Report on 2020-2022 Global Flood Events:
Case Analysis & Response Strategies

中国水利水电科学研究院
China Institute of Water Resources and Hydropower Research
ICFM
Flash Flood Program

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Contents

1. Analysis of the Global Water Cycle Change 1

1.1 Impact of Global Change on the Water Cycle 1

1.2 Flood Risk and Water Security in the Context of Global Change 2

2. Typical Flood Events in the Years of 2020–2022 3

2.1 Typical Flood Events in 2020 8

2.2 Typical Flood Events in 2021 9

2.3 Typical Flood Events in 2022 10

3. Case Studies 17

3.1 2022 Deadly Floods in Pakistan 17

3.2 Australia Floods 2022 18

3.3 2022 Disastrous Floods in KwaZulu-Natal, South Africa 19

3.4 2021 Typical Flash Floods in Germany 20

3.5 Multiple Flood Events in Japan 21

3.6 2020 Michigan Dam Failures, the United States 23

4. Major Response Strategies 24

4.1 The Netherlands: Adaptive Strategies for Flood Risk Management 24

4.2 Japan: River Basin Disaster Resilience and Sustainability by All 26

4.3 The United Kingdom: Flood Management and Climate Resilience Roadmap 28

4.4 The United States: Latest Climate Plans and Water Management Strategies 30

5. Summary 32

References 33

1 Analysis of the Global Water Cycle Change

Climate change has reshaped the spatial and temporal patterns of water cycle, posing a continuous threat to human survival and development in a way that modifies water availability and endangers water security. It also has multi-directional interactions with water-sediment processes, hydro-chemical processes and hydro-ecological processes. Water cycle variability has affected global change in a very obvious way. As the footprint of climate change and human activities increase, water cycle processes and fluxes have been altered, with significant impact on water resources, droughts and floods, and other extreme hydrological events. In the context of this changing planet, predicting the evolution and trend of extreme hydrological events has become a hot-button and frontier research topic in global water science today. Water cycle evolution and its role in climate change becomes an important basis underpinning global climate governance and response to climate change and water crisis. It is a major issue of concern for international organizations and governmental departments such as the Intergovernmental Panel on Climate Change (IPCC) and the National Science Foundation (NSF), as well as a key theme being frequently discussed by the International Geosphere-Biosphere Programme (IGBP) and the International Hydrological Programme (IHP), which has great theoretical significance and application values in supporting global climate governance.

1.1 Impact of Global Change on the Water Cycle

According to the IPCC Sixth Assessment Report (AR6) (2021), global average precipitation and evaporation are increasing with global surface temperature rise (high confidence), very likely with a range of 1–3% per °C based on coupled model estimates. Near-surface atmospheric moisture capacity grows by about 7% per degree of warming. Global precipitation is constrained by energy balance to expand slightly at 2–3% per °C. Increase in water vapor of the weather system in the context of global warming will generally wetter wet seasons and intensify heavy precipitation events with high confidence. Without massive reduction in greenhouse gas (GHG) emissions, global warming is projected to , with high confidence, cause substantial changes in water cycle at global and regional scales. Global annual precipitation over land is projected to increase on average by 2.4% (0.2–4.7% likely range) in the lowest emissions SSP1-1.9[1] scenario, and 8.3% (0.9–12.9% likely range) under the high emissions SSP5-8.5[2] scenario by 2081–2100, relative to 1995–2014. It is virtually certain that evaporation will increase over the ocean and very likely that evapotranspiration will increase over land, except for some arid areas.

The paper published in the *Journal of Climate* by the research team of the Institute of Atmospheric Physics of the Chinese Academy of Sciences (IAP-CAS) in 2020 revealed that global water cycle has changed since 1960 in a "wet-gets-wetter-dry-gets-drier" pattern, i.e., global water cycle has intensified by 2–4% for every °C rise in global average temperature (GMW, 2022a). Global warming by 2°C to the maximum this century under the Paris Agreement, relative to the pre-industrial level, would result in at least 4–8% magnification in global water cycle, implying more intense evaporation - especially in drier areas, and more intense precipitation -especially in wetter area. Evaporation, as a key driver of global water cycle, is currently one of the main focuses of research on related fields. A research team led by Madeleine Pascolini-Campbell from California Institute of Technology published a paper in *Nature* and demonstrated that the rate of increase in evapotranspiration has been twice as high as previous estimate due to global warming. Evapotranspiration has increased from 405mm in 2003 to 444mm in 2019, rising by about 2.30mm or 10% per year (Pascolini-Campbell et al., 2022).

1.2 Flood Risk and Water Security in the Context of Global Change[1,2]

Observations found that hot days extend by 2–8 days per decade in most areas of the world, with the average number in recent years tripling compared to 1961–1990, while extreme precipitation adds by 1% per decade. Sea levels keep rising as a result of glacial melting, with the rate doubling in the last decade (Sohu Business, 2022). These changes all have increased global flooding risks. According to the report of the United Nations Office for Disaster Risk Reduction (UNDRR) (CRED, 2022), there were 3,254 floods worldwide reported since ushering into the 21st century (2000–2019), accounting for 44% of all natural disasters, the highest percentage among all types of natural hazards; and increasing by 1.34 times in comparison to the 1,389 floods during 1980–1999. Across the globe, a wide range of areas are facing flood risks, among which 27% of the regions face moderate or high flood risks, while less than 40% have no flood exposure. Areas with the highest flood risks are mainly located in the coastal regions of eastern and southeastern Asia (including Chinese Taipei and the Pearl River Delta of mainland China, the Philippines, the coastal areas of Indonesia and Japan, and the Assam and Tripura states of India), the Paraná and Santa Catarina states of Brazil in South America, and the eastern coast of North America. Elizabeth Tellman, Assistant Professor at the University of Arizona, and her research team published a cover article in *Nature* (Tellman et al., 2021), revealing that the proportion of global population exposed to floods has grown by 24% since the turn of this century, ten times more than what the scientists previously predicted. Specifically, the percentage of population impacted by floods have increased by 2% in 70 countries and by over 20% in 40 countries. It is evident that the frequency and range of floods, as well as the proportion of affected population, have expanded globally over time since the 21st century.

The IPCC AR6 "Climate Change 2022: Impacts, Adaptation and Vulnerability" published in February 2022, predicted that the population potentially exposed to a 100-year coastal flood is projected to increase by about 20% if global mean sea level would rise by 0.15m relative to 2020; this exposed population may double at a 0.75m rise in mean sea level and triple at 1.4m. In addition to counting past floods, Elizabeth Tellman and her team also projected future flood disasters. Using the Aqueduct Global Flood Analyzer created by the World Resources Institute, they calculated the population at risk of floods in 119 countries worldwide from 2010 to 2030 based on massive data taken from MODIS observations . The result showed that, up to 758 million people will be exposed to a 100-year flood by 2030. People exposed to flood risks will outpace the overall population growth in 57 countries, particularly in Asia and Africa. Nine regions and 32 countries across four continents will have a sustained increase in flood exposure, among which, 4 African countries and India may see more than 20% growth of flood-prone population; 5 regions and 25 countries will have new flood exposure, mainly in Europe and North America. Due to climate change and demographic shifts, future flood exposure in rapidly urbanizing regions may be underestimated. GHD, a global company offering engineering and environmental service estimated that water-related risks could “wipe” US$ 5.6 trillion between 2022 and 2050. These all suggest that future flood risks will be on a continual upward trend. This report aims to pinpoint the causes of flood disasters and seek to improve the the measures for flood defense and management, in a bid to provide key support for climate change response and actions.

[1]SSP1-1.9: Five scenarios of shared socio-economic pathway (SSPx-y) are described for the Coupled Model Intercomparison Project Phase 6 (CMIP6), including SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 in the ascending order of anthropogenic radiative forcing. "SSPx" refers to the socio-economic pathway underlying the scenario, and "y" refers to the approximate level of radiative forcing resulting from the scenario by 2100. SSP1-1.9 is the lowest anthropogenic radiative forcing scenario.
[2]SSP5-8.5: Ibid., SSP5-8.5 is the highest anthropogenic radiative forcing scenario.

2 Typical Flood Events in the Years of 2020–2022

Figure 1 Distribution Map of Global Extreme Flood Events from 2020 to 2022

Global extreme flood events in 2020

Global extreme flood events in 2021

Global extreme flood events in 2022

Climate change has led to an increase in the frequency and severity of extreme weather events that have taken millions of lives over the past five decades. Referring to IPCC AR6 released in August 2021, climate change is unequivocally caused by human activities, so it is necessary to keep reducing GHG emissions and mitigating the impact of extreme climate-related disasters. This section is a review of extreme flood events on a global scale from 2020 to 2022, illustrating death tolls, flood types, geographical distribution, and economic losses.

