another region but within the same state ($A_t = A_1 + A_2$). The procedure for calculating the streamflow statistics (e.g., peak flows at different return periods) is as follows: First, NSS estimates streamflow statistics for the basin as if it was entirely located within each of the two regions. Then, NSS applies a weighting average of the two streamflow estimates based on the percentage of the basin area located within each hydrologic region. The following is an example of how the weighting is done:

$$Q_T = Q_T(\text{region#1}) \frac{A_1}{A_t} + Q_T(\text{region#2}) \frac{A_2}{A_t}$$

Where $Q_{T}$ is the area-weighted-average peak flow for a certain return period $T$, $Q_{T(\text{region#1})}$ is the peak flow estimated assuming the total drainage area located within region # 1, and $Q_{T(\text{region#2})}$ is the peak flow estimated assuming the total drainage area located within region # 2. Similar equations can be written if the drainage area spans more than two regions (e.g., $n$ number regions). A general form of this equation is:

$$Q_T = \sum_{i=1}^{n} Q_{T(\text{region#i})} \frac{A_i}{A_t}$$

This procedure is implemented automatically in NSS. The user needs to specify the different hydrologic regions crossed by the basin of interest along with information on the percentage of the basin’s area located within each region. The following figure is an example of the NSS interface showing the selection of three
regions crossed by a single basin. Note that the number of input variables needed for every region crossed by the basin may not be the same from one region to another; in this case, the user needs to specify the input variables that apply for each region accordingly.

In the second case (b), a similar procedure is followed when the drainage basin crosses the boundaries of two or more states. However, unlike case (a), NSS doesn’t perform the weighting of cross-state basins automatically; instead, the user must perform this procedure manually. In such situations, the user will need to use NSS for each state separately using the entire drainage area of the basin. Then, the user applies a weighting scheme to estimate the peak flow based on the percentage of the basin’s drainage area in each state. For example, if the basin crosses two states (A₁ in the first state and A₂ in the neighboring state), then average peak flow estimate is:

\[ Q_T = \frac{Q_{T(state#1)}}{A_t} A_1 + \frac{Q_{T(state#2)}}{A_t} A_2 \]

Where \( Q_{T(state#1)} \) is the peak flow estimated as if the drainage basin was entirely located in each of the two states.

**Measures of Uncertainty in NSS Peak Flow Estimates**

Like most statistically-based estimation methods, the streamflow estimates provided by NSS are inevitably subject to varying degrees of uncertainty and estimation errors. The degree of uncertainty (or accuracy) of the NSS streamflow statistics varies from site to site depending on the values of the independent variables (e.g., basin’s hydrologic and climatic characteristics) specified by the user as input into the NSS regression equations. Note that the NSS regression equations were originally derived and fitted for certain ranges of input variables. Therefore, basins with characteristics within such ranges will have higher accuracy for the estimated streamflow statistics, and vice versa. Information about the degree of uncertainty is provided as an NSS output within the same window where the streamflow statistics are displayed.

The NSS program reports the streamflow accuracy using different descriptive measures:

1. **Average standard error of estimate (%)**: This provides a measure of the average variation between the streamflow estimates based on the regression equations and the corresponding values derived from the gauging data for those stations used to develop the regression equations. The larger this number is, the less accurate the estimated flood peaks are.

2. **Average standard error of prediction (%)**: This is a more reliable (and preferred) measure of the average accuracy of the regression equations when applied to estimate flow statistics for ungauged sites. The average standard error of prediction is usually a few percent higher than the average standard error of estimate. The larger this number is, the less accurate the estimated flood peaks are.

3. **Equivalent years of record (years)**: This is another measure of accuracy and represents the number of years of “actual” streamflow historical record required to achieve the same accuracy as the regional regression equations. The larger the equivalent years of record required is, the less accurate the estimated flood peaks are.

4. **Prediction intervals (cfs)**: This is another way used in recent NSS analysis to specify the accuracy of the streamflow statistics. In general, prediction intervals indicate the probability that the true peak flow value for a certain site is within the given prediction interval. For example, if the 90% prediction interval for a 10-year peak flow at a certain site is specified as 340-445 cfs, this simply means that there is a 90% confidence that the true 10-year flood is between 340 and 445 cfs. Apparently, the narrower this interval is, the more accurate the estimated flood peak is.

