Lecture 3, August 31, 2010 (Key Points)

It was mentioned in lecture-1 that key developments during the 1960s led to *two disparate approaches to hydrologic analyses, one statistical and the other deterministic*. The statistical approach consisted of the regional (spatial) quantile analysis of annual flood frequencies in 'homogenous regions'. The US Geological Survey (USGS) developed it. The deterministic (spatially distributed) approach consisted of semi-empirical physical equations and was meant to predict flow hydrographs and peak flows on the time scales of individual rainfall-runoff events. It was also recognized in the early 1960s that the two approaches must be closely connected because physical rainfall-runoff mechanisms generating floods were the basis for the flood values used in statistical analyses. However, a general theoretical framework for connecting the two, i.e. how the physics of the system could be used to determine spatial statistical parameters began to develop only in the last twenty years.

We will review USGS regional quantile analysis as a starting point. Brutsaert (Ch. 13, Section 13.5, 2005) covers some of this material. Critical question: *Why are we starting the course from the end of the book and not from the beginning, e.g., chapter 2?*

Statistical Regionalization and Prediction in Ungauged Basins

The term *regional flood frequency analysis* refers to an engineering approach to analyze hydrologic data of annual foods and low flows using purely statistical methods, and extrapolate the information to ungauged basins within a *homogeneous region* where no information exists. Drainage basins in many parts of the world are ungauged or poorly gauged, and in some cases existing measurement networks are declining. Regionalization is a well-established approach to extrapolate information from gauged locations to ungauged basins The USGS has led the way to conducting regional analyses in the US. We will use the developments that occurred in the USGS to explain regional flood frequency analysis.

1. Let $Q(A)$ be a random variable denoting the annual floods from a basin of upstream contributing drainage area *A* within a "*homogeneous*" region. The p^{th} quantile denoted by $q_p(A)$ is defined as,

$$P(Q(A) > q_p(A)) = p \tag{3.1}$$

The inverse of the probability $1/p$ is known as the *return period,* T_r. If you are given stream flow record for *n* years, and m is the rank from largest to smallest, of a given flood, then Weibull's plotting position formula is widely used to estimate the probability *p* as,

$$p = 1/T_r = m/(n+1) \tag{3.2}$$

Brutsaert (2005, Section 13.2.4) gives an excellent discussion of the mathematical strengths of the Weibull's formula including its derivation.

2. As an application of the concept of return period, the probability of 1 or more events exceeding the quantile, $q_p(A)$ in n years is given by, $1-(1-(1/n+1))^n$. In the limit as $n \to \infty$, this expression becomes, $1-e^{-1}$= 1-0.368 = 0.632. This means that if an engineer designs a project for, say 100 year return period, then there is 63% chance that the design flood will be exceeded one or more times in the life of the project. It is important to remember this calculation because the concept of 100-year design flood is not always well appreciated.

USGS Regional Flood Frequency Analysis

1. Kinnison and Colby (1945) conducted the first regional flood frequency analysis for the USGS in New England, and developed the *index-flood method*. They had access to the hard work of Langbein (1947), which provided the drainage basin characteristics for their analysis. The index flood method chooses an "index-flood", say the mean annual flood, $q_m(A) = E[Q(A)]$, where $m = P(Q(A) > E[Q(A)])$. The mean annual flood is regressed against various physical descriptors, but drainage area is the most important, and many times the only descriptor used. Regressions of $\log q_m(A)$ against log *A* generally show log-log linearity, which can be expressed as (see eq. (13.90) in the Brutsaert's book),

$$q_m(A) = q_m(1)A^{\theta}, \tag{3.3}$$

2. The *main assumption* of the index flood method is that,

$$q_p(A) / q_m(A) = q_p(1) / q_m(1). \tag{3.4}$$

It means that the same flood quantile ratio q_p / q_m can be used for different size basins, as it does not depend on the drainage area. Then the various "non-dimensional flood frequencies" are plotted, and an average shape for the region chosen. The basin characteristics at a non-gauged site can be used to estimate the mean annual flood, and that, along with the non-dimensional average flood frequency distribution, can be used to determine the flood of any return period at an ungauged site.

3. Dalrymple (1960) documented the index-flood method, and the USGS developed a national flood-frequency program, based on the 14 parts of the United States into which the nation was divided by major drainage basins. The USGS began producing flood frequency reports on a state-by-state basis based on the index-flood method. A given state was divided into homogeneous regions, and a non-dimensional flood frequency relation was developed for each region. However, larger drainage areas were found not to fit the regional relations, and separate relations were developed for use along the major rivers in a state.

