# FLOOD ESTIMATION PHILOSOPHY

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ABSTRACT

The method used to calculate floods has a big effect on the answer, as well as the estimated impact of the flood, or damage. The more important the project the more sophisticated the method should be. Extrapolation for unmeasured extreme floods of a selected probability of non-occurrence cannot be perfect. The probability and risk tolerated will affect the answer sought. Deterministic, empirical and mathematical solutions can differ considerably and alternative methods may be compared to provide confidence in the answer. The paper reviews a history of flood estimation methods and suggests how to decide the answer for extremes in the face of a number of uncertainties.

INTRODUCTION

The hydrologist or engineer is sometimes asked what flood can be estimated for a particular site and what to do about it. There are no absolute rules yielding an answer and the response will depend on the education and experience of the person and the method used to arrive at an answer. Answers can vary widely unless there are set rules for deriving them. Even rules can vary considerably. The method used to calculate an answer may depend on the importance of the project. Simple answer methods coupled with estimated parameters may suffice for unimportant cases, and sophisticated models with considerable data will be required for important cases. Re-design of the system and stormwater management may be required to render the solution more acceptable, so details of potential floods may be required.

The method selected for flood calculation can depend on the background of the analyst. Academics often have preferred methods because they have a research driven position and may have developed methods or variants. Young graduates tend to recognize methods taught at institutes. Some prefer computer models, while older people may be more convinced by manual calculations. Engineering organizations and official institutions often provide guide manuals which highlight some methods.

The science of flood estimation has advanced considerably since the advent of computer software. But there are still many simplifications and doubtful assumptions involved. It pays to look back over the first investigations of flood magnitudes and the subsequent advancement of the science (Stephenson, 1981).

HISTORICAL DEVELOPMENTS

An early paper by Lloyd-Davies in 1905 proposed that the storm which produced the biggest flood for any recurrence interval was one with a duration equal to the concentration time of the catchment. That was assumed equal to the travel time down the catchment and that was related to the catchment area.

Those assumptions are carried forward to more modern methods including the Rational method. We are aware however that that is not always correct. Hydraulic theory shows that a water body reaction time can be faster than travel time. There are also odd shape catchments with the bulk of runoff closer to the mouth or outlet so critical storms shorter that the complete contributing catchment area can result in peak outflow. There may be retention dams or catchment properties which can affect reaction time. Nevertheless, the Rational theory is still used probably more than any other on calculating flood peak flows.

A more direct formula was also produced, the Birmingham formula; i=40/(20+t) where i is design rainfall intensity in inches per hour and t is the concentration time in minutes. This formula is reputed to produce excess rain intensity ie it allows for losses along the way. It was applicable to English rain for an acceptable recurrence interval of twice a year for short storms to 15 months for longer storm durations ie over 1 hour. Other formula used in the same region allowed for runoff only from impervious surfaces, and some formulae allowed varying impermeable surface areas.

Lloyd-Davies went further to enable individual drains in a catchment to be designed. He developed the Step method. This goes down the catchment from pipe to pipe allowing a bigger contributing area downstream but longer storm duration to account for longer travel time.

The assumption of unique travel time for a catchment simplifies the calculations. So a graph of contributing area against time can be plotted.

A further improvement by Watkins (1962) was the Tangent method designed to accommodate catchments which may have a long concentration time in total but the biggest flood can occur from a large portion of the catchment which may be closer to the mouth. Each contributing area is plotted against time to contribute at the mouth. A cumulative line is then drawn. Another similar line is drawn b back, where b is as in the rainfall intensity equation i=a/(b+t). Then the maximum flow is the proportional to the slope of a line tangential to both cumulative area curves. Q=aA/(b+t) where A is the area between the two tangent points and t is the horizontal distance between..

