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Opportunities and Challenges

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“Putting People at the Heart of What We Do”

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and delivered by

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INTEGRATED & ADAPTIVE FLOOD MANAGEMENT IN THE CONTEXT OF NATIONAL WATER POLICY

Ahmed Kamal

ABSTRACT

In Pakistan till 1976, main flood protection strategy was limited to construction of flood protection structures only, for which, Provincial Governments were responsible. However, after the disastrous floods of 1973 & 1976, national-level flood management through preparation of comprehensive flood protection plans was included through the placement of Federal Flood Commission at the national level mandated to ensure integrated flood management on country wide-basis through both structural as well as non-structural measures. The concept of integrated flood management lies within the framework of the Integrated Water Resources Management (IWRM). It considers the river basin as a unique dynamic system in which interactions between land and water resources ensure that every single change affects the other components in a positive or negative way. Pakistan’s first ever National Water Policy (NWP) recognizes the fact that climate induced intensification of floods, and erratic monsoon rains are major concerns for Pakistan. Water resources are inextricably linked with climate change and any change in climate is felt primarily through a change in water; frequency and intensity of water-related natural disasters/floods is, therefore, expected to increase with climate change. To address this, NWP outlines objectives closely relating to Integrated & Adaptive Flood Management (I&AFM) like: flood management to mitigate floods and minimize their damages; profitable use of flood water towards promotion of local irrigation practices; establishment of hydro-meteorological disaster risk reduction complied integrated water resources management regime; exploitation of vast potential of water generated through hill torrents; climate change impact assessment and adaptation for sustainable water resources development and management. The Policy advocates to pursue these objectives in the country through a number of interventions including: updation of flood protection plans, flood plain mapping and zoning, enactment of river act, modification/revision in reservoir operation rules, more robust and effective use of non-structural measures, hill torrent management for water conservation, nation-wide flood telemetry master plan and its implementation besides

1 Chief Engineering Adviser/Chairman Federal Flood Commission, Government of Pakistan, Chairman, Pakistan National Committee on Irrigation & Drainage (PANCID)
community based flood disaster management etc. The paper is an attempt to see the present pace of progress on implementation of these objectives taking them as a holistic framework of implementation of integrated and adaptive flood management approach.

**Keywords:** Flood protection, river basin, dynamic system, National Water Policy, erratic monsoon rains, climate change, integrated and adaptive, hydro-meteorological disaster risk reduction, enactment, reservoir operation rules, flood telemetry, Pakistan

1. **Introduction:**

The traditional approach to floods focused on reactive practices to reduce exposure to flooding and susceptibility to flood damage, mainly through structural measures. In the course of time, these ad-hoc interventions proved to be only partially effective and the acknowledgment of the necessity of a wider multi-disciplinary approach led to a paradigm shift from flood control to flood management.

Till 1976, main flood protection strategy was limited to construction of flood protection structure only, for which, Provincial Governments were responsible. However, after the disastrous floods of 1973 & 1976\(^2\), national-level flood management through preparation of comprehensive flood protection plans was included.

For that purpose, in January 1977, Federal Flood Commission (FFC) was established by the Federal Government. FFC was mandated to ensure integrated flood management on country wide-basis through structural as well as non-structural measures.

Important functions assigned to FFC towards non-structural management of floods included improvement of the flood forecasting & warning system and recommendations/SOPs for flood routing through the reservoirs.

The office of Chief Engineering Advisor was then designated as ‘Secretariat of FFC’; and subsequently it was renamed as Office of Chief Engineering Advisor and Chairman Federal Flood Commission (O/o CEA/CFFC).

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\(^2\) 1976 floods resulted into direct economic loss of US $ 3,485 million while that of 1977 US $ 338 million; life loss related to these two successive events was 425 No. and 848 No. respectively.
2. **Integrated & Adaptive Flood Management in the context of NWP:**

The concept of integrated flood management (IFM) lies within the framework of the Integrated Water Resources Management (IWRM). It considers the river basin as a unique dynamic system in which interactions between land and water resources ensure that every single change affects the other components in a positive or negative way. IFM aims to promote coordinated management of water resources so as to maximize the net benefits from flood plains while minimizing loss of life and damage to other properties.

Pakistan’s first ever National Water Policy (NWP) recognizes the fact that climate induced intensification of floods, and erratic monsoon rains are major concerns for Pakistan. Water resources are inextricably linked with climate change and any change in climate is felt primarily through a change in water; frequency and intensity of water-related natural disasters/floods is therefore expected to increase with climate change.

### 2.1 Policy Objectives on Integrated and Adaptive Flood Management:

Following policy objectives closely relate to I&AFM in Pakistan (Para-2 of NWP):

a) Flood management to mitigate floods and minimize their damages;
b) Profitable use of flood water towards promotion of local irrigation practices;
c) Establishment of Hydro-meteorological disaster risk reduction complied integrated water resources management regime;
d) Exploitation of vast potential of water generated through hill torrents; &
e) Climate change impact assessment and adaptation for sustainable water resources development and management.

Some of the objectives of NWP indirectly relate to flood management as they focus on cross-sectoral decision-making process and participatory approach required for ensuring I&AFM (Para-2 of NWP):

a) Promoting measures for long term sustainability of the Irrigation System;
b) Improving watershed management through extensive soil conservation, catchment area treatment, preservation of forests and increasing forest cover;
c) Promoting appropriate technologies for rain water harvesting in rural as well as urban areas;
d) Rainwater management in plains where it cannot be disposed of/diverted to the river;

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3 Approved by CCI on April 24, 2018
e) Upgrading water sector information systems for improved asset management and to derive evidence and data driven decision making; &

f) Promoting research on water resources related issues of national importance and building capacity/delineating roles and responsibilities of Federal research institutions and promoting coordination among them.

3. **National Targets under NWP for IWRM and I&AFM:**

To ensure integrated water resources and flood management in the country, NWP has set six (6) national targets to be achieved by 2030 which include:

(i) 33% reduction in the 46 MAF river flows that are lost in conveyance;

(ii) An increase of 10 MAF in existing water storage capacity mainly through construction of the Diamer-Basha and Mohmand Dam Projects;

(iii) At least 30% increase in water use efficiency;

(iv) Gradual replacement and refurbishing of decades old irrigation infrastructure;

(v) Real-time monitoring of river flows through inter alia telemetric monitoring to maintain transparent water accounting system; &

(vi) Development of a standardized and uniform mechanism for data collection of various parameters of water resources

3.1 **Investment Plan:**

To achieve IWRM and I&AFM targets by 2030, total investment needed by Pakistan’s Water Resources Sector, worked out in 2018 was Pak Rs 3,066 billion (US$ 27 billion), out of which, Pak Rs 186 Billion (US$ 1.7 billion) have been exclusively kept for flood control as federal contribution, especially for implementation of 4th National Flood protection Plan (NFPP-IV).

NWP advocates to pursue integrated flood management in the country through following important interventions:

a) **Updation of Flood Protection Plans** (National as well as Local) on a periodic basis - *NFPP-IV stands approved by the Government and a project based on it is under approval*;

b) **Flood Plain Mapping and Zoning** along River Indus and its tributaries (Kabul, Swat, Jhelum, Chenab, Ravi & Sutlej) - *In the back drop of 2010, 2011 & 2012 floods, Flood Plain Inundations Maps stand updated/ prepared*;
c) River Act for restricting/prohibiting permanent settlements in high and medium flood risk areas; to avoid growth of such developments in flood hazard areas that would make the flood protection facilities vulnerable to failure - *FFC prepared River Act for regulation of river’s flood plains and encroachments and circulated among the Provinces for enactment.*

d) Review of Reservoir Operational Rules and their optimization to ensure efficient and prudent decisions to control floods provided, however, that the safety of the dam, embankments, spillways, dam abutments, foundations and all other hydraulic structures is to be placed at no risk under any condition; (*SOPs for Mangla and Tarbela reservoirs have been updated and being exercised by the concerned dam authorities*);

e) Effective use of non-structural measures like flood forecasting and early warning systems to minimize flood losses through better forecasts and warning, through additional forecasting facilities, e.g. radars, and other monitoring equipment and flood forecasting computer software incorporating rainfall-runoff and hydrodynamic models; (*Necessary provisions being ensured through a separate project*);

f) Construction of additional flood protection facilities and improvement of existing infrastructure with greater emphasis on proper maintenance of the existing infrastructure; (*Necessary provisions being ensured through a separate project*);

g) Hill torrent management for conservation and mitigation of floods, on priority; (*Necessary provision being ensured through separate project*); &
h) Encourage community based flood disaster management initiatives; (*being ensured through concerned departments/stakeholders who are also members of FFC*).