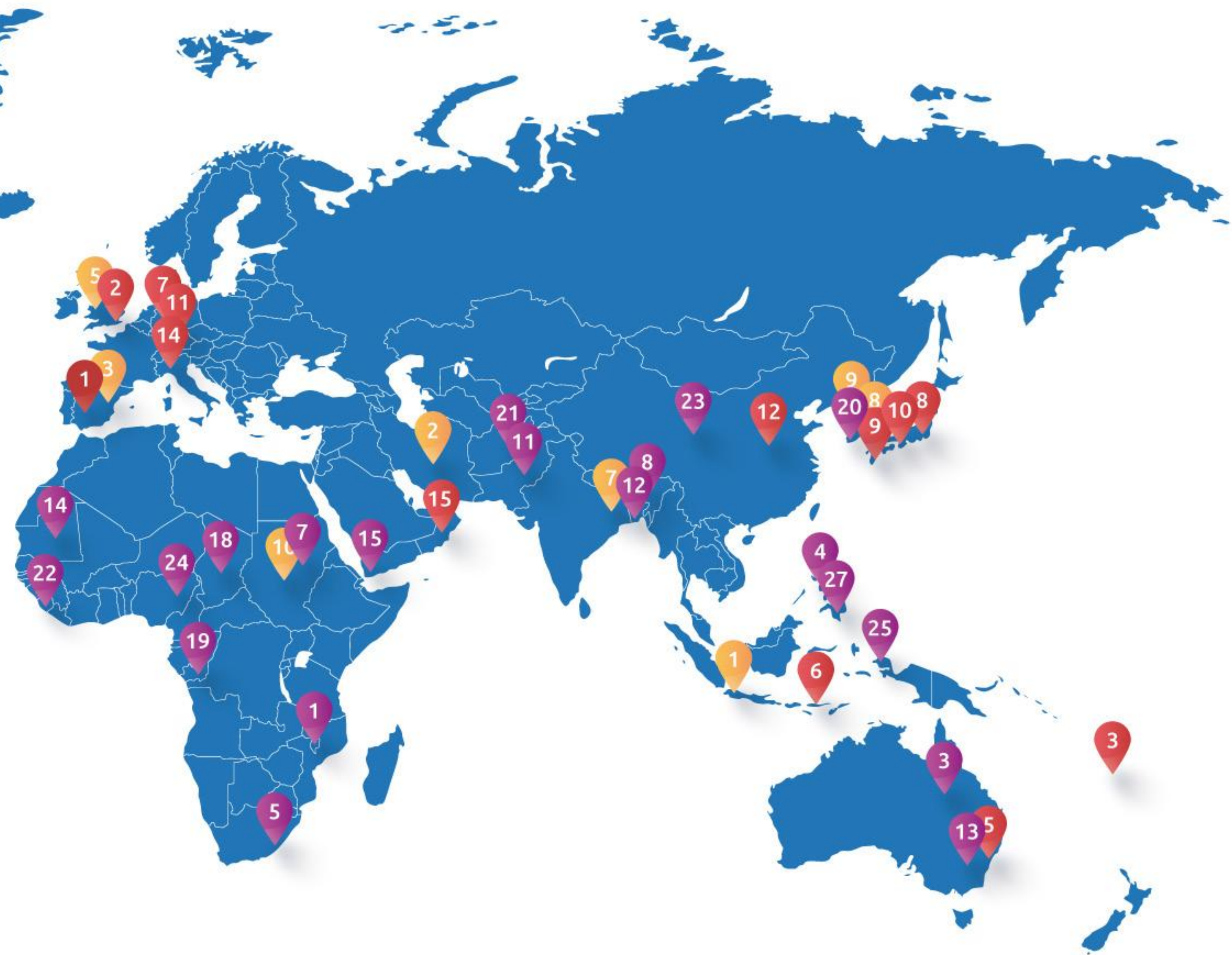


Table 1 Statistic Table of Global Typical Flood Events, 2020–2022

Year	No.	Country	Region	Start Time	End Time	Flood Type
2020	1	Indonesia	Jakarta	January 3	January 6	Urban flood, flash flood
2020	2	Iran	Sistan and Baluchistan	January 9	January 13	River flood
2020	3	Spain	Girona	January 20	January 23	Tsunami + typhoon, ice jam
2020	4	Brazil	Minas Gerais	January 24	January 29	River flood, flash flood
2020	5	UK	Wales	February 15	February 16	Tsunami + typhoon, river flood
2020	6	USA	Michigan	May 17	May 19	River flood
2020	7	India	India-Bangladesh northern border	May 20	May 23	Tsunami + typhoon, river flood
2020	8	Japan	Kyushu	July 4	July 20	River flood, urban flood
2020	9	South Korea	Seoul	August 1	August 9	Urban flood, river flood
2020	10	Sudan		September 2	September 14	River flood, urban flood
2020	11	USA	Louisiana	October 8	October 13	Tsunami + typhoon, urban inundation
2021	1	Spain	Madrid	January 8	January 9	Ice jam
2021	2	UK	North Wales, North-West England	January 18	January 20	River flood, urban flood
2021	3	Fiji		January 30	January 31	Flash flood, tsunami + typhoon
2021	4	USA	Texas	February 10	February 18	Storm
2021	5	Australia	New South Wales	March 17	March 23	River flood
2021	6	Indonesia	East Nusa Tenggara	April 4	April 9	Flash flood, tsunami + typhoon
2021	7	Germany	Bavaria	June 29	June 30	Urban flash flood
2021	8	Japan	Atami	July 3	July 4	Flash flood
2021	9	Japan	Aizome River Basin	July 3	July 4	Flash flood
2021	10	Japan	Sendai River Basin	July 10	July 11	River flood
2021	11	Germany	Rhineland-Palatinate, North Rhine-Westphalia	July 13	July 21	River flood, urban flood
2021	12	China	Zhengzhou, Henan	July 17	July 23	Urban flood, river flood
2021	13	USA	Louisiana, Mississippi	August 28	September 1	Tsunami + typhoon, flash flood
2021	14	Italy	Liguria region, northern Italy	October 4	October 7	River flood, urban flood
2021	15	Oman		October 3	October 4	Flash flood

Year	No.	Country	Region	Start Time	End Time	Flood Type
2022	1	Malawi		January 25	January 29	River flood
2022	2	Brazil	Rio de Janeiro	February 16	February 22	Flash flood, urban flood
2022	3	Australia	Queensland, New South Wales	February 26	March 1	River flood, urban flood
2022	4	The Philippines	Raijtai	April 10	April 19	Storm + typhoon, flash flood
2022	5	South Africa	KwaZulu-Natal	April 11	April 17	Flash flood, river flood
2022	6	Colombia		March 16	May 9	River flood, flash flood
2022	7	Sudan	Khartoum	May 9	September 26	River flood, flash flood
2022	8	India, Bangladesh	Assam in India, Sylhet in Bangladesh	May 22	May 25	Tsunami + typhoon, river flood
2022	9	Mexico	Oaxaca	May 29	June 1	Tsunami + typhoon, river flood
2022	10	USA	Montana	June 13	June 15	River flood
2022	11	Pakistan		June 14	September 15	River flood, flash flood
2022	12	Bangladesh	Gurugram, Lalmonihad, Sunamganj, Sylhet	June 20	July 6	River flood
2022	13	Australia	Sydney in New South Wales	July 4	July 8	River flood
2022	14	Mauritania	Tagant	July 25	August 3	River flood
2022	15	Yemen	Sana'a	July 25	August 17	Urban flood, flash flood
2022	16	USA	Missouri	July 26	July 30	Typhoon, river flood
2022	17	USA	Kentucky	July 28	August 2	River flood, typhoon
2022	18	Chad	N'Djamena	August 5	September 6	River flood
2022	19	Congo DR	Kinshasa	August 8	September 25	River flood
2022	20	South Korea	Seoul	August 8	August 12	River flood
2022	21	Afghanistan	Parwan	August 14	August 22	Flash flood, urban flood
2022	22	Sierra Leone	Freetown	August 17	August 19	Flash flood, river flood
2022	23	China	Qinghai	August 17	August 19	Flash flood
2022	24	Nigeria	Adamawa, Anambra, Bauchi, Benue, Ebonics, Jigawa	August 18	August 25	Flash flood, river flood
2022	25	Indonesia	West Papua	August 21	August 25	Flash flood, river flood
2022	26	Venezuela	Aragua	October 8	October 9	Flash flood, river flood
2022	27	The Philippines	Maguindanao	October 25	October 31	Flash flood, urban flood

There were 53 typical flood events during 2020-2022, with 11, 15, and 27 in 2020, 2021 and 2022 respectively, an increase of 36% in 2021 compared to 2020 and 80% in 2022 compared to 2021. Flood events numbered 21, 9, 8, 7, 4, and 4 in Asia, Africa, North America, Europe, South America and Oceania respectively, accounting for 39.6%, 17.0%, 15.1%, 13.2%, 7.5% and 7.5% of the three-year events. In terms of percentage by year and continent, Asia saw the largest percentage of flood events over the past three years, all exceeding 35%, followed by Europe in 2020 and 2021 (above 20%), and Africa in 2022 (nearly 30%), while North America ranked the third (above 10%). No major flood events occurred in South America and Africa in 2021, as well as in Europe in 2022. According to a UNDRR report, Asia is currently exposed to the highest flood risks as it experienced 41% of all the flood events worldwide, with 1.5 billion people affected, representing 93% of the global flood-affected population (CRED, 2022). The conclusion that Asia suffered from the highest percentage of flood events in this report is consistent with the UNDRR report.

