Flash floods
in arid and semi-arid zones

Prepared in the framework of the
International Hydrological Programme
by the Working Group of Project H-5-2 (IHP-IV)

Co-ordinator: Xiao Lin
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<td>Management of warning systems</td>
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<td>7.3.2</td>
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1. Introduction

One third of the world's land surface may be classified as arid or semi-arid. In such areas, on the one hand precipitation is rare and serious droughts occur frequently while on the other hand, flash floods may cause serious disasters.

The characteristics of flash floods are their short duration, small areal extent, high flood peaks and rapid flows, and heavy loss of life and property. Forecasting flash floods is difficult. Governments in all countries of the world are paying increasing attention to research into flash floods. There is a shortage of hydrological and meteorological data for the arid and semi-arid zones. Hydrological research is very deficient. Flash flood research is becoming increasingly important, particularly with regard to improved data collection techniques, defining flash flood types and the reasons for their formation, properties, and spatial and temporal distribution, forecasting techniques, warning systems and control measures.

Flash flood research in the arid and semi-arid regions is one of the subjects in the fourth phase of the International Hydrological Programme (IHP) or UNESCO. This technical report is one of the research results within IHP-IV Project H-5-2. This research project is an international and co-operative venture. The group members are Professor Xiao Lin (Rapporteur of the IHP H-5-2 project “Flash floods in arid and semi-arid zones”), Professor Zhang Guoqing and Professor Zhao Yinglin, Wuhan University of Water Resources, China; Dr Bouzaine, Tunisia; and Dr P. Givone, France.

Many textbooks and papers were referenced during the writing of the technical report, particularly the documents emanating from the International Symposium on Flash Floods in Arid and Semi-arid Zones, held in September 1994 in Xi'an, China, and the International Symposium on Hydrological Research and Water Resources Management Strategies in Arid and Semi-Arid Zones, held in September 1995 in Tashkent, Uzbekistan.

Special acknowledgements are due to Dr Habib Zebidi, Programme Specialist in the Division of Water Sciences, UNESCO, for his guidance and unfailing support for this project; also to Professor M. H. Diskin of the Israel Institute of Technology, Faculty of Civil Engineering, and to Wang Juemou, WMO Representative and Head of the Hydrological Forecasting and Water Control Center, China, for their valuable suggestions to the draft outline of this report. Thanks are also given to Mr S. Takei, Head of the UNESCO, Beijing office, for assistance with transmitting letters.

This report comprises eight chapters. Chapters 1, 6 and 8 were written by Professor Xiao Lin; Chapter 2 by Professor Zhao Yinglin; Chapter 3 by Dr P. Givone and Professor Xiao Lin; Chapter 4 by Professor Zhang Guoqing; Chapter 5 by Dr Bouzaine; and Chapter 8 by Senior Engineer Zhang Ruifang. Although the report attempts to reflect the most up to date research results and covers many aspects, it still leaves much to be desired. The authors sincerely hope that all participants will offer valuable opinions.
2. Definition of geophysical, climatological and hydrological characteristics of arid and semi-arid zones

2.1 Definition and scope of arid and semi-arid zones

At present, there is still no conformity in the definitions for arid and semi-arid. In spite of the many versions to be found in reference books, none of them are deemed to be satisfactory. The two terms arid and semi-arid are not exact. Different definitions may be appropriate under varying research problems and conditions. For example, in an agricultural context, “in general, the terms arid and semi-arid zone are applied to those areas where rainfall will not be sufficient for regular rain-fed farming” (FAO, 1981; Walton, 1969). Many other definitions have been developed based on climatological data, usually precipitation, evapotranspiration, temperature, radiation, etc.

De Martonne has suggested the following expression for use as an aridity index:

\[ X = P/(10 + T) \]  (2-1)

where \( P \) = mean annual precipitation, mm
\( T \) = mean annual air temperature, °C

Where \( X < 15 \), this area is considered to be an arid zone.

UNESCO has taken the ratio of precipitation to potential evapotranspiration (\( PET \)) as an aridity index:

\[
\begin{align*}
\frac{P}{PET} &< 0.03 & \text{hyperarid zone} \\
0.03 < \frac{P}{PET} &< 0.2 & \text{arid zone} \\
0.2 < \frac{P}{PET} &< 0.5 & \text{semi-arid zone}
\end{align*}
\]

where \( P \) = mean annual precipitation, mm
\( PET \) = mean annual potential evapotranspiration, mm, as calculated by the Penman formula.

In China, it is usual to take the precipitation and aridity index (\( PET/P \)) into consideration in the division of natural geographic regions (see Table 2.1).

The main point of this report is a consideration of flash floods, however, not to explore the definitions of arid and semi-arid zones, or to research hydrological phenomena or laws. It is therefore unnecessary to over-discuss the definition.

One-third of the world’s land surface may be classified as arid and semi-arid. Most of northwest China belongs to the arid and semi-arid zone, an area approximately 45% of the whole country; the arid zone represents 25% of the total area. These regions are found in the north of the Shanxi province, the middle and north of Ganshu province, most of the Qinghai province apart from the source of the Yellow River, and most of the Xinjiang province except for the inner river region and the Elqis River. A map showing the arid and semi-arid zones in China is shown in Fig. 2.1.
Table 2.1 The division of natural geographic regions

<table>
<thead>
<tr>
<th>Zone type</th>
<th>Annual precipitation (mm)</th>
<th>Aridity index</th>
<th>Annual runoff coefficient</th>
<th>Annual runoff depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainy zone</td>
<td>&gt;1600</td>
<td>&lt;0.5</td>
<td>&gt;0.5</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>Humid zone</td>
<td>800–1600</td>
<td>0.5–1.0</td>
<td>0.3–0.5</td>
<td>300–100</td>
</tr>
<tr>
<td>Semi-humid zone</td>
<td>400–800</td>
<td>1–3</td>
<td>0.1–0.3</td>
<td>50–50</td>
</tr>
<tr>
<td>Semi-arid zone</td>
<td>200–400</td>
<td>3–10</td>
<td>&lt;0.1</td>
<td>10–50</td>
</tr>
<tr>
<td>Arid zone</td>
<td>&lt;200</td>
<td>&gt;10</td>
<td>&lt;10</td>
<td>&lt;10</td>
</tr>
</tbody>
</table>

**Fig. 2.1 Regional classification of precipitation and runoff in China**

2.2 Climate and natural geographic characteristics of arid and semi-arid zones

The natural geography of the arid and semi-arid zones is complex and differs from site to site. However, the characteristics in common are infrequent rainfall, drought, poor vegetation cover, low cover ratio, serious soil loss and erosion, and high river sediment concentrations during the flood seasons.

The arid and semi-arid regions of China are located in the north west, far away from the sea and ocean. The climatology is that of the continental climate of the temperate zone, with sudden changes between cold and hot. Air temperature gradually decreases from south to north. Annual precipitation is less than 400 mm. The mean annual rainfall at the Tuokexun station in the Xinjiang province is only 3.9 mm, the lowest recorded in China. Precipitation is most concentrated between June and September, with storms of short duration and limited area. The distribution of annual precipitation is more complex because of the effects of atmospheric circulation and topography. Annual evaporation is in the range 1000–3000 mm, i.e. three to five times that of annual precipitation and sometimes even more than 60 times. The depth of annual runoff is generally 20–50 mm, or
even no runoff at all in some hyper-arid regions. There are a high proportion of strong winds in these zones, such that more than 24 days in a year will experience Force-8 winds, or even more than 60 days a year in some exposed regions. Because of poor vegetation cover and loose surface soils, once these high winds blow, dust pervades the air and blots out the sun.

2.3 Characteristics of precipitation in arid and semi-arid zones

Precipitation is the most important hydrological variable in the arid and semi-arid zones since, as in other areas, it is the origin of both surface water and groundwater. Because the arid and semi-arid zones are vast, the precipitation situation is significantly different in various regions. In a great majority of tropical areas, precipitation is concentrated in the summer months, as in the southern part of the Sahara, the north of Namibia, and the arid and semi-arid zones of India, Australia, Mexico, the United States of America and China. There are also some areas where precipitation is concentrated in the winter, mainly as snowfall, such as in the Aertai mountain areas of the Xinjiang province of China where snow represents 46% of the annual precipitation. Flash floods in arid and semi-arid regions result largely from storms and therefore more attention is paid to rainfall. In comparison with humid zones, there are many unique characteristics which may be summarized as follows:

2.3.1 Smaller frequency of occurrence of rainstorms

Rainstorms are random events, with a small frequency of occurrence in certain arid and semi-arid zones, and much smaller for certain fixed sites. For example, in the Tulufan and Talimu basins of China, rainstorm frequency is one per 15–30 years.

2.3.2 Lower magnitude of frequent storms

Extraordinary storms are rare and the magnitude of frequent storms is smaller. The mean annual depth for 24-hour storms fall within the range 20–30 mm in semi-arid zones, 10–20 mm in arid zones, and below 10 mm in the hyperarid zones of north-west China. It is about 10–25 mm in the western parts of the United States, and more than 100 mm in the humid zones of China. In other words, the more intense the drought conditions, the lower the magnitude of frequent storms.

2.3.3 Great yearly variation in storms

The yearly variation in storms in arid and semi-arid zones is very large. Not only is the coefficient of variation $C_v$ very high but so also is the coefficient of skewness $C_s$. For example, the $C_v$ of annual maximum 24-hour storm is less than 0.5 in the humid regions of China but is above 0.5 in the arid zones, sometimes even greater than 1.0. The value of $C_v$ increases a decrease in storm duration. In north-west China, the maximum 24-hour point precipitation is particularly large and at many points surpasses the annual precipitation value, as shown by the examples given in Table 2.2.

2.3.4 Short duration and high intensity of rare storms

The intensity of rare storms is always very high, especially for short duration storms in the arid and semi-arid zones. Because runoff is determined by rainfall intensity to a great extent, the consequences of precipitation are quite different for different rainfall intensities. In the arid regions of tropical zones, rainstorms result from short duration convective storms which usually last from 15 minutes to two hours and with a maximum intensity in excess of 100–150 mm/hour. In the arid zones of
Table 2.2 The ratio of 24-hour point precipitation to annual precipitation

<table>
<thead>
<tr>
<th>Province</th>
<th>Station</th>
<th>Max. 24-hour point precipitation P1 (mm)</th>
<th>Annual precipitation P2 (mm)</th>
<th>P1/P2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xinjiang</td>
<td>Anjihai</td>
<td>240.0</td>
<td>159.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Xinjiang</td>
<td>Ruqiang</td>
<td>73.5</td>
<td>18.0</td>
<td>4.1</td>
</tr>
<tr>
<td>Ganshu</td>
<td>Akeshe</td>
<td>123.3</td>
<td>37.0</td>
<td>3.3</td>
</tr>
<tr>
<td>Ningxia</td>
<td>Helanshan</td>
<td>21.5</td>
<td>209.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Inner Mongolia</td>
<td>Muduochaidang</td>
<td>1400.0</td>
<td>364.0</td>
<td>3.8</td>
</tr>
<tr>
<td>Inner Mongolia</td>
<td>Xilinhot</td>
<td>350.0</td>
<td>295.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Hebei</td>
<td>Dashanjingou</td>
<td>620.0</td>
<td>439.0</td>
<td>1.4</td>
</tr>
</tbody>
</table>

north west China, records for storms of less than one hour duration are greater than for other regions of the country. The "77.8" storm which occurred in Muduochaidang in Inner Mongolia in August 1977 is a special case whereby the rainfall over a 10-hour duration period reached 1400 mm. Such a storm event is rarely experienced except at Xinliao in the Taiwan province of China and indeed this record is the highest that has occurred on the mainland.

2.3.5 Specific significant localized features of storms

In the tropical arid zones the areal extent of every storm is variable but rarely more than 100–200 km$^2$ (commonly 30–60 km$^2$ in the Sahel). Areal extent in mountainous regions is much smaller and the localised nature of storms is very significant, such that the record from one raingauge at the storm centre may be quite large but that of adjacent raingauges quite small or even recording no rain at all. At the downstream Yangping station on the Kuye River in the northern Shanxi province in China the measured 12-hour rainfall reached 408.7 mm on 25 July 1971, equalling the mean annual precipitation for this region, while at the Taihezai station only 20 km away, the 24-hour rainfall was only 31.7 mm. Another classic case given in Table 2.3 is a 45-minute storm in the Huangpuchuan catchment ($F=3246$ km$^2$) in north-west China.

Table 2.3 Rainfall distribution of a 45-minute storm in Huangpuchuan

<table>
<thead>
<tr>
<th>No</th>
<th>Station</th>
<th>Time 7.15–7.30 (mm)</th>
<th>Time 7.30–7.45 (mm)</th>
<th>Time 7.45–8.00 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wulangou</td>
<td>23.0</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td>Deshengxi</td>
<td>38.0</td>
<td>106.0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Tiangetan</td>
<td>56.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Nalin</td>
<td>15.0</td>
<td>5.0</td>
<td>7.0</td>
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<td>4.0</td>
<td>4.0</td>
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<td>Hazite</td>
<td>11.0</td>
<td>3.0</td>
<td>10.0</td>
</tr>
<tr>
<td>7</td>
<td>Edaowan</td>
<td>3.0</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>8</td>
<td>Changtan</td>
<td>7.0</td>
<td>12.0</td>
<td>9.0</td>
</tr>
<tr>
<td>9</td>
<td>Gucheng</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.4 Pattern and characteristics of floods in arid and semi-arid zones

On the basis of a flood study of events in arid and semi-arid zones in north-west China, floods may be divided into three main types: rainstorm floods, snow- and ice-melt floods and mixed rain and snow-melt floods. If the reasons for the occurrence are different, then flood characteristics will also be different.

2.4.1 Rainstorm floods

Storms are the main reason for arid and semi-arid zone floods. The characteristics of storm floods may be summarized as follows:

(1) Sudden occurrence and rapid rise and fall

Flooding happens quickly and durations are short, often of only a few hours or half a day, rarely more than one day. The time to peak from the beginning of the rising limb of the hydrograph may be even as little as only 10 minutes. The flood hydrograph obviously shows a sharp peak, with rising and falling limbs changing suddenly. Some examples are given Table 2.4.

Table 2.4 Flood characteristics for the Wujiaochuan station on the Kuye River, China

<table>
<thead>
<tr>
<th>Date</th>
<th>Rise start</th>
<th>Peak flow</th>
<th>ΔQ/Δt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t_i(h)</td>
<td>t_p(h)</td>
<td>ΔQ(m^3 s^-1)</td>
</tr>
<tr>
<td>1954/7/12</td>
<td>7.0</td>
<td>10.0</td>
<td>7780</td>
</tr>
<tr>
<td>1959/8/1</td>
<td>16.5</td>
<td>20.6</td>
<td>10000</td>
</tr>
<tr>
<td>1961/7/22</td>
<td>11.4</td>
<td>12.4</td>
<td>8710</td>
</tr>
<tr>
<td>1966/7/28</td>
<td>15.8</td>
<td>17.0</td>
<td>8380</td>
</tr>
<tr>
<td>1967/8/6</td>
<td>0.0</td>
<td>5.6</td>
<td>6630</td>
</tr>
<tr>
<td>1971/7/25</td>
<td>8.0</td>
<td>9.7</td>
<td>13500</td>
</tr>
<tr>
<td>1972/7/19</td>
<td>20.0</td>
<td>22.4</td>
<td>6260</td>
</tr>
<tr>
<td>1976/8/2</td>
<td>12.5</td>
<td>14.7</td>
<td>14000</td>
</tr>
<tr>
<td>1977/8/2</td>
<td>7.3</td>
<td>9.9</td>
<td>8480</td>
</tr>
<tr>
<td>1978/8/31</td>
<td>4.4</td>
<td>5.0</td>
<td>11000</td>
</tr>
<tr>
<td>1979/8/11</td>
<td>5.9</td>
<td>6.6</td>
<td>6300</td>
</tr>
<tr>
<td>1989/7/21</td>
<td>15.5</td>
<td>16.4</td>
<td>9430</td>
</tr>
<tr>
<td>Average</td>
<td>8.06</td>
<td>11.84</td>
<td>10000</td>
</tr>
</tbody>
</table>

(2) Great yearly variation

The variation coefficient Cv and skewness coefficient Cs of peak flow are much higher than that of annual runoff. The reason for this is that the frequency of occurrence of large floods is smaller in arid and semi-arid zones.