The implementation of NWP recommendations aim at implementation of other important Government policies/plans like Vision-2025 of Planning Commission of Pakistan, National Climate Change Policy, National DRR Policy and Vision-2030 on water resources development in addition to better complying with the global frameworks like Sendai Framework on DRR, Climate Agreement/NDCs and SDGs etc. with regard to management of all sub-sectoral and cross cutting issues relating to water.

4. National Master Plan for Flood Telemetry

National Master Plan is the first of its kind ever developed in Pakistan. It will not only be a major improvement in our present flood management system, but it will also help in building confidence between the provinces in water distribution.

4.1 Rationale

The rational prevention of natural disasters, such as floods and droughts, is
strongly connected with a forecasting technology which cannot be achieved without hydro-meteorological observations. Adequate and accurate hydro-meteorological data at fine time scale is very important and it is essential to improve the monitoring infrastructures by taking advantage of modern technologies for remote areas and data management for performing a range of hydrological studies.

The existence of a dense telemetry network of instruments is found imperative to be able to model, predict, and plan for catastrophic events which have obvious negative impacts on public health and socioeconomic aspects in the country. To achieve the goal of better and advance monitoring of hydrological parameters through establishing telemetry networks, NFPP-IV was formulated in 2017, that aimed at improving the country-wide comprehensive flood management plan with focus on acquiring real time hydro-meteorological information through telemetry network for better flood forecasting.

NWP recommends telemetric monitoring as one of major interventions required to be implemented by 2030. It is one of the important national targets of NWP to ensure real-time monitoring of river flows through inter alia telemetric monitoring. NWP has also fixed target to maintain a reliable assessment of water resources in the country, federal and provincial water sector organizations must develop a standardized and uniform mechanism for data collection under a Master Plan.

4.2 Plan Scope

The Flood Telemetry Master Plan covers the following aspects:

- Inventory of Existing Hydrological Network in all Provinces with GIS Maps.
- Inventory of on-going installations for Hydrological Networks with GIS Maps.
- Proposed Flood Telemetry Networks for all the Provinces on minimum requirement basis with GIS Maps. along with implementation priorities; category
- Operation and Maintenance Mechanism for sustainable operation of the network.
- Establishment of Digital Hydro Data Center in Lahore under WAPDA, FFC would act as Co-Host.
- Establishment of Hydro-met Testing and Calibration laboratory

The Flood Telemetry Master Plan includes data acquisition through telemetry and Data Management through establishing Digital Hydro Data Center
Therefore, already installed manual stations are being recommended to be upgraded to new telemetry station network.

### 4.2.1 Basic Concept of Flood Telemetry Master Plan

The basic concept of this Flood Telemetry Master plan is presented in the Figure-1. The establishment of a Digital Hydro Data Center (DHDC) with WAPDA in Lahore, FFC as Co-host and Regional Data Centers in all the Provinces /Federal Line Agencies (FLAs) are recommended for an integrated data management. In addition, Data Ports would also be provided to all regional offices of Pakistan Meteorological Department (PMD) and Indus River System Authority (IRSA).

![Figure-1: Schematic map of Inter-connected Hydro-meteorological Observation Network and Data Centers](image-url)
4.3 Progress on other related Recommendations of NWP

Based on the objectives and national targets given in NWP and subsequent investment plan, share/ allocation for the water sector in Federal Public Sector Development Programme (PSDP) had increased during the last few years in line with target (of 20%) set by NWP for 2030. The provinces have also been requested to enhance their water sector allocation under their respective Annual Development Programmes (ADPs).

The present progress, towards achievement of flood management related NWP targets is given in a glance below:

4.3.1 Construction of Water Storages/Dams

Work on two mega dams (Diamer Bhasha Dam with live storage capacity of 6.4 MAF and Mohmand Dam with live storage capacity of 0.67 MAF) has been started. In Punjab Province Ghabir Dam, Papin Dam Project and Cherah Dam Project are under construction in Islamabad region through federal PSDP.

4.3.2 Rainwater Harvesting

In Sindh province, 28 small storage dams have been completed through federal funding whereas 7 more are in progress. Total storage capacity of the completed reservoirs is 166,743 acre-feet (i.e. 0.167 MAF), whereas, 85,191 acres area shall be benefitted. Under provincial ADP, 36 projects of construction of small storage dams / delay action dams, retention weirs and I.S.S.O (Impervious sub surface outflow) barriers have also been completed and 12 are in progress under provincial ADP. The total storage capacity of the completed dams is 230,951 acre-feet (0.231 MAF) whereas 91,409 acres shall be benefitted.

In Khyber Pakhtunkhawa (KP) 13 No. of small dams have been completed while 14 No. small dams are under various stages of execution. Reportedly work on two dam projects has also been started through financial assistance provided by the World Bank.

Consistent with NWP, Rainwater Harvesting is a relatively new and innovative concept being used in the country for water conservation for crops and livestock as well as groundwater recharge. Based on the countrywide data received so far 3,606 rainwater harvesting schemes in KP, 180 in Punjab and 60 schemes in Sindh have been completed.

4.3.3 Modernization of Irrigation and Drainage System

Provincial Irrigation Department (PID), Sindh is implementing a ‘Water Sector Improvement Project’ which aims to modernize irrigation & drainage system in a systematic way and deal with floods & drainage issues so as to increase agricultural production, employment and income through irrigation of over 1.8 million ha in Sindh province. The total cost of project is Rs. 30,353 million, out
of which World Bank Loan is Rs. 28,840 million and Rs. 1513 million is Sindh share. Overall progress is 85%.

PID KP has planned to expand/rehabilitate irrigation network in order to bring 300,000 acres additional area; increased ADP (from 7.4% to 11%).

Irrigation Department, Government of the Punjab has completed the rehabilitation/remodeling & modernization works at Jinnah, Taunsa, Baloki, and Khanki Barrages whereas rehabilitation/remodeling & modernization work was near completion at Sulemanki (99.96%) and in progress at Trimmu (91%) and Panjnad (52%). New Khanki Barrage has the enhanced capacity 11.0 lac cusecs as against old capacity of 8.5 lac cusecs. Capacity of Baloki Barrage has been increased from 2.25 lac cusecs to 3.8 lac cusecs.

Rehabilitation work at Trimmu (with capacity to be enhanced from 6.45 to 8.65 lac cusecs) is planned to be completed by June 2022. Rehabilitation work at Panjnad Barrage (with capacity enhancement from 7.00 to 8.65 lac cusecs) is likely to be completed by June 2022. In Sindh, rehabilitation and modernization of Guddu Barrage and its associated structures is under process. Rehabilitation of Sukkur Barrage is also ongoing.

Baran Dam Raising has been taken up by Irrigation Department, Government of KP which envisions raising the dam height from present 120 feet to 142.90 feet (by 7 meters), thus increasing its storage capacity from 12,500 acre-feet to 100,000 acre-feet.

REFERENCES

https://ffc.gov.pk/maps-2/
MEASURES TO CONTROL RIVERINE FLOODING IN THE CENTRAL INDUS BASIN: LEARNING FROM PAST EXPERIENCES

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ABSTRACT

The changing climate and increased frequency of natural disasters have provoked government agencies to better management in Pakistan. In the study, structural and non-structural measures opted to control the flooding scenarios in the central Indus basin are highlighted. The institutional level policy-making procedures are redefined and computer-aided new technologies are introduced in the Punjab Irrigation Department – PID, Pakistan. The flood risk and vulnerability are tried to reduce through the implementation of climate change adaptation (CCA) and disaster risk reduction (DRR) strategies. The Indus basin is facing low to high-intensity flooding scenarios almost every year in the recent past. Since the partition (1947 – 2015), flooding has caused a financial loss of more than 38 billion US dollars. The death poll indicates more than 12,000 human life lost and land degradation of about 0.7 million km is reported. The projected climate scenarios have suggested an increased frequency and intensity of floods in the future. The paper tries to review the flood management measures (structural, non-structural) practiced in Pakistan and mitigation strategies opted for by the PID after the disastrous flood of 2014.

