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Hydrologic estimates
for small hydroelectric projects

NRECA Small Decentralized Hydropower (SDH) Program

Hydrologic estimates for small hydroelectric projects

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Section 1

Introduction

A. The purpose of this manual

Technologically sophisticated procedures are available and widely used for the selection, planning, and development of hydropower. Most of them are not useful for small watersheds in developing countries, where few streams have been gaged and there is little long-term data on streamflow characteristics. Potential investors justifiably want detailed, comparative hydrologic analyses of candidate sites, but the cost of gaging all possible sites could make the front-end costs of mini-hydropower development excessive, not to mention time delays.

The methods presented include techniques for visual detection of clues to historical flood levels, guidelines for questioning inhabitants in the neighborhood of the stream, and equations and tabular data for calculating peak discharge from the scanty data likely to be available.

It is hoped that this approach will be tested on sites in many countries and that criticism and constructive suggestions will be passed on to NRECA so that these procedures can be further adapted, refined, and improved. Comments on this document* are welcome.

This manual describes methods and includes sample calculations for--

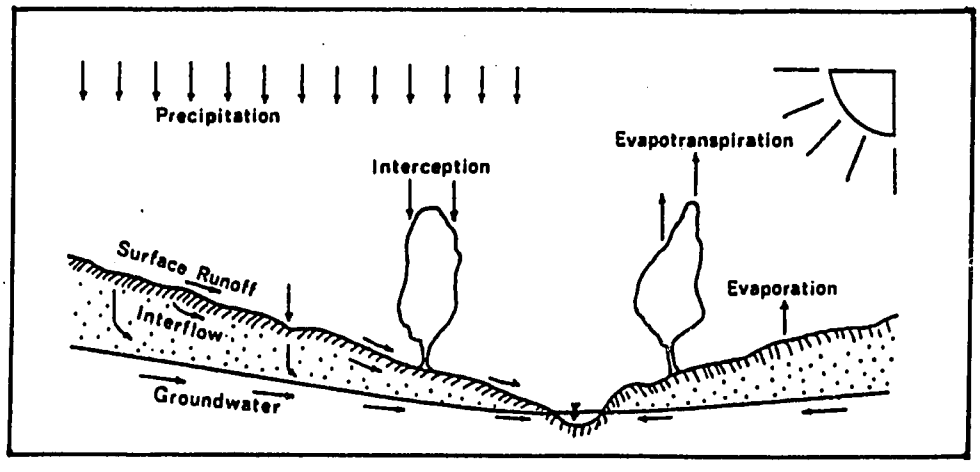
(1) Estimating the peak streamflow at a site, and
(2) Estimating the flow-duration curve at a site.

It describes ways to collect field data on historic flows for peak flow and flow-duration estimates and calculation techniques for peak flow and flow duration based on related meteorologic data and watershed characteristics. The methods described can be applied to watersheds of up to 1000 square kilometers in areas where snow accumulation and melt is minimal and where streamflows are not regulated by large lakes or reservoirs. These methods will provide reasonable hydrologic estimates when used by technical or professional persons. The hydrologic analysis of a site should require less than 5 days of technical or professional time.

The goal of this manual is to detail selected, simple methods for obtaining hydrologic estimates for small projects that use field

*This report was prepared for NRECA by Dr. Norman H. Crawford and Steven M. Thurin of Hydrocomp, Inc.

Figure 1
The hydrologic cycle



data usually available in developing countries. Comprehensive methods that use more extensive field data can be used for larger hydroelectric and water resource projects.

There is a short glossary at the end of this document.

B. The basis of hydrologic estimates

The hydrologic cycle (figure 1) operates continuously in all watersheds. The hydrologic information needed for a hydroelectric project are a peak flow and the flow duration at the site. The basic hydrologic processes that produce peak flow and flow duration at a site are described below.

Peak flows are caused by high intensity storm rainfall. Rainfall that moves as surface runoff into stream channels produces a "flood hydrograph." The rest of the rainfall infiltrates into the soil and is "lost." It will later evaporate or transpire or will provide groundwater flow into the stream.

The factors that must be estimated or calculated to estimate peak flows are the--

(1) Rainfall intensity and duration on the watershed
(2) Amount of "losses" or infiltration during the storm, and
(3) Flow time and storage in stream channels.

Flow duration for a watershed is the percent of time that flows exceed specific levels. The factors that control flow duration are the--

(1) Annual cycle of precipitation, potential evapotranspiration, and actual evapotranspiration in the watershed.
(2) Amount of rainfall that infiltrates and moves on subsurface flow paths into stream channels. Infiltration rates depend on the permeability and depth of the watershed soils.
(3) Subsurface flow velocities and the storage capacity of subsurface aquifers.

C. Limitations of the hydrologic methods presented in this report

These methods operate with limited field data and produce results of moderate accuracy.

The most important factor in the accuracy of a hydrologic estimate is the accuracy of the meteorologic data on which it is based. If the 24-hour--100-year frequency rainfall on a watershed is 60 mm, and a 45 mm amount is used in calculations, the calculation for peak streamflow will give an incorrect result.

The calculation techniques in this manual are based on sound hydrologic principles and represent the key processes in flood flows and continuous monthly streamflows. They do not include processes like snowmelt or detailed hydraulic routing and should not be used where snowmelt is a key process or where there are large lakes or reservoirs. They apply to small watersheds, generally of less than 1000 square kilometers.

Section 2

Hydrologic processes

The hydrologic cycle was sketched in figure 1. The water in the system comes from precipitation. It will either infiltrate through the land surface into the soil or move toward stream channels as surface runoff. Water that infiltrates may move as subsurface flow or may be evaporated or transpired by vegetation. In most watersheds, the amount of water lost by evapotranspiration is larger than the amount of water that becomes runoff. Runoff water moves over the surface as direct flow to streams or moves subsurface as delayed or groundwater flow. Direct runoff may cause floods, while the delayed subsurface flows provide continuous or low flows to the rivers.

Two types of information are needed for a hydroelectric site. First, the flood flow or expected maximum water level is needed to size a spillway (if any), to locate turbines and generators above the highest expected water level, and to design diversion structures or canals. Second, the statistical distribution of monthly streamflow volumes is needed to estimate the reliability of the site for the production of a given amount of electrical power and to size the turbine.

D. Peak discharge

Peak flows result from a combination of heavy rainfall and high soil-moisture levels, which prevent the water from moving into the soil. Peak flows on small watersheds are frequently caused by thermal or thunderstorm rainfall. Peak flows on larger watersheds are caused by a series of storms or by snowmelt.

Flood flows are plotted on special semilog scales. If flood flows are measured for a period of years, this historic data can be used to estimate the magnitude of floods statistically. Hydrologists refer to 50-year or 1-year floods, which are the flood levels that would probably be equaled or exceeded only once in 50 or 100 years. To estimate peak discharges, a hydrologist must estimate the maximum rainfall rates that will occur in a watershed for the duration or length of storms expected to cause a maximum flow. The runoff from this rainfall must then be estimated. The difference between the rainfall and the runoff will be the infiltration through the soil surface during the storm event.

When rainfall exceeds the capacity of the soil to absorb water, surface runoff occurs and enters the river channels, during and immediately after the rainstorm. It flows through the river channels and is measured at a streamgage as a flood hydrograph and a peak flow. When rainfall on a watershed is plotted together with streamflow from the watershed, the close relationship between rainfall and peak flow is clear.

The factors that determine the peak flow or maximum flow in a flood hydrograph are the intensity of the rainfall that causes the runoff; the amount of water that infiltrates and follows the slower, subsurface paths to the stream channel; and the amount of attenuation or subsidence of the peak flow as it moves through the river channels to the streamgage. The first factor, the intensity of rainfall over the watershed, is a characteristic of the climate of the region. In the United States, for example, a rainfall of 30 mm per hour is a "heavy intense storm" in Seattle, Washington, but it is a "light rainstorm" in Houston, Texas. Data on the intensity of rain that is to be expected in the watershed is needed.

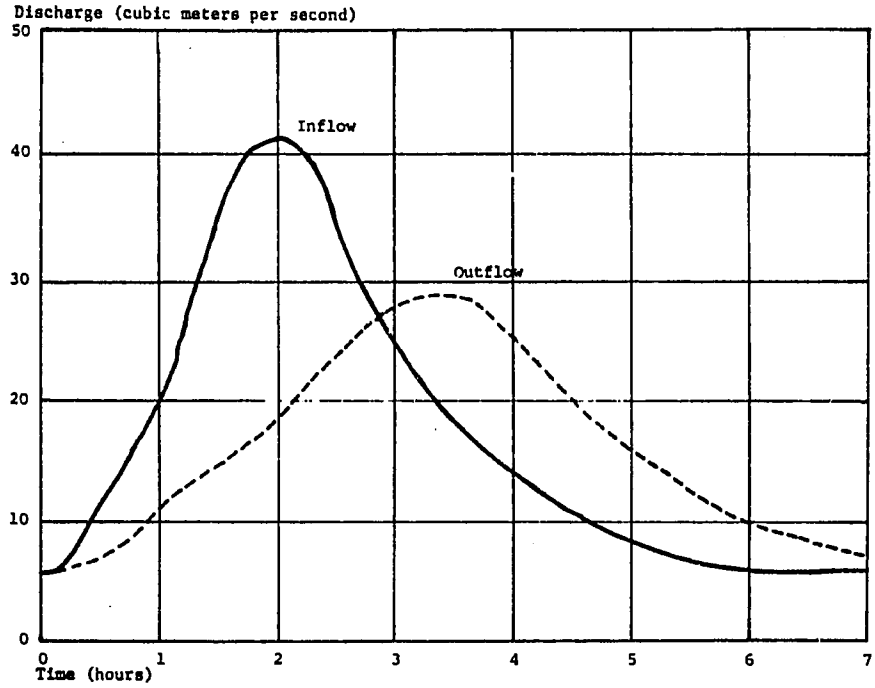
The second factor that determines flood magnitude is the amount of water that is absorbed through the soil to follow the slower subsurface flow paths. Infiltration rates or losses depend on soil properties and on soil moistures. Soils may range from tight, low permeability clays, to high permeability silt and sand. Soils with high permeability, like sandy loam soils and forest soils that have thick organic layers of decaying vegetation, absorb water quickly. In watersheds that have high infiltration capacities, surface runoff may be unknown. Soils of low permeability, such as clay, will absorb very little water and there will be surface runoff.

When a rainstorm breaks a long dry spell, soil moistures will be low and the amount of water that infiltrates or is absorbed by the soil will be high. If a rainstorm is the latest of a series of storms, soil moistures will be high and the amount of water absorbed by the soil will be low. The soil moistures that can be expected at different times of the year in a watershed are also a function of the climate. In humid climates where the rainfall is always well in excess of the potential evapotranspiration, soil moistures remain high. In arid climates where the potential evapotranspiration exceeds the rainfall, soil moistures are usually low.

The runoff that enters stream channels from the land surface may be modified substantially as water moves through stream channels toward a gaging site. Flood waters that enter a natural lake or reservoir are "routed" or attenuated as they move through the reservoir. The peak flow leaving the storage may be much less than the peak flow entering the storage. This is illustrated in figure 2.

Flow along natural channels in a river basin also tends to attenuate. The maximum rate of discharge, expressed in units of flow per unit of watershed area, tends to decrease as the flood moves downstream. Hydrologists account for this attenuation process by using "flood routing" or "flow routing" procedures. The amount of attenuation of a flood in a watershed depends on the length, shape, and roughness of the channels. If the channels have broad vegetated floodplains and if the flood moves out of the

Figure 2
Flow routing through storage

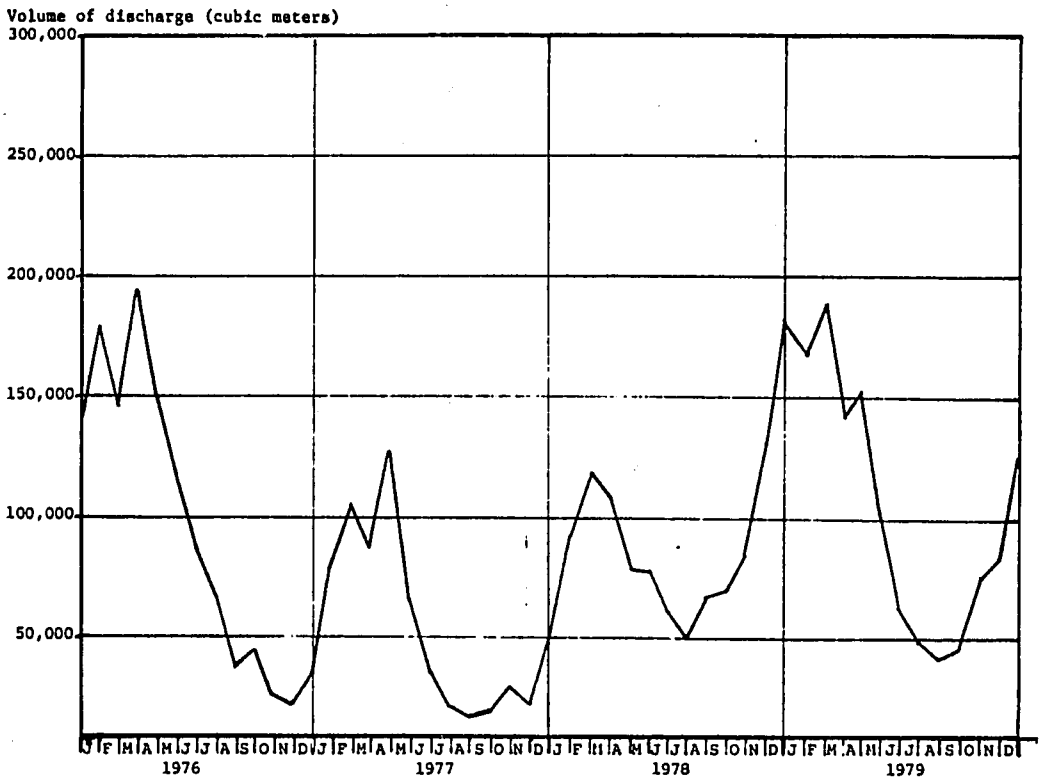


incised channels onto the floodplains, the attenuation of peak flows will be dramatic. If the channels in the watershed are narrow and steep, and flow velocities are high, the attenuation of flood peaks will be much less. If flows move into natural lakes, swamps, marshes, or manmade reservoirs, reduction in peak flow due to "reservoir routing" like that shown in figure 2 can be expected.