(3) High sediment loads

Because of poor vegetation cover, if an intense storm takes place and low velocities increase sharply, runoff becomes heavily sediment-laden, especially in erosion-prone areas. In north-west China the maximum silt concentration has been measured at 1600 kg m^-3, with a specific rate of surface soil erosion of up to 44 800 ton km^-2 y^-1. Mud-rock flows are likely in such areas.
2.4.2 Snow-ice meltwater floods

This is the kind of flood provoked by snow and ice meltwaters. The distinct characteristics are that the flood hydrograph is smooth and the specific discharge of peak flow is small. There are also small ‘saw-tooth’ shaped flood peaks on the hydrograph, occurring with a daily frequency due to diurnal temperature variations.

2.4.3 Mixed floods

The floods result from both snow-ice meltwater and rainstorms. In addition to the snow-ice meltwater flood characteristics, the hydrograph also shows features similar to rainstorm floods with a sharp peak in an otherwise smooth flow. In the 26-year maximum peak flow records from the Tuohai hydrological station there are 11 mixed floods with coefficients of variation (Cv) of only 0.28, obviously much less than the Cv for storm floods.

2.5 Characteristics of flash floods in arid and semi-arid zones

2.5.1 Suddenness of occurrence

Flash floods generally result from high-intensity storms of limited areal extent or perhaps through a glacier-dammed lake outburst. The time to peak may be only a few hours or even tens of minutes. Conventional forecasting methods cannot provide adequate warning and people have insufficient time to move away from the floods.

Because limited areal extent storms are concerned with local topography and small-scale synoptic systems, large-scale synoptic forecasting cannot give satisfactory results. Floods arising from glacier-dammed lake outbursts are similar to dam-break floods but the suddenness is more significant.

2.5.2 Randomness of areal distribution

The number of flash floods in large arid and semi-arid zones is not insignificant but at any given catchment the frequency of occurrence is indeed very small, perhaps only once in many years. Although flash floods at specific sites and during a certain period occur for specific reasons, the areal distribution is statistically random.

2.5.3 Complex formation reasons

Flash floods in arid and semi-arid zones may result from storms of limited areal extent, or snow-ice meltwaters, or a glacier-dammed lake outburst or dam-break, or a combination of all these factors. Mud-rock flow usually occurs with flash floods. The reasons for some flash floods are not yet clear.

2.6 Origins and factors affecting flash floods

2.6.1 Storm flash floods

Flash floods occur because of high intensity storms, steep slopes in the catchment, poor vegetation cover, high velocity flows (because the catchment has no capacity to resist and delay flow
concentration). Further, because of the dry climate, there are strong physical weathering processes in operation and with infrequent runoff to scour the land surface, there is much rock debris available to contribute to the mud-rock flows possible during high intensity storms.

2.6.2 Snow-ice meltwater and storm mixed flash floods

Air temperature is the controlling factor in these types of floods which occur frequently during high temperature years.

2.6.3 Glacier-dammed lake outburst floods

This type of flash flood results from the burst of a glacier dam across a lake outlet or a sudden release from a lake outlet. Such floods have the following characteristics: there is some regular pattern in their occurrence in both timing and frequency; the flood wave rise and decline is rapid; the duration is short; the kinetic energy is great and their transport capacity is strong.

The controlling factor in such floods is the thermodynamic circulation since this determines snow-ice melt rates and hence the ice-dam stability.

2.6.4 Dam-break floods

Such events arise when a storm occurs with a magnitude over and above the design limits on the structure or because of a failure in dam construction. The flood characteristics of such an event are the same as those arising from glacier-dammed lake outburst floods described in the previous section.
3. Basic concepts of flash floods

3.1 Definition and nature of flash floods

"Sharp and unexpected" are the two best words to use to characterise a flash flood and its hydrograph. More formally, a flash flood can be defined as "a flood of short duration with a relatively high peak discharge" (WMO-UNESCO, 1974). The more extensive definition of the National Weather Service (NWS-USA) is also interesting: "a flash flood is a flood that follows the causative event (excessive rain, dam or levee failure, ..., etc.,) within a few hours". Here are the two essential differences between a flash flood and a normal flood: first, of course, the speed with which it occurs but also (and perhaps mainly) the fact that the time interval between the observable causative event and the flood is less than four to six hours. The six-hours duration is generally proposed as the best 'break point duration' between a normal flood and a flash flood.

This means, in particular, that the standard and conventional flood warning techniques, models and organizations are not suitable for use with flash floods. This could also be a way to characterize flash floods, i.e. the consequence for social and economic organization, not the physical hazard itself. In this respect, a flash flood may also be defined as one that happens very suddenly, is usually difficult to forecast because the time to peak is very short and the rate of flood rise is very great. Damages caused by such floods are often very serious.

3.2 Formation of flash floods

It is useful to consider flash floods under two categories based on the type of causative event:

(1) Formation of 'natural' flash floods

These are floods which result from heavy rainfalls on natural (or substantially modified by man) catchments. In this case, the formation of the flood is bounded by the knowledge of the meteorological and hydrological causative regimes. For practical and operational reasons, these are called 'natural' flash floods.

(i) Abnormal weather changes causing heavy storms such as typhoon rainfall, tornado-related thunderstorms, or thermal convection storms which, if they occur in conjunction with advantageous topography for rainfall, lead to flooding.

In arid areas, rainfall is mainly caused by squall line and convective cloud mechanisms or sometimes by low intensity frontal rain, i.e. a medium-to-small weather system causing storm floods. Convection storms often take place at the beginning or end of the summer and winter; with many thunderclouds making up a storm cloud and with each thunderstorm containing several rain-forming cells building up and decaying within a matter of minutes. This is because if the cell is in an active state, the downdraught forces the uplift of a new convective cell, a regeneration process which
occurs often in a convective storm of one or two hours' duration. Convective storms generally have a central area of 1–5 km with virtually uniform rainfall, with the surrounding isohyets gradually reducing to zero within an area of less than 10 km. The rainfall intensity of convective storms is very large, more than 90 mm h⁻¹ occurring for several minutes. Different topography, soils, catchment vegetation, energy and water balances result in different distributions in precipitation, air temperature, etc. For arid areas, the heating of bare rock slopes causes air to rise rapidly, leading to convective cloud formation and resultant raindrop formation. Human influences can change both air composition and temperature through changes in vegetation cover and industrial emissions and have an important effect on climate.

(ii) Abnormal changes to the climate, as when mountain air rises and causes sudden falls in temperature which forms ice dams and which then break suddenly if there is temperature increase, or as a result of a storm on steep or unstable ground inducing mud and rock slides which in turn produce a temporary, artificial dam backing up water until the dam bursts to give the classic ‘ice-dam break’ flood.

(iii) Glacier lake outbursts resulting from the sudden release of the waters from a glacier, a glacier-dammed lake, a moraine-blocking lake or intra- and sub-glacial lakes. A glacier lake is formed by the accumulation of glacier meltwater; this flows along the crevice of an ice cave and quickly extends the cave. The ice dam may break under the action of the static water pressure and the stored water suddenly releases and causes the flood.

(ii) The formation of “artificial” flash floods
Some other types of flash flood can occur due to the sudden release of impounded water by the failure of a dam (or dyke) or other natural or man-made barriers. Generally, speaking, these flash floods have nothing to do with abnormal climatic changes, except in some very specific cases. For example, when the air temperature rises quickly and causes an ice-dam rupture; or as the result of a storm on steep or unstable ground such that the rainfall induces mud, snow and/or rock slides which lead to the formation of a ‘natural’ dam. If—or rather when (because all such natural dams are weak)—these dams break, it creates a dam- or dyke-burst flood which is a sort of flash flood.

3.3. Properties of flash floods

The hydrograph of a flash flood has very specific characteristics:

It generally has a single, very high, peak discharge, the flood volume is not necessarily important, the duration of the entire flood event is short, and — perhaps most important — the time-to-peak is within six hours.

For different reasons, flash floods often occur on moderate or small catchments with poor or sparse vegetation, steep slopes, poor soil development, some large impermeable areas, and a fast rate of flood rise. The following examples illustrate these general features.

- 13th August 1958, on the Yenshui River (China) whose 500 km² catchment is often dry, the recorded peak of a flood caused by a storm was 1220 m³ s⁻¹.
- 12 June 1984, in Chongli County, Hebei Province (China), occurred two storms with total rainfall of more than 100 mm. The flood areas were 22.5 km² and 27.7 km², respectively, and the storm intensity was very large.
- 25 June 1973, in Poil River, Shangyi County (China), total rainfall was 480 mm in 1.3 hours, with an average intensity of 369.2 mm h⁻¹, more than the maximum intensity (184 mm h⁻¹) previously recorded in the Hain Province (China) in August 1979.
- 28 July 1959, at the Chaupin Station, Shanxi Province (China) occurred a flood with a rise of 2820 m³ s⁻¹ h⁻¹.
The drainage area of the Bishandaur River, Jhelum basin (Pakistan) is 150 km². The peak discharge is 1840 m³ s⁻¹.

3.4 Differences between flash floods and normal floods

- The hydrograph of a flash flood is very sharp, with peak discharge higher than for normal floods and with the total flood volume quite small.
- The rising and falling limbs of the hydrographs of flash floods are very steep, with time-to-peak generally not more than 1 to 6 hours.
- 'Natural' flash floods generally occur on catchments of small to moderate size whereas normal floods may occur on any type of catchment.
- Flash floods frequently occur in basins with large impermeable areas, sparse vegetation, and steep slopes.
- Flash floods happen very suddenly and are usually difficult to forecast. The damages incurred are often very serious, including loss of human life. Normal floods can be forecast to give some warning and thus a certain amount of protection.
- Flash floods generally arise from extreme rainfall events and intensities. In arid and semi-arid areas the meteorological and hydrological regime is conducive to flash flood generation — thunderstorms, extreme and intense rainfall — a situation usually compounded by the vegetation and geomorphology of catchments in such areas.
- 'Artificial' flash floods may also arise through breaks in natural or man-made dams.

3.5 Distribution of flash floods

Flood peak discharges versus principal catchment characteristics have been plotted by Lo Chengzheng and Shen Guochang (1987), based on information and observations recorded in China and elsewhere. The results of this work show that for small catchments most of the extreme floods in China took place in the dry Yellow River catchment. The regions where the maximum flood parameters (peak discharge, time-to-peak, etc.) have been recorded are mainly distributed along the windward side of the Yan, Taihang, Funiu and Dabie mountains, in an arc facing east.

Similar features of extreme floods have also been noted in other regions where the main geographical and meteorological characteristics of the catchments concerned also relate to the windward side of very heterogeneous topography. Lo Chengzheng showed clearly that in the arid and semi-arid zone of the middle reach of the Yellow river, where mean annual rainfall is less than 500 mm, extreme floods from very intense storms can occur in some parts of the catchment, mainly due to the poor vegetation cover, the narrow shape of the sub-basins and steep slopes.

Similarly, J. E. Costa has plotted the relationship between flood peak discharges and catchment location in the USA. From this chart and from additional information on catastrophic flood events (i.e. when peak discharges would be related to record extreme floods), Costa found that the geographical locations of these catchments were well distributed along a curved belt on the west coast of America. This region is a transition zone between flat plains and the mountainous areas. Some of the basins in this region, in which conditions are generally favourable for the formation of extreme flood flows, have part of the catchment in the mountains and the rest on the coastal plain. These catchments have in common general meteorological features such as intense convection conditions favourable for rainfall, upwelling airflows, and high evaporation rates. The natural geography of these basins categorises them as arid and semi-arid, with the characteristic features of sparse vegetation and poor soil development.

Both meteorological features and natural geographical elements are important in flash flood
formation. For example, the catchments on the west coast of America are less favourable for storm generation than those of the east coast which is much wetter although the general conditions of the west coast catchments — geology, landcover and soil type — are particularly favourable for flood generation because of their rather thin soils, poor vegetation, large areas of bare rock and impermeable surfaces, water courses with narrow reaches, and narrow catchments with steep slopes.

In terms of seasonal distribution, flash floods in China, especially in the north-west area and semi-arid zones, occur in June to September, the best time for convective storms. 'Man-made dam-break' flash floods may, of course, occur at any time.
4. Statistical analysis of flash floods

Flash floods in arid and semi-arid zones are caused by:

- Unusual cloudburst events over advantageous topography
- Ice-dam or glacier lake sudden burst due to abnormal climate changes
- Dam-burst caused by natural factors or mankind-induced destruction.

Flash floods are those floods which happen very suddenly, are usually difficult to forecast and wreak huge damage. They are also events where the rate of flood rise or the peak discharge is very large. In any given region, such floods may not occur every year but yet may occur several times in any specific year because of the randomness and variation in the conditions which promote their formation.

4.1 Selection of flash flood data series

The two main approaches to flood frequency analysis are peaks-over-threshold and annual maxima. The first technique uses only those peaks which exceed a given threshold while the second selects the highest peak in each year of record; following on from the definition outlined above, the first approach is the most suitable for the selection of flash flood data.

In general, all peaks over a given threshold may be selected to form a flood peak series but we need to select flash floods only. The threshold is determined on the basis of the rate of flood rise and the predetermined flood peak (but note that if the rate of flood rise is small and not particularly sudden, flash floods will not differ significantly from normal floods).

Arshad M Sheikh (1994) has defined an index for flash flood magnitude, FFMI. FFMI is calculated from the standard deviation of the logarithms of annual maximum discharge, as follows:

\[
FFMI = \frac{x^2}{N - 1}
\]

where

\[
x = X_n - M
\]

\[X_n\] = logarithm of annual maximum discharge

\[M\] = logarithm of mean annual discharge

\[N\] = number of years of record

However, as we carry out flood frequency analysis using a peaks-over-threshold time series, some of the intervals may be surplus for annual values required in engineering design which requires translating frequency intervals into annual values, as follows:
\[ P = \frac{S}{n} P' \]

where

- \( P \) = annual frequency
- \( P' \) = frequency calculated by peaks over threshold
- \( S \) = number of peaks over threshold
- \( n \) = number of years of record

For some regions where flash floods occur frequently, a better method of selection of the sample series is the annual maxima approach because of better sample independence. Since the floods which occur in any one river basin may have different causes, there is also the question of how to divide flood types according to their origins.

4.2 Types of frequency curve

There has been relatively little study of different types of curves in flood frequency analysis and choosing which type of frequency curve to work with will depend on experience and custom. The Pearson Type II analysis, for example, is used extensively in China, while the Log-Pearson Type III is used in the USA. The Flood Studies Report (vol. I, NERC 1975) used goodness of fit indices computed for seven distributions of data from 35 long-term stations. These were extreme value Type I (Gumbel), gamma, lognormal, general extreme value (Jenkinson), Pearson Type 3, log-gamma and Log-Pearson Type III. This report recommends the general extreme value (GEV) distribution.

There were few data available for analysing flash flood flow frequencies in the past. Tang Qicheng, Qu Yaoguang and Zhou Luchao studied flash flood frequency curves in arid zones in 1992 and recommended Gumbel distribution curves for general use because the Gumbel distribution has just two parameters, whereas the shape of Pearson Type III curves depends on three parameters which although gives somewhat more flexibility are also harder to fit for the short flood peak series generally available for arid zones. If there are no historic floods available within the series, it is difficult to obtain a close fit. These parameters were computed for Pearson Type III, Kritsky-Menkel and Gumbel distributions for a 30-year run of data at the Sekla station on the Kunmalic River in the Xinjiang province of China, as shown in Figs 4.1 to 4.3.

![Fig 4.1 The Pearson Type III distribution curve of peak flow at Sekla station](image-url)
There are two important conclusions to note:

- The Pearson Type III distribution fits better than the Kritsky-Menkel distribution but neither type could be extrapolated to rare frequencies needed for design purposes.
- The Gumbel distribution not only fits more closely than the other two, it also produced a straight-line fit on Gumbel probability paper and arbitrary curve fitting is thus avoided. Since the Gumbel distribution is derived from extremes, it is suitable for the hydrological calculations of extreme value.