Keywords: Indus Basin, Flood Management, Disaster, Climate Change, Punjab, Pakistan

1. Introduction

Climate change has affected livelihood all around the world in many ways. The abrupt behaviour of global meteorological systems has become more intense resulting in the frequent occurrence of natural disasters (Munir, B.A et al., 2016; Munir, B.A., 2021). Fluvial floods form an unavoidable consequence of hydrology and topography characterizing a certain river basin. The changing behaviour of rainfall cause flooding and in most cases the flooding is resented by the people living in affected areas.

Globally, more than 520 million people are affected by natural disasters. However, 400 million people of total are directly affected by floods. The frequency of affected people is clustered mainly in Asia continent. During the period 1987 – 97, about 228,000 lives were lost in Asia accounting for 93% of flood related deaths. While more than 25000
people are killed every year by floods and other natural disasters. The estimated loss caused by these natural disasters ranges between 50 – 60 billion US dollars annually. The number of people affected by catastrophic floods may increase from one billion to double this number by 2050 (UN, 2004).

Pakistan is classified as among the most vulnerable countries that are prone to the changing climate. Climate change and substantiated natural disasters cause billions of dollars in loss to the economy of Pakistan, costing approximately 5% of the GDP – Gross Domestic Product. The frequency of catastrophic floods may increase to double by 2050. In recent decades, Pakistan has experienced two major flood events in 2010 and 2014. In August 2010, more than 1800 causalities were recorded and financial damages in the range of tens of billions of US dollars were reported in post flood assessments (Baig 2008).

The nature of flood types depends upon the geography of the area. The Indus fluvial plains are characterized as the most devastating due to the flat terrain, high population density, and economically developed conditions (Atiq et al., 2012). Torrential streams/Nullahs are the second most devastating source of flash floods in Pakistan. Cloud burst events and intensive rainfall at the local scale are also observed at other locations in Pakistan causing the inundation of urban settlements. The breaching of small dams causes an exceptionally high flood scenario in February 11, 2004. The Shadi Kor dam in Pasini was breached washing out more than 135 people in the Balochistan Province (IFRC, 2005; Javed and Baig, 2005).

The adverse topography of Pakistan tends to the spatial trends and high variability of the rainfall. The rangeland covers 59.3% of the total area receiving < 200 mm of the annual rainfall (ISDR 2005). The northern alpine region (Himalaya Range) receives more than 1000 mm of rainfall. The area is the main origin of monsoonal activities in Pakistan.

2. Fluvial Floods – Indus Basin

The Indus basin has an approximate area coverage of 944,000 km². However, 60% of the Indus basin lies in Pakistan (MoE, 2003). The Indus basin with its tributaries (Jhelum, Chenab, Ravi, and Sutlej) receives a major contribution of annual rainfall in the monsoon season (July – September). Furthermore, the catchment areas in the high altitudes contribute to the river flows by the means of snowmelt. Rivers in Pakistan experience very large variations of flow over the year. Normally the flood season is reckoned from July 1st to the end of August, but Chenab, Jhelum and eastern rivers in some years’ experience exceptionally high floods in September (Atiq et al., 2012).

The high flows are mainly controlled by Tarbela and Mangla in the Indus and Jhelum River basins respectively. There is no such main reservoir over the Chenab, Ravi, and Sutlej rivers’ catchments, which substantiates the high risk of floods in the lower plains of these catchments. However, the number of floods controlling structures (Headwork/Barrage) actively plays their role during the flood seasons in the eastern tributaries of the Indus Basin (Chenab, Ravi, and Sutlej). The main purpose of these structures is to control the high flood waves during the flood peaks in the monsoon season (Aslam, M 2018). However, these structures are used to divert the flows in the canals as per designed requirements. The spatial distribution of existing structures is shown in figure 1.
The Chenab River has a high frequency of historical floods. The high frequency of flood (Chenab River) represents the combination of snowmelt and rainfall induced systems (NDMA, 2013). The lack of flood control structures in the upper Chenab catchments also increase the risk of flood in the down plains. Furthermore, Ravi and Sutlej River catchment flows are controlled by the Indian territories. India has constructed multiple dams on Chenab, Ravi, Sutlej and Jhelum River catchments. Therefore, recorded flows are considerably lows at these rivers. The abrupt and sudden releases from Indian dam sites in the combination with monsoon rainfall systems results in high floods in these rivers. These rivers are also classified as snow-fed, therefore early spells of monsoonal rainfall sometimes combine with the peak snow melt rates resulting in high to exceptional high flows at Marala barrage (the most upstream river structure in Pakistan – Chenab River), Mangla reservoir (Jhelum river) and Tarbella (Indus river). Generally, high intensity rainfall spells of the monsoon system are limited to the eastern tributaries of the Indus basin. The substantiated fluvial floods inundated large agricultural areas and settlements. These floods damage lifelines, powerhouses and damage the socioeconomic activities in the central and southern plains of Punjab.

Figure 1: Existing flood protection structures and reservoirs - Punjab

3. Mega Flood - 2014

The frequency of low to high intensity floods in the rivers of Punjab is high. The historical peak flows of the Chenab River indicate that since 2000, the river has experienced medium to exceptional high intensity flood events every year. The recorded flows at Marala Barrage (Chenab River) classify the river as highly vulnerable to flood events.

The flood event of 2014 is classified as the second most disastrous event (after the mighty flood of 2010) in the last few decades in terms of exposure, damages, financial
losses, etc. The exceptionally high rainfall spells of late monsoon with high water discharges through the eastern tributaries of the Indus basin resulted in massive flood events in Punjab. Flood developed in river Chenab with contribution from the main river and Tavi components (Jammu Tavi and Munawar Tavi) in the beginning of September 2014. Discharge started rising at Marala Barrage on 4th September and a peak of 861,464 cusecs was experienced on September 06, 2014. This exceptionally high flood discharge moved along the river and caused heavy losses in the flow route to Panjnad Barrage where the peak was experienced in the early hours of September 17, 2014, and faded off on 18th September 2014. Dedicated flood fighting and rescue efforts did produce substantial results but the discharge escaping through breaches and cuts damaged general infrastructure, houses, crops, human lives, cattle and other public & private properties that existed in the flow route. The torrential flows in various torrential streams also caused havoc in the major industrial city of Sialkot (FFC, 2014).

According to post flood assessment reports of NDMA – National Disaster Management Authority, approximately 2.5 million people were affected by the flood event, and 129,880 houses were partially or fully damaged. Furthermore, more than 1 million acres of cropland were inundated. The flood damages reported by the NDMA and The International Disaster Database (EM-DAT) are shown in table 1.

Table 1: Flood Damages – 2014

<table>
<thead>
<tr>
<th>Affected Tehsils</th>
<th>Origin</th>
<th>River</th>
<th>Total</th>
<th>Total Affected</th>
<th>Total Damages (Billion US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sialkot, Narowal, Lahore, Gujranwala, Mandi Bahauddin, Gujrat, Hafizabad, Jhelum, Monsoo, Ravi, Jhang, Sargodha,</td>
<td>Chenab,</td>
<td>255</td>
<td>2.53</td>
<td>43.90</td>
<td></td>
</tr>
</tbody>
</table>
The extensive flooding was also caused by hill torrents (nullahs) in Sialkot, Narowal, Gujranwala, Sheikhupura and Lahore districts. The flood exposure was massive due to the combined impact of Palkhu, Deg, Aik and other torrential streams that directly influence the local communities. The spatial extent of flood events and inundation are shown in figure 3.

4. Flood Management in Pakistan

Pakistan has borne 23 significant flood events since its inception. In Pakistan flood management strategies and arrangements are based on i) Flood management measures, ii) legislative framework, and iii) Institutional setup. The foregoing study will review the flood management measures only.

4.1. Flood Management Measures

In Pakistan, flood management measures are mainly comprised of flood protection structures including embankments, studs, spurs and flood forecasting techniques. Flood protection structures are built as per requirement by the local provincial governments (Baig, 2008). After the establishment of the Federal Flood Commission – FFC, integrated flood management strategies are introduced at the national level. At a large spatio-temporal scale a National Flood Protection Plan – NFPP...
was introduced (FFC, 2009). The provincial administration receives technical and financial support through FFC for a better understanding and management of flood problems. In accordance with the FFC, the new flood management projects are executed to fulfill the needs, and/or integrated measures under NEPP. The flood management projects receive high weightage which serves high economic loss areas, and socio-economic vulnerability. NFPP plans are mostly financed by international donors including Asian Development Bank – ADB, and the funds are sanctioned for the projects having an economic internal rate of interest – EIRR of approximately 12% (FFC, 2009). The project’s EIRR is the average annual effective return of rate.

