

FLOOD FREQUENCY BASED DESIGN

Lawrence H. Woodbury, P.E. and
Rick R. St. Germain, P.E.
Houston Engineering, Inc.
Fargo, North Dakota

INTRODUCTION

The Red River Basin Flood Damage Reduction Work Group has proposed goals for flood damage reduction in the Red River Basin. One of the goals is to provide protection to intensively farmed agricultural land from a 10-year summer storm. The Work Group asked the Technical and Scientific Advisory Group to write this paper to explain what is meant by a 10-year summer storm in laymen's terms. **In its simplest form, this goal would mean a property has a 10% chance in any one year, during a summer storm, of being flooded by water from another property.** To understand what this means takes further explanation.

In general, all water resources projects are comprised of physical components such as channels, pipes and culverts, detention dams, erosion control structures and stilling basins, and drop structures or chutes. The engineering hydraulic design of these structures requires some knowledge as to the amount of water that will pass through the facilities. The amount of water is usually characterized in terms of volume (cubic feet, acre-feet, etc.), or volumetric rate of flow (cubic feet per second, acre-feet per month, etc.). The determination of flow rates for the design of hydraulic structures is commonly termed hydrologic engineering.

All water resources projects are planned for the future, and the hydraulic engineer is uncertain as to the precise conditions to which the works will be subjected. The structural engineer knows the intended loads for the structure but has no assurance that these loads will not be exceeded. He or she does not know when the earthquake loads may be exerted on the structure. This uncertainty is countered by making reasonable assumptions allowing a generous factor of safety. The water resources engineer is less certain of the flow that will affect the project. The hydrologic uncertainties are by no means the only ones in hydraulic design - future water requirements, benefits, and costs are all uncertain to some degree - but a serious error in the estimates of the expected hydrology can have devastating effects on the economy of the entire project.

Since the exact sequence of stream flow for future years cannot be predicted, something must be said about the probable variations in flow so that the plan or design can be completed on the basis of a calculated risk. Thus, the design of water resources projects is pursued based on a risk-based hydrologic design.

FLOOD FREQUENCY CONCEPTS

A commonly used parameter for determining the capacity of existing rivers or channels, or for the design of rivers, channels, dams and other hydraulic facilities is the return period of the

hydrologic event. The hydrologic event is defined to be a period of high discharge occurring after a time of heavy precipitation or heavy snowmelt runoff. The period of high discharge is usually characterized by volume of runoff (in acre-feet or cubic feet), peak rate of runoff (cubic feet per second or acre-feet per month), and duration of runoff (hours, days, or another time period). The return period is defined as the average elapsed time between occurrences of an event with a certain magnitude of peak discharge or greater. For example, a 25-year peak discharge is a discharge that is equaled or exceeded on the average once every 25 years over a long period of time. It does not mean that an exceedence occurs every 25 years, but that the average time between exceedences is 25 years. An exceedence is an event with a magnitude equal to or greater than the specified discharge value.

Sometimes the actual time between exceedences is called the recurrence interval. With this definition for recurrence interval, the average recurrence interval for a certain event is equal to the return period of that event. The concept of return period can also be applied to low flows, droughts, shortages, etc. In these cases, the return period would be the average time between events with a certain magnitude or less.

Regardless of whether the return period is referring to an event greater than some value or to an event less than some value, the return period can be related to a probability of exceedence. If an exceedence occurs on the average of once every 25 years, then the probability or chance that the event occurs in any given year is $1 \div 25 = .04$, or 4%. Thus, probability of occurrence and return period are directly related.

WHY DO ENGINEERS DESIGN FOR A SPECIFIED FREQUENCY?

Floods are significant climatically controlled random hydrologic events. The occurrence of floods is studied as a probability problem, and knowledge of the probability of flood occurrence is needed for a variety of engineering and economic reasons. These needs and potential uses have led to a considerable effort over many years to develop systematic procedures for analyzing flood probability.