Some other countries, e.g. Canada, have also obtained better results using Gumbel distribution for their analyses.
4.3 Statistical analysis for hydrograph design

In general, a design flood hydrograph consists of a design flood peak and design flood volume, i.e. the peak and volume of the hydrograph ought to equal the peak and volume derived from statistical analysis. The usual method is that the design peak and volumes of the variable controlling the durations are ascertained by frequency analysis and design criteria and the a typical flood hydrograph is selected from recorded hydrographs; the typical flood hydrograph can be enlarged based on the proportions of the flood peak and flood volume of various durations to finally obtain the design flood hydrograph.

The method for ascertaining the design flood peak and volume is that, after choosing the type of distribution curve, its parameters must be determined by estimation of moments, maximum likelihood or probability weighted moments. In China, a graphical curve fitting technique has been stipulated as the standard method for estimating parameters of hydrological frequency distributions.

The statistical parameters of flash floods — mean flood peak, coefficient of standard deviation and the ration of skewness (Cs) to variability (Cv) — are larger than for general floods. For example, in the yellow soil zone of China, in catchments less than 1000 km², the Cv of peak flows is >1.5, Cs/Cv is about 4, with Cv showing a tendency to decrease with an increase in catchment area.

Ding Jing, Deng Yuren and Wei Xueyan have proposed the fuzzy optimal curve fitting method for estimating the parameters of frequency distribution in hydrology. They consider that the significant advantage of this method is that uncertainties about the points on probability paper can reasonably be taken into account and treated more objectively based on some membership functions.

The design flood hydrograph can be obtained by enlarging the typical flood hydrograph. The typical flood hydrograph is chosen from the record data on large floods close to the design value and having regard for hydrograph shapes that may be particularly damaging. The enlarging method is a same-frequency method; peak and volumes of the typical flood hydrograph are enlarged separately to give equal design volumes. The enlargement factor of the flood peak is

\[ \alpha = \frac{Q_p}{Q_c} \]

where

- \( \alpha \) = the enlargement factor of the flood peak
- \( Q_p \) = design flood peak
- \( Q_c \) = the peak of the typical flood

The method for flood volume is the same. In general, when enlarging flood volume, adopt a dividing control duration. For example, if the duration of the flood hydrograph is 24 hours, then the control duration may be selected as three, six and 24 hours, i.e. select the three-hour period with the largest volume, then six-hour, then 24-hour.

\[ \alpha_3 = \frac{W_{3p}}{W_{3c}} \]

The enlargement factor of the six-hour flood is:

\[ \alpha_6 = \frac{W_{6p} - W_{3p}}{W_{6c} - W_{3c}} \]
The enlargement factor of the 24-hour flood volume is:

\[ \alpha_{24} = \frac{W_{24p} - W_{6p}}{W_{24c} - W_{6c}} \]

where

\( W_{3p}, W_{6p}, W_{24p} \) = the design flood volumes of three hours, six hours and 24 hours duration

\( W_{3c}, W_{6c}, W_{24c} \) = the flood volumes of the typical flood hydrograph of three hours, six hours and 24 hours duration.
5. Monitoring flash floods

5.1 Review of monitoring techniques

Because of the extreme rapidity of occurrence of flash floods, special techniques have been developed for their observation.

5.1.1 Observing the evolution of water stage

This phenomenon is the main manifestation of the flash flood: the quick rise of the water surface at a certain point in a stream. Indicators of various types can therefore be used to determine water level, either by readings taken by an observer at frequent intervals or recorded continuously by automatic or electronic instruments to give a chronogram of surface water elevation. As the flow velocity during the flood rise is frequently very high, particular attention must be paid to the installation of equipment. Instruments must be well protected against the current and well positioned to give significant and accurate information of water stage modification since a record of the flood peak alone is sometimes the only indicator of that a flash flood has occurred.

5.1.2 Determination of flash flood discharges

The rapidity of the flow during flash floods makes measurement problematic since the quick rise and fall of water level make it difficult to measure across a complete section. In such a case, rating curves are established for each vertical in the cross section and the discharge computed for every stage to allow the determination of global rating curves for the complete section.

5.1.3 Practical methods for measuring the flow discharge of a flash flood in Tunisia

Tunisia is located in the arid region of the Mediterranean, where stream water levels vary very rapidly and with large amplitude, i.e. several metres per hour have been observed. Finding the rating curve of a river section therefore needs continuous gauging, an operation which becomes more complex when the river bed is constantly changing. This instability imposes a need to establish many rating curves for the same section; generally, however, we never have enough measurements to produce an accurate rating curve trace.

To solve this problem, several measurements are made of velocity and area and then discharge (= V.A) are correlated with area. According to this correlation, a value for discharge can be found from knowledge of the cross-section only, which is easier to measure during a flood than the discharge because only two vertical points have to be located exactly — the surface level and the bed level (assuming the bed is horizontal). Executing these measurements repeatedly permits the determination of numerous discharge values which then allow the determination of an accurate discharge curve.
This method was used in several unstable rivers in the central area of Tunisia where traditional measurement techniques are difficult to undertake and where the use of the method outlined above has increased the accuracy of the discharge hydrograph.

5.2 Hydrological stations (including sediment transport measurements)

These will include all sites where complete or partial observation of one or several hydrological parameters are observed. The equipment in use may be very limited as, for example where it consists simply of a staff gauge fixed to the river bank or a raingauge for precipitation measurement, or more sophisticated with automatic recording devices having many sensors, perhaps even including automatic transmission back to a base.

The selection of equipment depends on the nature of the phenomena to be observed and the location of the site; the importance of site location being related to the quality of the information recorded and its contribution to the determination of the more significant parameters of the hydrological regime. In practical terms, other criteria must also be considered when selecting an observation site and the most efficient device to be installed, especially the accessibility of the site and resources of the management agency.

5.2.1 Classification of stations

Many classifications may be adopted, as summarised below:

**Base stations**
These constitute the national basic observation network and provide a national data bank of the relevant information. This network contains main and secondary stations. **Main stations** are designed to characterise the site and give good quality hydrological data; they are fully equipped and observed continuously. **Secondary stations** provide incomplete observations, since they are designed merely to complement the main network, the geographic location being chosen to extend the observation series and help determine mean local or spatial characteristics.

All the data collected from these stations constitute a database on which to improve the knowledge of the hydrological regime. The observational data series must be long enough to permit meaningful statistical extrapolations to be made, to develop suitable water resource studies and to achieve publication of yearbooks.

**Temporary stations**
The operational period of these kinds of stations is generally less than five years. Their main objectives are to answer specific questions when compiling a water resources inventory of limited area, to aid research on a specific hydrological parameter, or to test new equipment or methodological capabilities. They can be classified as follows:

**Research stations** — destined to improve the knowledge of one or several hydrological parameters or their interrelation. They are useful when experimenting with new hydrological equipment or techniques. The observations are very intensive and the operation period very limited.

**Project stations** — used to rapidly supply information on one or several particular aspects of the hydrology of a limited area in relation to a proposed hydraulic structure. The hydrological equipment employed is similar to that of a base station but the period of operation is limited.

Data collected from all these stations are stored in a database for use in water resource studies.
5.2.2 Observed parameters

Rainfall

*Cumulative rainfall* Standard or storage raingauges are used to quantify precipitation: standard gauges are observed daily or after longer periods such as monthly, seasonally or annually. The installation and maintenance of both instruments follows the same rules. *Rainfall intensity* Recording raingauges provide a continuous pen trace on paper fixed around a cylinder which allows short duration rainfall to be logged. Several mechanisms are used to move the pen such as floats, weighting devices, or tipping buckets which can be transformed into electrical pulses for storage locally or for remote sensing.

Water height

*Instantaneous levels* are the first characteristics of water level variation. It allows knowledge of flow discharge and determines the capacity status of reservoirs and the extent of the inundated area. Instantaneous levels are read on a staff gauge by a human observer standing on the river bank. *Continuous recording* of stage is now possible, using motion floats, variation in hydrostatic pressure, the variation in an electrical parameter when an electronic sensor is submerged. Derivation of the specific rating curve requires transformation of the parameters sensed to the actual height on the staff gauge.

Flow velocity and discharge

Velocity data are necessary to compute discharge and also to ensure the protection of a structure. Flow velocity is generally measured by current meters during traditional gauging operations. When the velocity is too high, float techniques are used such that discharge is measured by exploring velocity fields by current meter or by floats and combining them with cross-section size.

Sediment transport

River sediment transport is the most difficult feature to monitor and is done by one of two methods: a *global method* which consists of building a small reservoir at the outlet of a micro basin where runoff is measured by conventional equipment and the particles of sediment which remain in the reservoir are weighed to give a value for the sediment transport of the given basin. For large basins where dams have been constructed, the new topographic profile of the reservoir is compared with the previous profile and the mean annual sediment load determined. A *punctual method* as practised on hydrological stations where there is adequate equipment to allow the determination of sediment transport by multiple sampling through the cross section.

5.3 Real-time data monitoring

The time element is all-important in flood definition: a rapid flood is defined as such when its temporal progress and observed parameters are unusual. It is vital to know as early as possible the height and progression of a flood at an upstream site so as to forecast its evolution downstream; the earlier this knowledge is acquired, the greater the accuracy of the forecasts.

The time interval between the beginning of a flood at a given site and the time when such information arrives at the operational base must be short enough to allow forecasts to be computed and suitable decisions made to take effect in the downstream reaches before the effect of such an event actually reaches that area. To shorten this time lag, actual data or near real-time data collection systems are now in use.
5.3.1 Traditional methods

Human observers transmit warnings and detailed information to a central office by post, radio transmitters or telephone, etc. Such transmission techniques have limitations in that:

- they depend on the availability and conscientiousness of the person assigned to this task;
- they depend on the quality of the local communication networks which in many arid and semi-arid regions are often in poor condition;
- this type of data collection needs transcription by hand and is thus subject to human error.

5.3.2 New technologies

The teletransmision of information has existed for a long time through telegraph, telephone and radio but hydrological information transmission has only really been in existence since 1950. Recent advances in communication and data processing means that sophisticated means of data transfer are being progressively adopted in hydrology. Because of the improved performance in these new technologies, real-time data collection has become easier to achieve and it is now possible to implement a real-time forecasting system combining satellite, radio and radar data with mathematical models to produce opportune forecasts for both large and small regions.

Use of radio and telephone

A radio modem is connected to the data acquisition device for transmission of information to a relay or reception device installed at the collecting centre and, via another modem, to a processing device such as a micro-computer for data processing. Every station needs a dedicated telephone line and thus widespread utilisation of such techniques will depend on the efficiency of the national telephone network and the costs of communication between the outlying stations and the collection centre.

Use of satellites

The expansion in space technology has provided a huge boost to telecommunications over large distances, such that satellite transmission of hydrological information has now become commonplace around the world.

In the field, the operating principle consists of a data acquisition system (recording raingauges, etc.) coupled to a transmission device; satellites receive the data and then re-transmit to the earth where they are captured by the antennae of a data receiving station which can be several thousands of kilometres away. Two types of satellite are now exploited for hydrological data collection:

- Geostationary satellites where the satellite is in a fixed position relative to the earth, at an altitude of about 3600 km above the equator. This type of satellite offers users the possibility of transmitting information at fixed hours (1 to 24 times) during a day.
- Polar orbiting satellites circle the earth continuously at about 850 km altitude on a polar orbit, achieving a complete orbit in 102 minutes; when a local data receiving station is in view, data are received and stored.

Flood warning in Tunisia

Flood warning has been in operation in Tunisia for more than 30 years by VHF transmitter or telephone. In the Mejerdah Basin (the main river in Tunisia) instantaneous states are reported in graphical format and the corresponding level at the downstream station is determined. The effectiveness of this system was confirmed during the exceptional flood in March 1973 in the north of Tunisia. However, this modest system is to be modernised; the vocal VHF transmitters are to be replaced gradually by digital data transmission devices and a real-time data acquisition system is to be installed for reservoir control in the hilly areas using ARGOS system satellites.
5.4 Real-time data collection constraints and opportunities

5.4.1 Constraints

The advanced technology of modern equipment means that operation and maintenance personnel require special training. Instruction requirements, high quality means of communication and national service budgets therefore control the feasibility of running such systems and in many arid and semi-arid regions, where financial resources are limited, it is not possible to keep such systems in good operating condition.

However, international efforts have been made for several decades now to reinforce national hydrological services by providing significant training and resources. The AGRHYMET programme directed to the CILSS countries in West Africa is a pertinent example of how international efforts can be given to improve local situations and guarantee satisfactory technology transfer. But in spite of such efforts, real-time satellite data telemetry suffers some constraints.

**Technological constraints:** more training is required. The maintenance of traditional equipment needed only a small repair shop with basic equipment and a simply trained but conscientious technician. Modern electronic equipment needs specific accessories and a well-trained technician to diagnose faults and make necessary repairs. Sometimes components need to be sent back to the factory which may be in another country which requires additional funds.

**Tariffing constraints:** the high costs of equipment and satellite services are another major constraint in some countries in arid and semi-arid regions; the ARGOS tariff, for example, is some $1000 per year for one benchmark received at a local receiving station.

5.4.2 Opportunities and advantages

**Opportunities**

Because of the high costs, telemetry of hydrological data by satellite or other transmission systems is only justified where there is an immediate use for the data, as in the following examples:

- Flood warning and hydrological forecasting, where data collected and deployed in real time may prevent or reduce damage or safeguard human life.
- Remote sensing of extended regions in an observation network which by providing information on the operational state of the network can then limit the number of site visits which are too expensive to do regularly.
Advantages

- Real-time data transmission is essential for forecasting discharge and peaks in flood warning schemes;
- Remote sensing of monitoring networks to reduce the frequency of site visits;
- Safeguards observer availability and conscientiousness;
- Systems are fully automated which eliminates manual data transcription;
- Because data are stored instantaneously on magnetic tape, transcription errors are eliminated and the data are available immediately for data processing.

5.5 Flash flood investigation for ungauged catchments

In many arid and semi-arid regions, hydrological networks are poorly developed and the number of stations is very low. Studies on ungauged catchments need information on detailed catchment characteristics, particularly in the context of establishing regional rainfall-runoff relationships to estimate flow at ungauged sites. This knowledge could be improved in the following ways:

- Comparisons of soil and other catchment characteristics in ungauged catchments with those of gauged catchments in the region;
- Extension of the hydrological network beyond the ungauged catchment to include as much gauged river flow data as possible;
- Use of a computerised database to integrate catchment characteristics to select the appropriate flow statistics at ungauged sites.

5.6 Conclusions

Flash floods are one of the most impressive manifestations of the environment in which the effects directly affect human activity and security and whose origins and developments are not yet dominated by man. Efforts are now being made to increase that knowledge through the collection of reliable data using sophisticated technologies and improved forecasting methods through modelling development.

First experiments have shown that the use of such a system and new technologies can be advantageously exploited over large regions in spite of environmental difficulties. It presents substantial advantages for remote sensing networks, elaborating forecasts and database development, achievements which are indispensable to progress in water resources. The increasing costs of these technologies constitute a serious obstacle to their widespread use. To solve this problem it will be necessary to direct international efforts towards appropriate solutions, especially in the large areas of the arid and semi-arid regions; such action will be fully justified in better understanding of the environment on a global scale.
6. Flash flood forecasting techniques and models

Flash flood forecasting techniques have no intrinsic difference to those for normal floods, merely the need for speedy collection and translation of hydrological data to provide for fast operational forecasts. The key feature of flash flood forecasting is to identify quickly when the forecast flood is above the threshold rather than exact peak flow discharge and time of occurrence. Hence, flash flood forecasting does not require a complex model (Holtz and Pugsley, 1978).

At present, there are many flash flood forecasting methods available throughout the world, such as the simple models based on rainfall intensity, deterministic-conceptual rainfall-runoff models, complex flood routing methods, synoptic radar forecasting methods, etc. Countries which use satellite images for flash flood forecasting are few.

Each method differs because of the different reasons for flood formation, as discussed below.

6.1 Simplified forecasting techniques

6.1.1 Forecast methods for storm flash floods

Because a large proportion of flash floods result from rainstorms, the storm flash flood has been studied extensively.

Stage (discharge) relations
These are graphs correlating an observed stage (discharge) at one or more stations upstream with the corresponding stage (discharge), defined as the stage (discharge) on certain phase points of the flood wave which forms the stage (discharge) at the upstream and downstream sections. This is a simple, empirical technique, usually called the corresponding stage (discharge) technique. The discharge at an arbitrary point on a flood wave is called the travel discharge, the time over which the discharge travels from the upstream section to the downstream section is the travel time (t).

