Flood Handbook

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Principles and Applications

Edited by

Saeid Eslamian

Faezeh Eslamian

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Dedication

To Professor David Herbert Pilgrim (1931–2015) from UNSW, Australia, my late PhD Supervisor having more than 300 technical papers on Flood Estimation

Contents

PART III Past Floods

PART IV Flood Measurement and Estimation

PART V Flood Control and Uses

PART VI Flooding and Quality Aspects

Editors

Saeid Eslamian is a full professor of environmental hydrology and water resources engineering in the Department of Water Engineering at Isfahan University of Technology, Iran, where he has been since 1995. His research focuses mainly on statistical hydrology in a changing climate. In recent years, he has worked on modeling natural hazards, including floods, severe storms, wind, drought, pollution, water reuses, sustainable development and resiliency, etc. Formerly, he was a visiting professor at Princeton University, New Jersey, and the University of ETH Zurich, Switzerland. On the research side, he started a research partnership in 2014 with McGill University, Canada. He has contributed to more than 1k publications in journals, books, book chapters, conferences, and also as technical reports. He is the founder and chief editor of the *International Journal of Hydrology Science and Technology* (*IJHST*). Eslamian is now associate editor of six important publications: *Journal of Hydrology* (Elsevier), *Ecohydrology and Hydrobiology* (Elsevier), *Water Reuse* (IWA), *Arabian Journal of Geosciences* (Springer), *International Journal of Climate Change Strategies and Management* (Emerald) and *Journal of the Saudi Society of Agricultural Sciences* (Elsevier). Professor Eslamian is the author of approximately 65 books and 300 book chapters.

Professor Eslamian's professional experience includes membership on editorial boards, and he is a reviewer of more than 100 Web of Science (ISI) journals, including the ASCE *Journal of Hydrologic Engineering*, ASCE *Journal of Water Resources Planning and Management*, ASCE *Journal of Irrigation and Drainage Engineering*, *Advances in Water Resources*, *Groundwater*, *Hydrological Processes*, *Hydrological Sciences Journal*, *Global Planetary Changes*, *Water Resources Management*, *Water Science and Technology*, *Eco-Hydrology*, *Journal of American Water Resources Association*, *American Water Works Association Journal*, etc. UNESCO has also nominated him for a special issue of the *Ecohydrology and Hydrobiology Journal* in 2015.

Professor Eslamian was selected as an outstanding reviewer for the *Journal of Hydrologic Engineering* in 2009 and received the EWRI/ASCE Visiting International Fellowship in Rhode Island (2010). He was also awarded outstanding prizes from the Iranian Hydraulics Association in 2005 and the Iranian Petroleum and Oil Industry in 2011. Professor Eslamian has been chosen as a distinguished researcher of Isfahan University of Technology (IUT) and Isfahan Province in 2012 and 2014, respectively. In 2016, he was a candidate for national distinguished researcher in Iran.

He has also been the referee of many international organizations and universities. Some examples include the US Civilian Research and Development Foundation (USCRDF), the Swiss Network for International Studies, the Majesty Research Trust Fund of Sultan Qaboos University of Oman, the Royal Jordanian Geography Center College, and the Research Department of Swinburne University of Technology of Australia. He is also a member of the following associations: American Society of Civil Engineers (ASCE), International Association of Hydrologic Science (IAHS), World Conservation Union (IUCN), GC Network for Drylands Research and Development (NDRD), International Association for Urban Climate (IAUC), International Society for Agricultural Meteorology (ISAM), Association of Water and Environment Modeling (AWEM), International Hydrological Association (STAHS), and UK Drought National Center (UKDNC).

Professor Eslamian finished Hakimsanaei High School in Isfahan in 1979. He was then admitted to IUT for a BS in water engineering and graduated in 1986. After graduation, he was offered a scholarship for a master's degree program at Tarbiat Modares University, Tehran. He finished his studies in hydrology and water resources engineering in 1989. In 1991, he was awarded a scholarship for a Ph.D. in civil engineering at the University of New South Wales, Australia. His supervisor was Professor David H. Pilgrim, who encouraged him to work on "Regional Flood Frequency

Analysis Using a New Region of Influence Approach." He earned a Ph.D. in 1995 and returned to his home country and IUT. In 2001, he was promoted to associate professor and in 2014 to full professor. For the past 26 years, he has been nominated for different positions at IUT, including university president consultant, faculty deputy of education, and head of department. Eslamian is now director for the center of excellence in Risk Management and Natural Hazards (RiMaNaH).

Professor Eslamian has made three scientific visits to the United States, Switzerland, and Canada in 2006, 2008, and 2015, respectively. In the first, he was offered the position of visiting professor by Princeton University and worked jointly with Professor Eric F. Wood at the School of Engineering and Applied Sciences for one year. The outcome was a contribution in hydrological and agricultural drought interaction knowledge by developing multivariate L-moments between soil moisture and low flows for northeastern US streams.

Recently, Professor Eslamian has published the 11 handbooks by Taylor & Francis (CRC Press): the three-volume *Handbook of Engineering Hydrology* in 2014, *Urban Water Reuse Handbook* in 2016, *Underground Aqueducts Handbook* (2017), the three-volume *Handbook of Drought and Water Scarcity* (2017), *Constructed Wetlands: Hydraulic Design* (2019), *Handbook of Irrigation System Selection for Semi-Arid Regions* (2020), and *Urban and Industrial Water Conservation Methods* (2020).

An Evaluation of Groundwater Storage Potentials in a Semiarid Climate and *Advances in Hydrogeochemistry Research* by Nova Science Publishers are also his book publications in 2019 in 2020 respectively. The two-volume *Handbook of Water Harvesting and Conservation* (Wiley) and *Handbook of Disaster Risk Reduction and Resilience* (New Frameworks for Building Resilience to Disasters) are early 2021 book publications of his.

He was recently appointed as a World Top 2% Researcher by Stanford University, USA, in 2019 and 2020.

Faezeh Eslamian holds a Ph.D. in Bioresource Engineering from McGill University, Canada. Her research focuses on the development of a novel lime-based product to mitigate phosphorus loss from agricultural fields. Faezeh completed her bachelor's and master's degrees in civil and environmental engineering from Isfahan University of Technology, Iran, where she evaluated natural and low-cost absorbents for the removal of pollutants such as textile dyes and heavy metals. Furthermore, she has conducted research on worldwide water quality standards and wastewater reuse guidelines. Faezeh is an experienced multidisciplinary researcher with an interest in soil and water quality, environmental remediation, water reuse, and drought management.

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Part I

An Introduction to Flooding

1 Flash Flood

Definitions, Characteristics, Sources, and Analysis

D. R. Archer and H. J. Fowler

CONTENTS

1.1 INTRODUCTION

Floods as well as flash floods can occur in rivers as the result of storm rainfall over the catchment, but may also include those resulting from the failure of constructed or landslide-blockage dams and levee failures, or from the release of water impounded by ice jams or glacial lake outbursts. Flooding or flash flooding is also caused directly by surface water from intense rainfall before the water reaches a river. The aim of this chapter is to demonstrate that flash floods from various origins have the common feature of abrupt onset with a rapid rise in water level, sufficient to pose a threat to life. In this respect, they differ from what may be described as a “normal” flood in which an extreme level may be achieved but the risks associated with rates of rise are not so great. The chapter excludes coastal flooding arising from extreme tidal surges, waves, or tsunamis. In addition, meteorological origins including forecasting are not considered in detail whilst methods and procedures for flood warning for example through hydrological and hydraulic modeling are also excluded.

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1.1.1 Definitions

The term "flash flood" originated in the late 1930s but the description has had varied definitions by newspapers, dictionaries, and hydrologists. Dictionary definitions and implied definitions in the press are vague and hardly enable the reader to distinguish between a flash flood and a "normal" flood. Hence, *Webster's New College Dictionary* (2010) noted that a flash flood is simply "a sudden, violent flood, as after a heavy rain" whilst *Collins' English Dictionary* (2014) suggested "a sudden short-lived torrent, usually caused by a heavy storm, especially in desert regions." Both definitions use the word "sudden" but do not specify timing.