In summary, the problem of estimating peak flow on a natural watershed requires—

(1) Data on rain storms that will occur in the region, and on the maximum rainfall intensities that will occur.
(2) Estimates of the infiltration losses that will occur during the storm event. This infiltration will depend on typical soil-moisture levels and on the characteristics of soils in the watershed.
(3) The attenuation of peak flows as they move from the headwaters of the watershed through the basin.

Figure 3
Monthly flow volume in a stream



E. Minimum discharge

Low flow periods in streamflow can be seen in figure 3. The lowest flows are reached during droughts when very little rainfall has occurred for an extended period of time. Just as the peak flows or maximum flows are reduced by water that is absorbed through the soil surface, the low flows are increased by this infiltrating water as water is supplied to the stream channels by the subsurface or groundwater flow paths that were shown in figure 1. Thus, the factors that control the low flow in a stream are the length of the minimum rainfall periods, the amount of water that is absorbed through the soil surface during rainstorms, and the time needed for water to flow along the subsurface or groundwater flow paths.

The climate in the watershed controls the length of drought periods. In areas that have seasonal rainfall, there may be a drought for several months of each year. In these climates, the lowest flow will occur toward the end of the annual dry season and

will be much lower than the minimum flow in an area where rainfall occurs throughout the year. In arid climates where the potential evapotranspiration exceeds the rainfall, minimum flows will be less than in humid climates where the rainfall is greater than the potential evapotranspiration.

The subsurface flowpaths in a watershed are stable and predictable. If a watershed is known to have a minimum flow over a 10-year period of 10 cubic meters/second, it is unlikely that the minimum flow will suddenly drop to 2 cubic meters/second. Low flows respond to cumulative climate changes. One or two weeks of dry weather will not cause unusually low flows in a watershed, but low rainfall for a period of 6 to 36 months may result in the minimum observed low flow. A large subsurface groundwater storage will take months rather than weeks to react to a change in climate. Even limited observations of low flows are very helpful in documenting the low-flow regime in a watershed.

The hydrologic processes important to low flow in streams occur at and below the land surface. Water that is infiltrated at the land surface may move along the subsurface flowpaths into the stream channel with time delays ranging from weeks to years. These time delays are much longer than the time delays in channel flow. When water enters a river channel, the typical time delay to move to a downstream measurement point is hours to days.

But an important exception to this rule is a channel system that contains major lakes or marshes. They may store water during flood periods and release it slowly over a period of months, causing low flows to increase. Alteration of natural channel storage to increase low flows in a stream is the goal of a storage reservoir.

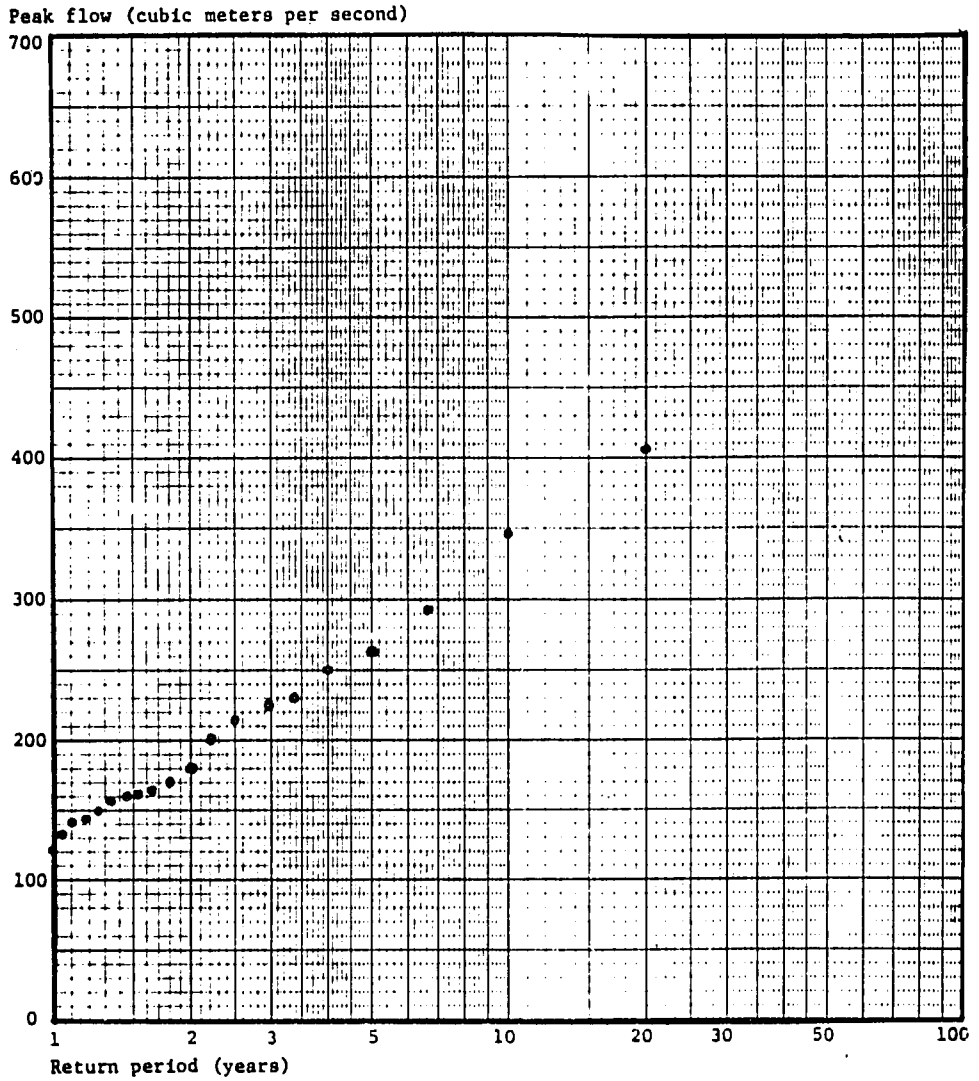
In summary, to estimate the minimum discharge in a stream, the important factors are the--

(1) Climate of the watershed and the duration of drought periods
(2) Infiltration of rainfall through the soil surface and water movement into the subsurface groundwater flow paths
(3) Typical time delays on the subsurface flow paths, and
(4) Marshes, lakes, or reservoirs (if any) that are present in the watershed.

F. Frequency of high and low flows

The continuous measurements of streamflow plotted in figure 3 showed both the high and the low flows from a watershed. It is sometimes convenient to reorganize these data to show the frequency of high or low flows separately on semilog graphs as in figure 4. For example, for high flows, the peak flow measured

Figure 4
Flood frequency: Peak flow vs. return period



each year for a series of years can be plotted. If 20 years of data are available, the flood flows are listed in order of magnitude and the highest flow is assumed to recur once in 20 years, the second highest flow, once in 10 years, the third highest flow once in 6.67 years, and so on. This allows the points to be plotted on the graph, as shown in figure 4.

Peak flows for many watersheds produce linear or near linear curves when plotted on semilog paper. These flood frequency curves are used to estimate floods for project design. A designer

might choose to design a structure for a once-in-100-year flood, a flood that would be equalled or exceeded an average of once every 100 years.

Flood frequency curves like figure 4 are strongly influenced by the maximum historic flood that has been observed. When historic flows in a watershed are not directly measured, newspaper accounts of the floodmarks or memories of local residents may be sufficient to estimate the maximum discharge for historic floods.

Minimum flows can be treated like maximum flows. A frequency curve of the minimum discharge each year could be prepared and plotted using the same procedure that was described for peak flows.

A very useful technique for graphically representing the continuous flow measured in a watershed is the flow-duration curve. To construct a flow-duration curve, assume that table 1 is the monthly volume of runoff for a year in a watershed. These runoff volumes are rearranged in order of magnitude in table 2. The data in table 2 are plotted in figure 5. It can be seen in figure 5 that the runoff equals or exceeds 100 million cubic meters 40 percent of the time. The runoff exceeds 175 million cubic meters 20 percent of the time.

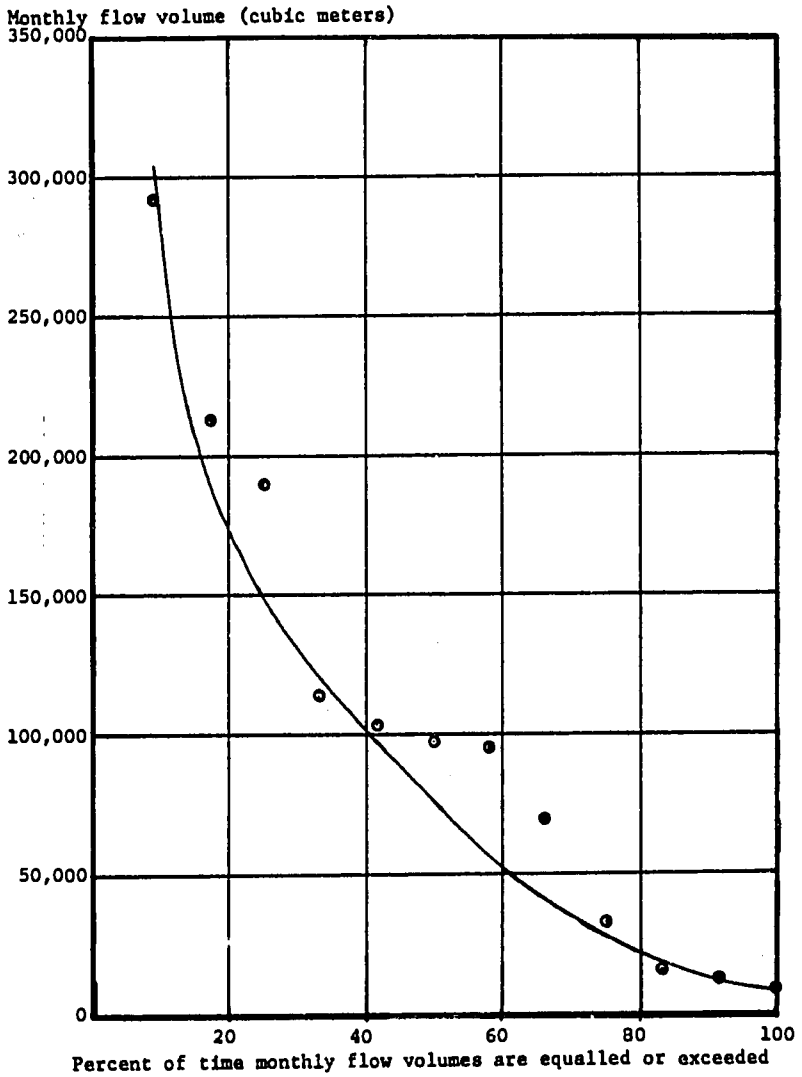
Table 1
Monthly runoff volumes

Month	Volume of runoff (cubic meters)
January	102,300
February	189,000
March	291,900
April	211,600
May	98,700
June	32,000
July	12,600
August	8,700
September	14,500
October	68,000
November	96,100
December	113,400

Table 2
Monthly runoff volumes in order of magnitude

Rank	Volume of runoff (cubic meters)
1	291,900
2	211,600
3	189,000
4	113,400
5	102,300
6	98,700
7	96,100
8	68,700
9	32,000
10	14,500
11	12,600
12	8,700

Figure 5
Flow-duration curve for monthly flow volume



The flow-duration curve is very useful for study of projects that divert water from a river for water supply, irrigation, or hydroelectric power production. Flow-duration curves can be constructed from any period of streamflow data but are more reliable if they are constructed for several years of streamflow data. Flow-duration curves use all of the streamflow information that is available at a site, while peak-flow and low-flow frequency studies select out maximum or minimum flows for analysis. In locations where very little streamflow data is

available, it may be feasible to construct the flow-duration plot but not peak-flow and low-flow frequency curves. Of course, both peak-flow and low-flow frequency curves and flow-duration curves increase in accuracy as the length of the basic data observations increases.

Section 3

Estimating peak flow at a site

To estimate the peak flow that could occur at a potential hydroelectric site, one should (1) study the watershed to find out what high flows have occurred in the past, and (2) study the data on the watershed to calculate what high flows might occur in the future. Section G describes how to perform field studies at a site to find out about past high flows. Section H shows how to calculate future peak flows using the available information about the watershed. Section I tells how to combine the answers from sections G and H to produce a final result.