The following are some important remarks that the NSS user should be aware of when interpreting the accuracy of the estimated streamflow statistics:

a. In the NSS user interface, the average standard error of estimate is given under a heading named...
“Estimation error, %,” while the average standard error of prediction is given under a heading named “Prediction error, %.”

b. The standard errors of estimate are provided by NSS only when the standard errors of prediction are not available in the individual statewide reports.

c. For most flood peak equations, the standard errors of estimate or prediction range from 30–60%. Few equations have smaller errors near 15% and some equations have errors greater than 100%.

d. The applicable ranges of basin hydrologic and climatic characteristics originally used to fit the regression equations are shown in the NSS user interface. A warning is given to the user of NSS when specifying input variables that are outside of such applicable ranges. If the users decide to proceed with using basin characteristics that are outside the applicable ranges, the streamflow estimates are said to be extrapolated. It is noted that the accuracies of extrapolated estimates are unknown; therefore, the users are advised to be careful with using such estimates in any further design or planning applications.

e. The eastern parts of the nation have equations with the smallest flood-peak standard errors, while the western and southwestern parts are characterized with the largest standard errors. This is usually related to various factors such as: length of streamflow historical records used in developing the regression equations, density of gauging stations, natural variability and effects of seasonal variation and sensitivity of streamflow to climatic and hydrologic drivers, and increased sensitivity to relief and aspect that are more pronounced in the west.

The NSS program uses the dimensionless hydrograph method to estimate flood hydrographs. To develop a hydrograph for a site or a watershed under consideration, the user needs to provide two pieces of information. The first is the peak flow value, which can be selected from the frequency output table produced by NSS. The second required variable is the basin lag time (LT). The lag time is a measure of the response time at the outlet of a watershed to a rainfall event. There are several methods and equations for calculating the basin lag time for rural and urban watersheds that vary by state, type of equation, and the required input variables. The NSS manual provides a state-by-state summary of these different equations (See Appendix B in the NSS user manual).

For the most part, the lag time (LT) depends on characteristics such as:
- Drainage area
- Main channel length and slope
- Peak discharge
- Mean annual precipitation
- Land use coverage in the watershed (e.g., percent of area covered by forest, impervious surface, etc.)
- Percent of storage area in the watershed

An example of such equations is the one used in Missouri for rural watersheds:

\[ LT = 2.79L^{0.39} S^{-0.195} \]

Where LT is the lag time (hour), and L (mile) and S (feet/mile) represent the length and slope of the main channel in the watershed, respectively.

In the case of urban watersheds, the NSS Program computes the hydrograph based on dimensionless hydrograph ordinates stored in the program. In this case, the lag time can be estimated by specifying the basin length in miles. However, for rural watersheds, the NSS doesn’t have lag time equations currently stored and therefore the user needs to come up with an estimate for LT.

**Estimation of Flood Hydrographs in NSS**

While the NSS program is mainly used to estimate flood peaks for different return periods, it can also be used to compute a hydrograph that represents average streamflow for a specified flood peak. This representative hydrograph is considered an average design hydrograph that can be used for some design applications, but should not be a representative of any particular rainfall distribution.
Preparation of NSS Input

The input variables needed to solve the regression equations can be obtained from various resources (e.g., maps, aerial photographs, atlases, Geographic Information System (GIS) data layers, statewide flood-frequency reports). Some of these reports and information are included on the NSS website; however, users may need to consult original reports or specific site information to obtain some of the input variables for the regression equations in their particular application. The estimation of input variables for a certain project site can be quite laborious and may involve a lot of manual work; therefore, the USGS has developed a web application known as StreamStats that automates this process and can be used to prepare input for the NSS computations.

Using StreamStat Web-Application for Preparation of NSS Input

Overview of StreamStat

The process of estimating streamflow statistics for ungauged sites using the NSS program involves several manual operations, especially those associated with estimating the input variables that go into NSS (e.g., watershed characteristics). An automated procedure, known as StreamStats, based on web applications has been developed by the USGS to automate the entire process. While this automated process is fast, more efficient, and probably more accurate than manual methods for estimating the NSS input variables and output statistics, the StreamStat program is not available for all states in the United States. The map shown below indicates the specific states for which StreamStat is available. Based on collaboration with state and local agencies, the USGS plans to eventually extend StreamStat availability throughout the nation. More information on the StreamStat can be found on the StreamStats Web page at http://streamstats.usgs.gov/

Implementation Status of the StreamStat USGS Program

The following is a summary of the key features and functionality of the StreamStat program:

- Using a web-browser, the user has access to a map-based user interface showing different states, their hydrologic basins and sub-basins.
- The user can select a certain ungauged site by clicking on it in the map.
- A web-application GIS program delineates the boundaries of the drainage basin.
- If needed, the user has the option to edit the boundaries of the watershed.
- The physical characteristics of the selected drainage basin, which are needed for the regression NSS equations, are computed by StreamStat.
- The computed physical characteristics are fed automatically into the NSS program to estimate streamflow statistics for the selected site.
- The results are displayed in the web browser window.
- The StreamStat application provides the capability to download basin boundary shape files and print maps shown in the user interface.
Example Application of StreamStat

2. Click on “State Application” on the left-side menu.
3. Choose a state of interest (Tennessee in this example).
4. Click on “Interactive Map”; the following window will open showing the state map and its main topographic and boundary features.
5. Use the zoom-in tool on the top menu. Keep zooming onto the site of interest. Keep zooming until you reach a scale (displayed at the bottom) of 1:2000 or less. You can also use the scale scrollbar to zoom into a certain area and scale. Assume you navigated and zoomed into your site of interest. If you zoomed in enough, you should see a link that says “Basin Delineation” activated.
6. Click on “Basin Delineation” and click on the stream location that represents the outlet of your watershed or drainage basin. The StreamStat web application will perform the stream delineation application (it may take a few minutes) and prompts you to confirm the results. The drainage boundary of the delineated basin is now displayed.
7. Click on “Basin Char” to select and display the physical characteristics of the delineated basin.
8. Select all characteristics and click on “Compute Characteristics”; the results are now displayed for the basin.