Descriptions in the hydrological literature are hardly more helpful. Kobiyama and Goerl (2007) listed 16 definitions, mainly from international and American agencies. Seven of these noted that the lag time between the causative rainfall and the occurrence of the flood is a defining feature of flash floods. The lag is said to be "short" or in some cases limited to a specified time, typically six hours (WMO, 1994; National Disaster Education Coalition, 2004), whilst Georgakakos (1986) adopted 12 hours as the upper bound. Seven definitions also note the occurrence of a rapid rise in water level but none actually specify a limiting rate of rise between a normal flood and a flash flood; one definition notes the possible occurrence of a "wall of water" (FEMA, 1981). Several indicated that flash floods occur over a small area (e.g., Kelsch, 2001) or that they occur in steep slope regions (Castro, 1996). Kelsch (2001) analyzed 22 flash floods in the USA with an average catchment area of 46 km^2.

In southern Europe studies of individual flash floods have mainly been defined by extreme rainfall totals and peak discharges (e.g., Huet et al., 2003; Lefrou et al., 2000). Gaume et al. (2009) compiled an inventory of 550 extreme flash floods in seven countries in Europe. Events were defined in terms of peak discharge, with rainfall duration less than 24 hours and on catchments generally less than 500 km^2. However, their selected floods were not characterized by speed of onset, so it is not clear how the selected events differed categorically from large "normal" floods. However, Douvinet and Delahaye (2010) described flash floods ("*crues rapides*") on the plateaus of north-western France, with many of the 269 compiled events occurring in dry valleys and they specifically referred to the speed of onset and to the intensity of short-period rainfall (< 1 hour).

The speed of onset or the rapid rate of rise in level in flash floods seems more hazardous than peak level with respect to personal safety or the cause of death. Few et al. (2004) noted that worldwide, "The speed of onset of floodwaters is a key factor determining the number of immediate flood-related deaths; few deaths from drowning occur during slow rising floods." However, the most devastating floods are those which combine a rapid rate of rise with an extreme peak magnitude. An American example is the flash flood in Oregon in 1903 which created a 5–15 m wall of water in Willow Creek and drowned 247 inhabitants of the village of Heppner, nearly a quarter of the population, destroying a third of its homes (Byrd, 2009). In Britain the worst post-war flooding disaster with respect to fatalities took place at Lynmouth in August 1952 when 225 mm of rain fell in 24 hours and a "wall of water" surged into the town; the tragedy claimed 34 lives (Dobbie and Wolf, 1953). In the United States, 80% of all flood-related deaths are attributable to flash floods, however defined (NWS, 2014). Barredo (2007) noted that 40% of the flood-related casualties in Europe from 1950–2006 were due to flash floods. Unsuspecting victims are often engaged in activities such as fishing or bathing in a river, at a sufficient distance from the source to be unaware of the hazard. A recent example is where a flood wave six feet high and 40 feet wide caused the death of nine swimmers in Ellison Creek near Payson, Arizona in July 2017 (Croft, 2017).

The floods outlined above occurred in rivers and had a meteorological origin. Intense rainfall also causes direct flooding as surface water (or pluvial flooding), principally in urban areas, before the water reaches a river. In addition, flash floods in rivers have a range of different causes, notably from the failure of natural barriers including landslide dam breaks, glacial lake outburst floods (GLOFS or jökulhlaups), and the release of water from ice jams as well as the failure of constructed barriers such as dams and embankments. Each of these types or sources of flash floods is exemplified, described, and analyzed in this chapter to illustrate the range of hydrological behavior and catchments typically affected. Examples cited here provide methods of analysis that may have wider application. In conclusion, a further flash flood definition is attempted which covers the full range of flash flood characteristics and sources.

1.2 METEOROLOGICAL FLOODS – RIVERS

1.2.1 Ethiopia – Arid Zone Flash Flood

The first example is given from the oldest description of a flash flood and is included as it illustrates several features common to flash floods. The explorer James Bruce (the first European to discover and explore the source of the Blue Nile) encountered the flood as he and his guides traveled along the bed of a ravine or wadi in his trek from the arid Red Sea coast to the Ethiopian Plateau in 1768 (Bruce, 1790; Hibbert, 1984).

> Late in the afternoon it began to threaten rain; there were long peals of thunder, and the lightning was very frequent. Suddenly Bruce heard a roar on the mountains above, "louder than the loudest thunder." The guides flew to the baggage and removed it to the highest ground as the river gushed down upon them "in a stream about the height of a man and the breadth of the whole bed it used to occupy."

As in many other flash flood occurrences, the source was an intense convective storm in the headwaters although there was no rain at the point of impact. It was the roar of the approaching wavefront with the entrained sediment load that alerted them to the danger. The guides clearly had previous experience of flash floods to respond effectively to the danger from the approaching wall of water.

1.2.2 River Tyne, England – Upland River Flash Flood

The following account is for the River Tyne, chosen for the availability of long records of river flow at several locations and associated rainfall data and also for descriptions of characteristics of observed flash floods that have rarely been reported. The River Tyne (Figure 1.1) rises on the Pennine plateau in England, with the highest point at 893 m OD; it has a catchment area of ~2,300 km^2 to the tidal limit. It is a perennial river with a mean annual flow at the lowest gauging station, Bywell, of ~45 m^3s^{-1} and a maximum peak discharge of 1,740 m^3s^{-1}, the greatest of any river in England (Archer, 1992). Annual maximum floods most commonly result from persistent rain in winter; flash floods also occur in summer with different characteristics. There are two principal tributaries, the North and South Tyne, but flash floods generally originate in the South Tyne.

Localized extreme rainfall occurred in the upper reaches of the South Tyne on July 30, 2002 (Archer and Fowler, 2018). The one recording rain gauge adjacent to the catchment recorded a total storm rainfall of 79.6 mm over a 10.5-hour period but it was the 26.2 mm in the first 15 mins of the storm at 11:30 which generated flash flood conditions at the Alston gauging station. Downstream the flood wave had exceptional rates of rise which persisted to the tidal limit, a distance of more than 80 km (Figure 1.2). The rate of rise in level (meters) and flow (m^3s^{-1}) for the shortest measurement interval (15 minutes) was extracted for four gauging stations on the South Tyne and Tyne (Table 1.1). The peak flow at Alston (118 km^2) was the Rank 1 flood in a 30-year record. Whilst the magnitude of the peak flow remained about the same down to the lowest gauging station at Bywell (2,175 km^2), the flood peak rarity diminished downstream and at no point reached even the median annual maximum (QMED). At Bywell the peak flow was only 0.42 of QMED.

In contrast, the steep wavefront was maintained to the Tyne estuary with notable 15-min increases in level of 1.22 meters at Featherstone and 1.33 meters at Bywell – the highest observed in the record. Fifteen-minute discharge increases of over 150 m^3s^{-1} were observed at Featherstone, Haydon Bridge, and Bywell (Table 1.1).