G. Field study

The field study of the watershed will answer the question, "How large have past floods been?" Two methods will be used to find out how high the water has been. The methods are to--

(1) Study the physical features near the stream to find signs of high water, and
(2) Talk to people living near the stream and to officials in the area about past floods.

Once the high water mark has been determined, you can use some calculations to find the flowrate for that water level.

These are explained below:

1. Physical signs of high water

The purpose of this section is to gain an understanding of how the water level in the stream varies. Write down the important observations that you make as shown in figure 6.

Flowing water moves many objects that it touches. Grass, branches, and other light objects float along near the water surface. Earth and sand are eroded by fast-moving water and carried downstream, or are left on beaches or in pools. To begin your survey of the stream channel, stand on the bank of the stream and watch the edge of the stream as it flows against plants and rocks or sand. Imagine that the water level is higher by 1 or 2 meters, and see what would be under water. Look for signs, like eroded tree roots or sand or gravel beaches, which indicate that the water has been at that level.

If water is not moving very fast or is flowing through bushes and trees, light objects which are floating will often become caught in the branches or left on floodplain lands when the water level goes down. Look for clumps of grass and sticks caught in the trees or on beaches as you move away from the stream.

Look at the general slope of the land towards the stream. Water will always form a flat surface. If you find a high deposit of old floated material, imagine that the water is at that level everywhere, and determine what area would be under water. Look at the ground at the same elevation as your high-water level. Are there signs that the ground has been under water? Look for large branches and logs which might have floated to the edge of the stream during a flood. Once you have found what appears to be the highest deposit of flotsam, look for other signs that the water was once at or near that level. Look for marks on trees or buildings or more branches or logs at the same height.

Look at the deposited material and try to determine how long it has been there. Is the organic material totally decayed? If so, it is probably more than 2 years old. Look for growth of vegetation which has occurred since the floating material was laid down. Wave action at high water levels will very quickly form a beach, eroding fine materials and leaving a deposit of sand and gravel along the stream bank. Signs of beach erosion can remain visible for several years after a major flood. How old are the plants which are growing over the sand deposits and eroded areas?

After getting some idea of how high the recent water levels have been, talk with local residents about high flows, as outlined in section G2. If you have some information from the plants and soil deposits near the stream, it will be easier to evaluate the recollections of residents about high flows. Keep in mind, however, that you may not have seen signs of any flood which occurred more than 2 or 3 years ago, while longtime residents may remember floods from over 50 years ago. You may learn of floods which were considerably larger than would be indicated by the evidence you have seen near the stream.

2. Interviews with residents and historical accounts

The next step is to use the knowledge of the stream obtained from your field survey to interview local residents and to draw conclusions about past flood levels. People who have lived for a long time near a stream may remember large floods quite well. If a historic flood was large and if water marks remained visible for some time, residents will know the highest water level and when the flood occurred. A sample of the interview notes you might take is shown in figure 6.

By talking with several people and by comparing their recollections, you may get accurate information on the largest floods in the past 50 years. Start an interview with a general discussion of the stream and of how it behaves throughout the year, and evaluate whether or not the person being interviewed is familiar with the river. Next, mention physical evidence of past floods near the stream. Finally, ask the person being interviewed to point out marks where the high water has been recorded or where he remembers high water.

Figure 6

An illustration of peak-flow field observations

10/27/81--Started field study, looking for high-water marks on east bank, 500 meters upstream from road crossing. Found large mass of decayed dry grass and branches 5 m above waterline in a tree. Debris appeared to be several years old. Observed other smaller bunches of debris at slightly lower elevations.

Found sand deposit 25 meters from bank. Significant plant growth indicates it has been there for at least 5 years. Elevation is 4.5 m above current water level.

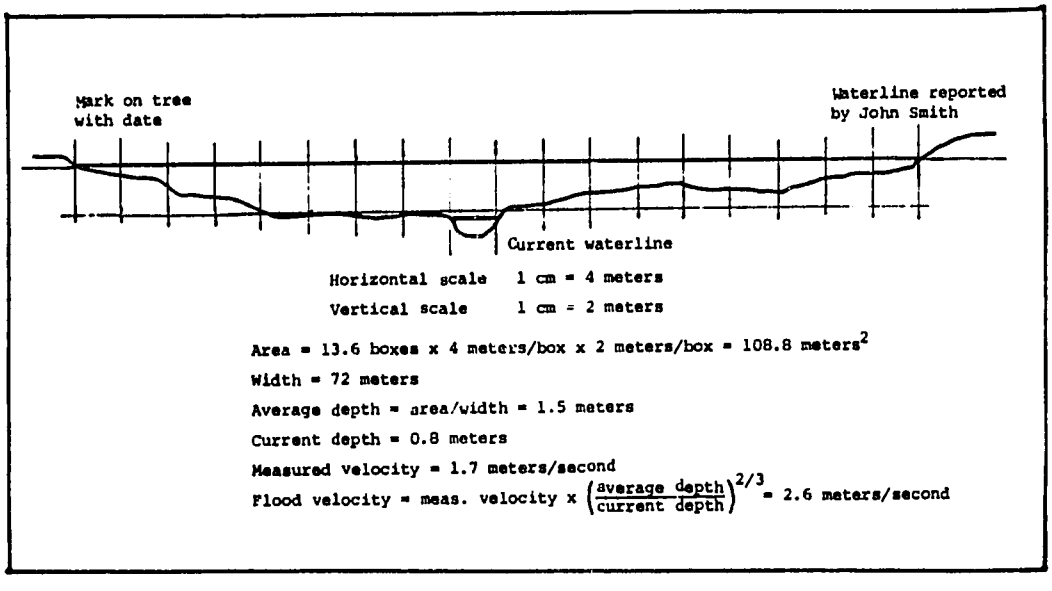
10/28/81--Talked to Paul Jones, oldest resident (75) living near the stream. He showed me a mark on his door where he said the water level was in storm of December 1953. He remembered his father telling him about a storm around 1890 which had been about 3 meters higher.

Talked to John Smith (62). He didn't know anything about flood in 1890. Highest water he remembered was marked on a large tree near his house. There was a date (December 16, 1953) written on the tree. Level agrees well with flood reported by Paul Jones. Smith also said he only remembers 2 times in the last 50 years when stream has dried up.

It is important to tell the people being interviewed that accurate data will help you design a successful and reliable project and that many data sources are being obtained for comparison. Be careful not to lead the person being interviewed. If a person thinks that describing high flood levels will help get a hydroelectric power plant, he may tend to exaggerate the level of flooding he remembers. Or if the person being interviewed thinks that you do not want to know about very high past floods, he may describe flooding as having been less than he actually remembers it.

To avoid problems of biased answers, talk to several people and get them to point out physical evidence of flood levels, like high-water marks on buildings. Ask for any available written documentation or photographs to confirm their reports. Dates when the floods occurred and a search for high-water levels at a number of nearby points may also help confirm reports of floods. Other ways of verifying residents' reports of high-water levels include searching old local newspapers, church records, or local government records of road or bridge repairs.

Figure 7
Stream cross section at flood stage



Once you have finished your field inspection and your interviews, examine the results as recorded in your notes. Ask yourself the following questions:

(1) Have you found a reliable water level for the largest flood which anyone remembers?
(2) Do you know when the flood occurred?
(3) Is there physical proof of the high-water level?

If the answer to all three of these questions is yes, you are ready to go on to the next step of calculating the flood discharge from the water level. If you have not been able to accurately document the largest flood, it may be necessary to use a slightly smaller, more recent high-water level that is better remembered and documented.

3. Calculating discharge from water level

The final step in a field study for peak flow is to transform the flood level you have determined into an estimated peak discharge. To calculate the flood discharge, you need to know the cross sectional area and the velocity of the stream at the peak water surface elevation. The cross sectional area of the stream may be calculated by first plotting the height above the ground of the peak water surface along a line perpendicular to the stream channel. Plot peak water depth measurements at regular intervals from the point where the high-water line touches the ground on one side of the stream, all the way over to the same point on the other side. Figure 7 shows an example of a stream cross section plot at flood stage.

The next step is to count the number of boxes between the ground surface profile and the high-water line. This number is then multiplied by the scale factors on your plot to yield the peak flood's cross sectional area. Figure 7 shows how this calculation is done.

After you have determined the area of the peak flood, you must determine the velocity of the flow. This can best be done by measuring off a stretch of 50 meters along the channel, then timing a floating object as the stream carries it through the 50-meter stretch. The velocity of the flow is then--

$$\text{Velocity} = \frac{50}{\text{average time to float through (stretch seconds)}} \quad \text{(Eqn 1)}$$

Throw the object into the center of the stream and make sure it doesn't strike anything as it moves through the reach. Time the object through the reach at least five times.

This velocity needs to be adjusted to take into account the higher velocities of flood flows. To do this, find or estimate the water depth near the center of the channel and the average water depth at flood levels from your cross section plot. Use these numbers as shown in figure 8 to find the factor by which you must multiply your measured velocity in order to get flood velocity. Once you know the flood velocity and the cross sectional area, multiply the two numbers together to obtain the peak flood discharge.

$Q = V \times A$ (Eqn 2)

H. Calculation of peak flows from watershed data

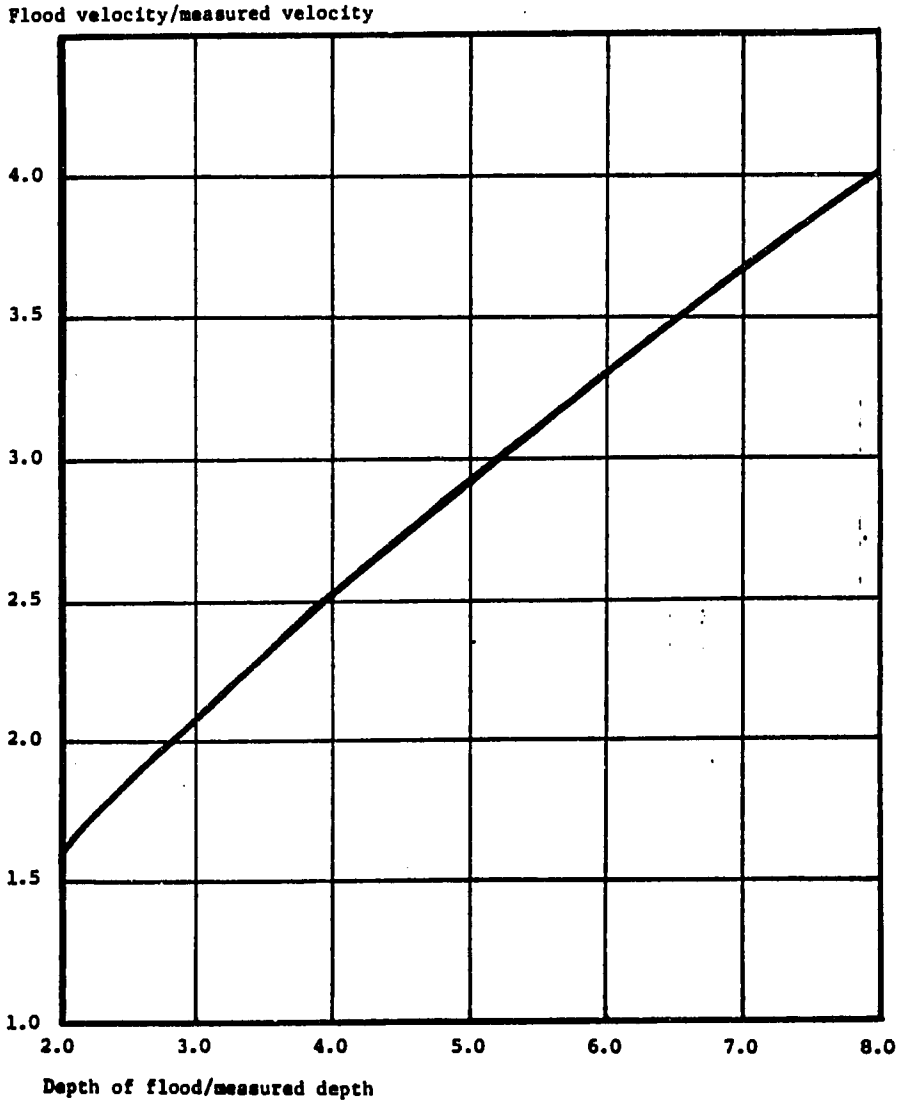
This section describes how to calculate the peak flood flow at a possible hydroelectric site using the available data on the watershed and the tables and figures presented here. The things that you will need are a contour map of the watershed and regional data on rainfall intensity for different storm or rainfall durations. Rainfall intensity is given in units of millimeters per hour. If 45 mm of rain is measured in 2 hours, the rainfall intensity is 22.5 mm per hour. Rainfall intensity will decrease as storm duration increases. In Boston, Massachusetts, for example, a rainfall intensity of 150 mm per hour will occur for storms of 10 minutes duration, but a rainfall intensity of 30 mm per hour will occur for storms of 4 hours duration.

The steps involved in calculating the peak discharge area--

(1) Using channel and watershed characteristics, determine the flow time for water to move through the watershed.