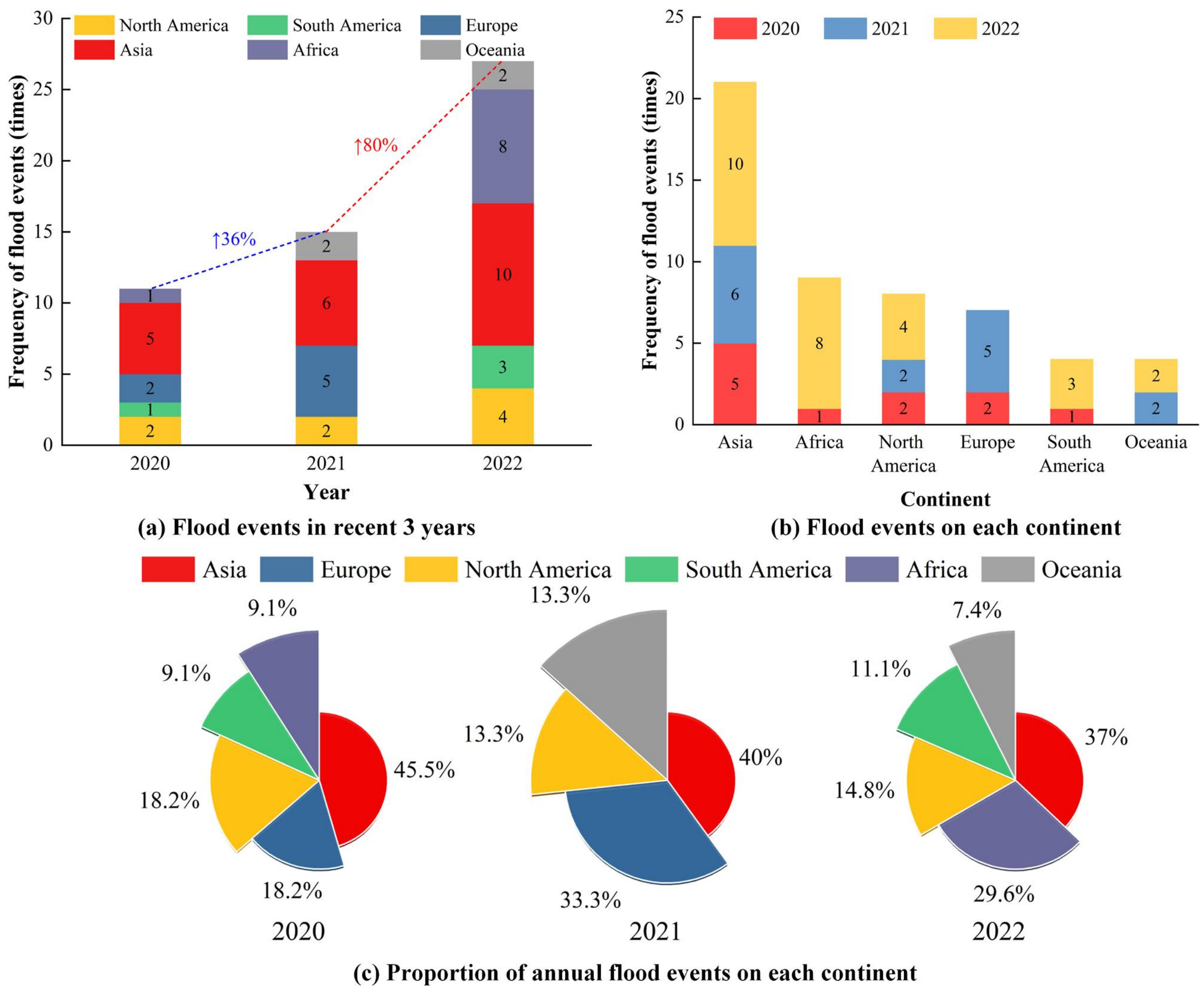


Figure 2 Statistical Analysis Charts of Global Typical Flood Events from 2020 to 2022

2.1 Typical Flood Events in 2020

January
Flash flood in Jakarta, Indonesia

Source: Ed Wary, Getty Images

January
Disastrous flood in Iran

Source: Alireza Masoumi, Getty Images

January
Storm Gloria in Spain

Source: Josep Lago, Getty Images

January
Catastrophic Rainstorm in Brazil

Source: Douglas Magno, Getty Images

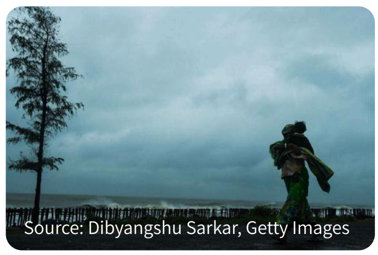
February
Storm Dennis in the United Kingdom

Source: Christopher Furlong, Getty Images

May
Michigan dam failures caused by rainstorm, the United States

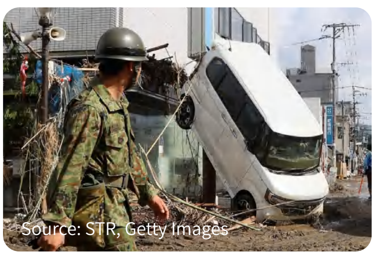
Source: Wilx.com

May
Cyclone Amphan in India and Bangladesh



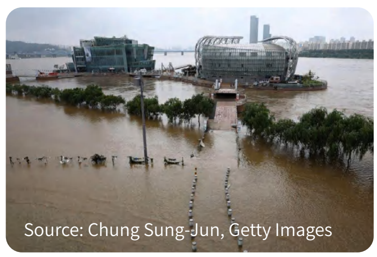
Source: Dibyangshu Sarkar, Getty Images

July
Flood and landslides in Japan



Source: STR, Getty Images

August
Deadly flooding in South Korea



Source: Chung Sung-Jun, Getty Images

September
Eextreme flooding in Sudan

Source: Mahmoud Hjaj, Getty Images

October
Hurricane Delta in Gulf of Mexico

Source: Pedro Pardo / AFP, Getty Images

Figure 3 Global Typical Flood Events in 2020

2.2 Typical Flood Events in 2021

Figure 4 Global Typical Flood Events in 2021

2.3 Typical Flood Events in 2022


Source: GMW (2022b)

1 Tropical Cyclone Ana Triggering Flood in Malawi

Tropical cyclone Ana passed through several areas in southern Malawi in late January 2022, causing severe damage. According to official Malawi statistics, over 990,000 people were affected in 17 of 28 districts of the country, with estimated 680,000 people in urgent need of humanitarian assistance.


Source: ICFM (2022a)

2 Devastating Flood in Petrópolis, Brazil

On February 15, 2022, Petrópolis, Brazil received more rainfall than the historical average for February, triggering flash flood and mudslides the next day that killed at least 171 people. In the worst-hit communities, landslide washed away more than 80 houses on the hillsides.


Source: ICFM (2022b)

3 Ravaging Flood in Australia

From February 25 to March 1, 2022, the cumulative precipitation reached 100–300mm in northern New South Wales and southern Queensland and exceeded 400mm along the coast. The southeast coast of Australia suffered from its worst flooding in decades, with nearly 20 deaths.


Source: BBC News (2022)

4 Tropical Storm Megi in the Philippines

On April 10, 2022, tropical storm Megi made landfall in the Philippines, hitting several villages near Baybay City in the central province of Leyte. At least 167 died in landslide and flood, with another 110 missing, and 1.9 million have been impacted.

Source: Reuters (Ward, 2022)

5 Deadly Flooding in Eastern South Africa

From April 9 to 13, 2022, cumulative precipitation reached 100mm in the east coast of South Africa with over 300mm in some areas. This intense precipitation process, which South Africa rarely witness in 60 years, led to flood and mudslides in KwaZulu-Natal province, causing 448 deaths and over 60 people missing.

Source: teleSUR (2022)

6 Heavy Rainfall in Colombia

From March 16 to May 9, 2022, heavy rainfall swept through 285 towns in 25 provinces of Colombia, affecting more than 18,100 households. At least 47 people were killed, 49 injured and 7 missing as a result of the heavy rains, according to Colombia's National Unit for Disaster Risk Management (UNGRD).

Source: AP (2022)

7 Destructive Flooding in Sudan

From May to September 2022, multiple floods amid heavy rains in Sudan took at least 146 lives while affecting more than 300,000 residents. Nearly 12,600 acres of farmland were ruined and more than 4,800 livestock killed; and at least 13,200 homes were destroyed and another 34,200 damaged in 15 states.

Source: ABC News (2022)

8 Floods in South Asia

From May 22 to 25, 2022, flood hit northeastern India due to seasonal heavy rains, with a death toll of 101 in Assam, while Bangladesh has reported at least 42 deaths during the monsoon rains. In June, flood raging in parts of these two South Asian countries displaced millions of people.

Source: CBS News (2022)

9 Hurricane Agatha in Mexico

In late May and early June 2022, hurricane Agatha made history as the post-1949 strongest hurricane struck Mexico. At least 33 people were missing and 11 dead and more than 40,000 have been affected by the hurricane.

Source: Floodlist (Davies, 2022a)

10 Widespread Flooding in Montana, the United States

On June 13 to 15, 2022, flooding struck Montana in the United States, triggering a statewide disaster that affected hundreds of families, severely damaged homes, roads and bridges, and disrupted power and water supplies, which has secured a disaster declaration.

Source: Xinhua News (2022a)

11 Deadly Flood in Pakistan

From June to September 2022, multiple disaster events caused by torrential rains occurred across Pakistan, killing more than 1,700 people and injuring 12,900 others. There were 33 million residents affected. In total, 1,393,000 houses were partially damaged and 891,000 completely destroyed, and 1,164,000 livestock died.

Source: 350.org (Jhumu, 2022)

12 Catastrophic Flood in Bangladesh

In late June and early July 2022, Bangladesh suffered from the worst flood in 122 years, which claimed 105 lives while displacing and affecting 7.2 million people each. Many roads and railroads were submerged, isolating the affected areas from the rest of the country.

Source: The Washington Post (Patel and Samenow, 2022)

13 Extreme Flooding in Sydney, Australia

In the first week of July 2022, a powerful storm hit Sydney, causing dam water levels to rise and rivers to flood amid days of heavy rains. Roads and hundreds of homes in and around Sydney were inundated. Damages from the fourth severe flood in Sydney since March 2021 amounted to billions of dollars.