4.1.1. Structural Measures

The old customs for flood management follow the provision of structural measures. Structural measures are related to physical provisions to reduce the risk of flooding. These include dams, dikes, storm surge barriers, etc. The existence of enough storage to mitigate the impact of super floods is of paramount importance for flood protection. These storages should be built both on-channel like Kalabagh and offchannel like Akhori and Rohtas etc. to attenuate flood peaks. In the historic 2010 floods, the Tarbela and Mangla reservoirs played a significant but limited critical role in lowering the flood peaks.

In Pakistan, more than 6,719 km of embankments have been constructed along the rivers and their tributaries. The embankments are constructed to control the over-bank flooding scenarios. Furthermore, more than 1375 spurs are also constructed for the protection of embankments (FFC, 2009). The Punjab province has a 3,334 km length of embankments with 494 no. of spurs. The flood scenarios in Indus and Jhelum River basins are attenuated due to the construction of Tarbela Dam – Indus and Mangla Dam – Jhelum in 1976 and 1964 respectively. Sedimentation has decreased the storage capacity of these dams. However, these structures still play a vital role in flood protection and management. Furthermore, the lives of Mangla and Tarbela are expected to expire in 2050 and 60 respectively (MoWP, 2002c; Haq and Abbas, 2008; Hashmi et al., 2009). Gomal-Zem dam in Dera Ismail Khan – D.I. Khan, and Mirani dam in Baluchistan are also constructed after 2000 for flood management. Numerous flood protection has been constructed on both sides of the rivers (Majeed and Khan, 2008), and delay action dams and protection bunds in Baluchistan (Contijoch, 2008) were constructed before the mighty flood of 2010. However, for the flood management of potential hill torrents of Dera Ghazi Khan – D/G.Khan area, a study was completed in 1984 by National Engineering Services Pakistan – NESPak. The project study was also taken into account by the Japan International Corporation Agency – JICA in 1992 (MoWP, 2002b). In 1998, a countrywide feasibility study on hill torrents was also performed by NESPak dividing the area into 14 potential hill torrential zones in North West Frontier Pakistan – NWFP, Punjab, Sindh, and Baluchistan. Furthermore, structural measures have been completed in some of the hill torrents.

4.2.2. Non – Structural Measures

Non – Structural measures are related to flood forecasting, flood warning, flood mapping, emergency evacuation plans, and land use zoning, etc. In Pakistan, nonstructural measures were not featured in flood management practices in the past. Furthermore, early warning systems have not been fully incorporated for flood management activities. The advanced and appropriate non – structural measure is considered as the backbone of flood management all over the world (Atiq et al., 2012).
The rivers in Pakistan are transboundary in nature and flow through the Indian territory. Pakistan is a low riparian country having limited options for flood management. The flood prediction in Pakistan is complicated. Scientific advancement and the advent of technology have sorted out flood problems by improving the strength of the pre-flood analysis. The emphasis is on quantitative flood forecasting and flood early warning systems. In Pakistan flood warnings and rainfall forecast is provided by the Flood Forecasting Division – FFD of the Pakistan Meteorological Department – PMD, however, contributions are also made by Water and Power Department Authority – WAPDA to improve the flood forecast (Atiq et al., 2012).

Pakistan lacks comprehensive land-use planning controls for effective flood management. Post flood assessments are carried out every year. Initially, flood risk zoning for the main rivers was initiated, whereas the calibration and risk assessment is under process.

The rainfall runoff modeling for the upper catchments of Jhelum, Chenab, Ravi, and Sutlej is practiced under the functioning of the Flood Early Warning System – FEWS. Recently, PMD has been funded by the world bank to install new automatic weather stations – AWS and weather radars for the improvement of rainfall forecast countrywide (ADB, 2008).

The catchment modelling becomes difficult as the number of different control structures and reservoirs have been constructed on the Indian side by the Indian government. Back in 1989, an agreement was signed between the countries to share the river flows and discharges in time for flood forecasting (Awan, 2003).

5. PID – Punjab Irrigation Department after Flood 2014

The unprecedented flood of 2014 resulted in the displacement of over 2.3 million people and severely affected 2,519 villages. After its recession, the Government of Punjab constituted a Flood Management Committee – FMC comprising ministers, parliamentarians, and technical experts with a mandate to study the existing infrastructure in terms of flood related impact and measures to mitigate it. The Committee widely concluded that any good flood control strategy shall comprise both structural and non-structural measures. The PID has developed a comprehensive framework on both ends.

5.1. Capacity Building – Structural Measures

Structural measures involve the engineering works which are constructed to contain, divert and control water. The PID is proceeding in a phased manner to rehabilitate and upgrade the barrages. In this regard, work on seven barrages has already been completed, while work on the rehabilitation of the last sick barrage is underway and will be completed by 2024. Similarly, technical experts were engaged to review and recommend site-specific solutions for the embankments having geotechnical issues. The rehabilitation works on these levees have been carried out with the financial assistance of major financiers. A comprehensive plan comprising four subprojects to manage Deg, Aik, Palkhu, Basantar, Hassri, Lela and Bhed Nullahs has been implemented. The hill torrents of Koh-e-Suleman region including Kaura, Vehova, Sanghar, SoriLund and Vidor have already been treated while work on the Suri Lund hill torrent is in progress. Efforts have also been made to ascertain the feasibility of dams on Kaha, Chachar, Mithawan and Vidor hill torrents being the permanent solution.
Irrigation Department has already installed 17 new additional gauges and 205 missing river mile gauges to cover the gaps in assessing flood levels. One of the major issues encountered during flood 2014 was inconsistent and unsystematic data received from the Indian side. Given the above, Pakistan Commissioner for Indus Waters is pursuing the matter with the Indian Commissioner for Indus Waters regarding the calibration of international gauges before each flood and shifting of reporting gauges upstream to allow more reaction time, but success is yet not achieved.

The Disaster and Climate Resilience Improvement Project – DCRIP was started with the aid of ADB to improve the structural gaps that were observed in the flood event of 2014. The approximate cost covers 7809 million Pkr. The DCRIP comprises of total 22 sub-projects to rehabilitate the existing flood protection structures and construction of new structures for flood mitigation strategies. Furthermore, the Flood Emergency Reconstruction and Resilience Project – FERRP was also initiated with an aid cost of approximately 2661 million Pkr. The spatial location of structures under these projects is shown in figure 4. However, the detail of sub-projects under DCRIP and FERRP is shown in tables 2 and 3.

Figure 4: Spatial locations of structural rehabilitation measures under DCRIP

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<th>Table 2: DCRIP</th>
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<table>
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<tr>
<th>ID</th>
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<th>Population Saved</th>
<th>Area Saved acre</th>
<th>Length of Embankment km</th>
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<tr>
<td>18</td>
<td>Rehabilitation and Upgradation of River Training Works U/S Balloki Headworks</td>
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Table 3: FERRP

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<tr>
<td>1</td>
<td>Remodeling of Left Marginal Bund of Qadirabad Barrage in Critical Reaches.</td>
<td>119,027</td>
<td>28,109</td>
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</tr>
<tr>
<td>2</td>
<td>Remodeling of Left Marginal Bund (LMB) of Marala Barrage.</td>
<td>349,933</td>
<td>74,586</td>
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<td>3</td>
<td>Remodeling of Sher Shah Railway Flood Bund.</td>
<td>63,058</td>
<td>9,399</td>
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<td>4</td>
<td>Remodeling of Muzaffargarh Flood Bund.</td>
<td>174,131</td>
<td>58,129</td>
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<td>5</td>
<td>Protecting Sarai Alamgir Abadies between Railway and G.T Road Bridges on the left Bank of River Jhelum.</td>
<td>28,000</td>
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<td>6</td>
<td>Construction of Jhelum City Flood Protection Bund Along Right Bank of River Jhelum.</td>
<td>166,398</td>
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<td>7</td>
<td>Remodeling of Right Embankment of Shujabad Branch, Akbar &amp; Nawabpur Flood Bunds.</td>
<td>587,918</td>
<td>18,693</td>
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<td>8</td>
<td>Selected Reaches of Jhang Flood Protection Bund and Thatta Mahala Flood Bund.</td>
<td>332,467</td>
<td>21,106</td>
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<td>9</td>
<td>Remodeling of Left Marginal Bund (LMB) Taunsa Barrage.</td>
<td>43,194</td>
<td>21,979</td>
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5.2. Capacity Building – Non-Structural Measures

These measures comprise flood forecasting, flood warning, flood mapping, emergency evacuation plans, land use zoning flood proofing in urban areas and education/promoting awareness in flood prone areas protected by levees, etc. Flood forecasting and flood warning systems are at present inadequate. Therefore, flood warning and forecasting systems all over the country need extension and improvement.
Installation of modern tools such as weather radars and software and the increasing capacity of individuals to interpret the data received from these radars to need immediate and critical attention. Weather radars have proved to be efficient and effective in measuring real-time precipitation. These radars can significantly improve the accuracy of meteorological forecasting which can help in better planning and preparedness for floods.