The design of a drainage channel or a culvert is a typical example where the selection of a design frequency runoff is critical. If one were to design these facilities for the largest flood possible, the occurrence of that flood event would be very infrequent. For example, if one were to design a channel system for a 100-year event, the channel would be required to convey the entire flow of the 100-year event and all floods of lesser magnitude. If a channel were designed for a 10-year event, then this channel could be expected to have its capacity exceeded for events greater than the 10-year event. That is, damages would occur for 25-year, 100-year, or greater events. Designing a channel system for the 100-year event would be much more expensive in terms of excavation requirements and culvert sizes than designing the same channel system for a 10-year event. However, the costs of constructing the larger channel may not outweigh the benefits of flood protection for the 100-year event. Thus, the selection of design frequency becomes an analysis of benefits received versus costs of a project.

The determination of a design frequency for a water resources project becomes a matter of economics. In some cases, such as the design of a high hazard dam, public safety may also

play a consideration in the determination of design frequency. That is, it may be desirable in the design of a high hazard dam to design for a very large return period such as a 500-year flood or larger.

Typical design frequencies that have been adopted in the Red River Valley for the design of drainage channels range from 2-year to 10-year. In some cases, major federal projects have been designed for frequencies as large as a 25-year return period. The selection of a 2-year design for a channel system may be dictated by the perception or reality of limited benefits to be accrued from the presence of the drainage system with a 10-year design. Therefore, a less costly project is determined to be more desirable. On the other hand, the design of a 10-year frequency ditch system would involve the realization of significantly more benefits in terms of flood damage protection and increased crop production.

The design of hydraulic structures such as dams, concrete chutes, and drop structures involves a significant capital investment. Should the capacity of these structures be exceeded, the economic loss would be substantial and replacement would be difficult. Therefore, the design frequency for structures such as these are usually of greater magnitude (50-year, 100-year, or greater). That is, the project owner is willing to expend more money in providing for hydraulic capacity in order to insure against an expensive loss or repair. As has been pointed out previously, an additional factor that enters in in the selection of design frequencies for such structures is the hazard potential for the failure of these facilities in terms of public safety.

DESIGN FREQUENCY VERSUS PEAK FLOW VERSUS STAGE

There are several common misconceptions concerning the meaning of design frequency and the conversion of design frequencies to flow rates or peak stages. For example, one perception is that a 10-year design flow rate is twice as large as a 5-year design flow rate. In fact, the 10-year design flow rate is approximately 1.36 times the magnitude of a 5-year flow rate, while the 50-year event is slightly more than twice the magnitude of the 5-year event. The following table represents some approximate relationships between the magnitude of peak discharges and their associated frequencies using the 50-year flood as the common denominator:

Comparison of 50-Year Event
with other Design Frequencies

Design Frequency Return Period	Percent of 50-Year Event
2	23
5	44
10	60
25	82
50	100
100	118

The above general relationships were derived from USGS relationships derived in 1997 for the Red River Valley. **More specific relationships exist for particular watersheds, however, the above table may be used as a guide in general discussions.**

The second misconception concerns the relationships between flow rate and stage. This misconception revolves around the idea that doubling the peak discharge will double the stage of the river or channel. In fact, as the stage in a river rises, the top width of the river also greatly increases. This is especially true when the river stage exceeds the normal bank capacity and expands laterally into the flood plain. When this happens, each additional foot of increase in stage multiplies the amount of flow rate conveyed by many times. Or, a very large increase in discharge will result in a very small increase in flood stage. Conversely, at very low flow conditions, a large increase in discharge may result in several feet of increase in stage. The same concepts hold for the volume of water contained in a lake or reservoir relative to the stage of the lake or reservoir. As the lake or reservoir increases in stage, each additional foot of stage increase results in an increase in volume many times greater than stage increases at low reservoir or lake level.