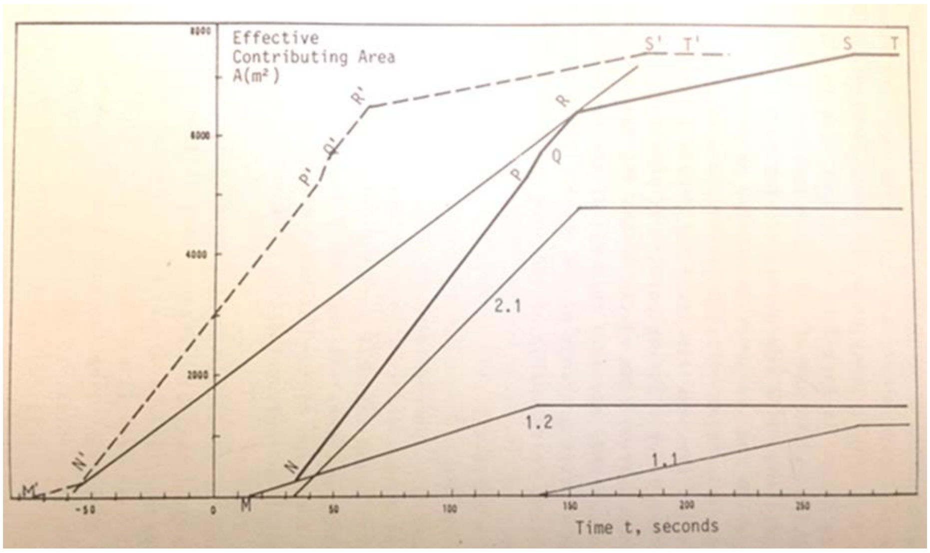


*Figure 1. Tangent method for drain networks.*

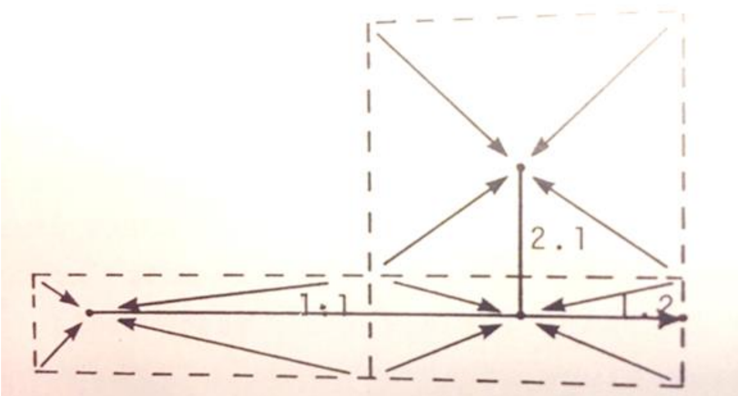


*Figure 2. Network used for tangent method.*

Escritt (1972) suggested using a rainfall intensity independent of storm duration for durations less than 15 minutes in England. This simplifies calculations. Eventually a simplified yet relatively comprehensive method evolved, named the Rational method;

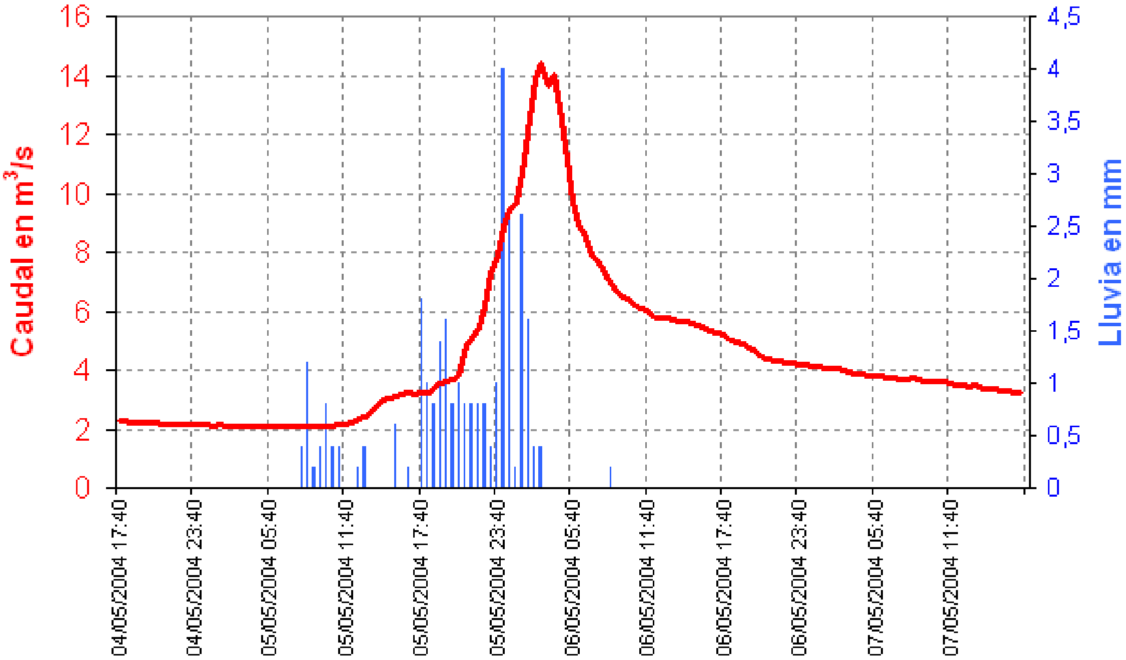


*Figure 3. Hyetograph, histogram(rain) and Hydrograph plot(flow rate)*

THE RATIONAL METHOD

The popular equation used to calculate peak flow is;