Adapting the climate changes, after the flood event of 2014, PID establish two flood resilience research units including the Flood Risk Assessment Unit – FRAU and Hydraulic Structures Safety Evaluation Unit – HSSEU in the year 2016. The HSSEU was created to check and analyse the health status of flood protection infrastructure, small dams, barrages, and other critical hydraulic structures in view of international practices. The set objectives of HSSEU are as under

I. To set out protocols for the safety evaluation of flood protection infrastructure, small dams, barrages and other important hydraulic structures
II. To carry out at least two inspections of flood protection infrastructure (before and after each flood season) and convey observations to field formation for rectification
III. To carry out periodical inspections of barrages, flood embankments, small dams, and other hydraulic infrastructures
IV. To refer complicated issues to engineering institutions or experts outside the department, if required
V. To maintain a database of the inspections, health status, geotechnical information, previous history and measures taken for repair and maintenance of flood protection infrastructure, small dams, barrages and other hydraulic structures for reference and decision making
VI. To ensure rectification of observations as suggested during safety evaluation and generate reports highlighting problems if any.

To meet up with the designed objectives by the competent members of FMC, the unit was equipped with the latest instruments including i) Ground Penetrating Radar (wheel mounted and manuals), ii) Drones (DJI Matrice 300 RKT), iii) Hydrographic Survey Boat.

In contrast, FRAU was established to use computer aided models to simulate contingencies and generate flood warnings. The unit (FRAU) also maintains the historical flood extent databases and participates in pre-flood and post-flood measurement activities. Furthermore, Pakistan Meteorological Department – PMD also shares the rainfall forecast and flood warnings are dissipated at sub-administrative levels. The information from multiple sources is collected and processed under different computer aided programs (HEC-HMS, PCSWMM, HEC-RAS, AI-schemes etc) for flood early warning systems as shown in figure 5.
Figure 5: Flood warning system steps in FRAU – PID.

Furthermore, the unit has enhanced its capabilities for hydraulic modelling using high resolution Digital Elevation Models – DEM. At a coarser resolution, the information has been generated and dissipated to the provincial disaster management authorities. These practices are made for the first time at such a large scale in Pakistan. The information is updated every two years or as per requirement. However, risk mapping and vulnerability hot spots are one of the regular practices of FRAU in the monsoon season. The extent based spatial flood risk at the provincial level and high-resolution flood extent from Marala to Khanki are shown in Figures 6 and 7 respectively.

5.2.1. Flood Atlas and Flood Plain Regulation Act

The mighty flood of 2010 was classified as a disastrous event in all aspects. It was observed that approximately all of the destructions were caused by the breaching of canal, river, and flood structures in Punjab. Therefore, complete information and knowledge of flood routes along with the identification of villages prone to the flood route by a specific breach location were of crucial need. For this purpose, Flood Atlas – FA was developed by FRAU in PID using Geographic Information System – GIS, Remote Sensing – RS techniques along with the aid of field measurements – auxiliary data. The published flood atlas is a complete guide to identify the vulnerable villages that may be affected in case of a breach near the locality.

In the recent past, urban sprawl and other socio-economic activities were increased in the vicinity of the Punjab rivers. The unplanned activities and construction further increased the vulnerability and risk factor at low intensity flood levels. The factor also affects the natural trajectory of the rivers. It was of utmost importance to control the further encroachments in the flood plains of the Punjab rivers. The PID reforms the regulatory policy framework for further development in the flood plains. The framework was approved at the government level in the form of the Flood Plain Regulation Act – FPRA in the year 2016. According to the new set rules of FPRA, all unauthorized developments are prohibited in the classified flood plains. For government projects, the FPRA committee will have the right to decide the project approval in the flood plains. However, Standing Operating Procedures – SOPs for Mangla reservoir were rescheduled to enhance the flood management systems in the Punjab province.
The established units improve the flood management systems in Punjab. The capacity building of these institutes further enhances the capabilities for non-structural measures and therefore better pre and post-flood management assessments.
6. Conclusion

In Pakistan, flood early warning and forecasting systems are classified in the weak category. The past mega event of 2010 was a good example of the weak capacities in Pakistan at that time. As a result, the event generated a disastrous situation in the country. The flood event of 2010 was followed by the mega flood event of 2014 resulting in massive destruction in the country. The global circulation and changing behavior of atmospheric parameters’ spatial patterns and intensity generates havoc in the Asian sub-continent.

To deal with the climate shocks, Pakistan requires realigning the plans, policies, and flood management activities to better prepare for DRR and Disaster Management. Learning from best international practices, several innovative flood management strategies have been developed and implemented in the central Indus basin based on the local site conditions and requirements. A comprehensive assessment was made during successive flood events, which proved to be a massive success but some of the efforts failed. It was also concluded that inappropriate regulation of Mangla Dam was a major contributor to the 1992 and 2014 floods in the Jhelum River. Therefore, revised SOPs were designed in 2015. However, there is also consensus among technical experts that Pakistan needs to enhance its storage capacity by building large and small reservoirs to deal with the climate shocks (floods and droughts).

The CCA schemes suggest improving the pre-flood management strategies. An effective flood early warning system is dependent upon accurate flood forecasting. The flood early warning systems should be expanded and updated continuously. In the context of non-structural measures, to enhance the flood mitigation strategies, PID has established HSSEU and FRAU to improve the flood management systems. The units with modified objectives and targets have managed the flood problems in a better way. The capacity building of these units with modern and advanced computer aided programs further enhances the capabilities and hence generated a better flood early warning system for Pakistan.

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SHORT-TO-MEDIUM RANGE RESERVOIR INFLOW FORECASTING USING DAILY ENSEMBLE RAINFALL FORECASTS IN A CONCEPTUAL MODEL

Amina Khatun1, Archana Mohite Ramchandra1, Chandranath Chatterjee2 and Rajendra Singh2

ABSTRACT

Reliable and accurate inflow forecasting to a reservoir with sufficient lead times plays a crucial role in flood management and development of early warning systems. The Mahanadi River basin in India suffered from frequent devastating flooding events in the recent decade. Especially in India, the flood forecasting systems are constrained with traditional method of gauge-based discharge estimation, limited network of real-time observed hydro-meteorological information and high biases in the input rainfall products. The present study aims to develop a flood forecasting system for the upper reaches of the Mahanadi River basin using an integrated MIKE 11 NAM-HD model and subsequently attempts to improve them by adopting an error-correcting framework. The calibrated/validated MIKE 11 NAM-HD model is forced with observed hydro-meteorological data for the hindcast period and two Numerical Weather Prediction (NWP) model forecast products, namely European Centre for Medium-Range Weather Forecasts (ECMWF) and India Meteorological Department’s Multi-model Ensemble (MME), separately for the forecast horizon (1 – 5 days). The errors of these two modelling setups are then updated using the MIKE 11 DA (Data Assimilation) framework. The inflow forecasts from the standalone MIKE 11 NAM-HD model are found to be acceptable up to 3 – days lead time with an NSE of 0.81 – 0.92 for ECMWF and 0.80 – 0.93 for MME rainfall input forcings. However, despite incorporation of error updating, marginal improvement was observed in both the cases up to 3 – days ahead. An in-depth investigation revealed that the error time series does not display high persistence (low serial autocorrelation coefficient after 1 – day lag time) at a daily temporal resolution. This led to the failure of the MIKE 11 DA model in providing substantial improvement of the lead-time inflow forecasts.