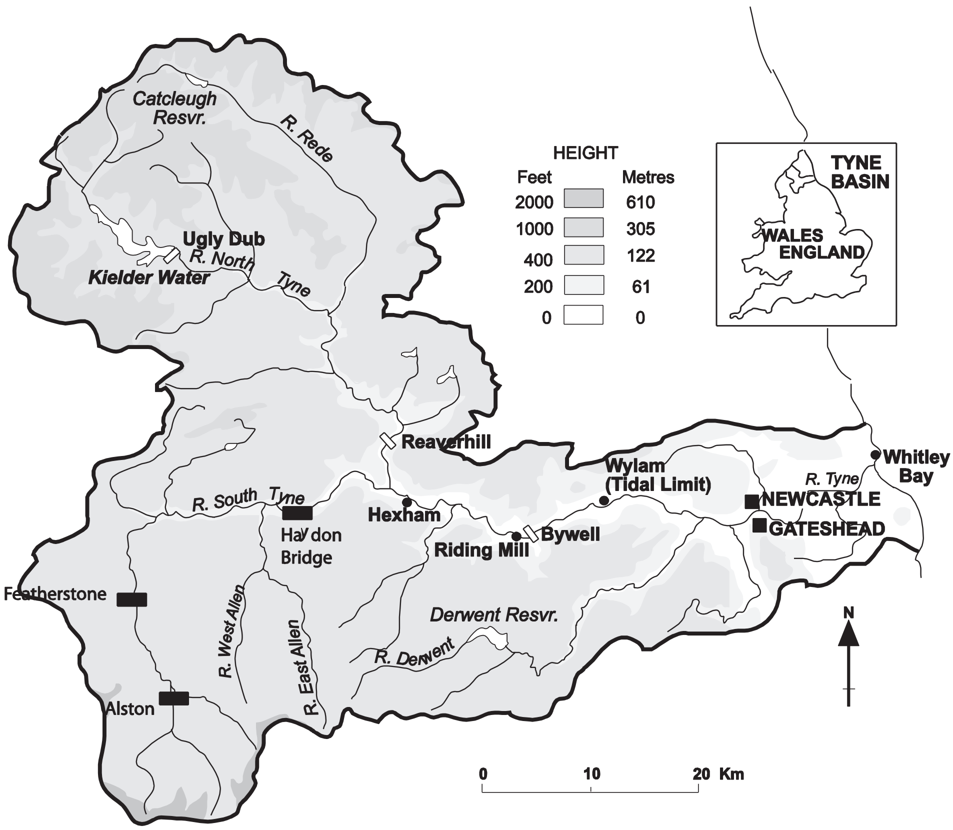

FIGURE 1.1 The River Tyne catchment showing gauging stations used in this analysis.

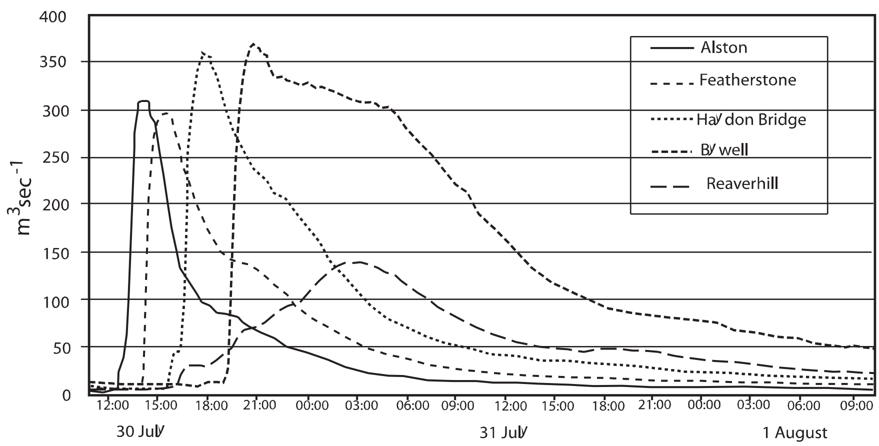

FIGURE 1.2 Progress of the flood wave down the South Tyne and main Tyne at Alston, Featherstone, Haydon Bridge, Bywell, and Reaverhill (North Tyne).

Although there were no fatalities in this event, such a rapid rate of rise poses a significant threat to life. The Tyne is noted as the best salmon fishing river in England and fishermen often stand knee-deep in the river. A rise of over 150 m^3s^{-1} in 15 minutes implies a rise of at least 10 m^3s^{-1} or 0.10 m in level in one minute. In such conditions, a fisherman would have little time to escape from the water to avoid being swept away. A fisherman on the South Tyne interviewed by the first author related how he stood on a gravel shoal near the bank casting his line when a colleague from the bank

TABLE 1.1

Maximum Rates of Rise in Flow and Level for 15-, 30-, and 60-Min Periods and Peak Flow for Four Stations on the Rivers South Tyne and Tyne

Station Catchment Area	Initial Flow Before Maximum 15-Min Rise m^3/s	15-Minute Maximum Rise in Q and H m^3/s and m	Start Time of Maximum Rise	Peak Flow m^3/s	Time of Peak Flow
Alston 118.0 km^2	63.7	116.9 0.748	13.00	310.7	14.00
Featherstone 321.9 km^2	2.3	165.7 1.333	14.00	293.5	15.15
Haydon Br 751.1 km^2	110.5	154.4 0.900	16.30	358.6	17.45
Bywell 2,175.6 km^2	22.9	169.9 1.220	19.15	367.0	20.45

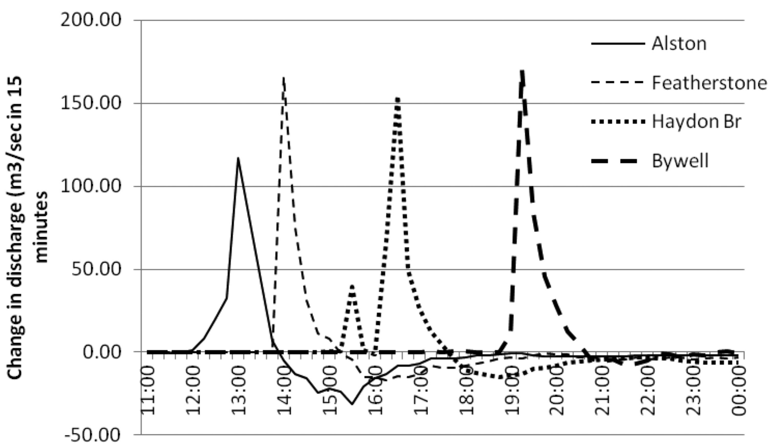

FIGURE 1.3 Change in discharge between successive 15-minute observations (rate of rise) (m^3/s) for flood events on the South Tyne and Tyne on July 30, 2002.

shouted a warning. The fisherman turned around and saw the approaching flood wave but before he could reach the bank he was engulfed and carried away. Initially, air in his waders provided buoyancy but soon became an impediment. Fortunately, he was carried close to the bank and made his escape; he could easily have lost his life.

The evidence from this example indicates that a wavefront can steepen as it moves downstream and this can persist over a long distance, some 80 km from Alston to the estuary. This behavior is in contrast to the normal storage attenuation of flood waves in natural channels. At the scale of Figure 1.2, the steepening is hardly evident but is clearly visible when the change in discharge between successive 15-min observations is plotted against time between Alston and Featherstone and between Haydon Bridge and Bywell (Figure 1.3). It is also notable that the lag time between rainfall and the ensuing flood wave at Bywell is greater than the six-hour limit normally attributed to flash floods.

1.2.3 River Wansbeck, England – Lowland River Flash Flood and the Value of Historical Data

Unlike the River Tyne, the River Wansbeck is a lowland agricultural catchment with a highest elevation of 440 m OD and a channel slope of less than 4 m/km; it is atypical of rivers on which flash floods normally occur. It has a mean flow of 3.3 m^3s^{-1} and a maximum recorded peak flow of 334.6 m^3s^{-1}. A very dry summer from May to July 1994 was followed on the Wansbeck catchment in northeast England by an exceptional thunderstorm with daily rainfall of > 70 mm at nine stations. However, a 15-min total of 30 mm at 15:15 recorded in mid-catchment was even more exceptional (Archer, 1994).