Feeding StreamStats Output into NSS
These characteristics can now be used as input to the NSS program to compute the desired streamflow statistics, generate flood-frequency plots, and produce hydrographs.

1. Start a new session for NSS and choose Tennessee as the state of your site.
2. Set up a new “Rural” scenario by clicking on “New.”
3. Our site falls in region “MultiVariable_Area_3_CDA_LT_30.2”.
4. Enter the site characteristics that you obtained from the StreamStats program; namely:
   5. Contributing_Drainage_Area = 0.25 square miles.
   6. Stream_Slope_10_and_85_Method = 228 feet per mi.
7. Continue by computing the peak flow statistics.

You can also generate a peak-flow plot by clicking on “Frequency Plot.”

A hydrograph can be generated by clicking on “hydrograph” after specifying the basin lag time (select 0.1 hours as an example):
Using StreamStats to Generate Streamflow Statistics

Alternatively, StreamStat can produce some of these calculations such as the streamflow statistics (but without plots). To do that, click on “Flow Stats” to compute the streamflow statistics of the selected basin. It is noted that StreamStats cannot be used to estimate peak flows in urban streams. This is because equations used for urban streams require an input variable that specifies basin development conditions (basin development factor). StreamStats and its GIS features cannot estimate this factor.

Summary

This chapter covered the regression equations used by NSS to estimate flow peaks for different return periods. Two types of equations were presented: rural and urban. For rural basins, the format and number of input variables in these equations vary from one state to another and within different hydrologic regions in the same state. However, the most common input variables are drainage area, channel slope, basin elevation, among others. For urban applications, a seven-variable nationwide equation is most commonly used. The chapter also emphasized the uncertain nature of NSS streamflow output and explained the four different uncertainty measures computed by the NSS program. Finally, another pre-processing software program, StreamStat, was introduced -- it supports NSS applications and facilitates NSS input preparation. StreamStat is a GIS web-based application that provides an automated procedure to compute basin and climatic characteristics and other relevant information necessary for NSS applications in ungauged sites. It can also be used to solve regression equations and obtain streamflow statistics.
Calculations of Hydrologic Design Peak Flows

Student Assessment

Select the best answer for each question and complete your test online at www.keepingyouinformed.com.

Final Exam

1. The NSS program can be used to compute flow peaks for _____.
   a. All types of streams
   b. Urban streams only
   c. Natural streams only
   d. Streams that have been modified with hydraulic control structures

2. The term “100-year flood” is a statistical designation and is used to indicate the chance (1-in-100) or probability (1%) that a flood this size will occur _____.
   a. During any given year
   b. Every year
   c. Every year in the next 100 years
   d. One year in the next 100 years

3. The magnitude of the peak-flow for a certain basin is expected to _______ with the increase of the design return period.
   a. Decrease
   b. Remain the same
   c. Increase
   d. Vary

4. The lag time is a measure of the _____________.
   a. Response time of a watershed to a rainfall event
   b. Time between a rainfall event and the corresponding flood
   c. Time to peak-flow
   d. Duration of a flood event

5. The most commonly required input variable for NSS applications is:
   a. Area of the drainage basin
   b. Perimeter of the drainage basin
   c. Climatic characteristics over the drainage basin
   d. Stream size

6. The NSS program combines statistics from different hydrologic regions using weights based on:
   a. Return period
   b. Magnitude of flow peaks
   c. Stream length in each region
   d. Sub-area located in each region

7. In interpreting the equivalent years of record as a measure of uncertainty, a smaller value of this measure implies that:
   a. The estimated flood peaks are less accurate
   b. The estimated flood peaks are more accurate
   c. The NSS analysis is completely unreliable
   d. None of the above

8. The lag time for a hydrologic basin depends on:
   a. Drainage area only
   b. Length and slope of main channel
   c. Land use coverage and percent of storage area in the basin
   d. All of the above

9. The seven-parameter urban NSS equations can be used to calculate flood-peak values:
   a. In all basins
   b. Only in basins where flow has not been modified or controlled
   c. In rural basins as well
   d. Only for certain return periods

10. Compared to basins located in the eastern parts of the nation, basins that are located in southwestern parts are characterized with _________.
    a. Same accuracy
    b. Higher accuracy
    c. Lower accuracy
    d. Comparable accuracy