Source: ICFM (2022c)

14 Disastrous Flooding in Mauritania

From July 25 to August 3, 2022, heavy rainfall triggered flood in parts of Mauritania, resulting in 14 deaths. It brought severe damage to 4,351 families and 28,926 people, and caused the destruction of 3,817 houses, the loss of 766 cattle, and the complete inundation of infrastructure in the affected areas.

Source: Carnegie Middle East Center (Nagi, 2020)

15 Heavy Rainfall in Sana'a, the Capital of Yemen

Heavy rains battered many parts of Yemen for nearly a month from mid to late July 2022, causing extensive human and property damage. The results include the complete collapse of one ancient building and the partial collapse of two other buildings in the ancient city of Sana'a, in addition to the collapse of the roofs of 11 ancient buildings, the partial collapse of the roofs of 49 ancient buildings, and the leakage of 500 ancient buildings to varying degrees.

Source: USA Today (Yancey-Bragg, 2022)

16 Rainfall-induced Flooding in Missouri, the United States

On July 26, 2022, record-breaking heavy rainfall triggered flash flood in St. Louis, Missouri, and surrounding areas, causing one death. As of the morning of July 26, rainfall reached 211mm in Lambert Field, surpassing the highest daily precipitation record of 174mm in the area during the 1915 hurricane.

Source: CNN (Elamroussi and Andone, 2022)

17 Destructive Flooding in Kentucky, the United States

In July and August 2022, heavy rain followed by flood claimed 37 lives in Kentucky of the United States. The record-breaking flood inundated large areas of homes since July 28, many of which were destroyed. Local officials deemed it as one of the most destructive floods in U.S. history.

Source: UN News (2022)

18 Devastating Flooding in Chad

Chad in central Africa suffered from severe flood due to extreme rainfall between August and early September 2022. A total of 340,000 people of 55,000 households have been affected. The surge in river levels destroyed 27 million m^2 of crops and farmlands.

Floodlist (Davies, 2022b)

19 Storm and Flood in Congo

Flood struck Lubutu of Maniema province in northeastern Congo after heavy rainfall on August 8, 2022. Areas of Lubutu town, Oso and Otaka were the most affected, with homes and infrastructure damaged. At least 6,634 people have been affected or displaced.

Source: CNA (2022)

20 Extreme Rainfall in South Korean Metropolitan Area

Persistent heavy rainfall battered southern Seoul and Incheon of South Korea since August 8, 2022, resulting in 13 deaths and 6 missing. The heavy rain caused flood in the metropolitan area, during which water inundated more than 1,000 cars and poured into the subway, and public facilities including railroads and dams were flooded or damaged. There also was a spate of ground subsidence and power outages, in addition to landslides in 28 sites.


Source: Xinhua News (2022b)

21 Flash Flood in Parwan Province, Afghanistan

In August 2022, pouring rains triggered flash flood in Shinwari and Sia Gard districts of Parwan Province, Afghanistan, causing 182 deaths and over 20 injuries and leaving more than 100 missing.


Source: allAfrica (Chironda, 2022)

22 Flood and Landslide in Sierra Leone

On August 17 to 19, 2022, flood and landslide caused by torrential rains claimed 8 lives in Freetown, the capital of Sierra Leone. Most of the main roads turned into rushing rivers after hours of intense rainfall, posing a serious threat to the lives and properties of local people.


Source: Chinadaily (Hou, 2022)

23 Flash Flood in Datong, Qinghai, China

Late on August 17, 2022, flood and mudslide lashed the mountainous areas of Datong Hui and Tu Autonomous County in Qinghai Province, China as a result of heavy downpours. According to Xinhua News Agency, 6,245 residents of 6 villages in the area were affected, and 16 people were dead and 36 missing as of August 18.


Source: Floodlist (Davies, 2022c)

24 Deadly Flood in Nigeria

More than 3,000 people were displaced in Jere Local Government Area and surrounding areas after torrential rains hit Nigeria on August 18, 2022. Flash flood killed at least 10 residents and injured three others, while destroying dozens of houses and key facilities in the affected areas.

Source: Sott.net (Davies, 2022d)

25 Extreme Rainfall in Indonesia

Flood and landslides killed at least three people in the province of West Papua on the island of New Guinea and affected more than 35,000 people in the provinces of Sumatra on August 21 to 25, 2022, after heavy rainfall enveloped western and eastern Indonesia.

Source: ICFM (2022d)

26 Disastrous Flooding in Venezuela

On October 8 to 9, 2022, floods and landslides caused by heavy rains occurred in the town of Las Tejeras, the state of Aragua, northern Venezuela, severely striking 21 districts under the jurisdiction of Las Tejeras and leaving 43 people dead and 56 missing.

Source: The Guardian (2022)

27 Tropical Storm Nalgae in the Philippines

On October 29, 2022, gusts and downpours swept most parts of the Philippines, including the capital Manila, after storm Nalgae made landfall in Catanduanes of central Philippines early morning. They spurred flood and landslides, leaving 121 people dead, 103 injured, and 36 missing. More than 3.18 million people have been affected, mostly in the province of Maguindanao.

3 Case Studies

This section analyzes global typical flood events occurred in 2020–2022 that featured heavy casualties, high economic losses, significant social impacts, and frequent occurrences.

3.1 2022 Deadly Floods in Pakistan

In 2022, Pakistan was drenched by post-1961 record monsoon rains that were ten times stronger than ever before, causing the Indus River to spill and even create a long lake with wide of tens of kilometers. Rainfall over Pakistan in July and August exceeded 180% and 243% of the post-1961 normal average respectively, even 350% in hard-hit southern provinces. By the end of August, the most affected provinces Sindh and southern Balochistan had received 590% and 726% more than the average rainfall respectively. The Government of Pakistan declared disasters striking more than 70 areas, approximately 33 million people had been affected by rains, floods and landslides. The disasters caused at least 1,700 deaths, more than 12,800 injuries, and losses of more than 1.1 million head of livestock. Houses, as well as infrastructure, were damaged, with more than 1.4 million houses partially damaged and 850,000 completely destroyed. This flood inundated one third of the country, affected 5.5 million hectares of croplands, 13,000km of roads, and more than 430 bridges. Economic losses amounted to 30 billion dollars, which surpasses 75% of the total economic losses of flood events over the past seven decades in Pakistan.

Global media blamed climate change and mismanagement, among other reasons, for the Pakistan disastrous flooding. According to the rapid attribution analysis of the authoritative team of international climate scientists, the population of Pakistan has increased from 38 million in 1950 to 236 million in 2022. Therefore, climate change caused by intensified human activities may have aggravated heavy rainfall in most parts of Pakistan, with a 50-70% increase in extreme rainfall. Due to poor flood management, appropriate arrangements were not made for early warnings and forecasts, information dissemination, danger zone identification, and evacuation, which disabled the quick response to affected populations. Unauthorized land use and construction, coupled with deforestation in flood-prone areas, has increased flood exposure. Moreover, large-scale exploitation of natural resources has undermined environmental sustainability. In this context, population growth implies more people are living in flood-prone areas. Provincial water administrations fail to make good use of flood control funds, while local governments are deficient in the maintenance of canals and waterways, which further impedes flood discharge of rivers.

In addition, the anomalous South Asian summer monsoon, the special topography of "high in the north and low in the south", and the initial high soil moisture have exacerbated the extreme floods in 2022. There were a number of monsoon in July-August, among which, the Indian monsoon was twice stronger than normal and remained extremely strong, and the strong South Asian monsoon brought abundant water vapor. Atmospheric circulation was abnormal. The strong westerly South Asian high at the upper troposphere significantly increased upper troposphere divergence in Pakistan, which is conducive to the occurrence and maintenance of heavy rainfall. The strong Indian summer wind carried abundant warm and humid airflow northward to Pakistan and northern India, and repeatedly interacted with airflow from the northern continent over these areas, thus producing several heavy rainfall processes. Pakistan is located at the junction of the Eurasian and Indian plates and the western Himalayan syntaxes, as well as the intersection of the Himalaya, the Karakoram, and the Hindukush mountain ranges. Its topography is characterized by high mountains in the north, high hills in the west, plains and hills in the center, and deserts in the south, with many dikes and dense irrigation canals in the plains. While the surge of water in upstream rivers flowed down from north to south, the strong rainfall in the downstream plains caused severe waterlogging, coupled with poor drainage, leading to severe prolonged inundation at high level that evolved into disastrous flooding. Several rainfall processes in July led to flash floods in Balochistan, which raised the water levels of rivers in the plain areas such as Punjab, increased soil moisture, and weakened the flood regulation capacity of local rivers and lakes, thereby aggravating the flood disaster.

Pakistan's current flood management are mainly plagued by the following problems: (1) Imperfect flood monitoring, forecasting and early warning system; (2) Unsystemic flood control planning and unharmonized flood control standards for the Indus Basin; (3) Shortage of pivotal flood control reservoirs in the Upper Indus Basin, hindering flood control on a basin scale; (4) Deficient drainage systems in the Lower Indus Basin; (5) Lack of effective emergency response plans for extraordinary floods; and (6) Prominent problems of sedimentation and river stability, etc. Post-disaster reconstruction and prevention in Pakistan require relevant funds and measures. It is necessary to improve structural measures such as dikes, reservoirs and irrigation systems, while taking into account non-structural measures such as building flood resilience and public awareness, so as to better cope with floods. Priorities at present are to improve flood forecasting and early warning technology; to strengthen water storage capacity in the basin by applying structural measures such as reservoirs; and to reduce disaster exposure through floodplain management measures, in order to mitigate and prevent flood disasters and safeguard the lives and properties of local people.