At the Mitford gauging station (catchment area 287.3 km^2), the 15-minute rise was 1.26 m, with an equivalent increase in discharge from 0.6 m^3s^{-1} to 44.5 m^3s^{-1} at 20:45. With a further half-hour travel time to the town of Morpeth on the Wansbeck, the flood wave arrived at dusk with riverside activity (including crossing stepping stones) at a low level; there were no reported incidents. Had it arrived a few hours earlier, the rapid onset of flooding had the potential to provide a serious risk of drowning. A plot of the annual maximum 15-min and hourly rates of rise for the Wansbeck at Mitford show that the 1994 event is an outlier in the series and more than double the previously experienced rate of rise in a 34-year period (Figure 1.4).

The allocation of a probability or a return period to such an unprecedented event within the gauged series is problematic given the uncertainty in the form of the tail of the rate of rise distribution. Assuming a generalized logistic distribution, the return period of the 1994 15-minute rate of rise is assessed as 140 years. However, if the 1994 event is excluded from the analysis the return period is several thousand years. In this case, historical information can provide useful further guidance. A search of newspaper and other records indicates the occurrence of two other flash flood events, probably of greater magnitude than that of 1994. On July 5, 1881, amongst other details it was reported that "the Wansbeck came down in a rolling flood, the wave being 3 or 4 feet deep." It carried a young boy away. An even more severe storm occurred on September 7, 1898, when 170 mm fell in three hours. Eighteen footbridges were washed away and roads were excavated in gullies to a depth of four to five feet (British Rainfall, 1898). The Wansbeck at Morpeth rose without warning. "It came with a strong head and increased volume so rapidly that it was in a few minutes rolling over the weirheads." With the addition of these two historical occurrences of greater magnitude, the apparently unprecedented event in 1994 becomes the Rank 3 event in approximately

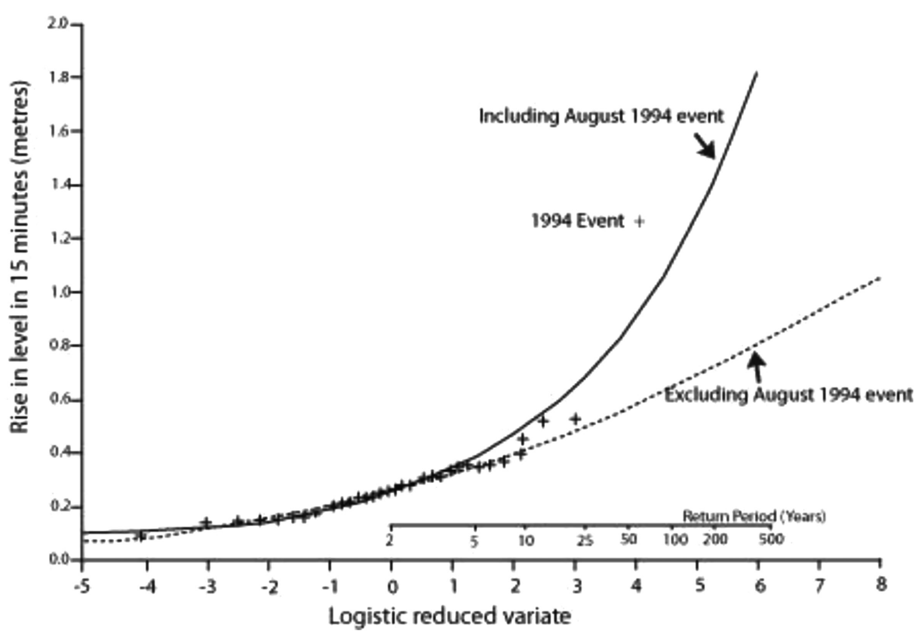

FIGURE 1.4 Frequency distribution of 15-min annual maximum rise in level 1979 to 2012 at Mitford including and excluding the August 1994 event.

160 years (the starting year of publication of the local newspaper) and a return period of ~62 years is suggested by the Gringorten plotting position formula.

It is concluded that flash floods can occur even on rivers of low to moderate slopes if the causative rainfall is sufficiently intense.

Historical records are being increasingly used to improve flood risk estimates of peak river discharges, given that most gauged records do not exceed 60 years (Hall et al., 2015). A compilation focused on peak flood levels has been made in the Chronology of British Hydrological Events based primarily on historical newspaper accounts (Black and Law, 2004). In Britain regional historical chronologies of flash floods from 1700 have also recently been compiled for northern and southwest England (Archer et al., 2019) and more recently for the whole of Britain (Archer and Fowler, 2021). This chronology includes surface water flooding in addition to those river events with rapid onset or marked rates of rise, including those described as "walls of water," descriptions of associated meteorological hazards of lightning and hail, and their morphological impacts. The chronology can be used to assess both catchment/location susceptibility to flash flooding, including historical occurrences where no recent events have been reported. As for the case of the River Wansbeck, recent floods can then be placed into the context of the pre-instrumental record. A comprehensive archive of flash flood events is required to advance analyses of flood climatology, hazard, and vulnerability (Borga et al., 2011).

1.2.4 River Rye, England – Transformation of Lag in Flash Floods

Response times of flash floods appear considerably reduced from those of "normal" floods. For the Wansbeck flood example, the lag from rainfall to peak runoff at Mitford was only 5.5 hours compared to average lag times of more than 9 hours. In the river Tyne example, wavefront velocities of 4.8 m/s were observed in the upper South Tyne and 3.4 m/s in the reach above the estuary.

Analysis for the River Rye in North Yorkshire in England provides a more detailed example. The River Rye drains the plateau moorlands of the Cleveland Hills in North Yorkshire and has a catchment area of 132 km^2. A catastrophic flood in June 2005 was extreme both in its peak discharge (400 m^{3}s^{-1} – 11 times QMED the median annual flood) and in its rate of rise in level (an increase in water level of 1.43 m over 15 minutes). The lag time was only one-third of the average for other floods (Figure 1.5) (Wass et al., 2008).

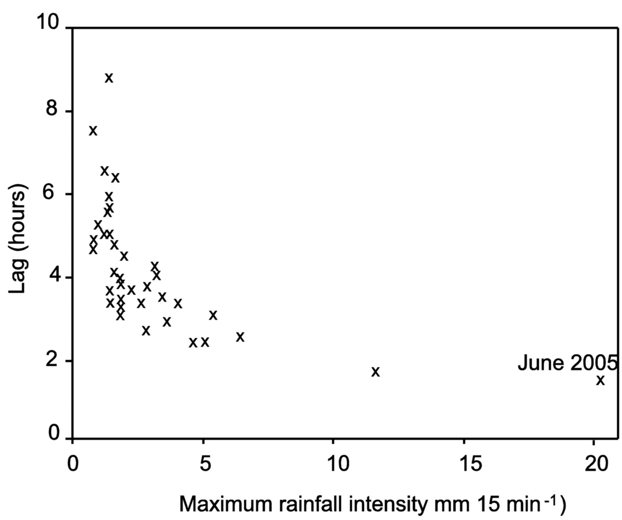

FIGURE 1.5 Lag time plotted against maximum rainfall intensity for the River Rye at Broadway Foot. (Source: after Wass et al., 2008.)

This observed reduction in lag in flash floods is critical for the reliability of flood forecasting and rainfall-runoff methods of flood risk estimation using the unit hydrograph procedure which assumes invariant lag. For example, the Flood Estimation Handbook (FEH) method widely used in Britain applies a fixed time-to-peak parameter (proportional to lag) which controls the speed of response (IH, 1999). In the case of the Rye, using the average lag based on "normal" floods was found to seriously underestimate the peak flow in the 2005 event (Wass et al., 2008). In a similar flash flood at Boscastle in southwest England in 2004, HR Wallingford (2005) had to reduce the time to peak of the unit hydrograph by a half and still underestimated the peak flow calculated from hydraulic considerations. Previous attempts to identify sources of variation in lag have focused on the relationship between lag and flood peak magnitude but found no statistical evidence for a shortening of response time (Kjeldsen et al., 2005). Wass et al. (2008) proposed a land phase mechanism for reduced response time where overland flow is concentrated into gullies, extending the channel network to make delivery to the river more efficient. However, Archer and Fowler (2018) suggested that channel travel time is also reduced where such translatory waves occur. Reduced lag in flash floods remains a serious operational and accuracy issue for flood forecasting and flood risk estimation for design.