Corresponding crest discharges and their occurrence times may be picked out on the observed discharge hydrographs of upstream and downstream stations of a river reach which has no local inflows from the intervening area. A correlation diagram may be drawn as shown in Fig. 6.1, where the left-hand side gives the corresponding crest stage relation and the right-hand side the relation of the time of travel with the upstream crest stage. Such a diagram can be used for forecasting such that the flash flood peak at the downstream station and its time of occurrence can be quickly forecast once the crest stage (discharge) of the upstream station has been measured.

The above method is very simple and can give good results under certain conditions such as when there is no scouring or silting in the river channel, no local inflows, no backwater effect downstream, etc. In practice, the problem is very complex. In the case where the changes in the external condition cannot be ignored, using the simple crest stage relationship above would lead to poor forecasts. It is thus necessary to add some additional parameters to the diagram. The commonly-
used parameter is the downstream simultaneous stage, which is the stage of the downstream station at the time when the upstream stage occurs. In addition, local precipitation over the intervening area is also taken into account. This method is suitable for a large catchment but not for rivers in mountainous areas.

Occurrence probability prediction of flash floods
The flash floods of small catchments are related to topography, especially in mountainous and hilly regions. Because the slopes of the catchment are steep and the storm and its corresponding storm occur virtually simultaneously, forecast techniques need to be simple and convenient. The most logical method is to establish a multi-variable regression equation or curves or relation tables according to the flood records and corresponding rainfall depth, rainfall intensity and antecedent soil moisture, etc. Given the values of the relevant variables, the forecast values can be estimated from the tables and the family of curves. For example, Zhao Xingmin analyzed many precipitation events of flash floods in the Hunan province of China to determine the conditions for generation of flash floods: these were accumulated rainfall in excess of 120 mm or high antecedent soil moisture, and a maximum 1-hour rainfall over 50 mm, or a maximum 3-hour rainfall over 100 mm, or a maximum 6-hour rainfall over 140 mm. He therefore selected rainfall intensity, rainfall depth (or sum of rainfall and antecedent precipitation) as the factors which determine the likelihood that flash floods may occur (see Fig. 6.2). According to the calculated antecedent precipitation index and measured or forecast rainfall depth, the flash flood occurrence information can be estimated from the intersection of the two variables, as shown in Fig 6.2. If the intersection falls in the probable occurrence region, flash flood occurrence information can be published.
Flood advisory table
Hydrologists at the American National Weather Service (NWS) have devised a simple river stage forecasting scheme using measured data from the hydrological network and expressed as a numerical table (see Table 6.1). The forecasting procedure consists of an index of antecedent soil moisture conditions and observed rainfall, stage and discharge (Undro, 1976; Monro and Anderson, 1976). Here, rainfall is recorded as areal average depth over the catchment. In Table 6.1 a certain water stage or discharge can result from various 3-hour rainfall totals, according to the soil moisture. Each column of 3-hour rainfall corresponds to a different antecedent soil moisture, which increases from right to left. A small rainfall can give rise to a large low if the antecedent soil moisture is sufficiently high.

How may the Flood Advisory Table be used for forecasting?
Example: the 3-hour rainfall depth is 3.5 inches at station B on river B and the flood crest stage is 21.0 feet at station B; the 3-hour accumulated rainfall depth during the night is 5.0 inches, so what is the forecast flood at station B?
Solution: First find the underlined row in the Table which corresponds to a stage of 21.0 ft. Move along the row to find the rainfall of 3.5 in. This column corresponds to the (unknown) antecedent wetness. Move down the column to find the new rainfall of 5.0 in. This is in the row corresponding to a stage of 31.0 ft and a discharge of 15900 ft³ s⁻¹, which are the forecast values. They are forecast to occur at the time of the middle of the storm plus the flood lag time given at the top of the Table.

The American River Forecasting Centres provide updated values for the soil moisture index once a week to the staff operating warning systems. As long as there are sufficient data on precipitation and river stage, most flood forecast methods are also suitable for flash flood forecasting.

Rainfall runoff correlograms
There are various types of rainfall runoff correlograms but we only introduce here those with rainfall intensity and contributing area as parameters. Based on the observational flash flood data, forecast empirical correlograms are shown in Fig. 6.3, where \( P \) = average effective rainfall over the catchment, calculated by

\[
\text{Fig 6.3 The correlograms of } P - F - P1 - Rs \text{ (left) and } R_s - F - P1 - Qm
\]
Table 6.1  Flood Advisory Table

<table>
<thead>
<tr>
<th>Stage</th>
<th>Flow rate</th>
<th>3-hour precipitation depth (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>14.0</td>
<td>3322</td>
<td>0.6</td>
</tr>
<tr>
<td>15.0</td>
<td>3561</td>
<td>0.6</td>
</tr>
<tr>
<td>16.0</td>
<td>3600</td>
<td>0.7</td>
</tr>
<tr>
<td>17.0</td>
<td>4360</td>
<td>0.7</td>
</tr>
<tr>
<td>18.0</td>
<td>4920</td>
<td>0.8</td>
</tr>
<tr>
<td>19.0</td>
<td>5480</td>
<td>0.9</td>
</tr>
<tr>
<td>20.0</td>
<td>6040</td>
<td>1.0</td>
</tr>
<tr>
<td>21.0</td>
<td>6600</td>
<td>1.0</td>
</tr>
</tbody>
</table>

22.0  7780  1.1  1.6  2.1  2.7  3.1  3.6  4.2  4.6  5.2  5.6  6.2  
23.0  7960  1.2  1.7  2.2  2.8  3.2  3.7  4.3  4.7  5.3  5.8  6.3  
24.0  8640  1.3  1.8  2.2  2.9  3.4  3.8  4.4  4.9  5.5  5.9  6.5  
25.0  9320  1.4  1.9  2.4  3.0  3.5  4.0  4.6  5.0  5.6  6.1  6.8  
27.0  11180  1.6  2.1  2.6  3.3  3.8  4.3  4.9  5.5  6.0  6.4  7.0  
28.0  12360  1.7  2.3  2.8  3.4  3.9  4.5  5.1  5.5  6.0  6.6  7.2  
29.0  13540  1.9  2.4  3.0  3.6  4.1  4.6  5.2  5.8  6.4  6.9  7.4  
30.0  14720  2.0  2.6  3.1  3.8  4.3  4.8  5.5  5.9  6.6  7.1  7.7  
31.0  15900  2.2  2.7  3.3  4.0  4.5  5.0  5.6  6.1  6.8  7.3  7.9  
32.0  16975  2.3  2.9  3.4  4.1  4.6  5.2  5.8  6.3  6.9  7.4  8.0  
33.0  18056  2.4  3.0  3.6  4.2  4.8  5.3  6.0  6.5  7.1  7.6  8.2  
34.0  19125  2.6  3.1  3.7  4.4  4.9  5.5  6.1  6.8  7.3  7.8  8.4  
35.0  20200  2.7  3.3  3.8  4.5  5.1  5.6  6.3  6.8  7.4  7.9  8.5  
36.0  21300  2.8  3.4  4.0  4.7  5.2  5.8  6.4  6.9  7.6  8.1  8.7  
37.0  22700  3.0  3.6  4.2  4.9  5.4  6.0  6.6  7.1  7.8  8.3  8.9  
38.0  24233  3.2  3.8  4.4  5.1  5.6  6.2  6.8  7.3  8.0  8.5  9.1  
39.0  25975  3.4  4.0  4.6  5.3  5.8  6.4  7.1  7.6  8.2  8.8  9.4  
40.0  27925  3.7  4.2  4.8  5.5  6.1  6.6  7.3  7.8  8.6  9.0  9.7  
41.0  30100  3.9  4.5  5.1  5.8  6.4  6.9  7.6  8.1  8.8  9.3  10.0  
42.0  32500  4.2  4.8  5.4  6.1  6.7  7.2  7.9  8.5  9.1  9.7  10.3  
43.0  35300  4.6  5.2  5.7  6.5  7.0  7.6  8.3  8.8  9.5  10.1  10.7  
44.0  38467  4.9  5.5  6.1  6.9  7.4  8.0  8.7  9.2  9.9  10.5  11.1  
45.0  42000  5.2  6.0  6.6  7.3  7.9  8.5  9.1  9.7  10.4  10.9  11.6  

\[ P = \sum_{i=1}^{n} P'F_i \]  \( (6-1) \)

where \( P' \) is the effective point rainfall (mm), \( F_i \) is the areal weighting factor for each raingauge and \( n \) is the total number of raingauges.

\[ F_i = \frac{A'}{A} \]  \( (6-2) \)

where \( A \) is the catchment area, \( A' \) is the controlling area assumed for each raingauge.

\( F \) is the percentage of contributing area in the total catchment.
\[ F = \sum_{i=1}^{n} F_i \times 100 \]  

(6-3)

where \( F_i \) is the contributing area weighting factor for each rain gauge and \( n \) is the total number of gauges in the contributing area, i.e. the total number of stations experiencing rain during the event. \( P_i \) is effective rainfall intensity (mm h\(^{-1}\))

\[ P_i = \frac{P}{T} \]  

(6.4)

where \( P \) is average effective rainfall over the catchment (mm) and \( T \) is the average effective rainfall duration (hour).

\[ T = \frac{1}{n} \sum_{i=1}^{n} T_i \quad T_i = \frac{t_i}{t_s} \]  

(6-5)

where \( T_i \) is the effective rainfall duration for each raingauge. \( R_s \) is rainfall depth (mm), calculated from the measured flood:

\[ R_s = 100W/A \]  

(6-6)

where \( W \) is the flash flood event volume (m\(^3\)) and \( A \) is catchment area; \( Q_m \) is the peak of the flash flood (m\(^3\) s\(^{-1}\)).

**Hydrometeorological methods**

Storm flood occurrence and magnitude are not only related to catchment topography, morphology and geographic location, and meteorological elements, but also to antecedent air circulation characteristics. Fan ChiZen *et al.* have predicted the flood magnitude and occurrence time and range for the Jilin province in China using departure from the mean location of the 500 hpa level in the atmosphere and the radius of pressure anomaly.

- **Forecasting storm-flood affecting range using departure central location of 500 hpa on Asia-European Continent**
  
  On a statistical basis, there are two lines of longitude with a pressure anomaly of zero on the map of 500 hpa when the flood occurred in May last year and three small independent areas of anomaly between both lines. In addition, the intensity and the location of departure activity centre are unusual. As long as we grasp the unusual factors in time we can surely forecast the flash flood area.

- **Quantitative forecasting using departure central value of 500 hpa**
  
  Floods are related to storms and storms are related to the antecedent circulation in the upper atmosphere. The different circulation types and situations will result in different synoptic processes and result in various types of storms. The location, range and strength of circulations are also determined by location, range and strength of air pressure centres. Values of anomalies in atmospheric pressure can indicate the antecedent circulation characteristics. A correlation diagram can be compiled for different rivers or geographical locations using positive or negative mean values for the antecedent months and the hydrological elements, as shown in Fig 6.4. The peak flow for January can be predicted for every year.

- **Forecasting peak flow occurrence time using affecting radius of departure activity centre.**
  
  The time of floods can be forecast from the size and location of atmospheric disturbances, see Fig 6.5.

In addition, there are methods based on the experience of meteorologists and statistical methods. The former tend to extend the current weather situation on the basis of weather parameters such as
Figure 6.4  Relation between departure centre and discharge azimuth

Figure 6.5  Relation between affecting radius of departure centre and peak occurrence time

dewpoint, probable precipitation, direction of the moving storm, etc. Statistical methods proceed with their forecasts through step-by-step multiple regression using the same weather parameters.
6.1.2 Peak flow prediction methods for glacier lake outburst floods

Glacier lake outbursts result from the sudden release of water/snow/ice from glaciers, a glacier-dammed lake, moraine-blocked lake, intraglacial and subglacial lakes, or from a break in an ice-dam. A glacier lake is formed by the accumulation of glacier meltwater which flows along the glacier crevices or cavities and quickly extends the cavity. The ice dam will break under the strain of the static pressure of the lake water and the stored water will release suddenly as a flash flood. The common form of the peak flow equation is:

\[ Q_{m} = a + bV \]  

(6-7)

where \( Q_{m} \) is the peak flow in m³ s⁻¹, \( V \) is the storage of the glacier-dammed lake in m³, \( a \) and \( b \) are empirical coefficients, and \( n \) is an empirical exponent. The coefficients can be calibrated by optimization methods.

The Chaque-Matthews formula is as follows:

\[ Q_{m} = 75 \left( V_{e} / 10^{4}\right)^{0.6} \]  

(6-8)

where \( V_{e} \) is the effective storage of the lake in m³, calculated from the surface water area and water depth or by aerial survey.

Zhang Xiangsong has given the equation below from a study on the Kyaga Thso lake, a typical glacier-dammed lake.

\[ Q_{m} = 2000 + 74.13W^{0.6} \]  

(6-9)

where \( W \) is the total storage in 10⁶ m³.

6.1.3 Forecasting methods for dam-breaks and dyke-break floods

The publication of a dam-break flood forecast is nearly always at the moment at which the dam-break happened. Where there are towns and developed regions, and important main communication lines downstream, the dam-break forecast is very necessary.

**Dam-break peak discharge calculation**

The simple methods for deriving the dam-break flood peak assume that the break is instantaneous.

- **Saint-Venant equation (A. Ritter solution)**
  
  First, it is supposed that there is no water downstream of the dam, that the river course is rectangular in section and the river slope \( \approx 0 \). It is also supposed that the inertia of flowing water plays a leading role and that flow resistance is neglected. According to these suppositions, the Saint-Venant equations and characteristic line theory, the dam-break flood wave describes a second-degree parabola, and the maximum dam-break flow rate can be calculated as

\[ Q_{m} = B h_{c} V_{c} = \frac{8}{27} \sqrt{g BH_{0}^{3/2}} \]  

(6-10)

where \( B \) is the rectangular section width, \( H_{0} \) is the water depth upstream of the dam, \( h_{c} \) is the instantaneous water depth during the burst, \( V_{c} \) is the flow velocity at the dam site, and \( g \) is the acceleration due to gravity.

- **J.J. Stoker method**
  
  This author has also studied the maximum flow rate calculation of the instantaneous overall dam-break under conditions of a rectangular river course and small river slope: neglecting
resistance and assuming a certain water depth (hd) at the dam downstream and hd/h₀ < 0.1384 gives the same equation as (6.10).

Dyke-break flow rate calculation
Dyke breaks do not occur instantaneously and frequently occur as a process. The calculations for dyke-breaks are therefore basically the same as for failures in earth-rock dams. The difference between the two is the calculation of the width of the break, b. For calculating dyke-breaks, the width of b is selected from the given range in Table 6.2. The empirical ranges of dyke-break characteristics in the table have come from practical dyke-break investigations and physical model experiments, and are mainly related to the material composition of a dyke.

<table>
<thead>
<tr>
<th>Terms</th>
<th>material</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Break mouth width, b(m)</td>
<td>earth or earth-rock</td>
<td>d/2 &lt;= b &lt;= 3d</td>
</tr>
<tr>
<td>Break time, T (h)</td>
<td>all material</td>
<td>0.1 &lt;= T &lt;= 3</td>
</tr>
<tr>
<td></td>
<td>earth or earth-rock</td>
<td>0.3 &lt;= T &lt;= 3</td>
</tr>
<tr>
<td>Break mouth slope, m</td>
<td>all material</td>
<td>0 &lt;= m &lt;= 2</td>
</tr>
<tr>
<td></td>
<td>earth or earth-rock</td>
<td>1/4 &lt;= m &lt;= 2</td>
</tr>
</tbody>
</table>

6.2 Forecasting models

6.2.1 Storm flash floods

Rainfall-runoff forecasting hydrological models
Storm flash floods are usually analysed by rainfall-runoff forecasting models. The method is to forecast the flood hydrograph of the catchment outlet using areal rainfall through two steps of runoff generation and flow concentration. Therefore, rainfall-runoff forecasting has first to forecast net rainfall and then forecast the flood hydrograph from the net rainfall.