Figure 8
Finding flood velocity

Flood velocity = measured velocity* (depth of flood/measured depth)$^{2/3}$



(2) From regional meteorologic data, determine rain intensity for the design storm. The duration of the design storm is assumed to be equal to the flow time for water to move through the watershed.
(3) Determine watershed losses, the "excess rains" or the amount of rainfall that becomes surface runoff, and the peak discharge.

This calculation method assumes that a peak discharge will occur when the storm duration is equal to the flow time for water to move through the watershed. This is an idealization of the actual interactions between storm rainfall duration and peak flow, but it gives peak flow estimates of reasonable accuracy.

Each step in the calculation is explained in the following sections and easy to follow examples have been included. For each step, your computations should be written down like the examples so that you may check your work.

1. Calculating the flowtime for water to move through the watershed. To compute the flowtime for water to move through the watershed, you will need to determine--

L = channel length in kilometers
ER = change in elevation between the highest point in the watershed and the site, in meters
AREA = watershed area, upstream of the site in square kilometers

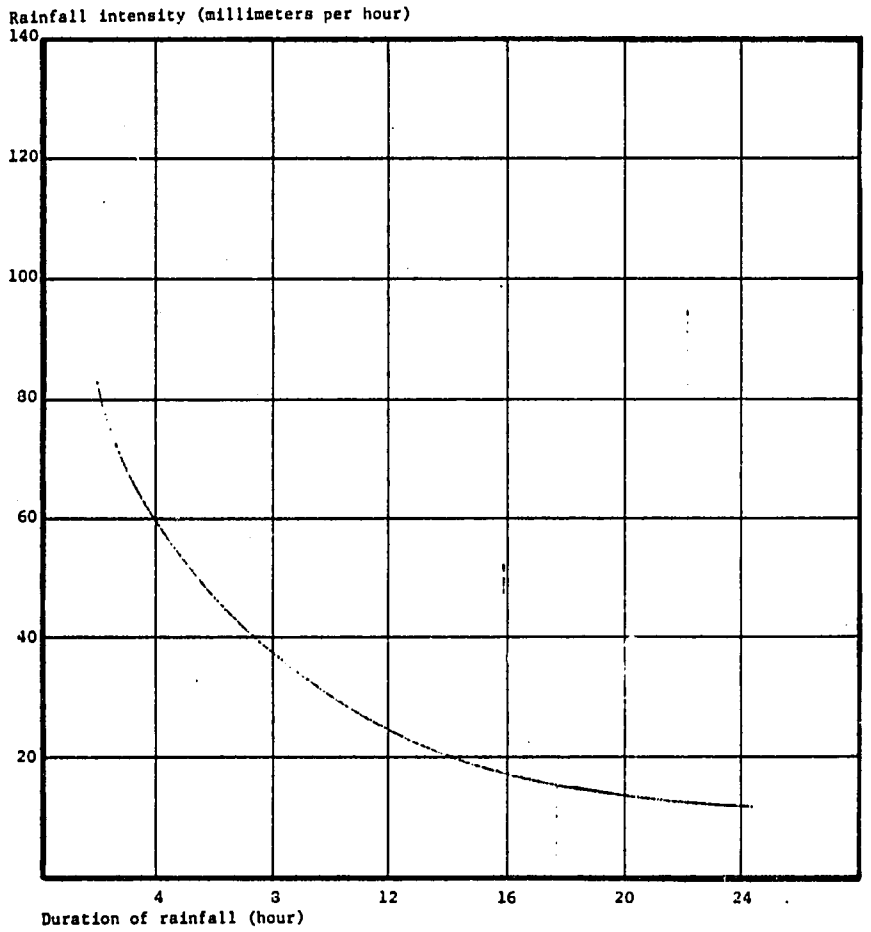
These data can be found from a contour map of the watershed. L and ER are used in Eqn 3 to calculate the flowtime (TF) through the watershed. This flowtime (TF) is assumed to equal the duration of the storm rainfall that will cause a peak flow. The duration of the storm rainfall is used to find the rainfall intensity during the storm (RI), using local data similar to that shown in figure 9. The storm rainfall intensity (RI) less a loss rate (LR) is used to find the rate of runoff or rain excess (XR) during the storm (Eqn 4). Finally, the excess rain is converted to flood peak discharge by multiplying by a necessary constant and the watershed area in Eqn 5.

The flowtime in hours (TF) can be calculated from L and ER using Eqn 3, or it can be read from figure 10.

$$TF = 0.95 \times (L^3/ER)^{.385} \quad \text{(Eqn 3)}$$

In Eqn 3, L is in kilometers, ER is in meters, and TF is in hours.

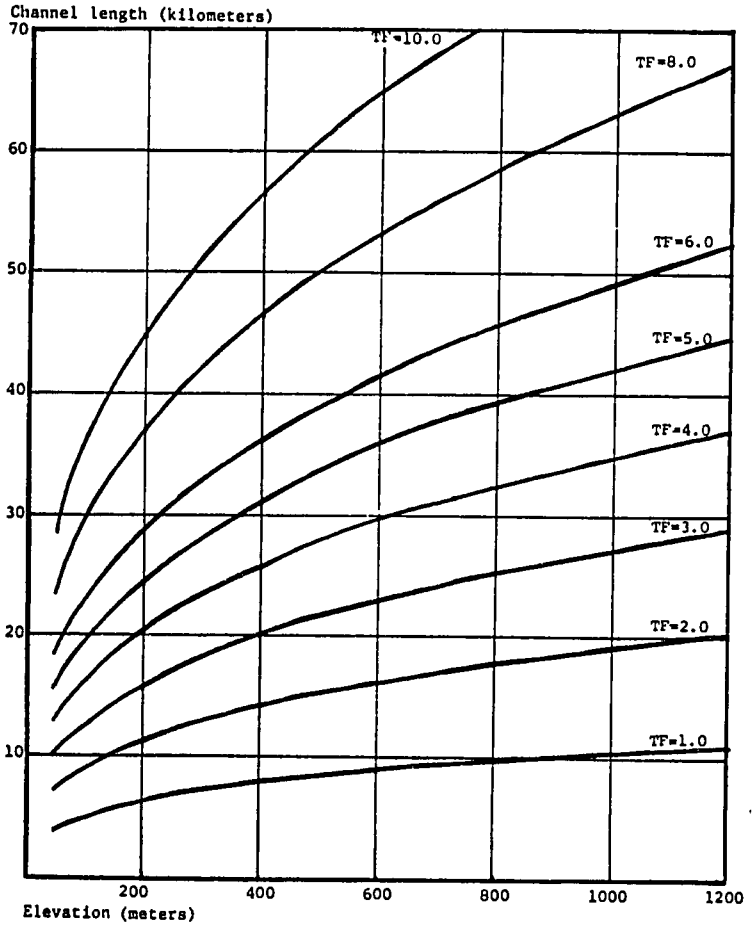
Figure 9
An example of rainfall intensity vs. duration of rainfall for a 50-year return period



2. Estimating rain intensity

Once you have calculated the TF from Eqn 3, use data on duration of rainfall versus rain intensity to find the rainfall intensity on the watershed. The relationship between rainfall duration and rainfall intensity is usually displayed graphically, as shown in figure 9. It may be possible to make a graph similar to figure 9 with your own data. Graphical plots of rainfall intensity versus duration of rain are often made for different statistical return periods. A rainfall intensity of 60 mm/hour for 4 hours duration would be equalled or exceeded once every 50 years, as shown on figure 9. To use figure 9, find the duration of rainfall in hours that equals TF on the bottom scale, intersect the line, and read the rainfall intensity (RI), from the vertical scale.

Figure 10
Flowtime for water to move through the watershed from watershed characteristics



3. Estimating excess rain and determining peak flow

Rainfall will be lost during a storm due to infiltration. Table 3 describes various soil types and gives a loss rate for each. Losses are greater in watersheds which have very heavy vegetation. A correction factor for vegetation density can be selected that is multiplied by the loss rate for the watershed soils to give the total loss rate for the watershed, LR.

Now that you have determined the rate of rainfall loss, you may calculate excess rain by subtracting your losses from the rainfall intensity. The total excess rainfall rate is then--

$XR = RI - LR$ (Eqn 4)

where XR, RI, and LR are all in units of mm/hour.

21 Estimating peak flow at a site

Table 3

Watershed loss rate and correction factor for predominant vegetation

Predominant soil type	Loss rate (mm/hr)
Impervious rock	1
Tight clay	1
Clay and silt	3
Silt and sand	5
Sand and gravel	10

Predominant vegetation	Correction to loss rate (multiply by)
Sparse--Little vegetation, bare soil, scrub brush	0.5
Moderate--Grassland, cropland, mixed forest	1.0
Heavy--Dense forest, tropical forest	2.0

Example: A watershed with clay silt soils and dense forest cover would have a loss rate of 3.0 mm/hour and a correction factor of 2.0 so its total loss rate would be 3.0 x 2.0 = 6.0 mm/hour.

The final step is to determine the peak discharge at the site from Eqn 5.

Peak flow (cubic meters/second)
= 0.28 x XR x watershed area (km^2) (Eqn 5)

where XR is excess rain in mm/hour and peak flow is in cubic meters/second. An example of a peak flow calculation is given in appendix A.

I. Determining final peak flow value

If you have been able to follow both the field survey and the calculation methods for determining peak flow, you will have two values for peak flow which may be quite different. This is to be expected. The remaining task is to evaluate the ι values in order to arrive at one best value. To do this, you will need to review the process by which you calculated each number and determine where there was likely to have been a large amount of uncertainty in your study.

Which method gave you a higher value? Was one value more than twice as much as the other? If the calculation method value was much larger, what was the return period for the rainfall intensity versus duration of rainfall data that you used? If it was more than 50 years, it should have given you a larger peak flow, because the field study interviews will document floods which have occurred within the past 50 years.

If the field study gave you a lower peak-flow value, compare the velocity figure you used in the field study to the average flood velocity, which is channel length divided by the flowtime through the watershed (TF). The two velocities should be fairly similar, although the field study velocity is likely to be lower. Try calculating the field study peak flow using the Chezy-Manning equation,

$$V = 1/n \; D^{2/3} \; S^{1/2}$$

where n is resistance to flow, D is mean depth in meters at flood stage, and S is the slope along the channel. In natural streams, mean depth (D in meters) can be assumed to be equal to the hydraulic radius and is the cross sectional area of the flow divided by its wetted perimeter. Slope (S) is in units of meters of elevation loss per meter of length along the channel, so it is dimensionless. Velocity (V) is in meters per second. For Manning's equation, typical values of n follow:

Clean, straight channel with sand bed	0.035
Winding channel, sand or gravel bed	0.045
Winding channel, gravel and stone bed, some streambank vegetation	0.06
Rocky, winding channel with pools and obstructions, streambank vegetation	0.08

Do the peak flows agree more closely now? If so, use the new value for the field study result.

In general, if the field study and calculation method results for peak flow agree within 30 percent, you might average them and use this as your final result. If you have reason to believe that one method was better than the other on your watershed, your final result could fall between the two results, but closer to the one on which you place the most confidence.

Section 4

Estimating the flow-duration curve at a site

This section gives methods for estimating the flow-duration curve at a hydroelectric site. Section J is a summary of field investigations for estimating flow-duration curves, and section K describes calculation methods for flow-duration curves based on meteorologic information.

The flow-duration curve is a most useful tool for evaluating low flows at a hydroelectric site. The flow-duration curve in figure 5 is repeated as figure 11. These data can be used to estimate the flow that can be used for power production 90 or 95 percent of the time. This gives an immediate indication of the reliability of power production at a site. For example, if a 20-meter head were available, the flow-duration curve in figure 11 would indicate that as 119-kW power source could be developed at 85-percent reliability, assuming an 80-percent overall efficiency for the project.