1.3 METEOROLOGICAL FLOODS – SURFACE WATER

Flash floods that are known as surface water or pluvial floods also result from intense rainfall before the water reaches a watercourse. Such floods can affect locations far from rivers in both rural and urban locations but it is in cities and towns that such floods have the greatest economic consequences.

Surface water flooding in rural areas causes the stripping of topsoil by sheet erosion in agricultural land and, even where covered by dense vegetation, can initiate the formation of gullies, debris flows, peat slides, and other types of mass movement. Figure 1.6 demonstrates the impact of intense rainfall on an upland peat landscape in the Wear valley in northern England in July 1983 where the highest rainfall of 104.8 mm in 2.5 hours was recorded at Ireshopeburn Farm but much greater totals were assumed on the neighboring hill where five peat slides occurred. Complete saturation of the peat caused its separation from the underlying substrate, with evacuation from crescentic areas and then sliding for several hundred meters with shear zones on each side throwing up spindles and blocks of peat, and hence into the nearest watercourse. Given the remote location, economic costs were limited.

However, in urban areas, severe costs are incurred by surface water flooding when runoff from intense rainfall exceeds the capacity of urban drainage systems. Given the short time interval between rainfall occurrence and the flood effect, many such floods are inevitably flash floods. Floods over the summer of 2007 in England had total estimated costs of £3.2 billion and the Pitt

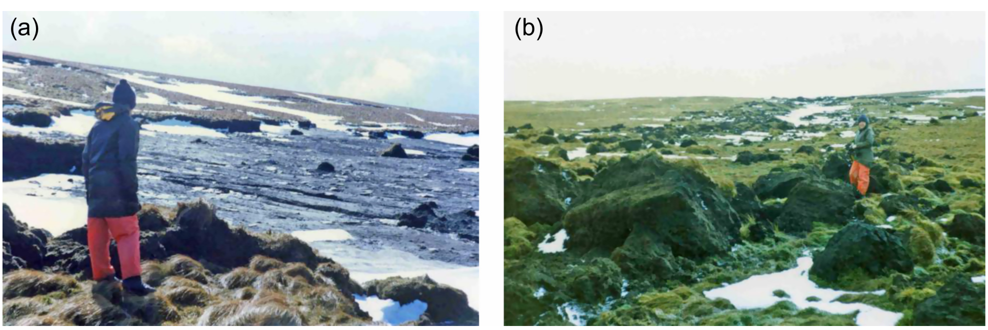

FIGURE 1.6 a) Evacuation zone of a peat slide in upper Weardale, photographed the following winter. b) The track of the peat slide.

Review (Cabinet Office 2008), which analyzed the nature and consequences of floods in the English Midlands, noted that some two-thirds of affected properties were flooded from surface water only. Flash flooding in urban areas provides additional hazards given the large numbers of people who are affected either as pedestrians or as occupants of cars. Smooth surfaces of urban roadways generate high velocities so that adults can be swept off their feet in depths of only 0.2 m and most cars set afloat at ~0.3 m. Many flood deaths are therefore caused by drivers attempting to ford flooded roads and underpasses.

Traditionally the removal of surface water runoff has been achieved by using gullies and underground pipe systems and most towns and cities are still dependent on such drainage networks. Urban drainage systems are designed to cope with floods resulting from a given intensity of rainfall expressed as a probability or return period for a given storm duration. Inevitably, extreme rainfall occasionally exceeds the capacities of sewers when the rate of surface water runoff exceeds the inlet capacity of the drainage system, when the receiving water or pipe system becomes overloaded, or when the outfall becomes restricted due to flood levels in the receiving water. In addition, in many historic cities, natural channels were bridged then culverted and filled in or built over but still form depressions in the urban landscape. However, with intense rainstorms, ancient river channels may be reactivated, and overflow and ponding occur where culvert capacities are exceeded. Archer et al. (2017) detailed such a surface water flood in Newcastle upon Tyne in 2012 following an intense thunderstorm; around 500 properties suffered internal flooding, many roads were damaged, and traffic was gridlocked for a number of hours.

Given the economic and human impacts of such events, intense efforts are being made to find general and detailed solutions. Many models have been developed to reproduce the flooding patterns in observed storms using combined information on the sub-surface drainage network and the configuration of the urban landscape. One such model is CityCAT (City Catchment Analysis Tool), developed at Newcastle University, which allows assessment of the effects of different flood alleviation measures (Glenis et al., 2013)The computational grid uses cell sizes to as little as 0.5 m to enable accurate positioning of buildings and intervening gaps where flow can concentrate. Simulation of free surface flow is based on the full 2D shallow water equations. The solution is obtained using high-resolution finite volume methods with shock-capturing schemes; these are able to accurately capture the propagation of flood waves. The model provides two types of visual outputs: time series of water depths and flow velocities at selected locations and snapshot maps of water depths and velocities at different times during the simulation. Using such models it is possible to identify bottlenecks in the network and to target effective solutions.

1.4 FAILURE OF NATURAL DAMS AND RIVER BLOCKAGES

1.4.1 Landslide Dam Breaks

Although, as noted above, intense rainfall can generate landslides falling into rivers in temperate regions, it is in the mountains of the world that mass movements can themselves cause havoc or subsequent floods when dams blocking rivers fail. The Himalaya-Karakoram-Hindu Kush (HKH) ranges are particularly vulnerable as they are the areas of highest relief in the world (Figure 1.7). Valley side slopes sometimes rise several thousand meters above the valley floor. Besides earthquake vulnerability, many physical and chemical processes are at work to create instability on slopes and to initiate movement, at catastrophic rates in landslides and avalanches.

Historically devastating floods have occurred in the Indus basin. In late 1840 the main stem of the River Indus was blocked by an earthquake-initiated landslide at the foot of Nanga Parbat for a period of some seven months and formed a lake stretching 55 km upstream. The estimated height of the dam was 209 m (Hewitt, 1983). The dam broke in June 1841 and drained in 24 hours; it swept away complete villages and towns and a force of 500 Sikh soldiers encamped by the river instantly perished (Becher, 1859). "The waters were seen by those who were there encamped to be coming

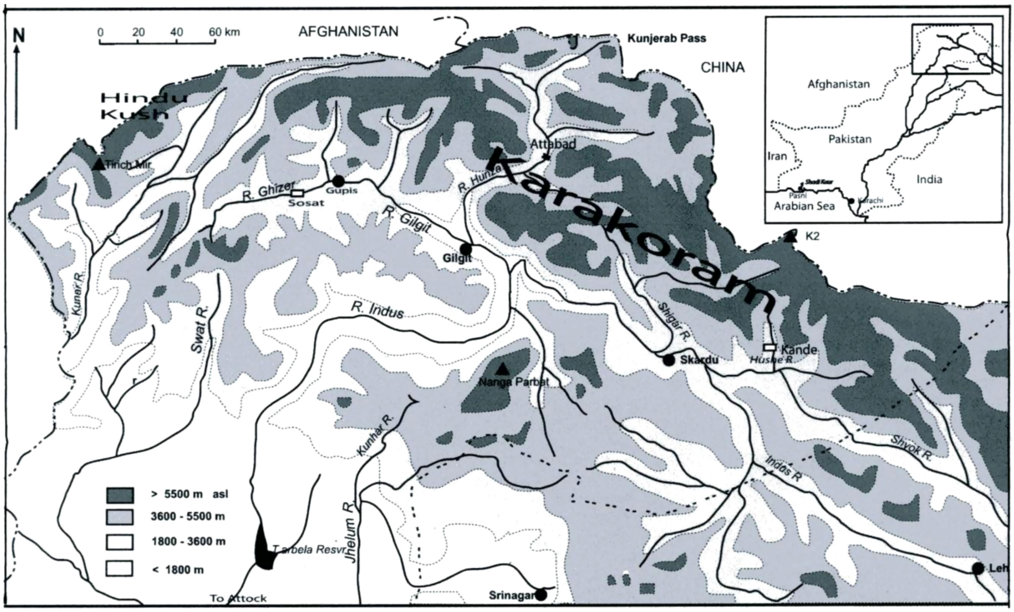

FIGURE 1.7 Northern Pakistan, showing the sites of landslide dam breaks and GLOFs mentioned in the text (inset: Pakistan, showing the location of Shadi Kaur dam break).

upon them, down the various channels and to be swelling out of these to overspread the plain in a dark muddy mass which swept everything before it" (Fairley, 1979). At Attock where the river discharges on to the plains, the river rose 25 m with an estimated discharge of over 50,000 m^3s^{-1} (Hewitt, 1968), where the mean annual maximum flow is ~15,000 m^3s^{-1}.