Runoff formation forecasting
In general, there are two types of runoff formation calculation: correlation methods and the method of subtracting losses from rainfall method. The former takes the antecedent precipitation index Pₐ or the antecedent soil moisture W as a parameter and establishes a rainfall-runoff diagram; the latter takes the infiltration curve as representative. In arid and semi-arid zones the annual precipitation is small, the vadose zone is narrow and soil moisture minimal, such that flash floods always result from rainfall in excess of infiltration. Because rainfall intensity is more important than volume for flood generation, the rainfall-runoff relationship is poor. The subtraction of loss methods are more suitable to such regions, especially when incorporating a rainfall-intensity parameter.

- Initial and later loss model
This is a simplified version of the infiltration curve method. It separates the infiltration process into two phases: and initial loss phase and a later loss phase (see Fig. 6.6), the former being the phase from the commencement of rainfall to that of runoff due to excess infiltration when all rainfall is lost and the latter being the period after runoff formation where the infiltration loss gradually decreases to a constant level. In practice, the application of the later loss process is summarized as an average loss process in excess of the infiltration periods and expressed by a mean infiltration rate f.
If $I > f$ then $f = \bar{f}$
If $I < f$ then $f = I$
where $I$ is the rainfall intensity.

The total effective rainfall $h$ (equal to total runoff) for a precipitation event can be calculated by

$$h = P - I_0 - \bar{f} T_c - P_u$$  \hspace{1cm} (6-12)

where $P =$ total rainfall depth (mm)
$I =$ initial loss, including interception, infiltration, surface retention and evaporation losses (mm)
$T_c =$ runoff formation duration (h)
$\bar{f} =$ average infiltration rate during $T_c$ (mm h$^{-1}$)
$P_u =$ rainfall depth during the time when the intensity does not exceed infiltration (mm)

Determination of $I_0$ : The rainfall before river flow begins to rise is thought of as the initial loss $I_0$ for a small catchment. Because the antecedent soil moisture $P_u$, mean infiltration rate $\bar{f}$ during the initial loss period, and the seasons all affect $I_0$, the relationship of $I_0$ and its elements is usually established for forecast use (see Fig 6.7).

The mean loss rate $f$ can be calculated using Eq. (6-12) for an observed flood and its corresponding rainfall data

$$f = \frac{P - I_0 - h - P_u}{T_c}$$  \hspace{1cm} (6-13)
Because $\tilde{f}$ and $t_i$ are not independent of each other, $\tilde{f}$ is derived by trial and error. A three-variable relationship can be established in a two-dimensional sketch (see Fig 6.8) where by plotting the value of $\tilde{f}$ versus $t_i$ and labelling the points with the corresponding values for rainfall depth during the runoff formation period $P_m$, the contours $P_m$ may be drawn for forecasting use. $P_m$ and $\tilde{f}$ can be obtained from the Rainfall-runoff advisory chart and table for ungauged regions in China.

Other runoff formation models

There are also infiltration curve methods for effective rainfall computation in arid and semi-arid regions. One of these combines the infiltration curve and the infiltration rate distribution curve to establish a model of runoff formation. The other method takes off losses using an experience infiltration curve and ignores the spatial distribution of the infiltration. An advanced parabola-type infiltration distribution curve model has been advanced which is based on the Philip single point infiltration equation.

Calculation of flow concentration

- Instantaneous unit hydrograph (IUH) model

The Nash instantaneous unit hydrograph can be described as

$$U(0, t) = \frac{1}{KT(n)} \left(\frac{t}{k}\right)^{n-1} e^{-i/k}$$  \hspace{1cm} (6-14)

where $n$ and $k$ are two parameters which need to be identified for any given catchment; $m_s = nk$, $m_s$ is a one-order moment around the origins, known as the time lag. $n$ and $K$ can be determined from the effective rainfall and surface runoff by moments method.

The Nash IUH is a linear concentration model. The spatial and temporal distribution of storms in arid and semi-arid areas is extremely non-uniform and the nonlinearity of concentration is very obvious, such that model parameters are much better corrected nonlinearly. In China, for example, $m_s$ and precipitation intensity relation $i$ may be found, i.e. $m_s = a^b$, where $a$ and $b$ are nonlinear parameters, which are estimated for a catchment. The parameter $n$ is stable. $n$ and $k$ were synthesized for gauged catchments and then used in ungauged catchment in many provinces in China.

- Other concentration models

Because of the extreme non-uniform distribution of a storm in time and area, the determination of concentration velocity is a key factor in the calculation of concentration. Concentration velocity
depends upon precipitation location and time and intensity. A variable integration mathematical concentration model has now been developed which combines the translation action with that of regulation storage action. A catchment random concentration unit hydrograph and river course concentration curve and calculation method for simulation of random concentration has also been developed which is much better able to solve the problem of non-uniform rainfall (both spatially and temporally), insufficient data and nonlinear concentrations.

**Rational formula model**
The rational formula model for small catchment developed by Prof Chen Jiaqi is widely used in China. The rational formula model is

\[
Q_m = 0.278 \frac{h}{\tau} F 
\]

(6-15)

\[
\tau = \frac{L}{V_r} 
\]

(6-16)

\[
V_r = m J^{1/3} Q_m^{1/4} 
\]

(6-17)

where \( F \), \( L \) and \( J \) are the catchment area in \( \text{km}^2 \), length in \( \text{km} \) and slope, respectively; \( \tau \) is time of catchment concentration, \( h \) is the rainfall during \( \tau \). \( V_r \) is concentration velocity, \( Q_m \) is peak flow. The key to using this model is to determine the value of \( m \) by first determining the representative \( m \) for a single station and then finding the synthetic \( m \) for the regions.

**Grey model**
GM(1,1) model is a linear first order differential equation model, expressed as

\[
\frac{dx}{dt} + ax - u (6-18)
\]

where \( \frac{dx}{dt} \) is the variation ratio of a variable, \( a \) and \( u \) are model parameters such that Eq. (6-18) is a linear combination of \( x \), \( u \) and \( \frac{dx}{dt} \).

In grey system theory, the model is established according to a generated series comprising accumulated observations of flow and the model parameters \( a \) and \( u \) are calibrated by the least squares method. When the original series has both equal time intervals and discrete values, i.e.

\[
X^{(0)}(t) = [x^{(0)}(1), x^{(0)}(2), ..., x^{(0)}(n)]
\]

The equation below is used to generate the series of accumulations

\[
X^{(1)}(k) + \sum_{m=1}^{k} x^{(0)}(m)
\]

The generated series thus obtained is:

\[
X^{(1)}(t) = [x^{(1)}(1), X^{(0)}(2), ..., X^{(0)}(n)]
\]

and its corresponding differential equation is

\[
\frac{dx^{(1)}}{dt} + ax^{(1)} = u (6-19)
\]

The solution of which is

\[
x^{(0)}(k + 1) - [x^{(0)}(1) \text{e}^{-at} + u/a] = \frac{u}{a} \text{e}^{-at} + u/a (6-20)
\]

The parameter value \( u = [u, u]^T \) can be determined by least squares, i.e.
\[
\hat{a} = (B^T B)^{-1} B^T Y_n
\]

where

\[
Y_n = \begin{bmatrix}
  x^{(0)}(2) \\
  x^{(0)}(3) \\
  \vdots \\
  x^{(0)}(n - 1) \\
  x^{(0)}(n)
\end{bmatrix},
\]

\[
B = \begin{bmatrix}
  -0.5x^{(1)}(1) + x^{(1)}(2) & 1 \\
  -0.5x^{(1)}(2) + x^{(1)}(3) & 1 \\
  \vdots \\
  -0.5x^{(1)}(n - 2) + x^{(1)}(n - 1) & 1 \\
  -0.5x^{(1)}(n - 1) + x^{(1)}(n)
\end{bmatrix},
\]

Assuming \( a \) in Eq (6-20) gives the time response equation; when \( k > n \), \( x(k + 1) \) is a predicted value.

### Catastrophe prediction model

Assume an original time series as follows:

\[
X^{00}(i) = [X^{00}(1), X^{(0)}(2), \ldots, X^{00}(n)]
\]

A catastrophe series for a flash flood takes in all the peaks over a selected level of discharge, at a threshold \( \xi \) (hence such a series is often called the 'Peaks over threshold' series). The new series is as follows:

\[
X^{\xi^{00}}(i) = [X^{\xi^{00}}(1), X^{\xi^{00}}(2), \ldots, X^{\xi^{00}}(m)]
\]

where \( m < n \), the corresponding time of the catastrophe values forms a catastrophe time series

\[
W^{00} = [W^{00}(1), W^{00}(2), \ldots, W^{00}(m)]
\]

The GM(1.1) model is established for the catastrophe time series and the future catastrophe time can be predicted.

### Prediction of unequal time-interval series

The GM(1.1) model is usually used in constant time-interval series. In the case of the unequal time-interval series, such as would occur in a catastrophe series, it may be translated into a fixed-interval series and then the GM(1.1) model applied.

### Exponential moving linear prediction model

Let the original series be

\[
X_{r+1}, X_r, X_{r-1}, \psi_r, \psi_{r-1}, \psi_{r-2}, \psi_{r-3}, X_0
\]

where \( X_r \) is the measured value, \( \psi_r \) (\( r \neq j \)) is the missing value (empty or zero). The missing values can be predicted by an exponential moving linear or nonlinear prediction model. Taking \( S_{r}^{(i)} \) as the first exponential moving value, then

\[
S_{r}^{(i)} = aX_r + (1-a)S_{r-1}^{(i)}
\]
Taking $S_t^{(2)}$ as the second exponential moving value, then

$$S_t^{(2)} = aS_t^{(1)} + (1-a)S_{t-1}^{(1)}, \quad a \in [0,1]$$

(6-25)

The linear prediction model is

$$\begin{align*}
Y_{t+r} &= a_r + b_r T \\
a_r &= 2S_t^{(1)} - S_t^{(2)} \\
b_r &= a(S_t^{(1)} - S_t^{(2)})/(1 - a)
\end{align*}$$

(6-26)

(6-27)

(6-28)

where $a$ is the weight coefficient, with an empirical range of 0.0 - 0.30. The start values of $S_0^{(1)}$, $S_0^{(2)}$ of every degree are approximate.

**Equal-dimensional grey number filling of gaps and synthesis of new information.**

From Eq. (2-23) above, the first step is to establish the GM(1,1) model according to $X_0, X_1, X_2, X_3, X_4$ and to forecast $X_5$. The second step is to add the forecast for $X_5$ to Eq. (6-23) and subtract the oldest term, $X_0$, and then re-establish the GM(1,1) model according to $X_1, X_2, X_3, X_4$ and forecast $X_6$. The third step is to add the forecast $X_6$ and observed $X_5$ to Eq. (6-23) and subtract $X_1, X_2$ and then obtain $X_7$ as in the second step outlined above. Similarly, the unequal time-interval series can be translated to a fixed time series step by step.

**Generation of adjacent values**

For the time series

$$X = [x(k)/k = 1, 2, ..., n]$$

then

$$X(k) = aX(k+1) + (1-a)X(k-1), \quad a \in [0,1]$$

is just an adjacent values generating number of $X(k+1)$ and $X(k-1)$ under the generating system $a$. If $a = 0.6$, the new information should be considered more important than the old. The spaces $\psi_i$ of an unequal time-interval series can be filled by the adjacent values to generate numbers.

Catastrophic prediction can only give a return period, not an actual date. Theoretically, the GM(1,1) model can be used for long-term prediction, but only the next one or two predicted values have any practical significance. Why? Because over time, some disturbances entering the system will have an effect on the system itself and prediction will break down.

In this method, the first step is to translate the catastrophic series into an equal time interval series and establish the GM(1,1) model to predict the next value; the second is to add the predicted value to the known series and subtract the oldest value, re-establish the GM(1,1) model on the new series and again predict the next value and repeat until the prediction objective has been achieved.

These grey system methods are only preliminary steps and there are still some questions to be answered such as, in the exponential moving methods, how does the magnitude of the weight coefficient $a$ govern the prediction accuracy; at present, $S_0^{(1)}, S_0^{(2)}$ are only determined by experience. If necessary, parameters may be optimized.

**Hydrometeorological models**

The key to flash flood forecasting is how to solve the problem of extending the lead time. The use of
quantitative precipitation forecasting (QPF) can achieve better results. There are several model procedures available for real-time QPF, such as that developed by K.P. Georgakakos introduced here. The first versions of the stochastic-dynamic, integrated meteorological hydrological models (Georgakakos, 1986a, b) coupled physically-based local precipitation prediction models with hydrological conceptual models of catchment response to produce predictions of site-specific real-time flood flows (or stage), as shown in Fig. 6.9.

![Schematic representation of a stochastic-dynamic hydrometeorological model](image)

Real-time versions of such a model for use with flash floods couples the precipitation components with the runoff-generating and flood-routing components through the law of water mass conservation and a state estimator which was used to update the model state variables from real-time observations. The model is capable of operating under the various conditions of data availability which exist in flash flood prone areas.

**Precipitation model**

This is based on surface air pressure, temperature and dew-point temperatures. The model equations are as follows:

\[
\frac{dx_p(t)}{dt} = f[u(t)] + h[u(t)]x_p(t)
\]  \hspace{1cm} (6-29)

and
where \( x_p(t) \) is the condensed water equivalent mass (or volume) of water at time \( t \) in a unit area column that extends from the bottom to the top of the clouds (in kg m\(^{-2}\) or mm m\(^2\)), \( u(t) \) is the vector of the precipitation model inputs (i.e., surface air temperature, pressure, and dewpoint) at time \( t \), \( \{ h[u(t)] x_p(t) \} \) is the outflow mass (or volume) rate of the condensed water equivalent from the cloud column at time \( t \) (in kg m\(^2\) s\(^{-1}\) or in mm m\(^2\) s\(^{-1}\)); \( f[u(t)] \) is inflow mass (or volume) rate of condensed water equivalent into the cloud column at time \( t \) (in kg m\(^2\) s\(^{-1}\) or mm m\(^2\) s\(^{-1}\)). It was obtained by the cloud updraft velocity and the mass of liquid water resulting from condensation during the pseudo-adiabatic ascent of a unit mass of moist air. Outflow is due to precipitation or local cloud-top anvil formation, while inflow is due to condensation and air mass ascent. The precipitation mass reaching the ground is collected between time instants \( t_{k} \) and \( t_{k-1} \), for \( k = 1, 2, \ldots \) \((\Delta t = t_{k+1} - t_{k})\) and is represented by \( y_p(t_k) \) (in kg m\(^3\) m\(^{-1}\)). The instantaneous precipitation rate at ground level is given by \( \{ \psi[u(t_k)] x(t_k) \} \) (in kg m\(^2\) s\(^{-1}\) or mm m\(^2\) s\(^{-1}\)).

**Surface runoff generation model**

The average depth of precipitation over a catchment is calculated by the Thiessen method. The surface concentration using a simple antecedent precipitation index (API) models the analytical form of which may be written as

\[
API(t_k) = API(t_{k-1}) \cdot q^{0.24} + \bar{y}_p(t_k)
\]

\[
U_c(t_k) = \left\{ \left[ \sum_{i=k}^{k-1} \bar{y}_p(t_i) \right]^{\mu(n)} + \mu(n) \right\}^{1/n} - \mu(t_k)
\]

\[
\mu(t_k) = c + [a + d s(t_k)] \cdot \exp(-b \cdot API(t_k))
\]

where \( API(t_k) \) is the antecedent precipitation index at time \( t_k \), \( s(t_k) \) is a predetermined seasonal index, \( t \) is the time of the storm initiation, \( U_c(t_k) \) is the surface runoff at time \( t_k \), \( q \) is an API daily reduction factor taken to be equal to 0.9, \( \bar{y}_p(t_k) \) is the average areal precipitation depth, and \( c, a, d, b \) and \( n \) are model parameters.