Q=C.i.A

Where Q is peak flow rate, C is a coefficient, i is design rainfall intensity and A is the catchment area. If SI units are used, they are in metres and seconds. If other units are used an additional correction coefficient is required.

i; i is the rainfall intensity selected. It is assumed a function of storm duration and probability. An equation often used to estimate i is

i=a/(b+t)^p

t is the storm duration. a , b and p are regional constants obtained from data from monitored storms. It is assumed the rain is uniform over the storm duration and across the catchment or sub-catchment selected. Point rain data may have to be corrected to allow for catchment size as it can vary across the catchment. The relevant storm duration is assumed equal to the concentration time of the catchment which is assumed equal to the runoff travel time down the catchment.

Design storm duration is often estimated from equations for catchment concentration time $t_c$ which in turn is estimated from an equation of the type;

$t_c=(kL_c^{e1}/H_d)^{e2}$

Where $t_c$ is the concentration time, $L_c$ is the effective catchment length and $H_d$ is the effective drop in elevation down the catchment. For example if L is in km and H in metres then the SCS equation gives k as 0.87, e1 as 3 and e2 as 0.385 for $t_c$ in hours.

The assumption is that critical storm duration is equal to the catchment concentration time, a unique number irrespective of rain fall intensity. Not only is this assumption wrong, but also the maximum runoff rate frequently results from a storm of duration shorter than the concentration time, because shorter storms generally are associated with higher precipitation rates. Longer storm durations may have a rain intensity less than the infiltration rate and detention time. So the theory that maximum runoff occurs when storm duration is equal to catchment concentration time, is generally erroneous.

C; The coefficient C is the most significant variable in many flood calculations. Depending on the value selected ( between 0 and 1.0), runoff can vary from zero to 100% of the rainfall. Theoretically an exact answer for runoff peak is possible, but only if the value of C selected is correct. There are many suggestions and rules for selecting a value for C. In the end the value selected can rarely be correct. That is unless it is calculated for a monitored storm and corresponding runoff. But it can be different for other storms.

Factors which can affect C are;

1. Topography ie ground slopes, shape of catchment, roughness, channelization
2. Ground cover and changes in this over time
3. Infiltration which can vary over time and depends on antecedent moisture in the soil and underlying strata
4. Obstructions and deviations in flow paths
5. Management interventions including detention storage dams
6. Precipitation pattern in time and space
7. Climate change effects

Rarely is all this data known but it is so difficult to assemble that a guess is invariably made for C to enable a calculation to proceed. It may be more comfortable to use a published value of C.

## PRECIPITATION AND RAINFALL PATTERNS

More attention has been paid to precipitation causing floods than other factors. This may be because rainfall data is more readily available than stream flow data at any selected site so it entices research. Rainfall is more a regional thing than site specific flow rate. Plots of storm intensity versus duration, rain variation in time and space and analysis of frequency of exceedance provide interesting research topics.

Rain seldom falls uniformly during a storm. In fact, storm cells move with the air and change shape and intensity over time making rainfall input to a model complicated. Usually, the rain is assumed to occur in uniform blocks to enable calculations to be simplified. The precipitation and moisture penetration during and prior to a storm also affects runoff. Groundwater may also seep out from the ground in places and at times.

A typical plot of rainfall intensity for a site as a function of storm duration and recurrence interval of exceedance is given below.

In general, long duration storms offer lower rates of precipitation. This may be due to differing types of storm, eg orographic, topographic, cyclonic etc. But there may be discontinuities in the trend due to unknown effects suddenly appearing eg El Nino effects. Climate models are trying to evaluate these effects.

Rainfall patterns have changed and are likely to change more in the future as climate changes. Oceans and the atmosphere have large impact on rain.