Not all such landslides break abruptly and cause floods; some are gradually eroded over a period of months or years and some remain with upstream lakes as permanent features of the landscape. In January 2010 a major landslide occurred on the Hunza River bringing with it the village of Attabad in which 20 people were killed. The blockage reached over 100 m in height and created a lake 21 km in length. During the following five months as the level gradually rose, downstream villages waited with bated breath to see whether the dam would fail when overtopped in June. Fortunately, it did not fail then or in subsequent years and has now been stabilized. The lake displaced 6,000 people from upstream villages and inundated over 12 miles (19 km) of the Karakoram Highway the only direct road link between Pakistan and China.

Landslide-generated floods on a smaller scale are not uncommon in the HKH as in other high mountains such as the Andes and Rockies. Dams caused by landslides are unconsolidated and unstable and may fail rapidly through overtopping or from piping failures. Even a blockage lasting 24 hours and its sudden release within one hour can generate a downstream flood more than an order of magnitude greater than the pre-landslide flow, with resulting devastating effects. In addition, such floods carry a very high sediment load from material picked up from the breached dam or the downstream channel through the increased capacity of the larger flow to transport sediment. Such a flood occurred at Gupis on the Gilgit River (northern Pakistan) in 1980 when the river was blocked for 36 hours (Hughes and Nash, 1986).

1.5 GLACIAL LAKE OUTBURST FLOODS (GLOFS)

Flash floods are also generated by the outburst of glacial lakes (GLOFs). The term jökulhlaup originally referred to subglacial outburst floods in Iceland, which are triggered by geothermal heating and occasionally by a volcanic subglacial eruption, but the term is now used synonymously with GLOFs. Bodies of water adjacent to glaciers are common in most glaciated regions and can range in size from small ice-marginal pools to lakes containing 10^9 m^3 of water. Such lakes may be held back or contained by lateral or end moraines which may be ice-cored and thus subject to subsidence on melting. They may be impounded by glacial ice, through which the water may be released by piping failures. In each case, there is the possibility of a catastrophic release of water through the failure of the ice or moraine dam, through overtopping, or by other means.

GLOFs are thus not a unique phenomenon with a common climatic control, a common topographic relationship to the glacial source, or a common triggering event. Blown and Church (1983) noted that the probability of dam failure and the magnitude of the outflow depend on: materials forming the dam, the geometry of the normal outflow, the hydrological regime of the lake, the nature of continued glacier activity, the length of time since inception, and the occurrence of a trigger event. Trigger events include exceptional storms, seismic activity, failure of sediments by piping, landslides or icebergs calving, and setting up large waves which cause overtopping (Ives, 1986). The predominant cause in one area may differ from the predominant cause in another.

There is a significant record of glacier dams in the upper Indus basin with 35 destructive floods recorded over the past 200 years – approximately one every six years (Hewitt, 1968, 1982, 1985). Most of the glacial lake outbursts in the Karakoram have resulted from the surging advance of glaciers across major headwater streams, blocking the river flow in an ice-free valley. Many caused severe damage and loss of life far downstream from the source of the flood. This mode of failure differs from the occurrence of glacier dams in the Nepalese Himalayas where most of the glacial lakes appear to be related to a period of rapid glacier retreat since 1960 (Watanabe et al., 1995). There has been a sharp increase in the number of glacial lakes over the past few decades in Nepal. The increase in glacial lakes in Nepal has not been matched by a similar increase in the Karakoram. However, the occurrence of surging glaciers continues in the Karakoram and still poses flood dangers for downstream residents and structures including hydropower schemes (Hewitt, 1998).

Even small glaciers on tributary streams of the Indus in the Karakoram have generated GLOFs with disastrous effects. A severe glacial lake outburst flood occurred on July 27, 2000, at Kande from a tributary of the Hushe River (a tributary of the Shyok). The outflow originated from the Kande glacier and villagers referred to a supraglacial lake on the glacier before the flood occurred. A previous flood had occurred from the same source on July 25, 1997, but was much less severe than the one in 2000. Kande village was virtually destroyed, with 124 houses and a primary school destroyed (Figure 1.8a). Flood boulders cover the entire surface and there is no remaining evidence of houses, cultivation terraces, or trees. Villagers heard a roar in the hills about ten minutes before the arrival of the flood (as in the first example from Ethiopia) and fled to higher ground; there were no casualties.

FIGURE 1.8 a) The Kande GLOF that destroyed the village including the school shown here. b) The lower track of the GLOF in the Sosat valley.

A similar GLOF occurred on July 29, 1995, at around midday; villagers at Sosat, where the Sosat River joins the River Ghizer/Gilgit, heard a roaring sound in the steep valley above the village (Figure 1.8b). Suspecting imminent disaster, they fled to higher ground. Very shortly afterward, a wall of water and debris hit the lower part of the settlement, killing four people and destroying the bridge, four houses, the Jamaat Khana (Ismaili mosque), and a micro hydropower scheme. The valley was spread with boulders up to about 1 m in diameter over a width of 100 m. The catchment area of the Sosat River is less than 50 km^2 ranging in elevation from 2,400 m above sea level on the valley floor to the catchment divide around 4,500 m. The Sosat glacier is a very small glacier, approximately 5 km in length at the head of the catchment, and is said by local residents to be static. There was evidence that the flooding originated from a blockage and release of meltwater from within the glacier, with a possible contribution from unusually heavy rainfall five days before the flood. The track from the glacier to the village has an increasing slope, with the lower steep slope shown in Figure 1.8b, with a deeply entrenched channel and high boulder berms. It is thought likely that in this section the flood wave accelerated and steepened, it incorporated any preceding flow which it overran and then acted as a lubricant at the base of the boulder-laden flood.

Sites where GLOFs and landslide dambreaks occur are often also seen as suitable sites for hydropower schemes, either on a small scale as at Sosat or on major rivers. Examples of disastrous failures in the Himalayas include the complete destruction of a newly constructed scheme at Namche in the Khumbu area of eastern Nepal in 1985 just before commissioning (Vuichard and Zimmermann, 1987), damage to a mini-hydropower plant on the Dudh Koshi River in September 1977, and damage to the Sun Koshi power plant on the Sun Koshi River (Yamada and Sharma, 1992) following an outburst flood of Zhengzanbo Lake on July 11, 1981 (Meon and Schwarz, 1993). Elsewhere, similar failures caused the destruction of the intake to the Huallanca hydropower station in Peru in 1950 (Reynolds, 1998). In 1934 the failure of an ice dam in the Chilean Cordillera resulted in many fatalities and destroyed a hydropower plant and three railroad bridges (Fernandez et al., 1991). Experience of recent or historic flash floods is essential in the design of such schemes.