**Flood-routing model**

The conceptual, nonlinear, reservoir-type flood-routing model of Georgakakos and Bras was used to propagate the flood wave downstream, up to the point or points of interest. The outflow \( y_x(t_k) \) from the \( n \)th reservoir at time \( t_k \) is the routing model output, as given by

\[
y_x(t_k) = \beta s_m^{-m}(t_k); \ k = 1, 2, \ldots
\]

where \( \beta, m \) and \( n \) are model parameters. \( s_m(t_k) \) is the water volume stored in the \( n \)th channel reach (a conceptual reservoir) at time \( t_k \) (in mm m\(^3\)).
Define also the vector nonlinear function $F(x, t)$ by
\[
F(x(t), t) = \begin{bmatrix}
  f_1[u_1(t)] + h_1[u_1(t)] \cdot x_{p1}(t) \\
  \vdots \\
  f_L[u_L(t)] + h_L[u_L(t)] \cdot x_{pL}(t) \\
  u_c(t_k) - \beta_{i_k}^m(t_k) \\
  \vdots \\
  \beta_{n_k}^m(t_k) - \beta_{n_k}^m(t_k)
\end{bmatrix}, \quad t_k \leq t \leq t_{k+1}, \quad k = 1, 2, \ldots \tag{6-36}
\]

In the last two equations, the subscripts 1 to $L$ refer to orographic zones.

To account for the model structure, model parameters and model input errors, a random error term — represented by the vector $W(t)$, the dynamic equation of the flash flood prediction — becomes
\[
\frac{d x(t)}{dt} = F(x(t), t) + W(t) \tag{6-37}
\]

An observation vector $Z(t)$ is defined with the elements $Z_{p1}(t_k), \ldots, Z_{pL}(t_k)$ and $Z_{d}(t_k)$ representing the precipitation observations at each orographic zone at time $t_k$ and the stream outlet discharge (stage) observation at the same time. Denoting by $V_p(t_k)$ and $V_d(t_k)$ two random sequences that represent the observation errors of precipitation and discharge (stage), respectively, a system observation equation can be written as follows
\[
Z(t_k) = G[x(t_k), t_k] + V(t_k); \quad k = 1, 2, \ldots \tag{6-38}
\]

Where $G[x(t_k), t_k]$ is defined by
\[
G[x(t_k), t_k] = \begin{bmatrix}
  \Delta \psi_1[u_1(t_k)] \cdot x_{p1}(t_k) \\
  \vdots \\
  \Delta \psi_L[u_L(t_k)] \cdot x_{pL}(t_k) \\
  \beta_{n_k}^m(t_k)
\end{bmatrix} \tag{6-39}
\]

and $V_{t_k}$ is defined by
\[
V(t_k) = \begin{bmatrix}
  V_p(t_k) \\
  \vdots \\
  V_p(t_k) \\
  V_d(t_k)
\end{bmatrix} \tag{6-40}
\]

with 1 elements equal to $V_p(t_k)$.

Equations (6-37) and (6-38) represent the state-space form of the models that constitute the flash flood prediction system. The most important components of the integrated model appear to be the state estimator and the precipitation predication component.

### 6.2.2. Glacier lake outburst flash flood

The magnitude of glacier lake outburst floods depend upon the height of the ice-dam; indeed, the formation of a glacier lake is determined entirely by the formation of an ice-dam. The dynamic changes in the height and length of the dam are related to the forward and backward movement of the glacier which is in turn determined by changes in precipitation and air temperature. The latter affects not only the amount of glacier meltwater but also the magnitude of flash floods. In essence, a glacier lake outburst is a synthesis of topographic and geological features, glacier movement,
meteorological and hydrological elements, with air temperature providing the key trigger mechanism for flooding.

**Forecasting time of occurrence**

*Forecast based on accumulated antecedent temperature*

Flash flood occurrence is related to the antecedent meteorological conditions which produced the glacier meltwater. If the air temperature was high and there is a large amount of meltwater, the likelihood of flash flooding is greater and therefore a diagram showing the relationship between antecedent temperature and extend of outburst flood is usually established. Before predicting flooding using such a diagram, the antecedent air temperature has first to be predicted by other methods.

For example, Li Jiang analysed the flash floods of the Kunmalik river, China, and found a good relationship between a yearly temperature (accumulated temperature) of ≥ 5°C and glacier outburst floods. Such high accumulated temperatures occurred four times during the period 1957-1980, in 1959, 1963, 1971 and 1978 respectively. Flooding has occurred in each of those years except 1963 when although the temperatures were high, the onset of the high temperature regime ran from 10 April 1963, some 1.5 months earlier than the following year when higher temperatures began on 25 May 1964 and which do give rise to a flood. Obviously, the higher accumulated temperatures in the early spring have no effect on ice and snow melt.

The difference between yearly and mean annual air temperature is called the departure of temperature and the relationship between flash floods and air temperature departure is also used to predict the year of occurrence. Li Jiangeng has studied the correlation between flash floods and air temperature departure at the 500 hpa level in the atmosphere in Hetian, China, and concluded that flash floods occur only in unusually high temperature years.

*Prediction according to changes in air temperature and hydrological regime*

Ice-dam formation is a pre-requisite for the occurrence of flash floods. A sharp decline in temperature may hasten river ice formation and create a dam which then concentrates flow into a glacier lake. Thus, sudden declines in temperature may provide clues about likely flood origins. Chen Yaning analyzed the relationship between the time of occurrence of glacier outburst floods and antecedent yearly temperatures for the Sikeshu river in the Tianshan mountains of China, as shown in Figure 6.10. He concluded that glacier floods occur more frequently at the lowest points in the year-by-

![Graph showing temperature variation and floods in the Sikeshu River](image)

*Fig 6.10  The relation between November (top) and December (bottom) temperature variation and floods in the Sikeshu River*
year temperature plots. Under certain temperature conditions, the physical properties of an ice-dam such as degree of freezing, compressive and shear strength, density and harness will be close to a given value for a given temperature. Such floods mainly occur in the period November to January.

Changes in the hydrological regime can be indicators of an impending ice-dam flood. For example, the intensity of the decline in flow rate is closely related to the speed of ice-dam formation. If river flow reduces sharply, the dewatering of the ice-dammed lake is insignificant and the lake will forma quickly and also outburst quickly under certain conditions.

Numerical modelling of the flood hydrograph
Since the late 1970s, many models have been developed to simulate glacier lake flood hydrographs. J.F. Nye (1976) successfully used his general equation for glacier tube flow in the glacier flash floods from the Grimsvotn lake in Iceland; this model has been developed later by G.K.C. Clarke (1982). G.E. Glazyrin (1976) has developed water course extension and kinematics equations for glacier flash floods. D.L. Fread (1984) has developed the dam-break flood model (DAMBRK) and the simplified model (SMDBK) which are applied in the United States, Canada and Nepal.

The Nye model simulates numerically the glacier dammed lake outburst flood based on equations for tunnel geometry, continuity, energy conservation and thermal transmission, and the empirical Gaukler-Manning formula. The simplified form of the equation is given below:

\[
\frac{\partial h}{\partial t} = \frac{S^{4/3} \left( -\frac{\partial V}{\partial h} \right)^{3/2}}{\rho_1 l \eta^{3/2}} + \frac{0.205S^{2/3}}{\rho_1 l \eta} \left( -\frac{\partial V}{\partial h} \right)^{4/3} \left( -\frac{\partial V}{\partial h} \right)^{2/3} \cdot K_w (\theta_0 - \theta) - K_o (P_0 - P_n) \tag{6-41}
\]

where \( s \) is the section area of the water course, \( t \) is time, \( \rho_1 \) is ice density \((0.9 \text{ g cm}^{-3})\), \( k_1 \) is the empirical constant, \( P_0 \) is static water pressure \((P_0 = \rho g h, g \) is acceleration due to gravity, \( h \) is ice thickness), \( P_n \) is water pressure, \( \rho_w \) is water density \((1.0 \text{ g cm}^{-3})\), \( \psi \) is flow potential energy, \( \theta \) is water temperature, \( \eta \) is the sticky rate, \( K_w \) is the thermal transmission rate: \( N \) is a constant, \( l' \) is effective potential heat of ice-melting, \( \theta_0 \) is the water temperature of the lake.

The Clarke model has simplified Eqn. (6-41) to account for both the geometric form and water temperature of the lake, to give:

\[
\frac{ds}{dt} = S^{4/3} \left( -\frac{\partial V}{\partial h} \right)^{3/2} + \frac{0.205S^{2/3}}{\rho_1 l \eta} \left( -\frac{\partial V}{\partial h} \right)^{4/3} \left( -\frac{\partial V}{\partial h} \right)^{2/3} \cdot K_w (\theta_0 - \theta) - SKP_1^n (1 - \rho_1 \omega h(t) \eta) \eta \tag{6-42}
\]

\[
\frac{dv}{dt} = \theta_{in} - Q \tag{6-43}
\]

\[
Q = S^{4/3} \left( -\frac{\partial V}{\partial h} \right)^{1/2} \tag{6-44}
\]

where \( h \) is the lake surface elevation, \( V \) is the water volume of the lake, \( Q_{in} \) is the inflow rate, \( Q_{out} \) is the normal outflow rate, \( n \) is an exponent of ice flow law (other symbols as for Eqn. 6-41). These equations introduce the effect of glacier lake geometry into the numerical analysis by an expression of \( h \) or \( h(t) \) which is obtained by curve fitting of observed data. The numerical model can only simulate the rising limb of the hydrograph and does not provide for any downstream attenuation.

6.2.3 Dam-break flash flood

Dam-break peak discharge calculation
For a local dam-break there are upward and lateral negative waves. The maximum flow rate lightly
lags behind the moment of dam-break. The maximum flow rate (see Eqn (6-10) must be multiplied by a correction coefficient, suggested by H. Rouse as \((B/b)^{1/4}\), where \(b\) is the top width of the dam-break mouth, \(B\) is the dam length; when \(h/H_o \leq 0.1384\) \((H_o\): water depth upstream of dam; \(h\): water depth downstream - see Table 6.2), the maximum flow rate of the local dam-break is given as:

\[
Q_m = \frac{8}{27} \sqrt{g} \left( \frac{B}{b} \right)^{1/4} BH_0^{3/2}
\]

(6-45)

For a local dam-break along a vertical line, as shown in Fig. 6.11 where the height of the remaining dam is \(h'\), the maximum flow rate is given by:

\[
Q_m = \frac{8}{27} \sqrt{g} \left( \frac{H_o - h'}{H_o - 0.827} \right) B\sqrt{H_0(H_0 - h')}
\]

(6-46)

**Fig. 6.11** Local dam-break along the vertical

If a dam breaks along the length and height instantaneously, the maximum flow rate is:

\[
Q_m = \frac{8}{27} \sqrt{g} \left( \frac{B}{b} \right)^{1/4} \left( \frac{H_0 - h'}{H_0 - 0.827} \right) B\sqrt{H_0(H_0 - h')}
\]

(6-47)

Eqn. (6-45) has been modified by an American river channel experimental station to produce:

\[
Q_m = \frac{8}{27} \sqrt{g} \left( \frac{BH_0}{bh} \right)^{0.28} bh^{1.5}
\]

(6-48)

while the Institute of Hydraulics Research of the Yellow River Conservancy Commission has derived the equation below from experimental results:

\[
Q_m = \frac{8}{27} \sqrt{g} \left( \frac{B}{b} \right)^{0.4} \left( \frac{11H_0 - 10h}{H_0} \right)^{0.8} \left( \frac{11H_0 - 10h}{H_0} \right)^{0.3} \times bh^{1.5}
\]

(6-49)

**Dam-site hydrograph calculation**

**Hydrograph calculation of overall instantaneous dam-break**

It is found from analysis of computed results and model experiment data that the dam-break hydrograph and the maximum flow rate \(Q_m\) are related to the initial flow rate \(Q_0\) and the releasable reservoir storage, \(W\). The dam-break hydrograph can be generalized approximately as a fourth-degree parabola or a 2.5th-degree parabola. The typical fourth-degree parabola hydrograph is shown below in Table 6.3, derived from the analysis of extensive experimental data.

The time taken to empty the water which is released by the reservoir is computed from

\[
T = \frac{kW}{Q_m}
\]

(6-50)

where \(k\) is a coefficient related to the form of the water course downstream and the water stage; generally \(k = 4-5\) for fourth-degree parabola and \(k = 3.5\) for a 2.5th degree parabola. After determination
of $T$, the hydrograph can be calculated from $Q_m$ and $Q_d$.

### Table 6.3 Dam-break flood hydrograph

<table>
<thead>
<tr>
<th>$t/T$</th>
<th>0</th>
<th>0.05</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q/Q_m$</td>
<td>1.0</td>
<td>0.62</td>
<td>0.48</td>
<td>0.34</td>
<td>0.26</td>
<td>-0.207</td>
<td>0.165</td>
<td>0.130</td>
<td>0.094</td>
<td>0.061</td>
<td>$Q_d/Q_m$</td>
</tr>
</tbody>
</table>

### Hydrograph calculation of dam-break by degrees

A dam-break is a very complex process. It is generally assumed that the break will happen a short while after the dam overflows, producing a steep rising limb to the hydrograph. The 11th Bureau of the Water Resources Department analysed the measured August 1975 dam-break data of the Banqiao reservoir, China, to give the hydrograph calculation equations below.

When $t/T = 0-1/3$

$$Q/Q_m = 5.18(t/T)^{5/3}$$

(6-51)

When $t/T = 1/3-1.0$

$$Q/Q_m = e^{-1.6(t/T-1/3)}$$

(6-52)

### Dam-break flood routing

**Calculation of flow rate for downstream dam-break**

An empirical formula is given as

$$Q_{m} = \frac{w}{\frac{W}{L} + \frac{V}{K}}$$

(6-53)

where $Q_{m}$ is the maximum dam-break discharge at $L$ away from the dam site and $V$ is the maximum cross-section average velocity during the flood period. This may be taken as the historical maximum value in gauged regions, with $V = 3.0-5.0$ m s$^{-1}$ in mountainous areas, 2.0-3.0 in hilly areas, 1.2-2.0 for lowland, ungauged regions. $K$ is an empirical coefficient: $K = 1.1-1.5$ in mountainous areas, 1.0 in hilly areas and 0.8-0.9 in the lowlands.

**Travel time of dam-break floods**

People may more attention to dam-break floods travelling downstream. The travel velocity is greater than that for a normal flood, with the maximum wave velocity at the dam site and the further away from the dam site, the faster the velocity decreases. The Institute of Hydraulic Research of the Yellow River Conservancy Commission developed a flood travel time formula based on physical model experiments. The formula for the duration of the rising limb of the hydrograph is

$$t_i = K_i \frac{L^{1.75} (10-h_0)^{1.8}}{W^{0.2} H_0^{0.35}}$$

(6-54)

where $h_0$ is the average water depth in the downstream section in $m$ before the time of arrival of the dam-break wave, ($h_0$ corresponding to $Q_d$). $K_i$ is a coefficient ($K_i = 0.65 \times 10^{-3} - 0.75 \times 10^{-3}$); other symbols as before.

The formula for the time of arrival i.e. the interval between the dam break and the maximum discharge downstream, is

$$t_2 = K_2 \frac{L^{1.4}}{W^{0.2} H_0^{0.5} h_m^{0.25}}$$

(6-55)

where $K_2$ is a coefficient ($K_2 = 0.8-1.2$), and $h_m$ is the average water depth calculated from $Q_{Ln}$.
7. Flash flood warning systems

7.1 A review of the flash flood warning concept

A flash flood is a rapidly responding natural phenomenon. To prevent extensive loss of live and damage to property requires people to take action quickly. For the small catchment, especially in mountainous areas, i.e. where the time of concentration is less than six hours, intense rainfall can create a flash flood. Such floods develop so rapidly that there is a large element of surprise for flood plain occupants. Generally, in these situations, the flood forecasting procedures used in large streams cannot be implemented rapidly enough to be effective in providing a forecast with a sufficient lead time. Moreover, flood estimation is very difficult because of the high spatial and temporal variability of the intense rainfall events that cause flash floods.

During the 1970s and 80s, the flash flood problem has drawn more and more attention. The World Meteorological Organization has promoted the establishment of flash flood warning systems through various projects and introduced some successful systems in the HOMS components and sequences. For example, the ALERT System (see HOMS sequence No. 0 1 0) is used in the USA and other countries. Many countries in the world have established or are establishing various kinds of flash flood warning systems appropriate to their own conditions with regard to climate, topography, economic development, flood plain population, existing flood management structures, warning time, financial capacity, prevention strategies and the management resources available for programme implementation. Generally, no matter which measures are used in the system, advanced or retrograde, complicated or simple, automatic or artificial, it must meet the following requirements: to transmit the flash flood messages immediately and accurately to the flood prevention administrations, community and people in advance, so that there is enough time to make efficient preparations: to act under the leadership of an organization or community according to previously made plans to evacuate from the flood plain to nearby highlands or some other safe place. In this way, flash flood can be minimised and flash flood prevention benefit maximised.