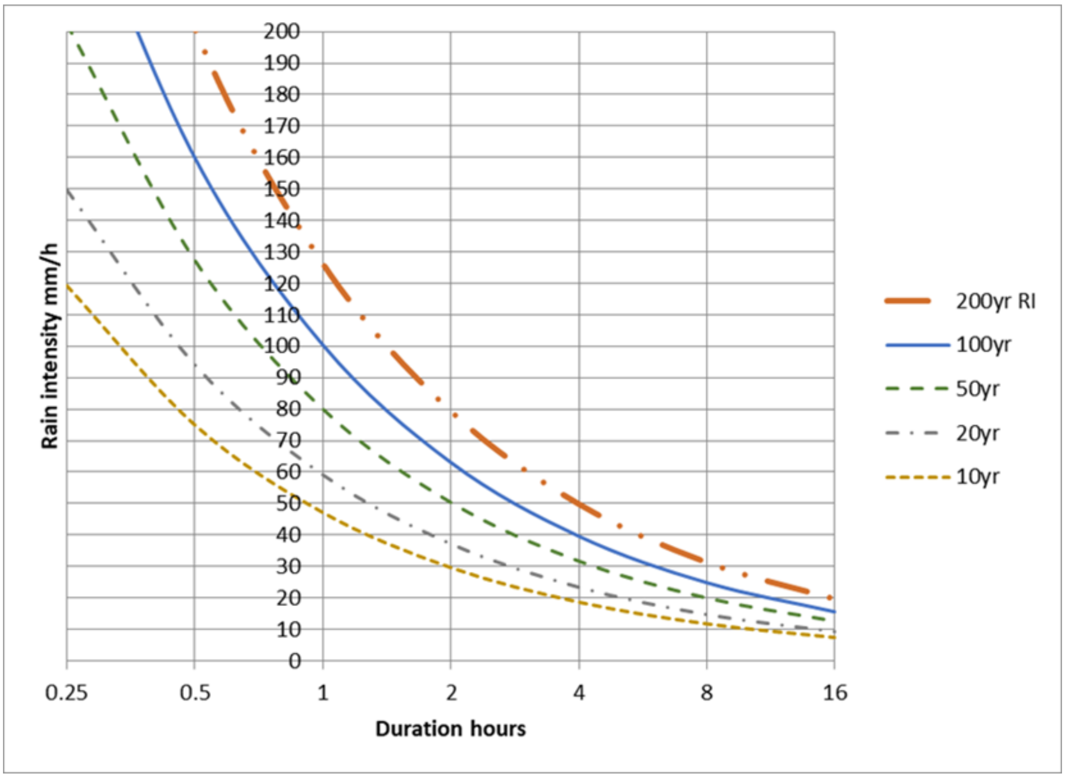


*Figure 4. Rainfall Intensity-Duration-Frequency graph for a site*

EMPIRICAL APPROACH

There is a lot of data on floods observed. In fact the only way of proving a theory is to compare with observations. Experience diagrams can be plotted of flood peak against catchment area. These can be on a regional basis or international. It does not mean that the envelope will not change in the future.