Keywords: Inflow forecasting, Ensemble rainfall forecasts, Conceptual model, MIKE 11 NAM-HD model, Error updating.

1. INTRODUCTION

Flood is one of the major natural calamities that leads to enormous devastation of life and property across various world river basins. Different structural and non-structural measures of flood management are used to minimize the damages due to flood havoc. However, due to construction and maintenance cost, permanent protection of all the flood prone areas by structural measures for different magnitudes of floods is not always possible. Hence, non-structural measures are used in combination with structural measures for flood management.

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Among different non-structural measures, flood forecasting is considered as an important tool for reducing the vulnerabilities and flood risks in flood prone areas (Rahman et al., 2012).

The freely available satellite based rainfall products from Tropical Rainfall Measuring Mission Multisatellite Precipitation Analysis (TMPA) such as the gauge-adjusted TRMM and data in its real-time form named as TRMM-RT (Huffman et al., 2007), are being widely evaluated in many world river basins for real-time flood forecasting. The global model outputs from European Centre for Medium-Range Weather Forecasts (ECMWF) provides NWP model forecasts across the world and has been used in the operational flood forecasting in different world river basins. Moreover, in India the operational multi-model ensemble (MME) of NWP forecasts are issued by the India Meteorological Department (IMD) since 2008. This product has been made available for real-time application, which is freely accessible in public domain (Bhowmik and Durai, 2012). Simulation results obtained from hydrological model using appropriate rainfall inputs comprise of some errors. Hydrological models associated with these types of errors are generally prone to be less accurate in forecasting. Therefore, error correction (termed as updating or data assimilation) of the model simulations, prior to the time of forecast is important in order to improve accuracy of forecasting results. Four types of updating methods have been reported (WMO, 1992; Refsgaard, 1997) which are: (i) input updating (Liu et al., 2015) (ii) parameter updating (Yang and Michel, 2000) (iii) state updating (Madsen and Skotner, 2005) and (iv) output variable updating (Nanda et al., 2019). Output updating is the most widely adopted method of updating in flood forecasting studies (Shamseldin and O’connor, 2001; Goswami et al., 2005; Nanda et al., 2019), however, in a single operational flood forecasting model framework, state updating (Madsen and Skotner, 2005; Moradkhani et al., 2005) is widely applied in hydrodynamic modeling for updating state of the river using real-time discharge/water level data along the river channel at different gauging points in the river.

2. METHODS

2.1 Description of the Study Area

Mahanadi river basin is one of the largest river basins in India. It ranks seventh as per basin area contribution and extends over an area of 1,41,589 km². The geographical extent of Mahanadi River basin is between 80°28’E to 86°43’E longitudes and 19°08’N to 23°32’N latitudes (Fig. 1). Average annual rainfall in the basin ranges from 1200-1600 mm, 90% of which occurs during monsoon season spread over from June to October. Average minimum and maximum basin temperature varies between 12°C and 40°C, respectively. Average monthly pan evaporation varies from 2.4 cm to 14.6 cm. Maximum land use/land cover of the basin is covered with agricultural land, accounting 54.27% of the total basin area followed by forest land (32.74%), wasteland (5.24%), waterbodies (4.45%) and builtup land (3.30%). The main soil types found in the Mahanadi basin are red and yellow soils, mixed red and black soils, laterite soils, and deltaic soils. As a hydrologic unit, the basin is divided into three parts (Fig. 1), namely, upper Mahanadi basin (UMB): basin area upstream of the Hirakud dam (83,400 km²); middle Mahanadi basin (MMB): basin area downstream of Hirakud dam to the Mundali station i.e., mouth of the delta (48,700 km²); and lower Mahanadi basin or Mahanadi delta: basin area downstream of Mundali station to the Bay of Bengal (9,489 km²). To control flood havoc in the delta region of the Mahanadi basin, different structural measures have been adopted along with flood forecasting as a non-structural measure (Parhi et al., 2012).

2.2 Methodology
Different meteorological inputs such as IMD observed gauge-based rainfall, satellite-based rainfall, and Numerical Weather Prediction (NWP) model forecasts have been used for the model development. Various modules of the MIKE 11 modeling software considered for the present study are MIKE 11 NAM (Nedbør Afstrømnings Model) Rainfall-Runoff (RR) model, MIKE 11 Hydrodynamic (HD) and MIKE 11 Data Assimilation (DA).

Figure 1. Map of study area showing Upper, Middle and Delta region of the Mahanadi River basin along with the delineated catchments for MIKE 11 NAM model.

Integrated MIKE 11 NAM-HD (henceforth called as NAM-HD) model setup is developed for the upper Mahanadi basin (UMB). The development of model setup is carried out in two steps: firstly, NAM and HD model setups were developed separately and then NAM-HD setups are integrated to assess model performance at the forecast (gauging) site of interest. The NAM-HD setup considered for the present study and the Performance Measures (PMs) considered for the assessment of the models are described in detail. MIKE 11 DA (henceforth called as DA) model is used in combination with NAM-HD for error correction in the forecasting results. The methodology used for MIKE 11 DA model setup for both basins is described below.
2.2.1 NAM model set-up

NAM model setup is prepared with nine parameters representing the surface zone, root zone and the ground water storages. The behavior of the NAM model during flood event is controlled by overland flow component, which affect the discharge component that contributes to the peak flows (Shamsudin and Hashim, 2002; Ilias et al., 2006). Catchment-wise mean areal values of rainfall (MAR) and potential evapotranspiration (PET) are the input forcings to the NAM model. The mean areal values are computed using thiessen polygon method. PET is computed for station temperature (maximum, Max and minimum, Min) data using Hargreaves equation (Hargreaves and Allen, 2003). NAM model is developed using observed (IMD) and NWP (ECMWF and IMD-MME) rainfall data. NAM model parameters’ optimization is executed automatically using the shuffled complex evolution (SCE) algorithm (Madsen, 2000). Calibration of NAM parameters is carried out using automatic calibration routine.

2.2.2 Calibration and validation of integrated NAM-HD model

Calibration and validation of integrated NAM-HD model of the UMB setup is carried out through two steps. First, calibration of MIKE 11 NAM model catchments using observed/satellite rainfall data is carried out for three scenarios of autocalibration criteria with three different objectives. Second, NAM model with the three different scenarios, each separately, is integrated to HD model. These three integrated NAM-HD setups are again calibrated for the Manning's roughness coefficient, n, in the HD model setup. Although, Central Water Commission (CWC) has provided n value as 0.033 for the river channel cross-section, more scenarios of n values in the range of 0.020 to 0.040 (interval of 0.002) are also considered for model calibration. Integrated MIKE 11 NAM-HD model results are calibrated and validated using only monsoon season (June-October) data for the years 2000-2007 and 2008-11, respectively. Different performance measures used for evaluation of calibration and validation results are: Nash-Sutcliffe Efficiency (NSE) index, Coefficient of determination ($R^2$), Mean absolute error (MAE), RMSE-observation standard deviation ratio (RSR), Percent error in volume/Percent Bias (PBias) and error in peak flow ($E_{peak}$) (Nash and Sutcliffe, 1970; Moriasi et al., 2007). Here, it is to be noted that only S3_UMB (the scenario presented in this study) is used for hydrological evaluation of satellite-based rainfall products.

2.2.3. Flood forecasting using NWP model meteorological forecasts

In this case (Case III presented herein), performance of S3_UMB is evaluated using observed hydro-meteorological data in the hindcast period and NWP model meteorological forecast (ECMWF or MME) in the forecast period for 1- to 5-day lead time. Prior to using them in the inflow forecasting framework, NWP model forecasts are evaluated to assess their ability to improve the forecasts at higher lead time. Flood forecasting performance of all the models developed herein for all three case scenarios are judged acceptable when NSE $\geq$ 0.75, $R^2$ $\geq$ 0.75, PBias = ±20% and RSR $\leq$ 0.50.