1.6 ICE BREAK-UP DAMS AND FLASH FLOODS

Ice jams or ice dams are a regular feature of many high latitude rivers and are found less frequently further south. They can occur during the period of early winter freeze-up or, more commonly and more severely, during spring break-up. Ice jams are accumulations of blocks and sheets of ice in the river channel that restrict streamflow. They form where breaking ice during melt comes into contact with an intact ice cover or where the channel gradient suddenly drops, for example at islands, bridges, or bends in the river. Depending on weather patterns and river morphology, ice jams can result in the upstream rise in water level of meters per hour and force ice floes to back up for several kilometers. Upstream rise in level does not necessarily (or usually) imply a rise in discharge or velocity but the potential rates of change in level are of such magnitude that they could be categorized as flash floods. Initially, ice jams reduce the downstream flow but sudden failure of the ice jam then releases a flood wave with a rapid increase in discharge and velocity as well as level that can cause extensive damage downstream. Such ice dam release floods with sudden onset can clearly be flash floods although rates of rise in level are rarely reported.

In addition to water damage, sharp-edged blocks of ice may be pushed more than ten meters above the water level and may damage structures in or near the river, including bridges and hydropower schemes. Figure 1.9 shows the effects of a very rare ice dam in Britain on the River Tees in 1982 where blocks of ice damaged the intake works of a water treatment plant.

The most severe cases for upstream flooding are for the great northward-flowing rivers of Russia, the Ob, Yenisei, and Lena, and the Mackenzie and Yukon rivers of North America. These northward-flowing rivers tend to have more ice jams because the upper, more southerly part reaches thaw first and the ice is then carried downstream into the still-frozen northerly part. In East Siberia, river ice jams constitute some third of all floods. Ice dams may be 20–30 km long, causing rises in water

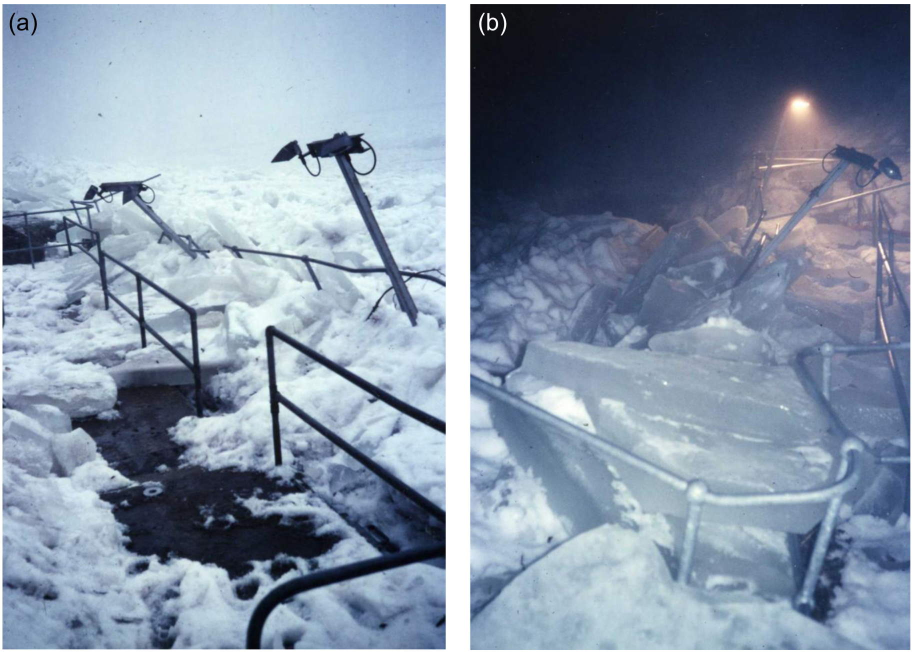

FIGURE 1.9 a) and b) Damage to intake structures at the Broken Scar Treatment works on the River Tees in northern England in January 1982 by ice jam and subsequent flood – a very rare phenomenon in Britain.

level of 8–10 meters in the River Lena (Korytny and Kichigina, 2011). Analyses of ice jam data in the US show that more frequent ice jam floods are observed in Alaska and northern parts of the contiguous United States, with New York and Montana being hotspots (White, 1996; White et al., 2006). The River Susquehanna in northern New York State seems particularly vulnerable. The economic cost of ice jam floods in North America was estimated at $300 million in 2017 (French, 2018). In Europe, ice jam floods have also been reported, for example on the Elbe, Oder (Mudelsee et al., 2004), and Vistula (Nachlik and Kundzewicz, 2016).

1.7 FAILURE OF CONSTRUCTED DAMS AND EMBANKMENTS

1.7.1 Dam Failure Flash Flood

To ensure comprehensive coverage of flash floods from the full range of sources, a description is provided of example flash floods resulting from a dam failure and an embankment failure and associated circumstances known to the authors.

Returning to the initial theme of flash floods in desert locations, a dam failure is examined on the Shadi Kaur, a river on the Arabian Sea coast of Pakistan. It is an area of extreme aridity, exemplified by the disastrous plight of the army of Alexander the Great as he made the journey back from India; they found little water and suffered severe losses of his army from thirst and heat (Woods, 1997). A gauging station on the river had been established in the late 1980s with daily gauge measurements and a cableway to measure flood flows. In eight years of record, the average duration of flow was only eight days per year. However, in that period, the cableway was twice destroyed by flash floods with estimated discharges of over 2,000 m^3s^{-1}. Figure 1.10 shows the measurement section with destroyed gauge boards and the boulders conveyed in one flood. In 2003 an earth dam was built just upstream from the gauging section, 485 m long and 35 m high. At a cost of less than $1 million to provide irrigation to nearby farms, it was built without a spillway with the presumed assumption

FIGURE 1.10 The gauging section of the dry Shadi Kaur in 1995, showing the damaged gauge boards (arrowed) and boulders transported in the flash flood.

that an initially empty dam would hold any incoming volume. On February 10, 2005, another flash flood overtopped the dam which then burst, resulting in the submergence of five villages, home to around 7,000 people, and the deaths of about 70 villagers. The coastal fishing town of Pasni was also submerged.

There has been no loss of life as the result of dam failure in Britain since 1925 but inadequate consideration of the sources and magnitude of risks (as well as poor maintenance) still results in dam failures and loss of life in many parts of the world.

1.7.2 Embankment Failure Flash Flood

Embankments to protect land and property along rivers are built to protect against floods of a given probability of occurrence. However, earth embankments often fail if overtopped and also when inadequate maintenance allows seepage through the bank. Such was the case in a flood on the River Tyne in 1995 when a bank was breached without overtopping due to seepage through rabbits' burrows (Archer, 2003). The breach spread and the flood rose rapidly in the "protected" area in Corbridge as a flash flood. The speed of encroachment and the rapid rise in level were far more serious for properties on the flood plain than they would have been if no embankments were in place. To demonstrate the speed with which a breach can develop, Figure 1.11 shows a sequence of photographs taken on the neighboring River Tees in 1992 with water flowing from a controlled washland back into the river. A farmer cut a shallow trench across a flood bank to allow water accumulated on a cropped field on the floodplain to drain back into the river after the flood. To his horror, in 20 minutes the trickle became a roaring torrent carrying with it shrubs and trees (Archer, 2003). This example illustrates the speed with which a breach, once initiated, develops in an earth dam or embankment.

1.8 FLASH FLOODS – HOMOGENEITY AND STATIONARITY

Flood risk assessment is commonly based on an analysis of recorded peak discharges or by the regionalization of such information for estimation at ungauged locations. Conventionally such

FIGURE 1.11 Sequence showing the progressive breach of a flood embankment over a 20-minute period on the River Tees. (Source: after Archer, 2003.)

analysis makes the assumption that the series of annual maxima from a gauging station are statistically homogeneous and stationary, that is, they are drawn from a single population of floods and that the future (and past) probability of occurrence is the same as that represented by the gauged sample. In some cases, the occurrence of flash floods from a variety of generating mechanisms makes these assumptions flimsy and with serious implications for flood design. This is especially the case when the mechanisms generate floods with quite different frequencies and magnitudes.