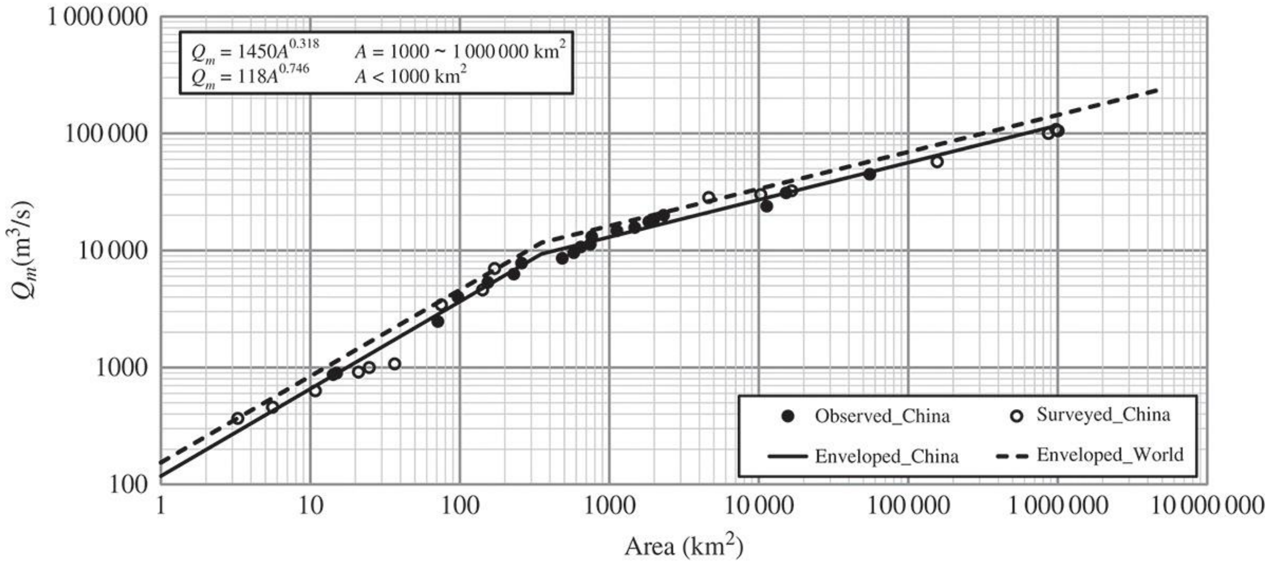


*Figure 5. Maximum observed floods (Chaoqun,2013)*

STATISTICAL PROJECTIONS

Various statistical distributions have been used to make projections beyond the period of observation. The selected probability distribution affects the estimate of extreme values, which may never be proven.

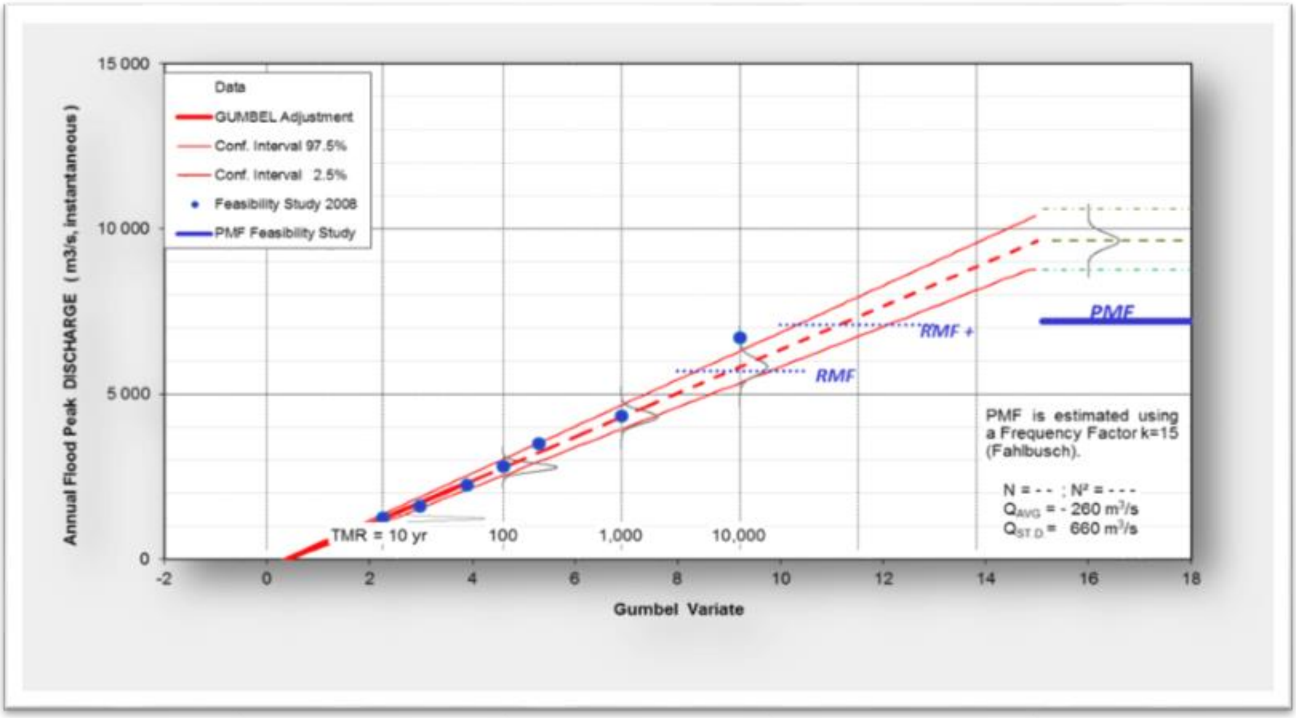


*Figure 6. Extrapolation Plot against Gumbel statistical variate (Fahlbusch, 2001)*