2.2.4. Methodology for integrated MIKE 11 NAM-HD-DA model

Data assimilation (DA) model in real-time flood forecasting system is used for updating the state of the system prior to the time of forecast, which provides improved initial conditions for the forecast. After the time of forecast, simulated forecast results are corrected using forecasts of model errors. MIKE 11 DA model uses sequential algorithm for assimilation. A sequential updating of the model solution is performed during a forward model integration in which the model forecast and the data are melded according to two different specific melding schemes, which are (i) Ensemble Kalman...
filter and (ii) Constant weighting function method. In the present study, constant weighting function method is used as a general filtering framework. Moreover, the constant weighting function is combined with error forecast model (autoregressive model, AR) to update the model in the forecasting period. Basantpur gauging station is selected as measuring stations in the UMB. As there is no intermediate gauging station available between base and forecast station(s), integrated MIKE 11 NAM-HD-DA setup during forecasting mode is developed for the S3_UMB (S3-DA_UMB). Forecasting results for the S3_UMB are updated with the observed discharge measurements at the Basantpur gauging station. Figure 2 illustrates flowchart for methodology used to develop integrated NAM-HD-DA model.

![Flowchart](image)

**Figure 2.** Flowchart of the methodology for development of flood forecast system using updating technique. $t$ is the time of forecast (tof) and $\alpha$ is the lead time in days.

As discussed earlier, integrated NAM-HD setup, S3_UMB is used to develop flood forecasting system for the UMB with model initial conditions generated using satellite-based rainfall and further forced with ECMWF or MME forecasts. Forecasting results obtained using both the forecast products for the basin is evaluated for 1- to 5-day lead times with the performance measures criteria $\text{NSE} \geq 0.75$, $R^2 \geq 0.75$, $\text{Pbias} = \pm 20\%$ and $\text{RSR} \leq 0.5$. Subsequently, forecasting results of S3_UMB are evaluated after data assimilation with the S3-DA_UMB setup.

### 3. RESULTS AND DISCUSSION

#### 3.1 Calibration and Validation of MIKE 11 NAM-HD Model

Integrated NAM-HD model setup, S3_UMB is calibrated as per the procedure discussed in earlier sections. As the present study focuses on flood forecasting, the
peak discharges play an important role to judge the model performances. Combination of overall root mean square error (RMSE), volume error and peak RMSE objective functions resulted in better performance of model in terms of overall error measures and peak error. The results reveal that during calibration using monsoon season data for the years 2000-2007, performance of the S3_UMB setup calibrated with NAM model and the HD model using $n = 0.033$ produce satisfactory results with very good agreement between observed and simulated discharge at the Hirakud reservoir. The performance measures during calibration are $\text{NSE} \geq 0.89$, $R^2 \geq 0.89$, $|\text{PBias}| \leq 4.92\%$, $\text{RSR} \leq 0.34$ and $\text{MAE} \leq 318.40 \text{m}^3/\text{s}$ for the model setup, which are considered satisfactory. Discharge simulation using S3_UMB is also evaluated at the Basantpur gauging station, upstream of Hirakud. The performances of the model setup is found satisfactory with $\text{NSE} \geq 0.82$, $R^2 \geq 0.82$, $|\text{PBias}| \leq 5.05\%$, $\text{RSR} \leq 0.43$ and $\text{MAE} \leq 248.63 \text{m}^3/\text{s}$.

S3_UMB is validated using monsoon season (June-October) data for the years 2008-11. The setup perform satisfactorily with $\text{NSE} \geq 0.93$, $R^2 \geq 0.95$, $\text{RSR} \leq 0.26$, $\text{MAE} \leq 456.15 \text{m}^3/\text{s}$ and $|\text{PBias}| \leq 17.62\%$. A little higher values of PBias indicate that the NAM model resulted in overestimation (positive bias) especially for low and medium flows. Peak error values show $E_{\text{peak}}$ within ±20% for most of the observed peak events. Performance of S3_UMB setup also validated at the Basantpur gauging station is found satisfactory with $\text{NSE} = 0.90$, $R^2 = 0.91$, $|\text{PBias}| \leq 5.97\%$, $\text{RSR} \leq 0.31$ and $\text{MAE} \leq 351.71 \text{m}^3/\text{s}$.

3.2. Flood Forecasting using Integrated MIKE 11 NAM-HD Framework with NWP Model Forecasts

Figures 3a-e shows the flood forecasting results of S3_UMB for 1- to 5-day lead time. For 1- to 3-day lead times, performances vary with $\text{NSE} = 0.81-0.92$, $R^2 = 0.83-0.95$, $|\text{PBias}| = 14.97-17.66\%$, $\text{RSR} = 0.28-0.43$ and $\text{MAE} = 615.48-851.84 \text{m}^3/\text{s}$ for ECMWF; whereas $\text{NSE} = 0.80-0.93$, $R^2 = 0.82-0.95$, $|\text{PBias}| = 6.87-15.33\%$, $\text{RSR} = 0.27-0.44$ and $\text{MAE} = 583.88-801.11 \text{m}^3/\text{s}$ for MME. Subsequently, the performance deteriorates at higher lead times. Thus, overall performance of S3_UMB for flood forecasting is found to be acceptable up to 3-day lead time with $\text{NSE} \geq 0.75$, $R^2 \geq 0.75$, PBias $\leq \pm 20\%$ and RSR $\leq 0.50$. It is seen that the S3_UMB model for Case-III provide acceptable flood forecasts up to 3-day lead time using a combination of model initial conditions generated from observed hydro-meteorological data with NWP model meteorological forecasts (ECMWF or MME).

3.3 Error Updating of Streamflow Forecasts

Streamflow forecasting results using the model S3_UMB are error corrected by integrating with the data assimilation framework (MIKE 11 DA module) in MIKE 11 software. The corresponding integrated model setup as used for inflow forecasting in the UMB is named as S3-DA_UMB. Error updating is carried out for the simulated discharges at the Basantpur gauging station, upstream of the Hirakud, using observed discharge measurements. The MIKE 11 DA module uses constant weighting method combined with AR1 error forecasting model for error updating. Updated discharge from Basantpur station is routed up to the Hirakud reservoir.

Performance of the S3-DA_UMB model improved marginally over S3_UMB (using either of NWP forecast) at 1-day lead time showing values of $\text{NSE} = 0.96$, $R^2 = 0.97$, $|\text{PBias}| = 12.97\%$, $\text{RSR} = 0.21$, and $\text{MAE} = 445.67 \text{m}^3/\text{s}$ for ECMWF forecast; whereas for MME, $\text{NSE} = 0.96$, $R^2 = 0.97$, $|\text{PBias}| = 9.84\%$, $\text{RSR} = 0.21$, and $\text{MAE} = 441.82 \text{m}^3/\text{s}$. Further, for higher lead times (2- to 3-day) forecasting, the improvement in forecasting results are also found to be very negligible over S3_UMB.
Figure 3. Inflow forecast results of S3_UMB for Case-III for 1- to 5-day lead time using ECMWF and NWP model forecasts.

Performance of data assimilation in S3-DA_UMB is also assessed in terms of improvement in peak flow events observed during the years 2008-2011. From the peak errors, it is observed that very negligible changes occur in $E_{\text{peak}}$ values due to DA process at 1- to 5-day lead times when compared with the setup without updating. This
shows that the data assimilation (DA) technique did not result in any significant improvement of the flood forecasts in the upper Mahanadi basin. The serial autocorrelation coefficient (obtained for S3_UMB) values are observed to be low and near to zero after 1-day lag, which depicts that error time series does not display high persistence. Hence, the model does not substantially improve the flood forecasting results using the DA method. It is seen in literature that when high temporal resolution data are available, the model performs better in updating the discharge/water level forecasts compared to the use of daily time series data with lower serial correlation values (Nalbantis, 2000; Wu et al., 2015).

4. CONCLUSIONS

Following conclusions are drawn from the present study:

i. Inclusion of NWP model meteorological forecasts in MIKE 11 NAM-HD setup (S3_UMB) during forecast period could extend the acceptable forecasts up to 3-day lead time.

ii. S3_UMB show $E_{\text{peak}}$ values within the acceptable limit up to 3-day lead time. Moreover, the peak error statistics of the models ECMWF as well as MME are very similar for up to 3-day lead time.

iii. The use of S3_UMB setup has an advantage over the other two setups as it requires only the observed and forecasted meteorological data as inputs and does not require the observed discharge data.

iv. Marginal improvement of S3-DA_UMB model over S3_UMB is observed for simulating the entire time-series at 1-day lead time. However, no significant improvement in the peak errors are witnessed for S3-DA_UMB model at any of the lead times.