A further aspect is that the problem of flash floods is not simply that of providing the necessary hardware but also that of organization. Generally speaking, the greatest benefit will come from adequate technical advice and community preparedness in advance of floods and the establishment of the appropriate flash flood warning system. In each case, the local community must be closely involved in the effective use of community action plans that guide the emergency measures required by the local situation. The importance of the advanced preparation can not be over-emphasized, because the time scale of a flash flood is too short to permit the development of an action plan, deployment of equipment, and establishment of communication channels after the flood threat becomes evident.
7.2 Flash flood warning systems

Flash floods require a fast acting data collection system: since ordinary data collection networks do not meet such a requirement, it is beneficial to establish telemetry system.

7.2.1 Equipment for flash flood warning systems

Local flash flood warning systems may include the following equipment and communication option (after Mogil et al.)

**Equipment:**
- Plastic rain gauge
- Staff river gauge
- Recording river gauge
- Tipping bucket rain gauge
- Electronic river level sensors
- Automated rainfall reporting stations

**Communication system - from observer to flash flood coordinator**
- Telephone
- Amateur radio
- Citizen-band (CB) radio
- Police, fire and other emergency radio

**Communication system - from automated equipment to flash flood coordinator**
- Telephone
- Hardwire
- Line of sight radio
- Satellite relay radio

Depending on local conditions, the alarm bell, tweeter or bugle, etc. can be used when urgent events happen. In mountainous area of south-west China, the UJ-2 mud-rock flow

![Diagram](image_url)  
*Fig 7.1 Transmitting and receiving flow diagram for UJ-2 type telemetry alarm equipment*
monitoring alarm equipment constructed by the Chendu Mountain Area Institute of the Chinese Academy of Sciences is used. This equipment has two parts: a transmitter and receiver as shown in Figure 7.1. It can work unmanned continuously for three months with abundant electric power. The communication distance is 8-12 hours and the monitoring distance 2.8 km.

7.2.2 Typical flash flood warning systems

In view of the short time involved and in order to provide continuous monitoring, all systems hopefully are automated. The typical flash flood warning system as developed by the National Weather Service of the USA is shown in Figure 7.2. It has three components: a river station, an intermediate station and an alarm station. The river station senses the critical water level for a flash flood and consists of a simple enclosed float switch and a weather-proof box containing a tone transmitter, battery and interconnecting circuitry. The intermediate station may be located up to 20 km away from the river station at a point where connection to AC power lines and a telephone line can be made. The river station is connected to the intermediate station by a pair of wires. The alarm station is located in an appropriate place within the community where there is continuous staffing such as police and fire stations and municipal buildings. It receives a continuous signal from the river station as a check on the system's operation status. When the critical level is reached at the river station an audible and visible alarm is activated. A monitoring switch enables a check to be made at the alarm station for power or other failures in the system.

More recently, event-reporting instrumentation has been developed. This may include both rainfall and river height observations and, operating on an event basis, can easily incorporate an alarm facility. Normal hydrological telemetry systems can provide much the same information provided they are interrogated frequently, for example, every 15 to 30 minutes. However, this may require too heavy a power drain on the system, particularly with older systems. Being forced to depend upon the operator to switch to more frequent interrogation during potential flash flood periods is not always reliable, hence the advantage of an event system.

Fig 7.2 A typical flash flood warning system installation (after the U. S. National Weather Service)
The most effective flash flood warning system is to use a quantitative precipitation forecast (QPF) to extend the watch lead time which is the key parameter in forecasting flash floods. This system is shown in Figure 7.3. It consists of the following tasks:

- **Collection of event-reporting**
  The local mini-computer accepts data from event-reporting gauges through a radio system and organizes the data into a convenient form.

- **Collection of telemark data**
  The local mini-computer interrogates available telemark gauges at a frequency determined by the rainfall rates being reported by the self-reporting gages. In order to perform this task, the computer must be equipped with the appropriate hardware and software. The hardware required includes a standard auto-call unit which allows the computer to dial the telephone, and an inexpensive Audio-Binary converter which is a device that converts audio telemark signals into computer-readable data which can be decoded by appropriate software.

- **Transfer of data to RFC computer system**
  The data collected by the field mini-computer is transferred to the River Forecasting Center (RFC), through Automation of Field Operations and Services (AFOS). The frequency of data transfer between the local site and the RFC is a function of rainfall intensity.

The Quantitative Precipitation Forecast originates at the Weather Service Forecast (WSFO), which has basic weather forecasting responsibility for the area of concern. The availability of real-time rainfall reports, transferred to the WSFO via AFOS and WSFO, provides precipitation guidance information, which is placed in the RFC computer for use by the hydrological streamflow simulation model. The streamflow simulation model uses the observed and forecasted precipitation to produce a streamflow discharge for a specific point on the stream in question. The model used by the Flash Flood Warning System is a version of the Sacramento Streamflow Simulation Model.

![Figure 7.3 Flash flood warning system](image-url)
which has proved to be very reliable in its ability to produce accurate streamflow simulations for small catchments. The RFC computer system produces a worded forecast in terms of river height which is monitored by the hydrologist and revised if necessary before it is transmitted back to the local mini-computer where it is displayed.

Some other simple warning methods are developed according to the local conditions, e.g. a simple warning device is an oil can with a small orifice as shown in Fig. 7.4. The electrode which is fixed at a certain level can indicate the water level which corresponds to the warning intensity of rainfall. An alarm lamp or buzzer warns people of the impending flash flood.

![Diagram of the flash flood warning device made from an oil can](image)

Some places in China use interrogation recording gauges such as the JY-10 pressure recording gauge, composed of gauge, automatic sensors, code, language consulting and telephone, etc. This gauge can determine water level through measurement of the weight of a water column above the height of the observation point, the pressure sensor changing the level message into a pulse signal and sending it through a second-order instrument (code and language consulting), coding it according to certain procedures and turn it into a stage signs upon which the recorder will record it or effect some language interrogation. When level station receives the signal, the automatic telephone will report the time and place at that level and then the warning system may raise the alarm by broadcast, whistle, light, etc. when it receives a critical water level signal so that the water condition may be checked by telephone and necessary preparations made for the flood.

7.2.3 Organization

The key to successful flash flood forecasting and warning is organization. This is beyond the remit of the hydrologist and meteorologist and a team of approach is required, involving all levels of government and related disciplines, particularly in the social sciences. There is little point in a forecasting and warning service providing timely and accurate forecasts if these do not elicit the appropriate public response. As flash floods require this response to be immediate, emphasis must also be given to the sociological aspects of flash flood warning programmes.

Although complete prevention of flash flood is impractical, if people are well organized, however, loss of life and damage to property can be reduced. For this to be achieved, the following tasks may be considered:

- To have a quick-responding and well organized agency which can coordinate all the related flash flood prevention agencies.

For example, in the United States a number of National Weather Service Forecasting Offices have a dedicated disaster preparedness meteorologist. In addition, meteorologists and hydrologists from
other weather and river forecast offices support the flash flood warning and disaster preparedness programmes. The U.S. National Weather Service (NWS) staff hold preparedness meetings with state, county and local officials, law enforcement agencies, school officials, amateur radio and CB groups and others to establish and maintain local warning communication systems and storm spotter and volunteer observer networks and to implement local flash flood warning programs. It is necessary for the NWS staff to work closely with the mass media to ensure that flash flood releases and safety information notices are rapidly and reliably disseminated. Encouragement of appropriate response by local officials and the public is achieved by distribution of weather safety literature in the form of pamphlets, slides, films and news releases.

The sociological aspects of warning systems have come under close attention in recent years. Recent disasters demonstrate continually that people do not know how to respond adequately to a flash flood threat. The interactions among related agencies are shown in Figure 7.5.

![Diagram of forecast dissemination and response](image)

Fig. 7.5 The "warning system" showing the complex interactions among agencies, dissemination subsystem, and the public

In China, there are flood control agencies (or headquarters) in every town, county, province with a State Flood Control Headquarters in Beijing under the State Council. During the flood season, people are on duty day and night (24 hours) in the flood control agencies or headquarters. Once the flash flood warning is received, the person on duty immediately informs the agency leader, then on to the higher headquarters who will recommend emergency measures or the movement of people out of the dangerous areas. In some cases, the army helps to evacuate people from danger.

- **Coordination of hydrologists and meteorologists.**
  Flash flood forecasting is one of the most difficult problems facing the hydrological and meteorological forecaster. It is one which can be solved only by the joint efforts of the meteorologist and hydrologist because of the lack of the time available and the dependence of the hydrologist on meteorological input, such as quantitative precipitation forecasts (QPF). New technology in terms of automatic event reporting rainfall and river level stations, remote sensing of areal rainfall by radar and satellites and improved methods of QPF are already demonstrating their suitability, and offer the main methods of providing adequate information about storm rainfall and runoff. Despite the fact that this technology is capital-intensive and demands an advanced level of expertise, some of the necessary tools for flash flood forecasting exist already in many countries. Development of these systems then becomes a question of funds, staffing and national priorities.
To have a well-conceived evacuation plan for flood-prone areas.

Since the flash flood is a very rapid natural process, it is difficult to predict and forecast. The main problem is to reduce, especially to save life. One of the ways is to move people through temporary evacuation of areas under flood threat.

### 7.2.4 Community involvement

For a flash flood warning system, the most important role can be taken through involvement of local community. The response of the public to warning and the saving of life and reduction of damage to property is the measure of success for the system. Flash flood systems handled by the local community avoid some of the inherent delays in both the collection of data and the dissemination of forecasts. Rainfall and river height data are all handled locally, and the responsibility for the preparation and dissemination of warnings are given to a designated local flood warning representative (or “coordinator”). Whenever possible, the local representative is given information about expected heavy rainfall and/or radar and/or satellite observations.

### 7.3 Management and operation of warning systems

#### 7.3.1 Management of warning systems

In order to keep the flash flood warning system in good working condition during the flash flood prevailing season, the following work should be completed:

- To establish a group for equipment maintenance. People in this group should have good knowledge of all the equipment including observation, warning, and communication devices. The main items of equipment should have spare parts.
- To have regular training courses for technicians.
- Before the onset of the flood season, inspection work must be done.

**Inspection of the warning system**

Inspect all types of observation devices to ensure their completeness such as all types of rain and water level gauges handled by people. Inspect all communicative systems to ensure that they are unobstructed, such as telephone, automobile sensor, various radios (including amateur radio, police radio, fire alarm radio, and other emergency radio) etc. The nation or community should allocate funds for repairing warning systems and adding devices.

To aid the inspection of local work for flood prevention, various types of propaganda should be operated before the season of flash flood to strengthen the flood prevention consciousness of residents and to emphasise the significance of flood prevention. Flood warning dissemination plans and concrete measures should also be checked. Alert exercises in relation to potential flash flood disasters should have been carried out before the flood so that residents are familiar with various warning sirens, and how to behave after hearing the signals. At the same time, flood prevention devices and water-avoiding devices should be checked. Recent disasters demonstrate continually that people do not know how to respond adequately to a flash flood threat (see for example, Gruntfest, 1977 and the Australian Institution of Engineers and others).

In the U.S., a number of NWSFOs have a dedicated disaster preparedness meteorologist. It is necessary for the NWSFO staff to work closely with the mass media to ensure that flash flood releases and safety information are rapidly and reliably disseminated.
7.3.2 Operation of a flash flood warning system

The flood control agencies and local organizations should have an effective plan to operate the flash flood system, the essential elements of which are as follows:

1. Volunteer rainfall and steam gauge observers;
2. A reliable and rapid local communication system with emergency backup;
3. A flash flood warning coordinator and alternative;
4. Forecast procedures;
5. A warning dissemination plan;
6. An adequate preparedness plan (including public education).

If the flood forecasts are made by a more centralised forecasting authority the same requirements exist, except that automatic data collection is usually necessary along with more efficient communication systems. Although in this case the forecasting authority prepares the forecast, there is still the need for a local coordinator to handle local dissemination and to ensure, as far as possible, the appropriate public reaction to these forecasts.

Flash flood warning systems handled by the local community avoid some of the inherent delays in both the collection of data and the dissemination of forecasts. That is, unless a computerised system such as is described above is available. Rainfall and river height data are all handled locally and the responsibility for the preparation and dissemination of warnings is given to a designated local flood warning representative (or “coordinator”). Whenever possible the local representative is given information about expected heavy rainfall based on meteorological forecasts and/or radar and/or satellite observations.

A network of rainfall and river height gauges is established in the area, all reporting to the qualified local flood warning representative. The representative is authorised to issue public flash flood warnings based on established procedures which take into account the flooding that will occur under different conditions of temperature, soil moisture and rainfall. On the basis of reported rainfall and these forecast procedures, the representative can prepare a localised flood forecast and issue a warning within a few minutes. Finally, successful operation of a flash flood warning system, whether it be a local or a centralised system, requires active community participation and planning, which in its simplest form needs very little financial outlay.

7.4 Issue and feedback of warning information

Flash flood warning systems should respect social problems. A forecasting agency should not make the mistake of considering its job is completed. In several countries, if meteorological conditions conducive to heavy rainfall are observed or forecast for an area, a notice is issued on radio and/or television. This alerts residents in the area to the potential occurrence of rainfall that could produce flooding. When flood-producing rainfall is reported it is followed by a warning. This advises the residents in the area to take necessary precautions against flooding. Fig. 7.6 (overleaf) shows the interrelationship of a warning and issuing system.
Fig. 7.6 Cooperative warning system
8. Strategies for flash flood prevention

In arid and semi-arid areas, on the one hand precipitation is rare and the area is often suffers serious drought while on the other hand, flash floods may also cause serious flood disasters. It is almost impossible to prevent a flash flood entirely since it usually comes unexpectedly but we can adopt some effective measures in accordance with the local conditions to reduce the loss of life and property. However, we should point out here is that continued economic development and population increase, the losses induced by flash floods are also increasing such that it has become a pressing task for us to take measures to lesser the damage caused by flash floods.

Many articles concerning flash flood prevention have been published in recent years. In the U.S. Corps of Engineers' pamphlet “Community Decision” many practical measures were proposed and their advantages and disadvantages discussed.

The usual measures may be divided in two kinds: engineering and non-engineering.

8.1 Engineering measures

Using engineering measures to control floods and lessen flood damage is a traditional method adopted all over the world in flood problems. Indeed, perhaps the continuing improvement in scientific and technological and in social financial capacity will permit engineering measures to play an even greater role. The specific content of each engineering measure varies because of different natural geographical conditions and properties of specific floods. The engineering measures used to lessen the damage of flash flood in arid and semi-arid areas also differs from those used in other geographic regions.

8.1.1 Building storage reservoirs

One of the principal hydraulic engineering measures used is to create a reservoir and thus control flooding through controlled releases to protect the downstream floodplain. However, because of its high cost, large losses through the flooding of large areas of land, accumulation of sediment and other limitations, it is a technique with limited use. Building a reservoir in arid and semi-arid areas, especially on the flood plains, means that the resultant high transpiration demand may often cause great loss of water, and that sometimes the soil around the reservoir may become salinised. For instance, in the XinJiang Autonomous Region in China, the area of secondary salinised soil is about one-third that of the cultivated land. Further, to our surprise, in the kashi district in South Xinjiang Autonomous Region, China, the area of the secondary salinised soil is over two-thirds of the cultivated area. Thus, depending on the reservoir alone cannot solve the problem of flood prevention. Although we have solved some flood control problems by reservoirs in the plains in the past, the resultant secondary problems arising are not negligible. Therefore, in arid and semi-arid areas, we should try to make full use of the reservoirs already built, and only then build some
additional valley reservoirs to meet the needs of flood control.

8.1.2 River basin management

Here the concept is to use river basin management to reduce surface flow. For example, at the point where rivers emerge from the mountains we can create shallow ditches along the contour line for flood diversion and interception. We can also create terraces and check dams on slopes plus some ploughing as essential supplementary measures. The result of such measures is that on the one hand we can weaken the power of the flood effectively, reduce the flood peak and lessen the harm to the downstream area; on the other hand, the flood waters can quickly infiltrate into the ground, some of which will percolate into groundwater and be stored in the aquifer or underground reservoir. Thus the utilization of the water resource can be greatly increased. In the Weigan River, XinJiang Province, China, we have made some notable achievements in reducing flood peak by means of flood diversion and flood interception channels.