1.8.1 Homogeneity

With respect to homogeneity, Archer (2002) noted that floods in tributaries of the upper Indus are usually generated by melting of snow and glacier ice with a prolonged seasonal peak which shows limited variation from year to year but floods caused by landslide dam-breaks or glacial lake outburst floods, although rare, can be very much greater in magnitude. Thus on the river Hunza (noted above for a dam that did not break), an instantaneous flood peak of 5,154 m^3s^{-1} in June 1967 exceeded the next highest maximum of 2,831 m^3s^{-1} in a 30-year record. Moreover, daily mean maxima and instantaneous maxima from snow and glacier melt show small differences; the mean ratio for Dainyor Bridge on the River Hunza was 1.08. However, for the June 1967 flood, the ratio was 2.50, a clear indication of a short-lived but extreme flash flood – but of unidentified origin. Even greater floods on the Hunza resulted from landslide dam-breaks in 1937 and in 1858 when a rockfall dammed the river for six to eight months and the resulting dam-break caused havoc along the course of the Indus to Attock where it emerges on the plains with a rise in water level of nine meters in ten hours. GLOFs also occur infrequently on the Hunza; Hewitt (1982) notes nine major GLOF floods in the 20th century with the last major event in 1960 causing destruction of downstream villages and irrigation terraces.

The evidence for the effects of non-homogeneity in temperate catchments is usually hard to detect even though it is recognized that annual maximum floods for a catchment may originate from frontal rainfall, convective rainfall, or snowmelt with differing underlying distributions. One case where it must be recognized is where permeable catchments are vulnerable to extreme rainfall of very infrequent occurrence where the intensity is sufficient to generate overland flow in excess of infiltration rates (Vafakhah and Eslamian, 2014). An example is the chalk catchment of the River Lud at Louth in eastern England where the mean annual flood discharge is 3.3 m^3s^{-1} in a 50-year record but the estimated discharge in a flash flood in 1920 was more than 40 times greater and resulted in 23 deaths in a 20-minute period (Clark and Arellano, 2004).

Failure to account for the occurrence of such rare but extreme floods, even when none are recorded in gauged or historical records risks serious damage or loss of riverside structures including bridges and hydropower schemes as well as loss of life. Flood design must make allowance for the potential occurrence of such extreme events. Catchment surveys, notably for glacial risks in high mountains, must also include geomorphological evidence for past flash floods.

1.8.2 Stationarity

The stationarity assumption in flood and water resources management has been challenged as a result of the magnitude of current hydroclimatic change with global warming. Milly et al. (2008) claimed that stationarity should no longer serve as a central default assumption. However, there have been dissenting voices. Lins and Cohn (2011) questioned whether the deviation from stationarity is sufficient to justify a complex deterministic characterization of the process. Matalas (2012) asserted that the assumption of stationarity has not yet been pushed to the limit of operational usefulness in the face of a changing climate.

Nevertheless, it seems worthwhile to consider the physical basis for future changes in flash floods driven by changes in global climate as well as seeking evidence for the nature of past changes. The most obvious potential for change is with respect to the effects of increased global temperature on the proportion of precipitation that falls as rain rather than snow and the potential for the progressive melt of glaciers. Glacial meltwater temporarily enhances water availability but may also increase the risk of GLOFs. Watanabe et al. (1995) noted evidence for the increasing incidence of glacier lakes and outburst floods in the Nepal Himalayas. Casassa et al. (2010) noted that temperate glaciers in Patagonia were receding at an accelerated rate, with consequent enlargement of glacial lakes, and also noted an increasing number of GLOFs. Similarly, Petrakov et al. (2012) recorded unprecedented down-wasting of glaciers in the Pamir and Tian Shan regions and an increase in the number and area of glacial lakes in Kyrgyzstan. Even though the glacial lakes in these mountains (like those described above in the Karakoram) are relatively small, their outbursts often produce destructive debris flows.

There is also the potential for change in the magnitude and frequency of floods resulting from ice dam break-up. Analyses by Rokaya et al. (2018) in Canada showed clear signals of climate change in the timing and magnitude of ice jam floods (IJFs), particularly in small basins; in western Canada, results showed increasing trends in magnitude and earlier trends in the timing of IJFs. However, over the longer term in Europe, a review of extreme floods in the Elbe and Oder over 500 years by Mudelsee et al. (2004) found a significant reduction in the number and proportion of extreme floods caused by ice jams in the 20th century compared with previous centuries as temperatures increased after the Little Ice Age. Ultimately the same reduction may be experienced in more northern latitudes as winter temperatures increase.

With respect to flash floods driven by convective rainfall, Kendon et al. (2014) used a very high-resolution climate model with 1.5 km grid spacing for the UK and showed a projected future intensification of short-duration rainfall in summer, with significantly more events exceeding the high thresholds indicative of serious flash flooding. This result has now been confirmed by other international studies which consistently show increases in intense short-duration rainfall events with warming (Kendon et al., 2017). However, this enhancement must also be considered in the context of natural climate variability. Archer et al. (2017), in compiling a comprehensive chronology of flash floods in two regions of Britain since 1850, found considerable decadal variability with high numbers in the late 19th century when global and regional temperatures were much lower. The reason behind these “flood-rich” and “flood-poor” periods is unknown but likely related to variations in large-scale oceanic and atmospheric circulation patterns. Villarini et al. (2009) noted that it may be easier to claim non-stationarity than to prove it through analysis of actual data.

1.9 SUMMARY AND CONCLUSIONS

Flash floods originate from a variety of mechanisms, from convective rainfall in temperate and tropical areas affecting both rivers and surface water, from the sudden release of water from natural blockages of rivers by landslides or ice jams, from glacier lake outbursts, and from the failure of river structures including dams and embankments.

The one feature which unites all these mechanisms as flash floods is their abrupt onset which can be characterized as a rate of rise in level that is a threat to life. The word “flash” implies an event that occurs so quickly that it takes victims by surprise with little opportunity for escape. This short time lag can be referred to as a “threat response time” distinguishing it from a catchment lag or response time. Threat response times may be nearly instantaneous and are typically measured in minutes for the most serious flash floods. As a means of distinguishing flash floods from “normal” floods a minimum rise of water level of 0.50 m in 15 minutes in rivers (0.30 m in 15 minutes in surface water floods) is proposed. In many flash floods, the rise may occur as a “wall of water” with a far greater rise in a shorter time. Flash floods in rivers are generated by intense short period rainfall and the rate of rise poses a separate and more severe threat to life than the peak level or discharge. It is therefore recommended that peak rate of rise statistics are derived as a standard component of gauged data processing.

Very high but prolonged total rainfall or peak discharge are not necessary conditions for flash flooding. Rainfall thresholds to initiate a flash flood may vary depending on the catchment characteristics and initial wetness but will generally be in excess of 40 mm in an hour. As shown by the example for the River Tyne, the rising limb of the hydrograph may steepen as it moves downstream without the need for blockage and release. The wavefront may propagate for tens of kilometers downstream to locations where no rain has occurred and where no threat is perceived. Flash floods predominate in small steep upland catchments and in urban areas, but can occur more rarely in lowland catchments given sufficiently intense rainfall.

Flash floods occur so rarely in individual locations or catchments that a long historical record is necessary to evaluate the risk of occurrence. The example of the River Wansbeck shows how historical information can be used to improve flood risk assessment. It is recommended that databases of historic (and recent) flash floods, such as those established for Britain be more widely prepared.

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Arid Zone Flooding

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Cementing “Stakeholder Collaboration” into Flood Risk Management

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Watershed Contamination by a Copper Mine with Flooding

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