3.2 Australia Floods 2022

(1) Multiple Floods in Lismore

On February 28, 2022, the first catastrophic flood occurred in Lismore, New South Wales, Australia, with the highest water level of 14.4m, which was 2m higher than the previous record high (12.27m in 1954) and much higher than the 10m-tall levee built in 2005 in the town. Located at the confluence of the Wilson River and Leicester River, Lismore, a bowl-shaped deep basin, currently has up to 30,000 residents living in flood-prone low-lying areas. Four people died in the flood, with more than 2,000 houses destroyed and more than 19,000 houses unlivable.

The second flood arrived in Lismore before residents had a chance to recover from the first one. Up to 279mm of rain fell on the area from 9am on March 29 to 6am on March 30, sending raging torrents of rain into the Wilson River. The water level for this round of flooding was projected to be 10.6m and ended up at 9.7m, forcing the already hard-hit communities of Lismore to evacuate again.

Lismore has seen frequent flood events before. In 1893, for example, three of the largest floods ever recorded hit Brisbane in a short period of time, which killed 35 people and displaced hundreds of others. Thus, this is not the first time that multiple floods occurred in Lismore. Lismore experienced the current multiple floods only five years after the last severe flood in 2017 with a flood height of 11.59m.

Rainfall in Australia is highly volatile, mainly due to El Niño and Southern Oscillation. In El Niño years, rainfall decreased sharply, and was more prone to drought . However, in La Niña years, wet weather increased, which raised the risk of flood.

The years 1893 and 2022 are both La Niña years. In summer, with wet weather, the overland flow capacity of rivers is lowered as soils are saturated, which in turn makes river basins more prone to flooding. Historical events clearly corroborate this. Hence, continuous large-scale flooding is more likely to occur in La Niña years. La Niña is the dominant factor of Lismore floods. Although levees can reduce the damage caused by floods, they can only withstand light to moderate floods. In the extreme floods that hit Lismore in February, the role of these flood control facilities was negligible. Floods become more unpredictable due to global warming, while the air is able to hold more moisture. It implies that an increase of extreme floods occur in the future, and perhaps the need to consider moving towns away from flood-prone areas.

(2) Extreme Flood in Sydney

In early July 2022, a powerful storm caused dam level rise and river overflow in Sydney amid days of heavy rainfall, inundating roads and hundreds of houses in and around Sydney. Many residents have been affected, in addition to severe damage to their properties and livelihoods and to the environment. This is the fourth major flood in Sydney since March 2021, with billions of dollars in damage.

Precipitation was observed to reach 200mm in many parts of Sydney during July 1–7. It was even more in the surrounding areas, approaching 700mm in some areas (nearly the same as London's annual precipitation). Publicly available data shows that Sydney's cumulative rainfall in four days was equivalent to that of one month and a half in the past. As of early July 2022, Sydney's cumulative precipitation totaled 1,769mm, 191mm higher than the historical record for the same period in 1890.

The excessive precipitation was a combined result of multiple factors: (1) Natural climatic factors, due to La Niña, the periodic cooling of the tropical Pacific Ocean increases the precipitation in eastern Australia, while the periodic cooling of the western Indian Ocean increases the precipitation in the south. In the positive phase of the Southern Annular Mode (SAM), the easterly winds bring the moist air from the Tasman Sea to eastern Australia, forming precipitation; (2) Anthropogenic climate change has warmed the atmosphere and the ocean, intensifying global precipitation events. Seawater temperature rise increases the intensity of precipitation. In this precipitation event, the warming waters off the coast of Australia (21–23°C) provided additional energy and moisture that accelerate the formation of trough and low pressure along the east coast, resulting in relatively concentrated heavy precipitation over a 24-hour period.

3.3 2022 Disastrous Floods in KwaZulu-Natal, South Africa

In 2022, South Africa experienced several rounds of extreme heavy rainfall due to La Niña, with the heaviest rainfall seen in many areas according to reliable records since 1921. Heavy rains began around April 8 and last several days. On April 11, a cut-off low pressure system with clockwise flow of air arrived on the east coast of South Africa, transporting warm, humid subtropical air to the coast, and producing widespread intense precipitation. The South African Weather Service (SAWS) issued a Level-5 warning for coastal areas and adjacent interior areas of KwaZulu-Natal province, which was subsequently upgraded to Level 8 and then to Level 9. From April 8 to 12, most areas in KwaZulu-Natal received more than 50mm of rainfall, and more than 200 mm of rainfall in coastal areas, with the greatest intensity of rainfall in the cities of Durban, Lembeh and Ugoo. Virginia Airport recorded 304mm of rainfall in 24 hours from April 11 to 12. Continuous heavy rainfall triggered severe floods and landslides in southeast of South Africa, killing 448 people, displacing more than 40,000 residents, and destroying more than 12,000 houses. Flooding also caused severe damage to infrastructure such as roads, health service centers and schools.

On May 20, South Africa was hit by another round of heavy rainfall. SAWS issued the highest level of warning (Level-10 red warning) for KwaZulu-Natal based on rainfall trend forecasts. Due to days of rainfall, roads, houses and electrical infrastructure in northern KwaZulu-Natal were severely damaged, of which the damage to infrastructure made rescue operations difficult. The May floods across KwaZulu-Natal were caused by several factors, predominantly climate change. According to the World Weather Attribution (WWA), climate change has doubled the probability of floods in South Africa, for example, increasing the chance of a 40-year flood to that of a 20-year flood. WWA said that climate change would make rainfall more intense and frequent in the future. Apart from the influence of climate change, greater vulnerabilities and larger casualties were related to the fact that many infrastructures and communities have not yet recovered from the April floods, and some marginalized groups have been forced to relocate to more flood-prone areas.

3.4 2021 Typical Flash Floods in Germany

Three flash floods with some similarities in hazard characteristics occurred in Germany during the 2021 summer. These events were all triggered by large-scale low-pressure air currents moving toward central Europe, such as storms Xero and Bernd. Then, short-term intense rainfall produced a large amount of surface runoff due to low infiltration capacity. In some places, rainwater accumulation led to flash floods as topography varies among regions. By comparing these flash floods in terms of duration, affected range, disaster pattern, and causalities/economic losses, the largest one hit the Eifel region with rainfall lasting for nearly 14 hours, causing 181 deaths in addition to 10 billion euros in economic losses.

(1) Landshut Flood

Landshut is located in the River Isar valley which is 5km wide and 400–500m above sea level. The local government built a flood channel as the main way of flood control, in order to protect old urban areas along the river from flooding. The data prove that the River Isar has indeed not flooded in recent years. However, on June 29, 2021, Storm Xero moving northeastward from France to Germany brought short-term intensive rainfall with a return period of 100 years to Landshut. The precipitation in the Landshut downtown reached 58mm within one hour according to local precipitation observation station, triggering an urban flash flood. But, the critical factor is not the intensity of rainfall but the impervious pavements and urban structures that hindered rainwater discharge. In addition, drainage system renovation and green roof construction are compromised by a large number of historic buildings and roads in need of protection, which weakens the flood control capacity of this time-honored city.

(2) Devastating Flood in the Eifel Region

The devastating flood in the Eifel region in western Germany on July 13–14 was the worst natural disaster met by Germany in 2021. Eifel is located in the mid-range mountainous range with deep and narrow valleys. It covers an area of about 5,000 km^2 at an altitude of 100–500m. As Bernd remained for days in the region, the 24-hour rainfall in some areas broke the 70-year record, reaching about 153.5mm. Historical comparison of peak discharge indicated that this flood was at a similar magnitude to the 1910 flood. In Erftstadt, infrastructure including drainage and power systems suffered considerable damage, and post-disaster reconstruction was particularly difficult. Following the upstream flood, the water stage in the Steinbachtalsperre Dam, built in 1934–1936 near Cologne, kept rising because the spillway was blocked by a large amount of debris from destroyed houses, trees, and various floating objects. Piping was also found in many places of the dam, posing a threat to 15,000 residents. It took the local government five days to stabilize the situation.

(3) Flash Flood in Berchtesgaden

On July 21, the low-pressure system Bernd rotated from northeast to southwest. As clouds were partially blocked by mountain chains due to the terrain of Berchtesgaden (a village surrounded by mountains at an altitude of 600–2700m), summer thunderstorms stroke mountainous areas with lower evening temperatures, carrying rainfall of 65mm in four hours. However, the intensity of rainfall was not the primary factor of the flash flood. Long-duration downpours in the hilly areas generated intensive surface run-off and made creeks over overflowed. At the same time, torrents on steep slopes caused mudslides and landslides, destroying houses and facilities within the village. The typical flash flood in Berchtesgaden was related to soil sealing caused by earlier lighter rain and local special geological environment. As the underlying surface did not have sufficient capacity to absorb the subsequent heavy rain, surface runoff soared. Prolonged rainfall concentration in mountain cirques with high slopes was critical to the flash flood. While flood protection in Berchtesgaden is difficult due to complex topographic structures, infrastructure construction in flood hazard areas also aggravated disaster damage over the last decades.

The similarities of the three flash floods in Germany could be summarized as: (1) Heavy rainfall is the trigger for these floods, but the disasters were a combined result of rainfall intensity, temporal and spatial distribution, and topographical conditions in different regions; and (2) Climate change and human activities have certain impact on the frequency and damage of flood events. It is necessary to improve forecast accuracy in a targeted manner and establish flood drainage and storage areas, reservoirs and other structures to minimize disaster losses. Policymakers and the media are advised to raise people's flood vigilance and environmental awareness to better respond to potential extreme flood events.