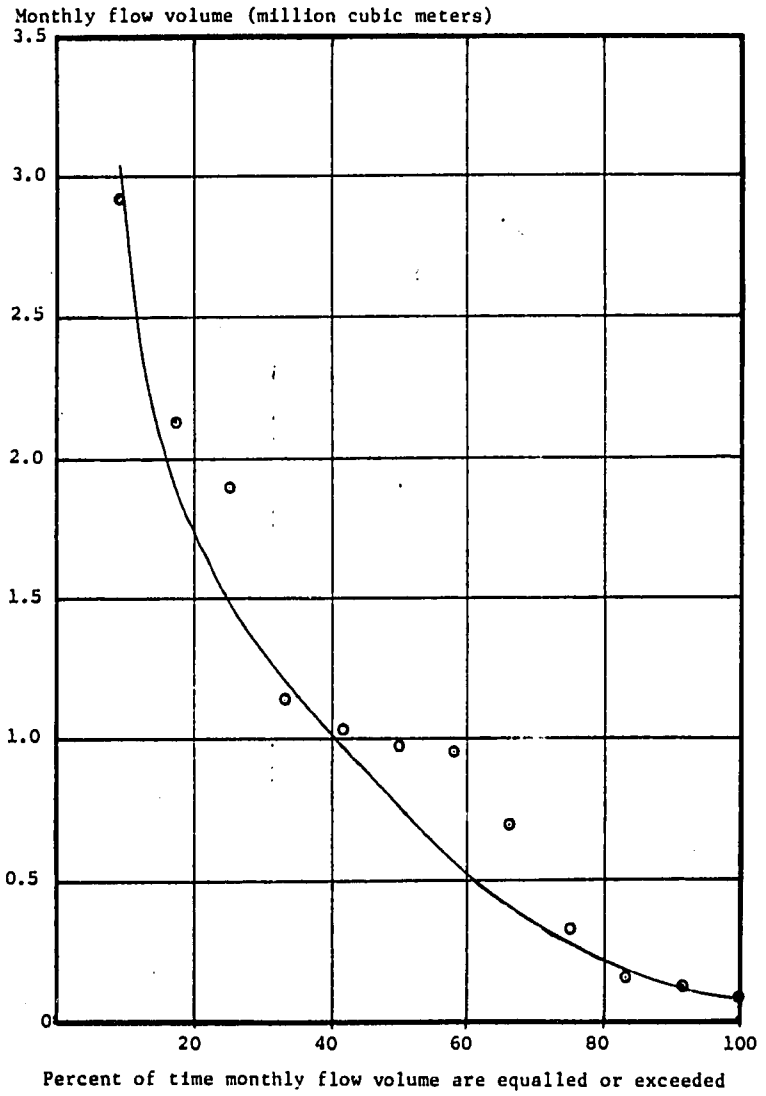
J. Field investigation for estimation of flow-duration curves at a project site

People who live near a river or who divert water from a river are likely to remember the typical stage at different times of the year. High and low stages as well as normal stages throughout the year will be known to local residents, even though they will not know the corresponding discharge. Knowledge of stage can be converted to discharge using a stage-discharge rating curve. A stage-discharge rating curve can be constructed using measured cross sections at two or more stages and calculating flow velocities at each stage, as was described in section G3. Discharge at a given stage is the flow velocity times the cross sectional area of the flow at that stage. When stage-discharge ratings are plotted on log scales, linear or near-linear curves are found. Figure 12 is an example of a stage-discharge rating curve.

To construct a flow-duration curve, the following sources of information might be used.

(1) Are there lakes or reservoirs on the stream? Stage records over a period of years at a lake or reservoir can be used to calculate streamflow volumes entering the reservoir. When monthly stage records exist at a reservoir, locate a reservoir stage versus reservoir volume chart for the reservoir. The streamflow volume entering the reservoir each month will be the reservoir volume at the end of the month, less the reservoir volume at the first of the month, plus the volume of water released from the

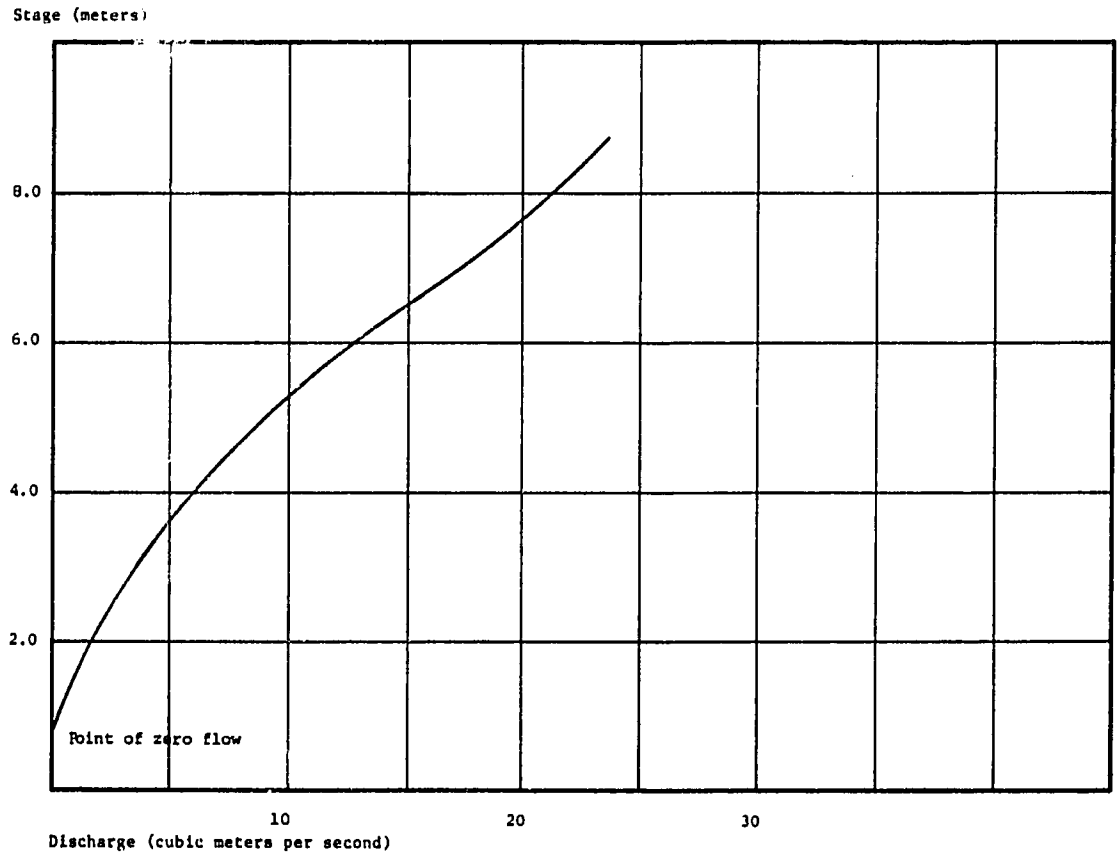
Figure 11
Flow-duration curve for monthly flow volumes



reservoir during the month. If a stage versus reservoir volume chart is not available, one can be made from maps of the reservoir area at different elevations, since the increase in reservoir volume between two elevations is the elevation increment times the reservoir surface area.

(2) Correlation of low flows on a regional basis is possible. Do streamflow records exist on nearby, similar streams? The U.S. Geological Survey has summarized commonly used methods for regional correlation of flows in Water Supply Paper No. 1975, titled "Generalization of Streamflow Characteristics from Drainage-Basin Characteristics," by D. M. Thomas and M. A. Benson (55 p.).

Figure 12
Stage-discharge rating curve



(3) Review any existing data on flow duration compiled in the region in previous studies.

(4) Question local residents, particularly people who are using the stream in some way: ferry operators, irrigation farmers, or people who divert water for water supplies. What stages are expected by season of the year? If rainfall in the region is seasonal, what stages are typical of the lowest flow month of the year? What stages are expected during high-flow months? What is the lowest stage that residents remember? How does the lowest stage that residents remember compare with the typical low stage that is observed each year?

(5) In some watersheds, low-flow conditions are associated with poor water quality. Is there sometimes unacceptable water quality, such as very high salt content? When does this condition occur?

(6) Are there water intakes along the river? Have these water intakes ever been relocated because of low stage in the stream?

Where monthly streamflow can be calculated from lake or reservoir

Where monthly streamflow can be calculated from lake or reservoir levels, as in (1) above, or if regional studies to relate flow at a site to nearby gaged streams are done as in (2) above, the data can be used to construct a flow duration as was done in section F. If regional studies of flow duration already exist from (3) above, flow-duration curves will be available.

When interviews are used to establish seasonal stages, as in (4) above, use Manning's equation described in section I or float measurements to establish a stage-discharge relationship, as was described in section G3. Convert stages to discharge to estimate monthly flows for a typical year. These mean monthly flows can be used to construct a flow-duration curve as in section F. If the field interviews, (5) and (6) above, give clear evidence of occasional low flows that are substantially less than the minimum expected annual flow, a multiyear flow-duration plot might be made.

To make a multiyear flow-duration plot, estimate monthly flows for additional years and include the historic low flows. If your field information shows the minimum flow in an 8-year period, 8 full years of estimated monthly flows should be used to construct the flow-duration curve. These additional monthly flow estimates ensure that the lowest historic flow correctly influences the flow-duration curve: the lowest monthly flow in 8 years is a 99-percent condition; in other words, in 95 months out of 96 this minimum flow would be equalled or exceeded.

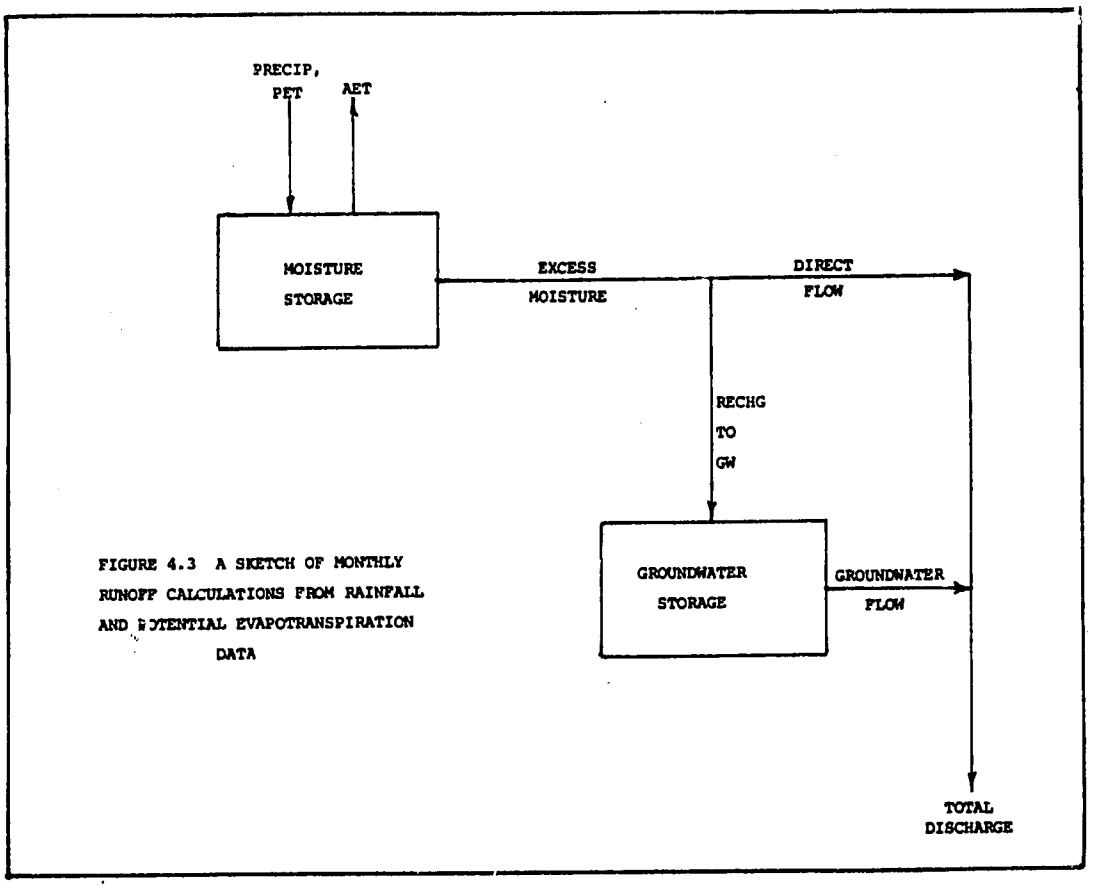
K. Calculations of a flow-duration curve from meteorologic data

Streamflow results from precipitation. Flows of water from the land surface during and immediately following precipitation create flood hydrographs and peak flows. Water that is absorbed by the soil during rainstorms moves as subsurface flow into stream channels and provides low flows in periods when rain does not occur. Flow-duration curves are based on continuous streamflow data. On ungaged streams where streamflow measurements are not available, precipitation and potential evapotranspiration records can be used to calculate continuous flows. The calculations mimic key hydrologic processes: infiltration of water into the soil profile, surface runoff, and flow along subsurface flow paths into the stream.

The calculation method described in this section uses monthly precipitation and potential evapotranspiration data to calculate monthly streamflow.

When the calculated monthly streamflows are found, they are used like observed flows to calculate the flow-duration curve. A

Figure 13
A sketch of monthly runoff calculations from rainfall and potential evapotranspi.ation data



sketch of the calculations is shown in figure 13. The time of flow in strem channels in small watersheds is usually less than 1 day and this time of flow can be neglected when monthly interval runoff volumes are calculated.

Calculations of monthly flows from meteorologic data are based on the water balance in the watershed. The water balance equation is—

Precipitation - actual evapotranspiration + storage = runoff.

The water balance equation applies to the watershed over any time interval. Where precipitation, actual evapotranspiration, and runoff are the volumes of water entering and leaving the watershed in the time interval, and storage is the change in soil moisture and groundwater storage in the time interval, the initial storages less the final storages. Water is held in storage in the soil, in groundwater aquifers, and in lakes and snowpacks. All water flows

into or out of the watershed are assumed to be included in the runoff.

The following steps can be used to calculate monthly runoff and a flow-duration curve from meteorologic data; they are described in the following sections.

(1) Assemble 5 or more years of concurrent rainfall and potential evapotranspiration data.

(2) Estimate the watershed characteristics of the basin.

(3) Calculate, using a tabular form, the monthly streamflows for 5 or more years based on these rainfall and potential evapotranspiration data.

(4) Calculate the flow-duration curve using the calculated monthly streamflows, as would be done if observed data were available (section F).