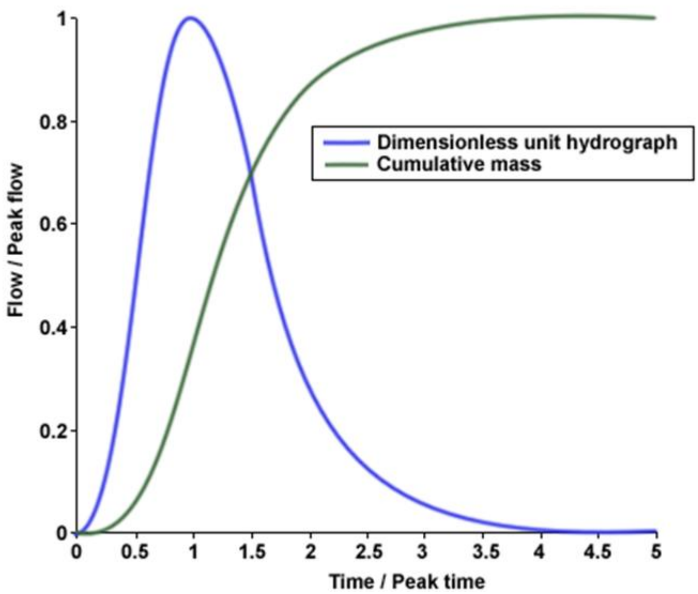


*Figure 7. Dimensionless unit hydrograph from cumulative mass flow curve*

HYDROGRAPHS AND UNIT HYDROGRAPHS

Runoff increases during excess rain and after peaking falls. The initial and end flow is base flow and this must be subtracted when manipulating the rainfall-caused runoff. Hydrograph shape is a function of catchment and storm characteristics. The hydrograph is important particularly if flood routing is achieved, that is reduction in the peak flood due to detention of water, in a reservoir, over a flood plain or in channel.

SCS METHOD

The United States Soil Conservation Service (SCS, 1972) approached flood estimation from a different angle. They have done extensive research into soil moisture retention for agricultural purposes. They allocated curve numbers to different soils based on how much moisture can be absorbed by soils before runoff commences. When the maximum soil moisture content is reached runoff is equal to rainfall. There is an adjustment for antecedent soil moisture. The extrapolation of the theory to runoff estimation is less tenuous than the estimate of moisture retention.