3.5 Multiple Flood Events in Japan

(1) 2020 Kyushu Floods

In July 2020, a total of 14 rivers in seven prefectures of Kyushu in Japan flooded due to heavy rainfall, bringing huge losses to Kyushu, among which Kumamoto and Kagoshima experienced river floods, landslides, and mudslides. The maximum inundation and depth on the embankments of the Kuma River was nearly 10m according to GIS mapping by using the images obtained by helicopters and SNS. Damage in Kumamoto includes 67 people missing or killed, 630 houses destroyed, 5,746 houses inundated, 2 dike locations breached, and 13 bridges lost.

Weather maps, satellite images, and rainfall radar maps at 9:00 am on July 3 and 4 showed that local rainstorms formed by linear rain bands hit central Kyushu Island, causing the Kuma River Basin the most serious flood damage areas. The Kuma River Basin with an area of 1880 km^2, flows from its mountainous areas to plain areas through a long and narrow valley. Fierce floods from mountainous areas in the upper reaches triggered by heavy rainfall could not be discharged quickly and smoothly to plain areas due to backwaters in the long narrow valley. As a result, the basin between the mountain to the valley was most severely affected. Historically several severe floods had happened in this area. The peak flow was 5700 m^3/s in the July 1965 flood and 5500 m^3/s in July 1982. The 24-hour rainfall during the July 1965 flood was 161.9mm, but that of the 2020 floods was more than doubled to reach 410mm. The flood peak in 1965 was 5.05m, but hit 7.25m in 2021, higher than the historical average maximum level of the last five decades. A comparison of the 2020 Kyushu floods, the 2018 Western Japan floods, and the 1985 typhoon floods revealed that large water vapor from the South China Sea and the Pacific Ocean has gradually concentrated in Japan since 1958, and directly led to frequent heavy rainfall.

(2) Shizuoka Mudslide on July 3, 2021

On July 3, 2021, a large-scale mudslide broke out in Shizuoka Prefecture, Japan, due to days of heavy rainfall. Shizuoka is located in central Japan, between Tokyo and Osaka, with an area of 1388.74 km^2 and a population of 690,000. The disaster mainly affected Atami City in eastern Shizuoka, involving 41,508 inhabitants in an area of 61.55km^2. As a result of the massive mudslide, 9 people died, 130 houses were washed away, and approximately 120,000m^2 of sand and soil lost in the Izu Mountain area of Atami City.

According to the observation of Japan Meteorological Agency, the persistent rainfall in Shizuoka began on July 1, and reached 313mm within 48 hours by 12:00 a.m. on July 3, which was much higher than the monthly average for July. In Atami City, 72-hour precipitation amounted to 409.5mm by 17:00 p.m. on July 3, about 1.7 times of the average rainfall for July.

Due to global warming, intense rainfall events increase in Japan, leading to more frequent landslides. The valley where this mudslide occurred was filled with at least 54,000m^3 of earth and rock blocks. About half of the mud flowed down, breaking through a concrete barricade built upstream and rushed into the community below. Thus, a major factor of the disaster may have been the government's conversion of residential land upstream of the catchment area, which led to a decrease in soil and water conservation capacity.

(3) Atami Mudflow on July 3, 2021

On July 3, 2021, a mudflow starting from the Aizome River hit Izusan in Atami. As a result, 26 people were killed and one was missing, 131 houses were fully or partially destroyed, roads were closed for 26 days; and water supply was suspended for 1,100 households. The mudflow occurred at least ten times. Water content was estimated to be 31–36% and velocity to be 8–11 m/s as rainfall of 20–30 mm/h was observed during the mudflow, in addition to the total rainfall of 500 mm four days before.

The mudflow of such a magnitude was a result of three main factors: i) Prolonged heavy rainfall. The frontal rain system stayed over Japan for a prolonged period and appeared with a high-pressure system over the Sea of Okhotsk. The slow-moving, almost stationary systems caused extreme weather events; ii) Land use changes in the affected area. For residential purpose, large-scale filling was conducted by the local government in 2011, exacerbating land exposure and soil erosion and making the valley prone to debris flow. The total volume of soil collapsed was 55,500 m^3 during this mudflow; and iii) Delayed decision making for evacuation. The local government issued the evacuation order as Level 5 Alert 35 minutes after the outbreak of the mudslide, which aggravated the impact of the mudflow.

(4) Floods in the Sendai River Basin on July 10, 2021

On July 10, 2021, a flood occurred in the Sendai River Basin after the seasonal plum rains frontal system and a relatively static convection system formed in the middle reaches invoked heavy rainfall that far exceeded the design capacity of local flood control facilities. No inundation from the major rivers was observed in this event thanks to flood mitigation measures implemented after the 2006 catastrophic flood, such as dredging rivers and building flood channels upstream and downstream. Flood control capacity of the Tsuruda Reservoir was sufficient owing to dam upgrading. Short duration and spatial distribution of rainfall was also conducive to water storage. As a result, casualties of this flood were much lower than those of the same period in 2006. However, the situation would have been worse if rainfall concentrated in the upper or lower basin.

The reason behind these mudflows and floods in July 2021 can be summarized as follows: The frontal rain system stayed over Japan for a prolonged period, and appeared with a high-pressure system over the Sea of Okhotsk (which is typical at the end of the rainy season from June to mid-July). The slow-moving, almost stationary systems caused extreme weather events.

3.6 2020 Michigan Dam Failures , the United States

In May 2020, dam failures occurred in Michigan, the United States, as a stalled low-pressure system and weather frontal developed in the southern Great Lakes brought intense rainfall to southeast Michigan. The rainfall reached 100–200 mm over three days from the morning of May 17 to the afternoon of May 19. Due to heavy rainfall, historic flooding already occurred in several rivers on May 18. In particular, the Tittabawassee River in Midland County experienced the worst flood in its history. Therefore, on the same day, all dams in the region were running with gates wide open. The Chappel Dam on the Cedar River upstream had an overtopping near the generator house on one side, but was able to mitigate and prevent failure after the efforts made by dam operators and engineers.

Dam failures occurred on May 19. At 0:30 am, dam operators became aware of the serious problem and worsening situation, thus initiating the emergency action plan process for all four dams on the Tittabawassee River to release a prompt warning message. At 3:30 am, Smallwood Dam sounded the siren because high water levels were concerning. From morning to afternoon, state government officials, safety office officials, and dam engineers were all working at the Edenville Dam site to address safety issues. Nevertheless, floodwater broke through the easternmost part of the Edenville Dam at 5:45 pm, causing the worst dam failure in Michigan's history, and continued to rush through the Sanford Dam at 8:00 pm. Although gates were already open, the water level at the Sanford Dam rose rapidly due to discharge from the Edenville Dam, finally leading to dam overtopping and outburst. The Tittabawassee River crested at 10.68m on May 20. Until May 22, inundation could still be observed on the satellite. This historic flood recorded the worst in the cities along the Tittabawassee River and caused grave damage to infrastructures such as buildings, roads, and bridges.

In this case, the Argonne National Laboratory referred to *A Guide to Public Alerts and Early Warnings for Dam and Levee Emergencies* issued by the United States Army Corps of Engineers, which focuses on how the public receives the warnings and takes prompt protective action. It helped nearly 11,000 people evacuate in advance, avoiding a night-time evacuation on dark. This case also shows that local awareness of flood risk was heightened due to the extensive flooding experienced in 2017, and community-wide concerns over aging infrastructure and dam maintenance and reliability were raised as well.

4 Major Response Strategies

This section provides a review of the latest flood-related strategies of major countries advanced in water management around the world.

4.1 The Netherlands: Adaptive Strategies for Flood Risk Management

(1) Delta Plan on Flood Risk Management

In 1953, the Netherlands was hit by the great North Sea flood caused by heavy storm surge and sea defenses breaches. Afterwards, the Dutch rainwater management began to rely on the massive engineering networks. The authorities for water resources, transportation and infrastructure launched the Delta Works as an effort in lowering or avoiding the impact of storm surges and river floods in the country, through strengthening the flood protection system consisting of coastal dunes, dikes and storm surge barriers. A total of 62 movable steel sluice gates were built nationwide, enabling the river dikes to protect the country fom a 1250 -year flood; and in Amsterdam, The Hague, and Rotterdam, the dike systems are capable of defensing a 10,000-year flood. The project further shortened the coastline by 700km through the construction of *Afsluitdijk* (sea dam), which contributed to promoting agricultural productivity, developing waterway and ports, and fostering new industries.

Figure 5 The Delta Works (consisting of four primary and six secondary barriers, distributed near the Rhine, Meuse and Scheldt rivers)
Source: Urban Planning International (Cao, 2019)

More recently, the Delta Plan on Flood Risk Management has become the new guideline in the Netherlands. Its typical features are linking short-term actions to long-term goals, valuing and incorporating flexibility, considering multiple strategies or adaptive approaches in a rational manner, and integrating different way of investment.

The Deltacommis, organized by a group of Dutch scientists and politicians responsible for governing and responding to floods, has defined acceptable levels of risk. Primary flood defense facilities are divided into four categories:

- Primary dikes that protect rivers, lakes and seas from flooding;
- Dikes and other infrastructures that connect continuous flood defense lines to dike protection regions;
- Primary flood defense measures aim to protect dike regions along rivers, canals and lakes with secondary hazards, or dikes separating two regions based on different safety standards (e.g., 1250- and 2000-year flood return periods);
- Primary dikes partially protect the Dutch dike regions, that are formally not under Dutch control as they are located in Belgium or Germany.