1. Rainfall and potential evapotranspiration (PET) data. Streamflow calculations require monthly rainfall on the watershed and monthly potential evapotranspiration data. Rainfall data that is observed in or near the watershed must be found. National meteorologic services or agricultural agencies maintain records of meteorologic stations, but records at individual stations are often incomplete. Records from two or three stations are needed to fill in missing records. Adjustments are usually needed to estimate watershed rainfall from precipitation gage records. Rainfalls often increase with elevation, and gages are usually placed in villages along river valleys. Meteorologic and agricultural services prepare maps of mean annual rainfall. These maps can be used to adjust gaged rainfall and to estimate rainfall on the watershed.

Potential evapotranspiration is the amount of water that would evaporate from the watershed if water supply were ample. The actual water loss, called actual evapotranspiration, is less than or equal to the potential evapotranspiration. The potential evapotranspiration may be estimated and published by a national meteorologic services office.

The potential evapotranspiration is quite uniform from year to year. A mean monthly distribution of potential evapotranspiration will be sufficient for purposes of calculating monthly runoff.

2. Estimating watershed characteristics. The tabular calculations of monthly flows described in section K3 use three coefficients that represent watershed characteristics. They are--

NOMINAL = an index to the soil moisture storage capacity in the watershed
PSUB = the fraction of runoff that moves out of the watershed as baseflow or groundwater flow
GWF = an index to the rate of discharge from the groundwater storage to the stream

NOMINAL, PSUB, and GWF are watershed characteristics that will change from one watershed to another. NOMINAL is the soil-moisture storage level that permits half of any positive monthly water balance to leave the watershed as "excess moisture," where excess moisture is either direct runoff or groundwater flow. The soil-moisture storage level varies and may be less than or greater than NOMINAL. When the soil-moisture storage is less than NOMINAL, most of any positive monthly water balance is retained in the soil moisture. When the soil-moisture storage is greater than NOMINAL, most of any positive monthly water balance becomes direct runoff or an addition to the groundwater storage. NOMINAL is stated in millimeters.

PSUB is the fraction of runoff that moves out of the watershed on subsurface flowpaths rather than as direct or surface runoff. The total flow that a watershed provides consists of surface or direct runoff that creates the peak flows and subsurface flows that provide the low flows. Low permeability soils that have low infiltration capacities yield large amounts of surface or direct runoff and low sustained discharges. Soils that have high infiltration capacities yield higher sustained discharges. Therefore streams that have high minimum discharges are those with highly permeable sandy soils and fractured or permeable subsurface geology. PSUB is dimensionless.

GWF is an index to the time of flow along subsurface flowpaths that enter the stream. It is the fraction of the total volume of water on groundwater flowpaths that will enter the stream in the current month. GWF is dimensionless.

These watershed characteristics can be estimated for ungaged streams using the following guidelines.

NOMINAL = 100 + C x mean annual precipitation, where C is approximately 0.2 in watersheds with precipitation throughout the year and 0.25 in watersheds with seasonal rainfall. The value of NOMINAL can be reduced by up to 25 percent in watersheds with limited vegetation and thin soil cover.

Table 4

NRECA flow-duration model: Tabular calculation of monthly runoff volumes

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
DATE	PRECIP	PET	MOISTR STORAGE	STOR RATIO	PRECIP /PET	AET/ PET	AET	WATER BALANCE	EXCESS MOIST RATIO	EXCESS MOIST	DELTA STORAGE	RECHG TO GW	BEGIN STOR GW	END STOR GW	GW FLOW	DIRECT FLOW	TOTAL DISC
(mo/yr)	(mm)	(mm)	(mm)	NOMINAL = 410			(mm)	(mm)		(mm)	(mm)	(mm) PSUB=.61	(mm)	(mm)	(mm) GWF=.64	(mm)	(mm)
1/80	356.3	21.7	500.0	1.22	16.42	1.00	21.7	334.6	.70	234.2	101.9	141.9	25.0	166.9	106.8	90.7	197.6
2/80	196.4	38.4	601.9	1.47	5.12	1.00	38.4	158.1	.86	135.7	22.4	82.8	60.1	142.9	91.4	52.9	144.4
3/80	145.6	79.1	624.3	1.52	1.84	1.00	79.1	66.5	.89	58.9	7.6	35.9	51.4	87.4	55.9	23.0	78.9
4/80	59.8	118.3	631.9	1.54	.51	.89	104.9	-45.1	.00	.0	-45.1	.0	31.5	31.5	20.1	.0	20.1
5/80	26.9	155.4	586.7	1.43	.17	.76	118.8	-92.0	.00	.0	-92.0	.0	11.3	11.3	7.2	.0	7.2
6/80	11.6	171.5	494.8	1.21	.07	.63	108.1	-96.5	.00	.0	-96.5	.0	4.1	4.1	2.6	.0	2.6
7/80	19.9	191.6	390.3	.95	.10	.54	103.3	-83.4	.00	.0	-83.4	.0	1.5	1.5	.9	.0	.9
8/80	33.7	154.7	314.9	.77	.22	.52	80.2	-46.5	.00	.0	-46.5	.0	.5	.5	.3	.0	.3
9/80	17.2	137.9	268.5	.65	.12	.41	56.7	-39.5	.00	.0	-39.5	.0	.2	.2	.1	.0	.1
10/80	299.6	88.9	228.9	.56	3.37	1.00	88.9	210.7	.16	32.8	177.9	20.0	.1	20.1	12.9	12.8	25.7
11/80	275.8	41.7	406.8	.99	6.61	1.00	41.7	234.1	.49	115.2	118.9	70.3	7.2	77.5	49.6	44.9	94.5
12/80	350.0	29.8	525.7	1.28	11.74	1.00	29.8	320.2	.74	237.7	82.5	145.0	27.9	172.9	110.6	92.7	203.3

PSUB = 0.6 is a median value. PSUB would increase to 0.8 in watersheds known to have highly permeable soils and would decrease to 0.3 in watersheds with low permeability or thin soils.

GWF = 0.5 is a median value. GWF would increase to 0.9 in watersheds that have little sustained flow and would decrease to 0.2 in watersheds known to have reliable sustained flows.

Watershed characteristics can be estimated from limited field data on historic streamflows. The characteristic that controls runoff volumes is NOMINAL. Increasing NOMINAL will decrease runoff and decreasing NOMINAL will increase runoff. The actual evapotranspiration (AET) increases when NOMINAL is increased, and the AET/PET ratio in table 4 will change. When some historic flow data is available, the calculations in table 4 can be repeated for different values of NOMINAL until the calculated flow volume and the historic flow volumes agree. In some cases, the rainfall amounts that are assumed to occur on the watershed may need to be adjusted. A change in rainfall on a watershed of plus or minus 10 percent will change watershed runoff by a least 10 percent.

The fraction of excess moisture that moves as subsurface flow (PSUB) and the rate of outflow of subsurface or groundwater flow (GWF) control the low streamflows between storms. A value for GWF can be found when little rainfall occurs for 2 or more months. When rainfall does not occur, GWF = 1 - (streamflow volume in current month / streamflow volume last month). Alternately, if monthly measurements of streamflow are made during a period when rainfall does not occur, GWF = 1 - (streamflow today / streamflow one month ago). Calculated values for GWF will vary, so GWF should be calculated for different months when observed flows are available. The lowest calculated value of GWF is usually the most reliable estimate.

When NOMINAL and GWF are established, the value of PSUB can be considered. PSUB increases or decreases the volume of water moving on the subsurface flowpaths. If, for example, the following monthly streamflows are available from field measurements and calculations, PSUB needs to be increased.

	June	July	August	September
Observed	1070	642	385	231
Calculated	720	432	259	155

In this example, the calculated flows are all too low and more subsurface flow volume is needed. Note that GWF for both the calculated and the observed monthly flows is 0.4, so changing GWF would not improve the calculated streamflows.

The trial calculations to establish watershed characteristics that are outlined above can be done for nearby streams and the watershed characteristics that are found may be assumed to apply to the ungaged stream that is being studied. Watershed characteristics usually change only moderately within a region and changes will correlate with changes in vegetation, soils, and subsurface geology.

3. Calculations of monthly runoff

Calculations of monthly runoff are made using a tabular sheet, as in table 4. A step-by-step procedure for computing data in this table follows. These calculations can be done with a hand calculator or adding machine, but a flow chart and a FORTRAN program for handling the calculation are given in appendix B.

Initial steps: Select the values of the coefficients representing watershed characteristics and enter them in the column headings: NOMINAL above column (5), PSUB above column (13), and GWF above column (16).

Initial or starting conditions are needed for the soil-moisture storage (column (4)) and the groundwater storage (column (14)). If rainfall is seasonal and the tabular calculation begins in the dry season, the initial storages will be low. Typical values would be an initial soil storage of 10 percent of NOMINAL, and groundwater storage of 5 percent of NOMINAL. In watersheds with uniform rainfall through the year, an initial soil storage equal to the NOMINAL, and an initial groundwater storage of 20 percent of NOMINAL would be expected.

Calculations that begin in the wet season would have an initial soil storage of 125 percent of NOMINAL and an initial groundwater storage of 40 percent of NOMINAL.

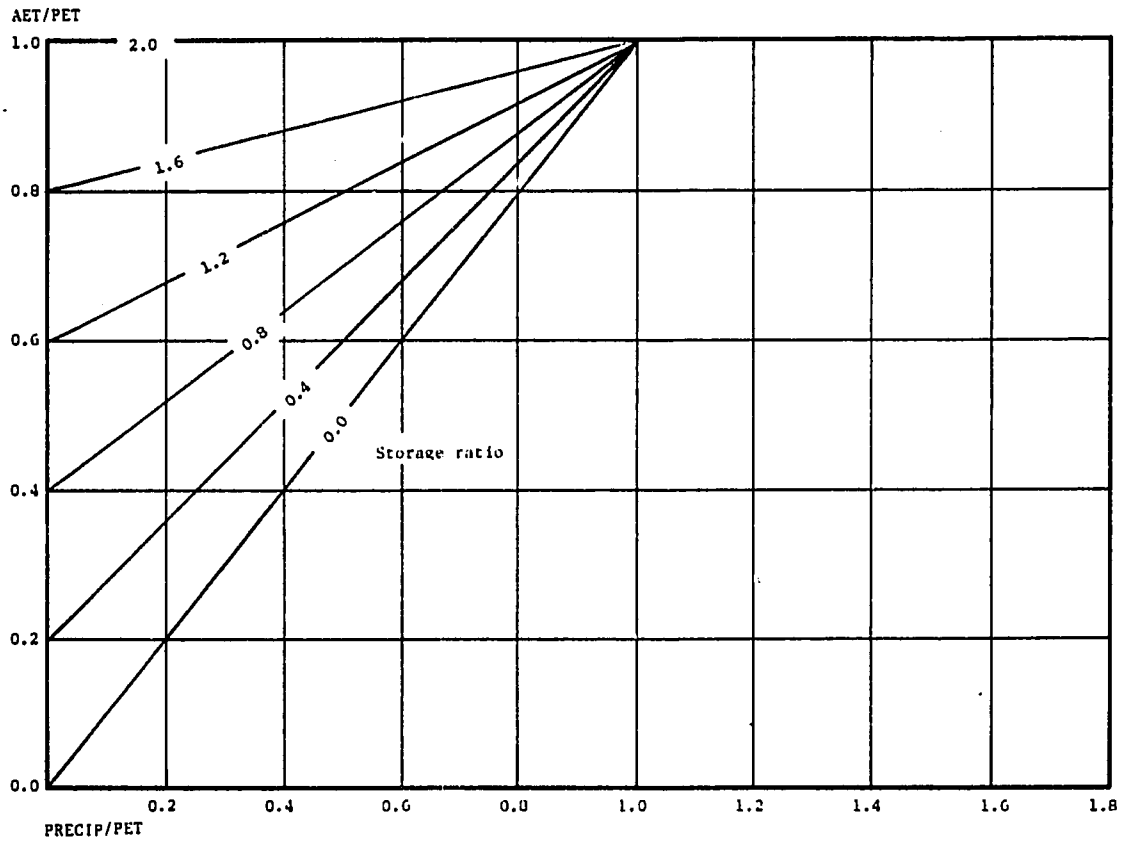
The effects of initial storages in a water balance calculation "damp out" over a period of 6 to 12 months. There are two ways of avoiding bias caused by unknown initial storages: The first year of calculated monthly flows could be ignored and not included in the flow-duration curve. Alternately, the values of soil and groundwater storage that are found at the end of the first year of calculations could be accepted as representative of typical storages at that time of year. These storages could then be entered as the best estimate of initial conditions for the watershed and calculation could be redone using these storages.

Enter the initial soil moisture in column (4), and the initial groundwater storage in column (14).

The rest of this section will lead you through the use of table 4.