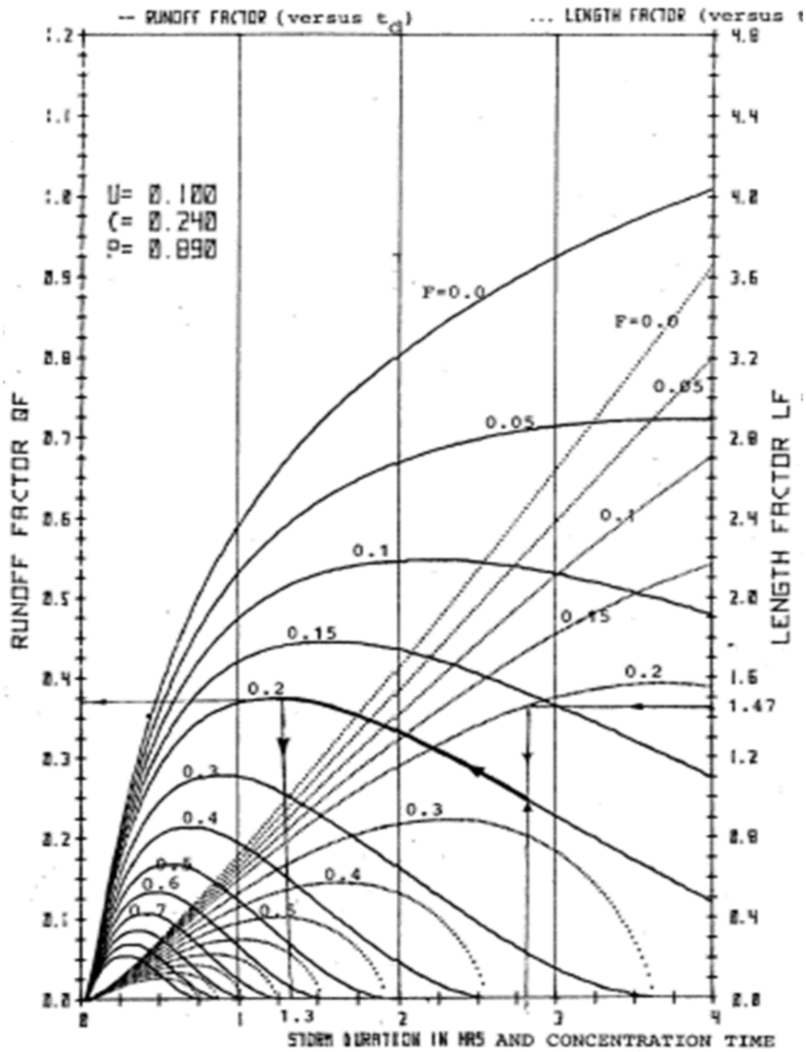


*Figure 8. Nomograph for peak flow using kinematic theory (Stephenson, 2002).*

KINEMATIC THEORY

The next step in sophistication is to use kinematic theory to calculate runoff from rainfall input. Kinematic theory assumes wave form travel of water ie the depth of runoff affects rate of movement of the waterfront, whereas the old fashioned linear theory assumes the reaction rate is only a function of the catchment. Kinematic theory assumes uniform flow along a waterway and further hydrodynamic theory is used to model dynamics of acceleration and deceleration (Stephenson and Meadows, 1986). The theory produces simple design equations, more sophisticated than Rational method etc but less comprehensive than full hydrodynamic theory. Some models eg HECRAS switch to the more accurate equations for design of training works.

To use this graph ,

$LF=L/36aA^{2/3}$
$QF=10^5Q/BaA^{5/3}$
$a=S^{0.5}/n$
$i=A/(c+t)^p$
$t_c$=concentration time in h, t=critical storm duration in h, L= catchment length in m, B=catchment width in m, A=fitted constant in mm/h, c=fitted constant in h, p= fitted exponent (all from fitting to rain data), S=slope, n=Manning number, u=initial abstraction in mm, U=u/A, F=f/A, f=infiltration rate in mm/h.
Then calculate LF, enter graph from left to find concentration time $t_c$ for known F. However, critical storm duration may be less than concentration time so go up the solid runoff line to its top and read QF on the left.

Apart from simplistic equations and graphs the kinematic equations have been incorporated into computer models, eg Stephenson, 2002b.

COMPUTER MODELS

Many of the above theories can be incorporated in computer models and there are a number of commercially available models for applying to specific runoff problems. There are very sophisticated variations possible to build into models, ie catchment and precipitation details (eg Abbott et al, 1986). Data can be derived from GIS (Geographic Information Systems) or maps, surveys and Lidar data banks. The more sophisticated models use kinematic or hydrodynamic theory (US Corp of Engineers, 2021).

Once the user is familiar with a model, alternative scenarios and management practices can be studied. The assumptions behind the calculations must be recognised to be confident of the model output results.

PROBABILITY AND RISK

Important or dangerous projects are generally designed to withstand an extreme flood. That may be designated a 1 in 100 year or 1 in 1000 or 1 in 10 000 year frequency for example.

An interesting concept is to design for a PMF or Probable Maximum Flood. This flood is unlikely to have occurred at any site. So how is it calculated? One could extrapolate other measured floods using some form of probabilistic graph paper. Some suggest there is a relationship between the 1/10000 year flood and the PMF (Zhou et al, 2008). Or some suggest using a PMP (Probable Maximum Precipitation) with a rainfall-runoff model (WMO, 2006). That opens even more unknowns; precipitation source, movement and atmospheric conditions.

Really, we are looking for a flood figure which is unlikely to occur or one we can handle. If we introduce Risk into the consideration it becomes more complicated. Ie not only should there be a low probability, there should also be little damage if it did occur. Risk is the product of probability and damage. Dam design suggestions attempt to consider risk by classifying dams depending on the damage likely if they fail. And at the same time introduce another factor; should the consideration assume a worse flood than PMF etc by considering the probability of the structure collapsing?

The economics also needs consideration. If possible cost implications are high then another solution/ dam may be considered. Or a greater risk could be considered by establishing warning systems or subsidies. The risk could be increased for minor structures and where the implications of flooding are not significant. Roads often have dual or triple drainage allowance. Drain pipes and surface inlets could take the majority of floods and occasionally the road surface could be inundated. And with an even lower probability the kerbs could overtop and endanger homes/assets around. Typical design flood recurrence intervals are;

Road surfaces 2 years
Road drains 20 years
River banks 50 years
Rural bridges 100 years
Minor dams 1000 years
Major dams 10 000 years

When looking at extremely unlikely events, the significance of climate change increases in perspective. Climate change effects on rainfall intensity and pattern, as well as catchment cover change, are likely to be significant over coming decades and centuries (eg Fowler et al, 2021). These will impact on extreme floods especially (Kundzewicz, 2014). In addition to natural causes there are man-made causes of floods. These could include dam-break, malfunction of gates and controls and regional changes in landform. The probability of multiple factors occurring, independently, sequentially or as a domino effect needs evaluating.