(2) Dutch Room for the River Program

Between 1993 and 1995, riverside residents in the Netherlands faced a worrying situation, when water levels became very high and dikes could barely controlled the water stage. This led to an evacuation of 250,000 residents out of safety consideration. The rising water levels also seemed to be worse and more frequent in the future. To that end, the government decided to secure higher discharge capacity of rivers to avoid flood events. In response, a national program - *Room for the River* was officially launched by water department, in a bid to give rivers more space to cope with higher water levels. Relevant measures were taken at more than 30 locations across the country to create more room for rivers to discharge the floodwater, while improving the environment and ecology of the riverine areas.

(3) National Strategy on Spatial Planning and the Environment

In the recent decade, some European cities have transformed from traditional "gray infrastructure" to nature-based solutions, in order to improve the urban capacity of retaining and purifying water, reduce economic losses from floods and droughts, towards more livable cities. The Netherlands is attempting to build more "Blue-Green Infrastructure (BGI)", yet the implementation of sponge cities is governed by decisions made at local level, e.g. municipal level. Accordingly, the implementation of sponge city elements is not yet fully mainstreamed.

The Netherlands has recently announced a new strategy called the National Strategy on Spatial Planning and the Environment (NOVI), which provides a sustainable perspective for urban development programs involving areas including water and soil system, so as to address the imbalance between urban growth and ecosystem (or its services) conservation. Specific principles include: (1) By introducing BGI, the resilience of the city to water crisis such as droughts, floods, and water pollution will improve. BGI can also provide important additional ecosystem services and sociocultural benefits, and enhance the adaptability of the water system to uncertain future changes in climate and land use; (2) Interventions should foster or contribute to the preservation or restoration of indigenous (man-made) water systems. In many cases, most of the indigenous water systems no longer exist in modern cities as canals and detention ponds have been landfilled to meet the huge land demand of urban development. These indigenous water systems have evolved over many decades or even centuries. Restoring indigenous water systems to the maximum extent will promote sustainable development; and (3) Interventions should contribute to better overall performance of the city. These interventions should not conceived as isolated, ad hoc interventions, but as ones that are interactive and impactful to the entire urban water system. Adopting this principle requires a strategic and integrated approach at the city-scale, and sustainable management of stormwarter without shifting its problem to the neighboring area.

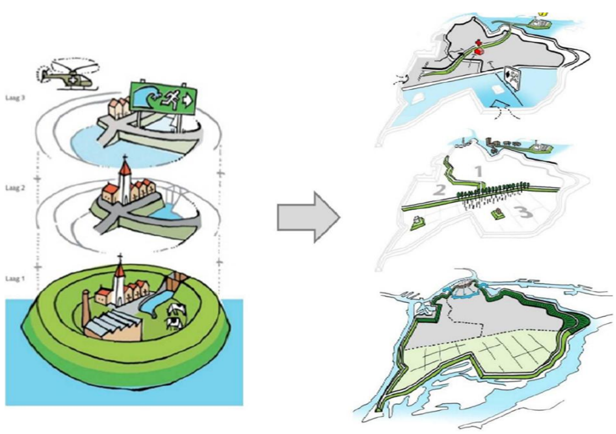


Figure 6 Multi-layer Protection Program in the Netherlands Source: Dutch National Water Plan (2008)

Figure 7 Resilience to Flood in Dordrecht
Source: EPA

(4) The Multi-Layer Safety Approach

Due to factors such as unique geographical location and climate change, the Dutch efforts on flood resilience began in 2008 through the multi-layer safety (MLS) approach by constructing a three-layer resilience system. The three layers include: (1) Protection, i.e. the primary dike system (10,000-year flood protection standard). Standards for flood control structures are established based on flood risk and disaster loss analysis to foster a system of flood control structures; (2) Sustainable spatial planning. The national space is zoned by secondary dikes and water structures for multiple purposes, with the concept of "Room for the River"being highlighted; and (3) Emergency response and disaster relief, which mainly deal with extreme floods, including better coordination between emergency service providers, managerial decisions, communication models and evacuation plans, building more flood resilient cities such as Dordrecht.

4.2 Japan: River Basin Disaster Resilience and Sustainability by All

Japan has experienced floods multiple times since 2013. Drawing upon the lessons learned from frequent floods, the country continues to revise its flood management measures accordingly. In May 2015, the Flood Risk Management Act was amended, stipulating the maximum amount of rainfall for possible rescue operations. Later, Rebuilding Flood-Conscious Societies, a policy outlining that large-scale “Class A” rivers shall be managed by the national government, and small and medium“Class B” river basins shall be managed by prefectural governments, were issued. The policy have played a positive role in raising public awareness of flood control, protecting injured victims and disabled groups, as well as promoting economic development, etc. In May 2017, the Flood Risk Management Act was further amended; the Mega-Flood Management Committee was set up, and drilling for emergency evacuation and accessible transfer for disabled groups were carried out. In 2020, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan undertook a large-scale flood management reform by introducing a new policy of River Basin Disaster Resilience and Sustainability by All. In the past, Japan’s flood control relied on structural measures with clear role allocation, implemented mainly in river basins and floodplains by administrators from divisions involving rivers, sewage, erosion and sediment control, and coastal management. The new policy considers river basins as spaces that include watershed and floodplains, and takes comprehensive, multi-layered actions, including flood prevention, exposure reduction and disaster resilience. It calls on all stakeholders in river basins, including the national government, prefectures, municipalities, private enterprises, residents, and water users, to take actions for enhancement in disaster resilience and sustainability.

In response to this new policy, the Japanese Government reformed the legal framework and planned investment strategies. River administrators across the country have begun to upgrade long-term river management policies and revise medium-term river improvement plans. Meanwhile, the concept of “Society 5.0” was proposed as a new blueprint for Japan to build a technology-based society by establishing digital institutions and accelerating social digital transformation.

(1) Flood Prevention

In catchments, rainwater harvesting and storage facilities will be improved, and agricultural reservoirs will be effectively used for flood control. These measures are expected to be implemented by prefectures, municipalities, enterprises, and residents. In river areas, construction, upgrades, and effective use of dams and pre-discharge in water utilization dams will be combined for flood control. In addition, flood detention capacity integrally with land use will be upgraded; river channel excavation will be carried out while setting back levees and improving erosion control dams and rainwater drain facilities to ensure and improve the discharge capacity of river channels;

levees will also be strengthened to make them last a long time even when overlapping.

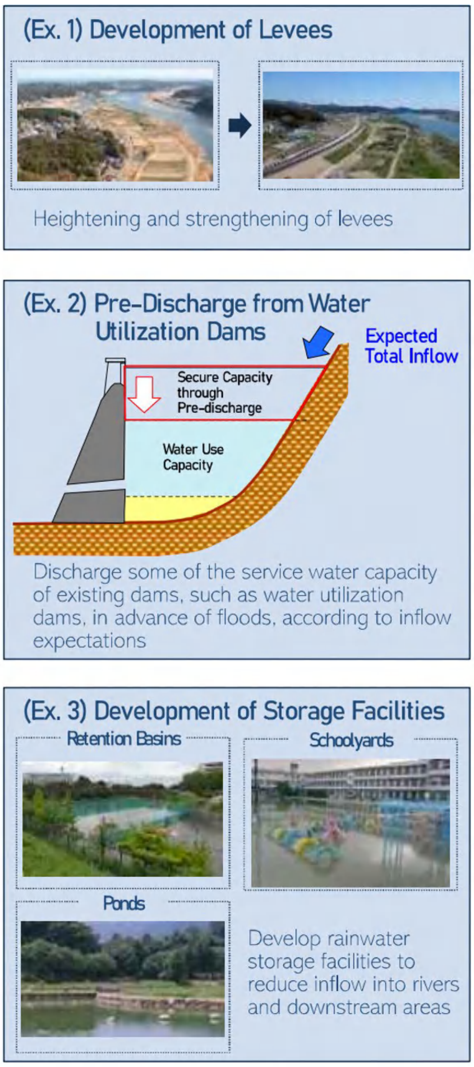


Figure 8 Examples of Flood Prevention
Source: Ministry of Land, Infrastructure, Transport and Tourism, Japan (2020)

(2) Exposure Reduction

In floodplains, land use restrictions should be considered while encouraging relocation, and flood risk information should be visible in real estate transactions while improving credit instruments. Local residents will be guided to lower risk areas, promoting safer ways of living. Inundation areas will be localized by installing bank structures and utilizing existing facilities to function as secondary levees.

Figure 9 Examples of Exposure Reduction
Source: Ministry of Land, Infrastructure, Transport and Tourism, Japan (2020)

(3) Disaster Resilience

In floodplains, risk information will be ensured in sufficient area by promoting the designation of probable inundation zones. Evacuation systems will be reinforced by developing long-term prediction technologies and acquiring real-time inundation and breach detection technologies. To minimize economic damages, anti-inundation measures should be prepared with business continuity plans (BCPs) for factories and buildings. To promote safer ways of living, flood risk information should be provided in real estate transactions while promoting anti-inundation preparedness through financial tools. Technical support systems will be improved for affected local governments by strengthening the Technical Emergency Control Force (TEC-FORCE, managed by MLIT). Also sluice gates should be improved to eliminate inundation promptly.

As a key water organization in Japan, the International Centre for Water Hazard and Risk Management (ICHARM) under the auspices of UNESCO contribute to this new policy by creating and sharing scientific knowledge, enhancing resilience and sustainability, and increasing the capacity of society to cope with disasters. ICHARM will make efforts in the five priority areas under the IHP, and strengthen its international information network to better understand water-related hazards in other countries/regions. ICHARM is also dedicated to tranning professionals that could make contributions to a resilient and sustainable society, and to share scientific knowledge based on Japanese experience.