8.1.3 Building flood protection dykes

A flood protection dyke to limit the river flowing along its designated course can, to a certain degree, protect the river valley and its neighbouring areas from the disaster of flooding. Since the cost of a dyke is comparatively low, it is a widely used technique. At present, however, the designing standard of dykes is generally low in arid and semi-arid regions and should be raised on the basis of financial considerations pertaining in different places.

8.1.4 Clearing obstacles in the water course

Clearing away obstacles and dredging up mud in water causes to improve the discharge condition, enlarge the flood carrying capacity of the river, lower the water level are all useful remedial techniques to prevent a river from backing up through anthropogenic sources. On many we have begun to carry out multiple-purpose and solid constructional developments, such that the interests of different levels and all walks of life in society are involved. In order to manage the river properly, we must constitute the necessary legal framework. The people’s committee of Datong city, Shanxi province, China, has promulgated “The River Law of Datong city’ which greatly promotes the work of river management and obstacle clearing.

8.1.5 Building flood diversion storage and creating flood retardation areas

Since its flood control ability is limited, when a dike is used as a means of flood protection, appropriate flood storage and retardation area should be constructed as a means of lowering the flood peak, storing and retarding flood while the flood overtops or surcharges the protection of the dike.

Such a flood diversion storage area may not be used every year, and may even be left unused for several or even tens of years. Moreover, many years after its initial construction the flood diversion area achieves a certain value; especially the area to which the flood had been diverted and thus fertilised the soil, and many people may easily get off their guard against flood. All these things mentioned above add difficulties to the work of flood protection. Therefore, government departments should not only control the extent of agriculture, industry and population, but also should ensure sufficient information dissemination on the value of striving for prevention the first place and be sure that people prepared to contribute to the work of flood diversion. First of all, all the departments responsible for the flood diversion should strengthen their work of informing, leading and organizing and try to make every village, every family, every person aware of disaster prevention; at the same time, they should also take specific measures in flood prevention.
The Chinese Ministry of Hydraulics has promulgated the "Outline of Instructions on the Safety and Construction of the Flood Storage Retarding Area" issued in Sept. 15, 1988, as follows:

(i) The communication system should always be unobstructed. In those flood storage areas where flooding is frequent, two sets of communications hardware is necessary.

(ii) The content of flood forecast and warning should be based on the regulations and requirements of the hydrometeorological department and flood prevention headquarters. The content should include the estimated flood level, flood volume, time of flood diversion, route for emergency flood evacuation and retreat, the time limit of retreating, and so on.

(iii) The warnings must spread over the whole region, including isolated areas which are cut off from the outside. Warnings can be spread by means of telephone, broadcast, television, sirens, buzzers, hanging flags, striking gongs, shouting, guns, or informing door by door, etc.

(iv) The warnings should be sent out only by the flood prevention headquarters. Miswarning is not permitted. As soon as the warning is sent out, all means of flood evasion should be put into action.

If there is any failure resulting from a delay in action, the person on duty should be held legally responsible.

There are two kinds of flood evasion measures:

Flood evasion on site

(i) Protective zone (around-village dam). In the densely populated and high altitude villages, we can build embankments for flood protection people.

(ii) A flood avoidance platform may be applicable in areas where the opportunities for flood storage are greater and flood stage is not so high. Some highlands may be designated as temporary flood avoidance places according to the topographic condition and through a little construction work.

(iii) Flood avoiding buildings. In areas where flood storage is extensive, people may be instructed to build houses above the level of flood, which may then be used as schools or for other public facilities and as a safe place to which people and important property can be moved to while the flood is being diverted.

In addition, we also have flood avoidance buildings which have reinforced concrete structures where residents and important possessions can be moved to the higher floors of the building while the flood is diverted. It is also possible to use the top of dykes as emergency flood avoidance refuges and then retreat to safer places as soon as the flood has passed by. These measures are not only effective for flood protection but are also applicable to those areas frequently disturbed by flash floods.

Safe retreats

If the flood level becomes too high in the flood storage areas, inhabitants must have provision for safe retreat.

(i) A check must be made of the basic situation, with the provincial government checking population details such as the total number of family units, livestock and valuable property within the area that need to be moved away before the flood comes.

(ii) The route for retreat and the settlement of inhabitants must also be considered.

Local government should plan road and highway construction in accordance with the need for both escape routes and the road building requirements of urban and rural areas, the administrative and transportation conditions.
The inhabitants should be settled temporarily by family, based upon detailed plans drawn up circulated beforehand so that everyone knows which route to take and which house to move to while retreating.

According to the different flooding frequencies encountered and the extent of previous injury, some countries have management plans for flood-prone areas such that no permanent structures are permitted to be built below the 5-year flood level and existing structures are not permitted to be expanded. In the areas below the 5-20-year flood level, only those structures which have a fairly high economic value are allowed and must be equipped with flood protection measures. In the areas where there is a return period of 20-50 years, there is no limit on building but structures must be equipped with adequate warning and protection measures. The management strategies outlined above have been adopted in towns and cities by rivers in the Sichuan province in China following the 1987 floods.

Risk analysis is undertaken in some areas in China. Much experience has been gained from quantitative analysis, calculations, and the economic benefit of diverting and storing flash floods in flood detention basins. For example, in Mote Zhuo Qi of BaoTou city in China, calculations on the hypothetical benefit have proved that in arid and semi-arid areas, a flood detention basin is an important role in protecting and making use of a flash flood from many rivers.

8.2 Non-engineering measures

It could be assumed that building appropriate hydraulic engineering structures could reduce flood disasters effectively. However, dams and dykes are designed in a definite or specific standard, and once the over exceptional flood occurs, the resultant dam-break or dyke-breach will wipe out completely all the social and economic systems which will have developed under the protection of flood-control engineering over a long period of time.

During the struggle against floods, people gradually come to realise that the human being can only control a nature disaster to a certain extent because of the limitations in certain levels of science and technology along with financial capacity and material resources. It is impossible and also unnecessary to build engineering structures in many areas. Instead, we can use non-engineering measures instead of the engineering measures with the added advantage that there is fairly little influence on the environment. When we evaluate these non-engineering measures, we should consider all kinds of additional factors, including those relating to the economy, society and laws, compared with the engineering measures.

Non-engineering measures can change the sensitivity and influence of a flood. Land use planning, flood forecasting and warning, and property protection, etc. all contribute to the sensitivity of flooding while flood insurance, flood rescue and public awareness are the main measures which change the influence of flood.

Although experts from different countries have different ideas about their extent and range, non-engineering measures have still played a significant role in reducing flood disaster. Many people have thus agreed to strengthen the non-engineering measures to reduce flood disasters.

8.2.1 Establishment of unified command and disaster management system

Disaster reduction and prevention is a strongly synthetic form of system engineering. Only a perfect and unified command and management system will give practical protection for disaster reduction. From the central to local administration units at different levels disaster reduction organization and systems should be established, to unify plans, command the activities and disaster reduction work within office's own range of authority and thus strengthen the social disaster resisting ability by means of effective coordination.
8.2.2 Establishment of monitoring systems for forecasting and warning

Flood forecasting and warning are important non-engineering measures. Taking preventative measures is the least cost method of disaster reduction. Flood monitoring can gather timely disaster information, flood forecasting and warning can effectively reduce flood disaster loss. The science of flood forecasting has been greatly advanced by the forecasting method which combines meteorology and hydrology, and the advent of automatic long-distance new technology. A great deal of practical flood forecasting methods and models have been developed all over the world, which play a great role in disaster reduction.

The aim of flood forecasting is to predict the flood-peak level, the time and the numerical value of flood-peak discharge in a certain river, at a specific place. The aim of flood warning is to give advance notice that a flood will occur. To be effective and valuable, forecasting should be timely and exact. Improving warning precision and increasing the prediction period will remain important goals. Although some countries have used flash flood forecasting systems to different degrees, only in America is there a national programme for research on flash flood forecasting; in arid and semi-arid areas particularly, flash flood forecasting is still very weak. In order to improve flash flood forecasting in arid and semi-arid areas, we should do well to:

(i) Enhance hydrological and weather data collection to improve our knowledge of flash flood and provide better warning capabilities, in particular, making use of modern detection instruments. In arid and semi-arid areas with vast territory, scarce population, and variable precipitation, it is impossible and uneconomical to establish a larger number of precipitation stations and hydrographic stations than normal. At present, there are few surveying stations in such regions. In the near future attention should be given to establishing various types of station, some gauging at fixed intervals, some at cyclical intervals, some involving water levels, and some combined with various engineering structures. In the distant future, it may become possible to establish unmanned hydrologic gauging stations through the arrival of automatic equipment, such as long-distance transmission of rainfall and water level data. We should make full use of radar to cover a wide range of precipitation.

(ii) Enhance scientific research on disaster reduction; systematic study of the mechanisms controlling the occurrence, formation, and decay of such phenomena, we can provide a scientific basis for disaster reduction and prevention.

(iii) Combine hydrological information with weather information to improve flood forecasting in the long or short term. Because rainstorms happen with violent strength over a short period in arid and semi-arid areas, they often lead to ferocious flash floods and even if the rainfall information forecasts the flood, the prediction period still cannot meet the demands. Moreover, because the rainstorm does not occur in the same time and place as the runoff, it is difficult to calculate runoff yield. In addition, the nonlinear influence of any confluences makes flood forecasting difficult in the short term.

In order to make up for inadequate flood forecasting in the short term, some of way of taking into account a combination of hydrological and meteorological data will be beneficial, such as to consideration of the precursive weather and the character of the flash flood, further analysis on unusual weather characteristics in the early days of the flood, and to make full use of all kinds of influential indices, such as solar activity, the atmospheric circulation, El Nino phenomena for the previous period, etc. Even if we are only able to forecast the mid and long term qualitatively, this information can be combined with short-term flood forecasting to improve disaster reduction and prevention significantly.
8.2.3 Benefits from plantation forestry

By changing the land use cover, plantation forestry can improve catchment conditions, prevent flood disasters and erosion effectively. Large-scale planting of trees and grass has an obvious result, as for example, in the White Hollow of Tennessee in the USA where the flood hydrograph changed dramatically following large-scale plantation from 1935 to 1947. The flood peak discharge reduced by 85 per cent and the duration from one hour to eight hours.

First, plants help to improve the ability of the land to store water; thus, forests have gained the name of "green reservoir". Second, while reducing the overland flow, plants also reduce the loss of water and soil, and increase the infiltration ability of soil. Third, through the interception of rainfall, the absorption of rainfall by the leaf litter, and soil infiltration, forests have a large capacity for detention and a powerful influence on flood flow. Lastly, through this reduction of the speed of water converging within the river basin, forests can control the flood and lower/retard the flood peak.

In practice, hydraulic engineering measures combined with afforestation can reduce flood disasters more effectively. One typical example is the sharp contrast between the Han-Tai-Chuan river basin and the Bu-er-si-tai-gou river basin in Yike-zhao Ally, Inner-Mongolia, China. On 21st July, 1989, a heavy storm of about 186 mm precipitation hovered over those two river basins. In the Han river basin where the $D. A. = 874 \, \text{km}^2$ and which has been subject to engineering and afforestation measures for six years, the flood peak flow is $3100 \, \text{m}^3 \, \text{s}^{-1}$; in the nearby Bu river basin the $D. A. = 545.9$ and which has never been subject to any remedial or alleviation measures, the peak flow is $4300 \, \text{m}^3 \, \text{s}^{-1}$. The area of the former river basin is 1.6 times that of the latter but its flood peak flow is only 72% of the latter.

8.2.4 Adequate preparedness for flood disaster management

Make close connections between the flash flood disaster sub-division and local land exploitation and economic development administrations. Although the unexpected flood is an event of stochastic frequency, the distribution of flash floods is an objectively existing reality. Based on current research on flash flood occurrence, we can assess the characteristics and likely degree of damage for a certain area. This knowledge can not only act as the basis for reducing and avoiding damage but may also provide the scientific proof for economic development plans. The department responsible for the work should have different plans, different ways of using land, and carry out different policies for avoiding and dealing with disaster, according to the different risks inherent in different regions, as discussed earlier in Section 8.1.5.

8.2.5 Setting up flood disaster evaluation and policy-making

Before a flood occurs (based on reports of meteorological and hydrological phenomena), its scale and temporal characteristics should be evaluated. After the flood has occurred, the severity of the event and the possibility of other consequent disasters it may have brought about (such as epidemic disease, plague) should also be evaluated and appropriate action.

Establish an expert policy-making system based on disaster evaluation to serve as the scientific policy to reduce and avoid disasters.

8.2.6 Flood insurance

In essence, flood insurance is a way to change the burden of losses. By making society assume the role of underwriter, it not only lessens the burden on government but also ensures that people receive compensation in time to rebuild their homes. This is beneficial both for economy recovery and social stability. Therefore, insurance is an effective way to make good economic loss brought about by flood and it plays an important role in preventing disasters.
8.2.7 Rapid action for disaster alleviation

Government departments should make preparations before an emergency because rescue is a necessary part of fighting against flood. Means for dealing with floods includes rescue for projects and for people life and property. Rescue work includes: rescue teams, equipment, transportation, communication, illumination, etc. Life saving activities must include equipment to save lives, doctors and nurses, medicine, gifts, clothes and other back-up services.

The preventative measures outlined above are mainly concerned with the flash flood brought about by storm but they are also relevant in the situation of a flood brought about by dam burst or dyke breach; some different measures may be needed with glacier lake outburst flood and ice-dam burst floods. For example, in order to reduce the peak discharge and the storage volume of a glacier lake, it may be necessary to blast, dig (by manual or mechanical means) or aerial dropping of explosives, etc. to destroy ice blocks, to pump from the lake, use all kinds of prevention measures to get rid of any of the factors which may lead to the glacier lake collapse, including some hidden dangers such as unstable ice or rock, unstable moraine area.

There are many ways to prevent flash floods but no matter how well any one method works, its effect is always limited; it has both advantages and disadvantages, and no one method any of the others. The best way is to plan unilaterally and make reasonable arrangements according to local conditions, perhaps by combined methods, so as to prevent flash floods more effectively.

8.3 Case studies

The people who live in the arid and semi-arid areas of China have summarized a set of effective methods to prevent flash flood during their long struggle with floods. Let us take the Shan-xi province of China as an example to illustrate their prevention measures. These can be mainly divided into two parts: one is engineering measures, including farm engineering which is aimed at slope management, such as bank up borders, bench terraces, cut-off ditches, check dams, elutriation, etc. while at the same time implementing appropriate afforestation and stocking density.

Management techniques which are aimed at ditch improvement vary for different river reaches. For example, engineering management of upstream sections aim at preventing gully head expansion, so the work of gully head protection is located at primarily upstream, including the building of terraces, falls, cofferdams, check dams, etc. Engineering management of the midstream (front of slope section) may use swamps or wetlands to detain the flood, or build drainage channels or build dykes to retain the flood because, after the ditch outlet, the topography becomes gradually flatter and the most dangerous thing is to create a freshet. Engineering management of the downstream section (mouth of river section) where agriculture and economic activities are very prosperous, puts emphasis on promoting advantages and avoiding disadvantages, and management techniques are mainly composed of pilot floods to irrigate and reduce pollution.

The other kind of precaution are the non-engineering activities which include legislation, under the guidance of the contemporary "Water Law" and a unified leadership, to draft specific rules to obey. Adopting effective measures to promote the disaster prevention ability of society and awareness of disaster prevention, strengthens government’s function in disaster prevention. It is important to have a prevention plan beforehand. For example, in 1982, Xin-Shui county organized 24 units, 392 households and 3,500 people to be evacuated immediately after they received the flash flood forecast; in this way, they greatly reduced the loss. Since floods last only momentarily, reinforce the work of forecasting and warning as, for example, in the city of Yan-Quan where people are called upon to forecast flood by watching ditches — a very simple and effective technique.
Bibliography


RICHARDS, M.M. and CLARK, R.A. Systems for preparing timely flash flood warnings.
ASHAD M SHERIK. 'Flash flood management in PAKISTAN', Pakistan Council of Research in Water Resources, Islamabad.