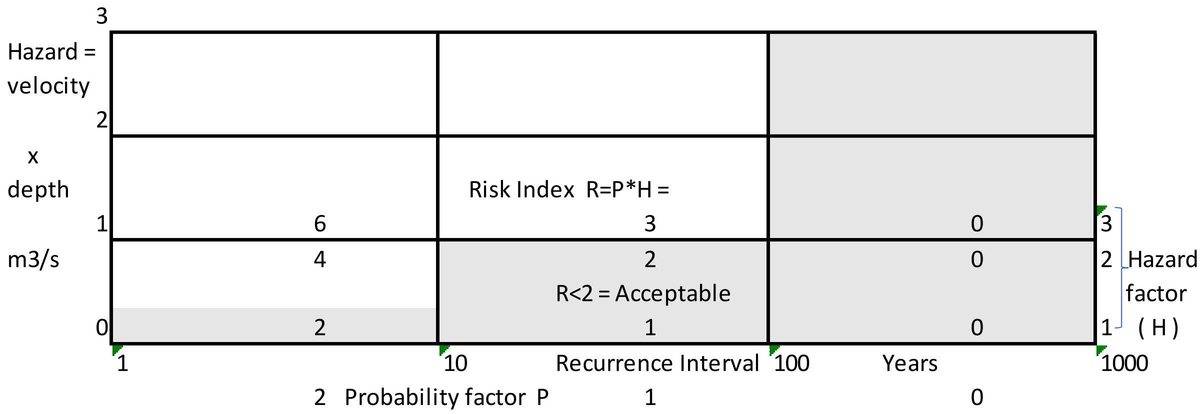


*Figure 9. Flood risk is a function of probability and hazard (Stephenson, 2002).*

Apart from the low probability of an extreme flood occurring (related to flow records and extrapolations) there are other uncertainties. Climate change, and topographic changes, are uncertainties which relate to risk. And the whole process of mathematically extrapolating flood numerical values is uncertain. If we are to make an allowance of such unknowns, it could increase the magnitude of floods to consider.

The most concerning factor not often mentioned is demographics and population growths. Population growth at a rate we are not able to compensate for is the main reason behind climate change and land use. Population control may be easier to control than changing the environment to suit but it is loaded with implications. It will indeed involve political decisions but they are also easier to change than the environment. The future holds an interesting conclusion.

As an alternative to selecting a flood to design for, an interactive solution could be sought. For example, a dam could be designed to reduce flood magnitude or risk (Graham, 2007). The effect of flood routing can be optimized (at a structural cost but impact reduction). Or the risk (downstream) could be reduced by relocating or redesigning endangered things.

APPLICATION EXAMPLE

To illustrate the possible range of estimates a dam under design in a mountainous remote region had the following figures;

Catchment area 3300km$^2$

Rational method flood peaks; 100yr 2700m$^3$/s,

Flow peaks for recurrence intervals over 100 years were obtained by extrapolation ie 10 000 yr 6600m$^3$/s, PMF 7200m$^3$/s.

Extrapolation of observed regional floods indicated PMF 7000 m$^3$/s.

Computer models allowing estimates of conditions indicated a possible PMF of 10000m$^3$/s.

A world PMF diagram indicated PMF for worst world conditions and applicable catchment area of 20000m$^3$/s.

The dam owner considered accepting a PMF of 10000m$^3$/s for checking this dam. This was after considering design data for other dams in the region and the consequences and costs of incorrect selection.

## CONCLUSIONS

Whatever you do it is unlikely to produce a perfectly correct answer for extreme flood peak magnitudes. The most you can hope for is an answer satisfying the client or public and yourself that it is the best you can do after considering hydrology and risk, and the possibility of controlling the flood. You should therefore compare alternative answers using different approaches and best data you can find. Try to calibrate and verify your calculation method using whatever observed data you can find. The effort you go to should be a function of the importance of the result or structure envisaged to control the flood. Discuss the answers and consequences with all parties before proceeding with design.

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