Figure 10 Examples of Disaster Resilience
Source: Ministry of Land, Infrastructure, Transport and Tourism, Japan (2020)

4.3 The United Kingdom: Flood Management and Climate Resilience Roadmap

(1) National Flood and Coastal Erosion Risk Management Strategy Roadmap

In June 2022, the Environment Agency of the United Kingdom officially launched the Flood and Coastal Erosion Risk Management Strategy Roadmap (abbreviated as FCERM), which sets out the actions to be taken over the next four years to tackle various types of flooding and coastal erosion, representing a major step forward in adapting to the changing climate.

Underlined by the Roadmap, at least one in six people in England are exposed to river and coastal flooding, with many more at risk of surface water flooding. This calls for better planning for and adaptation to the impacts caused by climate change, while making every effort to protect risky communities to ensure minimum damage to people and properties from flooding and coastal change. The Roadmap outlines a long-term vision of creating a nation resilient to flooding and coastal change to the year 2100, with 3 ambitions underpinned by a set of strategic objectives and measures including climate-resilient places, infrastructure resilience and public awareness. The Environment Agency will be delivering the Roadmap with many partners including local authorities, local drainage boards, farmers, environmental groups, infrastructure providers and the insurance sector. The Roadmap will directly support the implementation of the £5.2 billion Programme of Flood and Coastal Erosion Risk Management investment, and also incorporate the government's £200 million Flood and Coastal Resilience Innovation Fund.

Key actions from the Roadmap include:

(i) Developing a new national assessment of different flood risks that will provide data and mapping to inform future risk and investment decisions;

(ii) Working with coastal groups to update the policies and actions in Shoreline Management Plans so they reflect adaptation to a changing climate;

(iii) Working with national infrastructure providers, including National Highways and Network Rail, on joint investment opportunities to improve the resilience of national infrastructure;

(iv) Working with the Water Services Regulation Authority (Ofwat) to ensure that water company assets are resilient and contribute to better flood risk outcomes;

(v) Working with Natural England, the Wildfowl & Wetlands Trust, and other partners to collate evidence and case studies to help mainstream nature-based solutions;

(vi) Working with Flood Re and the insurance sector to develop a communications program for homeowners to signpost advice and support on the benefits of property flood resilience; (vii) Developing new training materials with the Town and Country Planning Association to help improve skills and capabilities on flood risk and development planning;

(viii) Working with the Environment Agency's supply chain to ensure all flood and coastal projects adopt low carbon technologies that contribute to zero carbon targets;

(ix) Continuing to improve the Environment Agency's digital public platform on flood risk and early warning; and

(x) Working with the Department for Education, schools, and children's charities to improve young people's knowledge of flood risk and climate change.

(2) Property Flood Resilience

Over the past two decades, the United Kingdom has experienced a number of floods that have posed a grave threat to individual and commercial properties across the country. To reduce flood-caused losses, the government began to put more emphasis on property resilience to flood. The Property Flood Resilience Roundtable in 2015 suggested that the government is responsible for helping the public protect their own properties from flooding, and therefore proposed an action plan to improve property flood resilience. After one year, the Property Flood Resilience Action Plan was published by the UK Department for Environment, Food and Rural Affairs, which guides the implementation of measures to improve the flood resilience of private and commercial properties.

Figure 11 Property flood resilience measures in the United Kingdom
Source: BeFloodReady

4.4 The United States: Latest Climate Plans and Water Management Strategies

In recent year, the United States has developed a set of plans and strategies regarding climate change and water security to mitigate and tackle climate-driven disasters.

(1) Climate Adaptation Plan 2022 Progress Report

The Department of Defense (DoD) of the United States, along with other federal agencies, released the Climate Adaptation Plan 2022 Progress Report in October 2022 (DOD News, 2022; IITE, 2022). DoD has identified climate change as a security issue that is critical to the country. The Progress Report summarizes the steps DoD has taken to address climate-related challenges since the Secretary of Defense Lloyd J. Austin III signed the 2021 Climate Adaptation Plan on September 1, 2021.

Some of the main updates of actions are demonstrated here: (1) Implement climate-informed decision-making by incorporating climate considerations and energy resilience into key strategy and planning documents to operationalize climate adaptation and mitigation (priority strategy); (2) prepare, through training and equipment, combat forces capable of operating under the most extreme, adverse weather and terrain conditions (priority strategy); (3) improve the resilience of natural infrastructure (priority strategy); (4) assess supply chain resilience and how purchasing power can be leveraged to spur technological innovation and deployment, and build a network of domestic and allied supply chains to meet national security needs (priority strategy); (5) enhance climate adaptation and resilience by strengthening and expanding partnerships (priority strategy); (6) assess climate risk and vulnerability through online data tools to achieve mitigation goals; (7) incorporate climate change into education and training programs across the military and civilian workforce; (8) encourage more engagement of native tribes in virtual sessions listening to their demands for climate adaptation; and (9) consider environmental justice into decision making.

(2) White House Action Plan on Global Water Security

The Biden-Harris administration released the White House Action Plan on Global Water Security in June 2022 (White House, 2022). The Action Plan states the role of water as the source of life and its significance in powering global economy. It also quotes the definition of water security as outlined by the United Nations, which implies sustainable access to safe drinking water, sanitation, and hygiene services, as well as water to sustain ecosystems and for agriculture, energy, and other economic activities. The Action Plan underscores the ties among water resources, climate disasters and social stability, suggesting that sound water reserves and good water quality could contribute to higher quality of life for people.

To achieve the vision of a water-secure nation, the Administration identified 3 key accordingly:

1. Advancing the US leadership in the global effort to achieve universal and equitable access to sustainable, climate-resilient, safe, and effectively managed WASH services. The United States will work with local, national, and trans-national governments; regional entities; implementing partners; civil society organizations; and the private sector to jointly drive progress in this regard;
2. Promoting sustainable management and protection of water resources and associated ecosystems to support economic growth, build resilience, mitigate the risk of instability or conflict, and increase cooperation. The United States will make substantial efforts in water data collection and provide training on available tools to support data collection; provide expert technical assistance that increases the capacity of water management institutions; and encourage and support the development of water use agreements among stakeholders who share water resources; and

3. Ensuring that multilateral actions could mobilize cooperation and promote water security. The US government will elevate efforts to promote water cooperation through regional and multilateral fora, including but not limited to the Group of Seven (G7), the Group of 20 (G20), the United Nations, and associated organizations and initiatives.

Figure 12 Monocrystalline silicon solar panels are placed for energy production at Lackland AFB, Texas
Source: DOD News (2022)

Figure 13 A helicopter drops flame retardant onto a forest fire
Source: DOD News (2022)

5 Summary

The water cycle could intensify by 2–4% per °C increase in global average temperature. Relevant studies project that a future 2°C increase in temperature (the upper limit of the Paris Agreement target) would enhance the global water cycle by at least 4–8%. Globally, 3,254 flood events occurred from 2000 to 2019, accounting for the highest percentage of 44% among various natural hazards, and less than 40% of the area was impervious. From 2000 onwards, the proportion of the flood-hit population has risen by 24%, with the increase by more than 20% in 40 countries. It is evident that the frequency and coverage of floods and the proportion of the affected population have all expanded since the 21st century as the global water cycle has accelerated over time. This report statistically analyzed 49 typical flood events taking place during 2020–2022. The results showed that the growth rate of extreme flood events soared from 20% to 125%; Asia, Africa, North America, Europe, South America and Oceania experienced 38.8%, 18.4%, 14.3%, 12.2%, 8.2% and 8.2% of the total flood events respectively. The severity of flood increased as well; for example, the 2022 Pakistan floods caused economic loss more than 75% of the total economic losses by floods over the past 70 years.

In the face of more frequent flooding events, countries have adopted a series of strategies and measures accordingly, specifically both in structual and non-structual way. Structural methods include dike safety management measures. As introduced in Chapter 4, the Netherlands has launched the Delta Plan on Flood Risk Management, raising the standards of dikes with the Zuiderzee Works and the Delta Works as major projects; and lately towards a resilience planning, which regulates soil and water resources through spatial planning. The United Kingdom has put more emphasis on the flood resilience of buildings in recent years, and released an action plan on property flood resilience in 2016 to provide guidance for the public on actions to improve flood resilience of private and commercial properties. Non-structural methods require new policies and actions incorporating flood resilience building and public awareness raising, etc. For example, UNDRR announced that the 2022 International Day for Disaster Reduction focused on the theme of "Early Warning, Early Action". This showcased a UN effort to take the lead in actions through applying technologies such as informatics and digitalization, in a bid to ensure that every person all over the world is protected by early-warning systems within five years. Japan's policy of "river basin disaster resilience and sustainability by all" calls on all basin-wide stakeholders, including the national government, prefectures, municipalities, private enterprises, residents, and water users, to take joint actions for disaster resilience and sustainable development. Major non-structural methods include pre-disaster preparation and emergency evacuation based on early warning; seeking public support so that local governments could carry out pre-disaster preparation and emergency evacuation in a prompt manner; climate change impact assessment to support better post-disaster reconstruction; and community-based emergency evacuation drills to achieve mutual support and self-help. For instance, in the United States, DoD has identified climate change as a critical national security issue, incorporated climate change into education and training programs across the military and civilian workforce, and invited various native tribes to virtual listening sessions, etc.

Future flood control strategies may need to further combine both structural and non-structual measures, and draw upon nature-based solutions that integrate green, blue and gray spaces within basins or cities through multi-purpose and targeted programs, with a view to achieving flood management goals and promoting social, economic and environmental sustainability in a holistic way.

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