RAINFALL FREQUENCY-DURATION-RUNOFF RELATIONSHIPS

An important factor in the hydrology of water resource projects is the concept of rainfall and runoff. The amount of runoff from a rainfall event is dependent on a variety of factors, including retention, infiltration, and evapotranspiration. The amount of retention, infiltration and evapotranspiration that occurs is related to such things as soils, vegetation, slope, antecedent moisture conditions etc. A common method of estimating runoff from rainfall is the method presented in the Soil Conservation Service's (now called the Natural Resource Conservation Service) National Engineering Handbook. The method is commonly referred to as the "curve number" method. This variable used in this method includes soils, land use, vegetation, slope of the land, antecedent moisture conditions and storm duration. Knowing these variables, the hydrologist can predict the amount of runoff that can be anticipated from the watershed. This method is applicable to both urban and rural landscapes.

The duration of a rainfall event is important in the design of most water resource projects, especially those having a storage component. The duration of a design storm generally gets larger with the project drainage area. For typical urban storm sewer design, (when detention ponds are not used), the design storm is generally less than 1 hour. In this application, the designer is generally designing for high intensity storms of short durations where peak flow rates are more important than the actual runoff volume. In flood storage design projects, the duration of a storm is commonly greater than 24-hours. The designer will generally look at a number of durations to determine which storm is the most critical. An important tool used by the hydrologist is rainfall intensity-duration-frequency curves. These curves are usually developed statistically from information gathered at weather recording stations.

The following table illustrates some of these relationships. The information is typical of a small rural area in the central Red River Valley area. The amount of rainfall and runoff will vary slightly from these typical values depending on your location, the size of the watershed being investigated, and the landscape features. These values should be used for general discussions only.

Typical Rainfall Frequency Duration Runoff Relationships
Summer Conditions

Return Period	Duration	Rainfall	Runoff
10-year	24-hour	3.57"	1.35"
100-year	24-hour	5.25"	2.65"
10-year	10-day	6.39"	2.00"
100-year	10-day	9.35"	4.12"

This example assumes a curve number of 75 (24-hour) and antecedent moisture condition II (typical of conditions prior to a storm event).

In northern climates, snowmelt is usually the cause of most floods especially when combined with a spring rain. The Red River Valley is no exception. This is a complex phenomenon and it is difficult to say there is such a thing as a typical spring flood. The Hydrology Guide for Minnesota by the U.S. Department of Agriculture (Figure 1-12) has developed a frequency-runoff relationship for the 100-year, 10-day event that includes spring snowmelt. The following table illustrates the volume of water that can be expected during the spring runoff from a small watershed in the central Red River Valley. Again, the amount of runoff will vary slightly from these typical values depending on your location, the size of the watershed being investigated, and the landscape features.

Typical Frequency Duration Runoff Relationships
Including Spring Runoff

Return Period	Duration	Runoff
10-year	10-day	3.8"
100-year	10-day	5.7"

From this data, it is apparent that the spring events produce the largest volume of runoff.

REFERENCES

1. Linsley, R. K. and Franzini, J. B. (1979). *Water Resources Engineering, Third Edition*. McGraw-Hill Book Company, New York. 110 pp.
2. Weather Bureau, U.S. Department of Commerce. (1963). *Rainfall Frequency Atlas of the United States for Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years*. Technical Paper No. 40.
3. Weather Bureau, U.S. Department of Commerce. (1964). *Two-to-Ten Day Precipitation for Return Periods of 2 to 100 Years in the Contiguous United States*. Technical Paper No. 49.
4. Lorenz, D.L., Carlson, G.H., and Sanocki, C.A., U.S. Geological Survey. (1997). *Techniques for Estimating Peak Flow on Small Streams in Minnesota, Water-Resources Investigations Report 97-4249*. Mounds View, Minnesota
5. U.S. Department of Agriculture, Soil Conservation Service. *Hydrology Guide For Minnesota*. St. Paul, Minnesota.