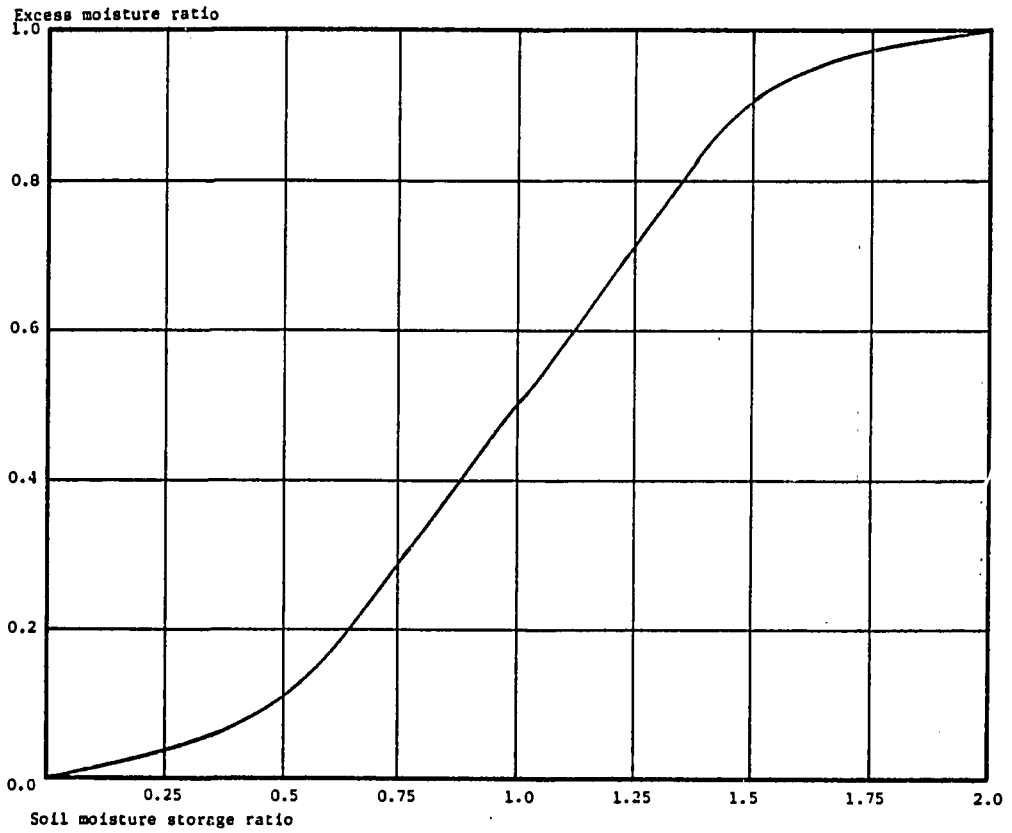
Column	Instruction
(1)	Enter the month and year of the data.
(2)	Enter precipitation (PRECIP) on the watershed for the month (gage rainfall must be adjusted to represent watershed rainfall).
(3)	Enter potential evapotranspiration (PET) on the watershed.
(4)	MOISTR STORAGE was entered previously as an initial condition or from the prior month calculation.
(5)	Calculate the soil storage ratio (STOR RATIO), the value in column (4) divided by NOMINAL.
(6)	Calculate the ratio PRECIP/PET, column (2) divided by column (3). Enter the result in column (6).
(7)	Enter figure 14 with PRECIP/PET and the STOR RATIO (column (5)), and find the value of the ratio of actual to potential evapotranspiration, AET/PET. Enter the value of AET/PET in column (7).
(8)	Calculate AET as PET multiplied by the AET/PET ratio, column (3) times column (7), and enter AET in column (8). (See figure 14.)

Figure 14
AET/PET ratio as a function of PRECIP/PET and soil-moisture ratio



(9)	Calculate the WATER BALANCE for the month where WATER BALANCE = PRECIP - AET, column (2) less column (8). Enter the result in column (9).
(10)	If the WATER BALANCE is positive, enter figure 15 with the STOR RATIO (column (5)), and find the excess moisture ratio (EXCESS MOIST RATIO). If the WATER BALANCE in column (9) is negative, the EXCESS MOIST RATIO is zero. Enter the EXCESS MOIST RATIO in column (10).
(11)	Calculate the excess moisture (EXCESS MOIST) where EXCESS MOIST is the EXCESS MOIST RATIO times the WATER BALANCE, column (10) times column (9). Enter the result in column (11).
(12)	Calculate the change in soil storage (DELTA STORAGE) where DELTA STORAGE is WATER BALANCE minus EXCESS MOIST, column (9) minus column (11). Enter the result in column (12).
(13)	Calculate the recharge to groundwater storage (RECHG TO GW) as PSUB times EXCESS MOIST, PSUB times column (11). Enter the result in column (13).

Figure 15
Soil-moisture storage ratio



(14)	BEGIN STOR GW was entered previously as an initial condition or from the prior month calculation.
(15)	Calculate the end of month groundwater storage (END STOR GW) by adding the RECHG TO GW in column (13) to the BEGIN STOR GW in column (14). Enter the result in column (15).
(16)	Calculate the groundwater discharge to the stream (GW FLOW) where GW FLOW is GWF times END STOR GW or GWF times column (15). Enter the result in column (16).
(17)	Calculate the direct runoff to the stream (DIRECT FLOW), where DIRECT FLOW is EXCESS MOIST less RECHG TO GW, column (11) minus column (13). Enter the result in column (17).
(18)	Calculate the streamflow as the DIRECT FLOW plus GW FLOW, column (17) plus column (16). Enter the result in column (18). This result is in millimeters and can be converted to cubic meters for the month by multiplying by the watershed area in square kilometers times 1000.

Reset initial conditions for the next month:

The BEGIN STOR GW for the next month is END STOR GW less GW FLOW, column (15) minus column (16). Enter this result in column (14) for the next month.

The beginning MOISTR STORAGE for the next month is the current MOIST STORAGE plus DELTA STORAGE, column (4) plus column (12). Enter this result in column (4) for the next month.

The tabulation steps are repeated until all of the months of precipitation and potential evapotranspiration have been considered. Note that in table 4 the EXCESS MOIST RATIO in column (10) has been entered as two significant figures. The EXCESS MOIST in column (11) was calculated on a small calculator that retained more than two significant figures for the EXCESS MOIST RATIO.

L. Determination of the flow-duration curve

The procedure to draw a flow-duration curve was described in section F. To make a flow-duration curve from calculated monthly flows, list all of the monthly flows which were computed in column (18) of table 4. The flows should be listed in order of magnitude. Next, calculate the percent of months each flow volume is equalled or exceeded. Plot the flow-duration curve as shown in figure 11.

Section 5

Determining the final answer

This manual provides methods for calculating peak flows and flow-duration curves for ungaged watersheds from both field investigations and hydrologic calculations. If all the procedures in the manual have been completed, you may have the following results:

Table 5
Example of Rio Targa estimates

Peak Flow	Cubic meters per second
Field estimates	27
Hydrologic calculations	21

Flow duration

Percent of time flow is equalled or exceeded

Percent of time	Discharge from field estimates	Discharge from WATER BALANCE calculations
0	--	--
10	4.0	3.7
20	3.2	3.3
30	3.0	3.0
40	2.7	2.9
50	2.1	2.7
60	2.0	2.6
70	1.8	2.4
80	1.7	2.3
90	1.6	2.2
95	1.5	2.1

Which data are most reliable and what "answers" should be used?

The method described in this manual can be used for watersheds throughout the world where hydrologic and meteorologic information vary in quantity and quality. There is no simple, universal rules that can be given as to when to use the field estimates and when to use the hydrologic calculations for the peak flow and flow-duration curve results. Hydrologic estimates from both direct field investigations and calculations from meteorologic data are uncertain.

Uncertainty can result in field investigations from the short period of observation and inaccurate reports. Uncertainty in hydrologic calculations from meteorologic data comes from inaccurate input data, simple hydrologic calculation techniques, or use of calculation techniques that are not suited to the watershed being studied. For field observations, short observation records are to be expected. Recent floods may be remembered accurately, but floods more than 10 or 20 years ago may be forgotten, or may be remembered as "larger than life." The goal of this manual is to estimate floods of once in 50 to 100 years recurrence intervals. Residents who have never observed a 100-year flood usually do not believe its magnitude.

The final judgment on whether to place more confidence in the field observations or the calculation method will have to be made by the analyst who has participated in the investigations and done the calculations.

One guide to making the judgment is the sensitivity of an answer to uncertainty in the data on which it is based. Table 6 is a summary of uncertainty and sensitivity for peak flow estimates and table 7 is a summary of uncertainty and sensitivity for flow-duration results.

In the example of Rio Targa, assume that uncertainty in watershed stream length and elevation causes the time of rainfall to vary plus or minus 1 hour and that this change alters rainfall intensity plus or minus 10 percent. Further, the rainfall uncertainty is plus or minus 15 percent, and loss rate uncertainty is plus or minus 50 percent. Peak flow calculations made using the limiting high and low data might show that rain excess is plus or minus 30 percent. This would mean that peak flows from the hydrologic calculations from 15 to 28 cubic meters/second would be equally feasible. At the same time, if a 28 cubic meters/second peak flow is found based on extrapolations from limited field observations, one might conclude that any answer from 22 to 32 cubic meters/second would be equally feasible.

In this case the analyst might select a final answer from the range of 22 to 28 cubic meters/second (figure 16), where the results from both field methods and hydrologic calculations overlap.

Sensitivity analysis can be done for flow-duration data as well. An upper bound and a lower bound for a calculated flow-duration curve would be found by considering the uncertainty in precipitation and potential evapotranspiration inputs and in the watershed characteristics (NOMINAL, GWF, and PSUB). Calculated flow-duration curves will be most sensitive to uncertainty in monthly precipitation and potential evapotranspiration amounts.

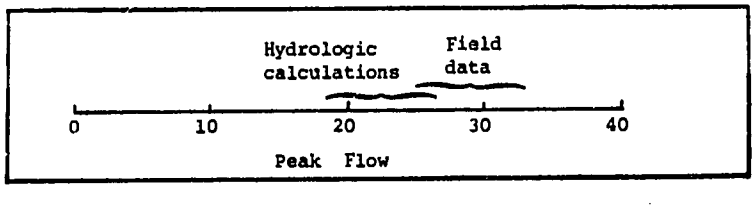
Table 6
Peak-flow sensitivity

Physical and meteorologic data inputs	Effect on peak flow
Rainfall data (for example, the 10-year, 6-hour rainfall on the watershed)	Peak flow is very sensitive to rainfall and often shows a percentage change equal to or greater than the change in rainfall data. If rainfall increases 10 percent, the peak flow may increase 15 to 50 percent
Time of flow through the watershed	Peak flow is sensitive to the time of flow through the watershed since this time of flow is assumed equal to rainfall duration, and different rainfall durations change the rainfall intensity on the watershed.
Loss rates	The sensitivity depends on how the loss rates compare to the rainfall rates. If rainfall is 35 mm/h and loss rates are 5 mm/h, doubling the loss rate to 10 mm/h changes direct runoff from 30 to 25 mm/h.
Field data on peak flows	Estimates of design flows based on limited field information are very sensitive to the maximum ranked flow found in the field. When a "frequency plot" like figure 4 is used, make the plot with and without the highest field estimated data point. This often sharply changes the flow at a 50- or 100-year return period.

Table 7
Duration-curve sensitivity

Physical and meteorologic data inputs	Effects on flow-duration curve
Rainfall	The percent change in streamflow and the flow-duration curve for a given percent change in rainfall will exceed the percent change in rainfall. If rainfall increases 10 percent, streamflow will increase by more than 10 percent. Sensitivity to rainfall is greater in arid climates than in humid climates.
Potential evapotranspiration	A change in potential evapotranspiration will change streamflow in humid climates. In arid climates, streamflow is less sensitive to potential evapotranspiration.
NOMINAL--the index to soil moisture storage capacity	Runoff volumes will change as NOMINAL is increased, particularly in arid climates with seasonal rainfall.
PSUB, GWF--the fraction of flow moving to subsurface groundwater flowpaths and the outflow rate from groundwater storage	These watershed characteristics change runoff timing but not runoff volume. Increasing PSUB causes low flows to increase. Reducing GWF causes the minimum annual flow to increase.

Figure 16
Selecting a final answer for peak flow from sensitivity analysis



Appendix A

An example of peak-flow calculation:

Dry Creek Watershed near Cloverdale, California

L = 28 kilometers
ER = 620 meters
AREA = 230 square kilometers

$TR = 0.95 \times (L^3/ER)^{.385}$
$= 3.75$ hours

From figure 10, RI = 68 millimeters per hour

Using table 3, soil type is silty clay, vegetation is sparse

LR = 3 x 0.5 = 1.5 millimeters per hour

XR = RI - LR = 66.5 millimeters per hour

Peak flow = 0.2778 x (XR) x (AREA)
= 4300 cubic meters per second

An example of calculated monthly flows

An example of recorded monthly flows and calculated monthly flows for Dry Creek near Cloverdale, California. The area of Dry Creek is 225 square kilometers and rainfall is seasonal, with an average of 1510 mm per year. The watershed characteristics for this basin are NOMINAL = 410, GWF = .64, and PSUB = .61.

Water year		Recorded runoff (mm)	Calculated runoff (mm)
1979:	January	135.	198.
	February	134.	144.
	March	50.	79.
	April	24.	20.
	May	7.6	7.2
	June	2.6	2.6
	July	0.6	0.9
	August	0.2	0.3
	September	0.1	0.1
	October	3.3	26.
	November	72.	95.
	December	206.	203.
1980:	January	171.	205.
	February	140.	149.
	March	72.	35.
	April	15.	13.
	May	21.	4.5
	June	4.0	1.6
	July	1.3	0.6
	August	0.4	0.2
	September	0.2	0.1
	October	0.9	0.04
	November	30.	34.
	December	268.	222.