4. The fact that larger drainage areas did not fit the general relations, and the general opinion that a single non-dimensional flood frequency relation did not hold in general, led to the establishment in 1956 of a research project on flood frequency analysis headed by Manuel Benson. Benson held several strongly held views, which influenced the direction of USGS methods in flood frequency analysis, and thus the direction outside the USGS. Benson did not believe that any distribution held for floods in general, so that data should be plotted and the floods of each return period (or probability, because return period is the reciprocal of probability as shown in eq. (3.2)). Thus, the problem of plotting position became important. The USGS chose the Weibull plotting position given in eq. (3.2). The USGS chose the annual flood series rather than the partial-duration series (all floods above a given base) because of its statistical properties. Langbein (1949) had shown that the two series were directly related. *Benson further believed that flood frequency curves for recorded streamflows should not be extended much beyond their period of record.*

5. Benson (1960a) first published a history of flood frequency methods up to 1960, then produced a pair of reports on regional flood frequencies in New England (Benson, 1960b) and the Upper Rio Grande (Benson, 1960c). The latter two papers laid down the procedures, now called the quantile method, adopted by Benson and followed, with some amendments, till to today. The quantile method is so called because the flood frequency relations for each measured site is estimated and values are picked off at chosen probabilities of occurrence, or quantiles.

6. Many different frequency functions are available but the USGS commonly uses log-Pearson type III (Brutsaert, 2005, Section 13.4.4) for historic administrative reasons that we will not discuss here. For the same return period, the quantile at each station is regressed against physical descriptors, of which drainage area is the most important, and many times the only descriptor used. The regression equations so obtained are then used to make predictions within the same region where no stream flow data exists. Regional flood and low frequency analyses have served as engineering solution to the predictions in ungauged basins (PUB) problem.

7. The quantile regression approach has been extended to water quality and other physical variables as well. But the approach lacks any connection with the physical processes that transform rainfall to runoff and generate floods and low flows. Different district offices of the USGS publish annual reports on regional flood and low frequency analyses.

Rainfall-Runoff Models For Deriving Flood Frequencies

1. Federal agencies other than the USGS often use deterministic rainfall-runoff models for flood frequency analysis. The general procedure is to estimate a storm, which is designed to produce a peak of a given frequency when used in conjunction with a deterministic rainfall-runoff model. The two most well known are the HEC-1 model of the Corps of Engineers (Hydrologic Engineering Center, 1990), which actually

is a suite of models from generalized unit hydrograph methods through distributed parameter rainfall-runoff models, and the well-known SCS Curve Number model (Soil Conservation Service, 1973). The SCS model has been adopted by many local flood control agencies because of its simplicity of use. Although developed originally for design of farm ponds, and the original use was for storm volumes, with a warning that it was not to be used for continuous streamflows, the SCS method is now widely used for deriving excess rainfall for use with the SCS unit hydrograph to generate peaks of given recurrences.

2. The most advanced attempt to use deterministic rainfall-runoff model to obtain a flood frequency distribution is that of Eagleson (1972). He took a distribution of rainfall and passed it through a representation of the basin as a response function to generate a flood frequency distribution. He demonstrated that a deterministic representation of basin could be combined with knowledge of the statistical rainfall characteristics of the basin to derive a flood frequency distribution for the basin. However, the approach has not been developed to the point of application in practice.

Impact of USGS Regional Flood Frequency Equations

1. The statistical approach of the USGS is data intensive, and depends on their extensive stream-gauging network. A Federal Interagency Committee undertook an inter-comparison of methods for the prediction of flood frequency discharges at ungauged sites, and the USGS quantile method was minimum variance and least biased of all the models compared (Newton and Herrin, 1981). Various improvements have been made by the USGS in their estimation of quantile discharges. They use a generalized least squares method and give a weighted estimate of the at-a-station data and the regional data. They are moving toward an approach, which uses all nearby data to determine a unique discharge at any ungauged site, rather than deriving standard regional flood frequency equations.

2. Because of the USGS regional approach and its wide use, many studies of regional flood frequency methods have been undertaken. The USGS has developed an "equivalent length of record" for their regional equations, and has developed worth of data and network design approaches based on the statistics of their data network.

Reading Assignments:

1. Sections 13.2.1, 13.2.2, 13.2.3 (review of probability)

2. Sections 13.2.4 and 13.5.2.

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