Appendix B

A Fortran program for calculating monthly runoff volumes

```
$CONTROL FILE=1-10,CROSSREF ALL,LABEL,LIST,LOCATION,MAP,SOURCE,STAT
$CONTROL LINES=80
C
C
      PROGRAM NRECA
C
C
      INTEGER MONTH,YEAR
C
      REAL AET,AVMST,DELSTOR,DFLOW,ETRAT,EXMRAT,EXMST,FLOW,GWFRAT,
     1     GWRECH,GWSTOR1,NOMINAL,PET,PRECIP,PRERAT,PSUB,STORAT,
     2     STORAGE,SF,BALANCE,MONPET(12),TOTAET,TOTGWF,TOTDF,
     3     TOTFLOW,TOTSF,TOTRGW,TOTPRE
C
C     FORMATS
C*****************************************************************
C
101    FORMAT(1X,20X,30HNRECA FLOW DURATION MODEL      )
C
102    FORMAT(1X,28X,104HSTOR  PRECIP   AET/   WATER   MOIST EXCESS  DEL
     1TA  RECHG  BEGIN   END     GW  DIRECT TOTAL   MEAS      )
C
103    FORMAT(1X,132HDATE  PRECIP  PET  STORAGE  RATIO /PET     PET   AET
     1' BALANCE  RATIO  MOIST STORAGE TO GW  STOR   STOR   FLOW   FLOW
     3 DISC  RUNOFF      )
C
104    FORMAT(1X,2I2,1X,15(F6.1,1X),F5.1,1X,F6.1,1X,F8.1)
C
105    FORMAT(2I2,3F10.0)
C
107    FORMAT(1X)
C
108    FORMAT(6F10.0)
C
109    FORMAT (1X,20H   NOMINAL STORAGE= ,F5.1,10H   PSUB=  ,F5.3,
     1  10H  GWFRAT=  ,F5.3)
C
110    FORMAT(1X,32H          TOTALS FOR THE YEAR 19,I2)
C
111    FORMAT(1X,6HPRECIP,F7.1,6H  AET ,F7.1,8H  GWRECH,F7.1,8H  GWFLOW
     2  ,F7.1,8H  DIRECT ,F7.1,13H  TOTAL FLOW ,F7.1,8H  OBSRVD,F7.1)
C*****************************************************************
C
C     INITIALIZE VARIABLES
C
      READ(8,108) STORAGE,GWSTOR1,NOMINAL,PSUB,GWFRAT
      WRITE (6,101)
      WRITE (6,107)
      WRITE (6,109)  NOMINAL,PSUB,GWFRAT
      WRITE (6,107)
      WRITE(6,102)
      WRITE(6,103)
C
1     CONTINUE
```

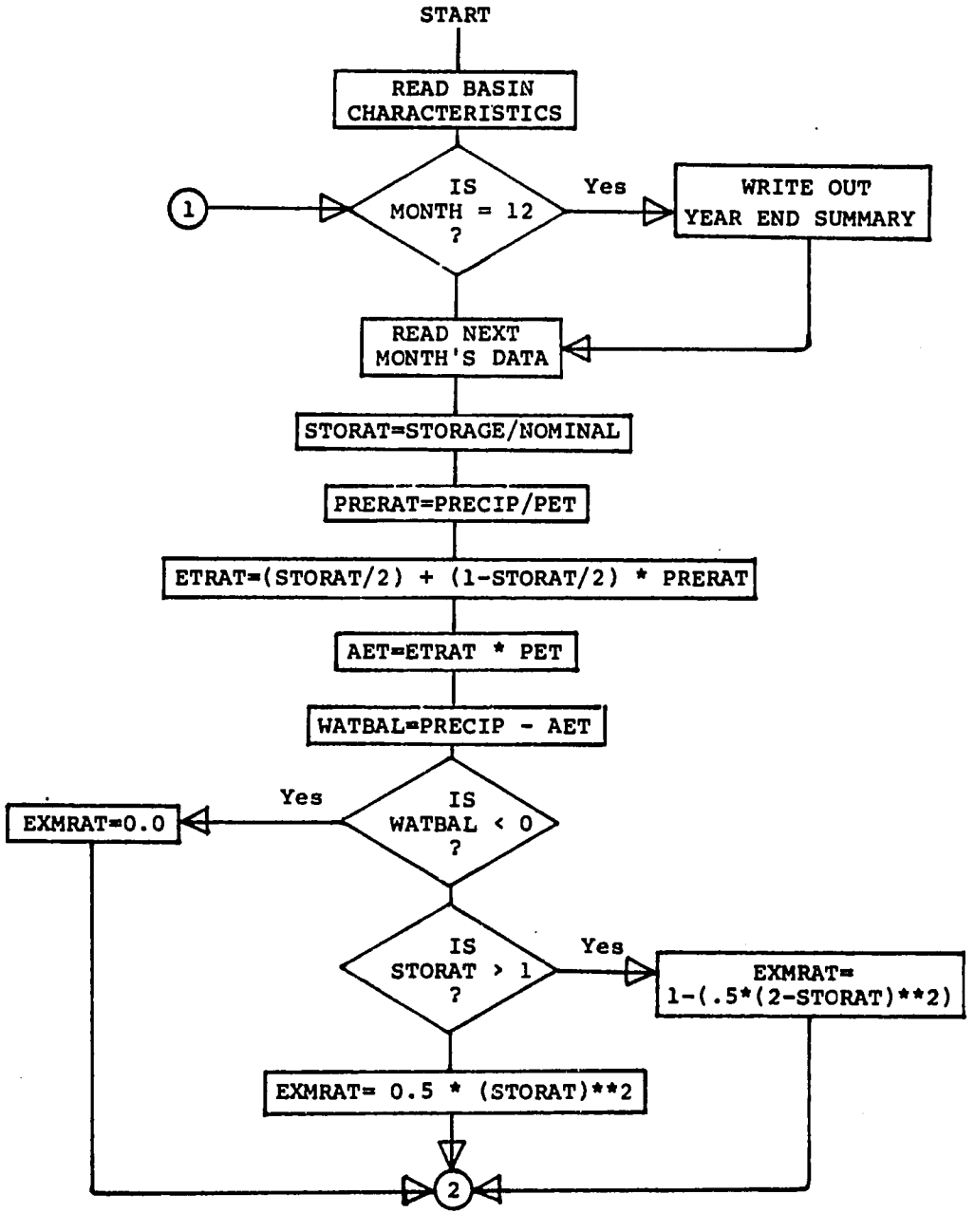
```
C
C     PERFORM ANNUAL SUMMARY
C
      TOTPRE=TOTPRE+PRECIP
      TOTAET=TOTAET+AET
      TOTRGW=TOTRGW+GWRECH
      TOTGWF=TOTGWF+GWFLOW
      TOTDF=TOTDF+DFLOW
      TOTFLOW=TOTFLOW+FLOW
      TOTSF=TOTSF+SF
      IF(MONTH.NE.12) GO TO 2
C
C       WRITE OUT YEAR END SUMMARIES AND ZERO TOTALS
C
        WRITE (6,107)
        WRITE(6,110) YEAR
        WRITE(6,111) TOTPRE,TOTAET,TOTRGW,TOTGWF,TOTDF,
     1               TOTFLOW,TOTSF
        WRITE (6,107)
        TOTPRE=0.
        TOTAET=0.
        TOTRGW=0.
        TOTGWF=0.
        TOTDF=0.
        TOTFLOW=0.
        TOTSF=0.
2     CONTINUE
C
C     READ DATA ON PRECIP AND POTENTIAL EVAPOTRANSPIRATION
C
      READ(8,105,END=6) MONTH,YEAR,PRECIP,PET,SF
C
C
C
C     CALCULATE INITIAL STORAGE RATIO
C
      STORAT= STORAGE/NOMINAL
C
C     CALCULATE AVAILABLE MOISTURE RATIO
C
      PRERAT=PRECIP/PET
C
C     CALCULATE ACTUAL EVAPOTRANSPIRATION
C
C       FIRST SOLVE FIGURE A FOR AET/PET
C
        ETRAT= (STORAT/2) + (1. - (STORAT/2)) * PRERAT
        IF (ETRAT.GT.1.0) ETRAT=1.0
C
C       NOW SOLVE FOR AET
C
        AET=ETRAT * PET
C
C     SOLVE FOR WATER BALANCE
```

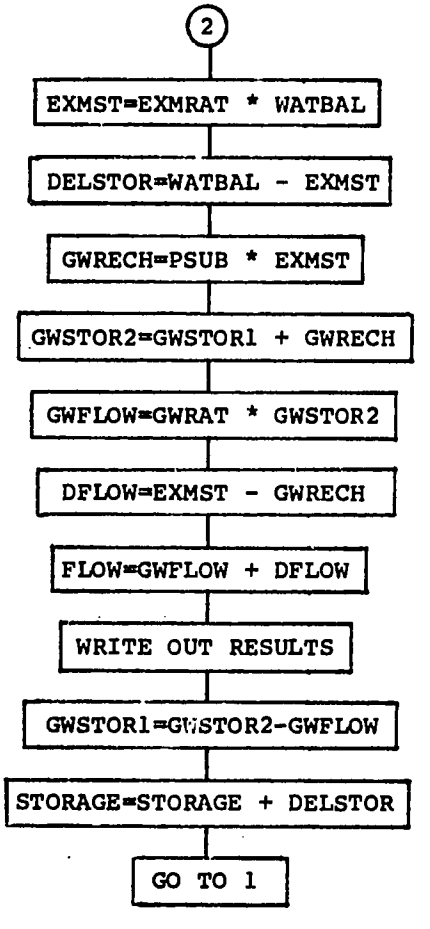
```
C
      WATBAL= PRECIP - AET
C
C       IS THE WATER BALANCE POSITIVE ?
C
        IF (WATBAL.LT.0.)  GO TO 4
C
C          FIND EXCESS MOISTURE RATIO FROM FIGURE B
C
C          IF STORAGE RATIO IS LESS THAN 1.
C
             IF (STORAT.GT.1.) GO TO 3
             EXMRAT= .5 * (STORAT)**2
             GO TO 4
C
C          IF STORAGE RATIO IS GREATER THAN 1.
C
3          CONTINUE
           EXMRAT= 1. - (.5 * (2. - STORAT)**2)
C
C          IF STORAGE RATIO IS GREATER THAN 2.
C
             IF (STORAT.GT.2.) EXMRAT=1.0
4       CONTINUE
         IF (WATBAL.LT.0.0) EXMRAT=0.0
C
C       CALCULATE EXCESS MOISTURE
C
        EXMST= EXMRAT * WATBAL
C
C       CALCULATE CHANGE IN STORAGE
C
        DELSTOR= WATBAL - EXMST
C
C       CALCULATE RECHARGE TO GROUNDWATER
C
        GWRECH= PSUB * EXMST
C
C       CALCULATE GROUNDWATER STORAGE
C
        GWSTOR2 = GWSTOR1 + GWRECH
C
C       CALCULATE GROUNDWATER FLOW TO THE STREAM
C
        GWFLOW = GWFRAT * GWSTOR2
C
C       CALCULATE DIRECT RUNOFF
C
        DFLOW = EXMST - GWRECH
C
C       CALCULATE TOTAL STREAMFLOW
C
        FLOW = GWFLOW + DFLOW
C
```

```
C       WRITE OUT RESULTS
C
        WRITE(6,104) MONTH,YEAR,PRECIP,PET,STORAGE,STORAT,PRERAT,ETRAT,
      1 AET,WATBAL,EXMRAT,EXMST,DELSTOR,GWRECH,GWSTOR1,GWSTOR2,GWFLOW,
      2 DFLOW,FLOW,SF
C
C       RESET INITIAL CONDITIONS
C
        GWSTOR1 = GWSTOR2 - GWFLOW
        STORAGE = STORAGE + DELSTOR
C
C       LOOP BACK FOR NEXT MONTH'S DATA
C
        GO TO 1
C
C       END OF DATA
C
6     CONTINUE
        STOP
        END
```

Appendix C

NRECA flow-duration model (flowchart)




2
EXMST=EXMRAT * WATBAL
DELSTOR=WATBAL - EXMST
GWRECH=PSUB * EXMST
GWSTOR2=GWSTOR1 + GWRECH
GWFLOW=GWRAT * GWSTOR2
DFLOW=EXMST - GWRECH
FLOW=GWFLOW + DFLOW
WRITE OUT RESULTS
GWSTOR1=GWSTOR2-GWFLOW
STORAGE=STORAGE + DELSTOR
GO TO 1

Actual evapotranspiration (AET)--The evaporation and transpiration that occurs from a watershed.

Aquifers--Soils that transmit subsurface flows in quantity.

Floodplains--Areas along a stream that are under water during a flood.

Flow-duration curve--A graph of the percent of time a given flow at a site is equalled or exceeded.

Groundwater outflow--Discharge or flow from groundwater aquifers into stream channels.

Hydrologic cycle--The continuous processes of rainfall, evaporation, and runoff that occur on the watershed.

Infiltration--The absorption of water into the soil.

Peak streamflow--The maximum discharge expected at a site.

Potential evapotranspiration (PET)--The amount of evaporation and transpiration that would occur from a watershed if water supplies were always available.

Spillway--The design discharge of overflow sections of a dam.

Storage--The capacity or the current amount of moisture held in the soil or in groundwater aquifers.

Timing characteristics--Time of flow for surface runoff or channel flow in a watershed.

Transpiration--The movement of water through plants from roots to leaves and evaporation from the surface of leaves.

Watershed--The area of the land surface that drains to the site.