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ADAPTIVE FLOOD RISK MANAGEMENT†

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ABSTRACT
Based on the worldwide experiences, the most important challenges of flood engineers are:
• managing substantial increase of flood risks with limited resources;
• avoiding adverse environmental consequences of flood control projects;
• coping with uncertainty in all relevant aspects.

Now in second decade of the 21st century, it has become obvious, that the approach to flood management is increasingly adaptive and non-structural. In the last decades, adaptive management has been extensively utilized in environmental and restoration projects. In this context, adopting the strategies of adaptive management in water engineering and flood management appears to offer great advantages. Adaptive management is a structured, iterative process of optimal decision making in the face of uncertainty, with an aim to reducing uncertainty over time via system monitoring. The strategies of adaptive flood management are as follows:
• adaptability (changing threat to opportunity);
• flexible decision making (to cope with uncertainties);
• monitoring and vigilance;
• learning while doing;
• application of new knowledge and technologies;
• avoiding costly irreversible mistakes;
• updating the objectives;
• extensive risk recognition;
• focus on long-term management rather than construction;
• resilience;
• harmony with environment;
• passive and active adaptive management;
• stakeholders participation;
• enhanced real time reactions. © 2020 John Wiley & Sons, Ltd.

KEY WORDS: gestion adaptative; gestion des inondations; des incertitudes; risque; approches non structurelles

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RÉSUMÉ
Sur la base des expériences mondiales, les principaux défis des ingénieurs en inondation sont les suivants:
• gérer une augmentation substantielle des risques d’inondation avec des ressources limitées;
• éviter les conséquences environnementales néfastes des projets de lutte contre les inondations;
• gérer l’incertitude sous tous ses aspects.

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Au début du 21e siècle, il est devenu évident que la gestion des inondations est de plus en plus adaptative et non structurelle. Au cours des deux dernières décennies, la gestion adaptative a été largement utilisée dans des projets environnementaux et de restauration. Dans ce contexte, l’adoption des stratégies de gestion adaptative dans les domaines de l’ingénierie de l’eau et de la gestion des crues semble offrir de grands avantages. La gestion adaptative est un processus structuré et itératif de prise de décision optimale face à l’incertitude, dans le but de réduire l’incertitude au fil du temps via la surveillance du système. Les stratégies de gestion adaptative des inondations sont les suivantes:

- adaptabilité (évolution de la menace en opportunité);
- prise de décision flexible (pour faire face aux incertitudes);
- surveillance et vigilance;
- apprendre en faisant;
- application de nouvelles connaissances et technologies;
- éviter les erreurs coûteuses et irréversibles;
- mettre à jour les objectifs;
- une reconnaissance étendue des risques;
- mettre l’accent sur la gestion à long terme plutôt que sur la construction;
- résilience;
- harmonie avec l’environnement;
- gestion adaptative passive et active;
- participation des parties prenantes;
- réactions améliorées en temps réel. © 2020 John Wiley & Sons, Ltd.

MOTS CLÉS: gestion adaptative; gestion des inondations; des incertitudes; risque; approches non structurelles

INTRODUCTION

Adaptive management (AM) is a structured, iterative process of optimal decision making in the face of uncertainty, with an aim to reducing uncertainty over time via system monitoring. In this way, decision making simultaneously maximizes one or more resource objectives and, either passively or actively, accrues information needed to improve future management. Adaptive management is a tool which, can be used not only to change a system, but also to learn about the system (Holling, 1978). Because adaptive management is based on a learning process, it improves long-run management outcomes. The challenge in using the adaptive management approach lies in finding the correct balance between gaining knowledge to improve management in the future and achieving the best short-term outcome based on current knowledge (Stankey and Allan, 2009).

Adaptive management can proceed as either passive adaptive management or active adaptive management, depending on how learning takes place. Passive adaptive management values learning only insofar as it improves decision outcomes (i.e. passively), as measured by the specified utility function. In contrast, active adaptive management explicitly incorporates learning as part of the objective function, and hence, decisions which improve learning are valued over those which do not (Holling, 1978), (Walters, 1986). In both cases, as new knowledge is gained, the models are updated and optimal management strategies are derived accordingly. Thus, while learning occurs in both cases, it is treated differently. Often, deriving actively adaptive policies is technically very difficult, which prevents it being more commonly applied. Key features of both passive and active adaptive management are:

- iterative decision making (evaluating results and adjusting actions on the basis of what has been learned);
- feedback between monitoring and decisions (learning);
- explicit characterization of system uncertainty through multi model inference;
- Bayesian inference;
- Embracing risk and uncertainty as a way of building understanding.

Adaptive management is particularly applicable for systems in which learning via experimentation is impractical.

HISTORICAL BACKGROUND OF ADAPTIVE MANAGEMENT

The use of adaptive management techniques can be traced back to ancient civilizations. For example, the Yap people of Micronesia have been using adaptive management techniques to sustain high population densities in the face of resource scarcity for centuries (Falanruw et al., 1989).
The origin of the adaptive management concept can be traced back to ideas of scientific management pioneered by Frederick Taylor in the early 1900s (Haber, 1964). While the term ‘adaptive management’ evolved in natural resource management workshops through decision makers, managers and scientists focusing on building simulation models to uncover key assumptions and uncertainties (Bormann et al., 1999).

Two ecologists at the University of British Columbia, Holling (1978) and Walters (1986), further developed the adaptive management approach as they distinguished between passive and adaptive management practice. Kai Lee, notable Princeton physicist, expanded upon the approach in the late 1970s and early 1980s, while pursuing a post-doctorate degree at UC Berkeley. The approach was further developed at the International Institute for Applied Systems Analysis (IIASA) in Vienna, Austria, while Holling was director of the Institute. In 1992, Hilbourne described three learning models for federal land managers, around which adaptive management approaches could be developed, these are reactive, passive and active.

Adaptive management has probably been most frequently applied in Australia and North America, initially applied in fishery management, but received more broad application in the 1990s and 2000s. One of the most successful applications of adaptive management has been in the area of waterfowl harvest management in North America, most notably for the mallard (Johnson et al., 1993), (Nichols et al., 2007).

ADAPTIVE MANAGEMENT IN ENVIRONMENTAL PRACTICES

Applying adaptive management in a conservation project or program involves the integration of project/program design, management, and monitoring to systematically test assumptions in order to adapt and learn. The three components of adaptive management in environmental practices are:

- testing assumptions is about systematically trying different actions to achieve a desired outcome. It is not, however, a random trial-and-error process. Rather, it involves using knowledge about the specific site to pick the best known strategy, laying out the assumptions behind how that strategy will work, and then collecting monitoring data to determine if the assumptions hold true;
- adaptation involves changing assumptions and interventions to respond to new or different information obtained through monitoring and project experience;
- learning is about explicitly documenting a team’s planning and implementation process and its successes and failures for internal learning as well as learning across the conservation community. The learning enables conservation practitioners to design and manage projects better and avoid some of the perils others have encountered (Stankey et al., 2005).
- open standards for the practice of conservation lay out five main steps to an adaptive management project cycle (Figure 1). The open standards represent a compilation and adaptation of best practices and guidelines across several fields and across several organizations within the conservation community. Since the release of the initial open standards (updated in 2007), thousands of project teams from conservation organizations (e.g. World Wildlife Fund (WWF)), local conservation groups, and donors alike have begun applying these open standards to their work.

ADAPTIVE MANAGEMENT IN OTHER PRACTICES AS A TOOL FOR SUSTAINABILITY

Adaptive management as a systematic process for improving environmental management policies and practices is the traditional application; however, the adaptive management framework can also be applied to other sectors seeking sustainable solutions such as business and community development. Adaptive management as a strategy emphasizes the need to change with the environment and to learn from doing. Adaptive management applied to ecosystems makes overt sense when considering ever changing environmental conditions. The flexibility and constant learning of an adaptive management approach is also a logical application for organizations seeking sustainable methodologies. Businesses pursuing sustainable strategies would employ an adaptive management framework to ensure that the organization is prepared for the unexpected and geared for change. By applying an adaptive management approach the business begins to function as an integrated system adjusting and learning from a multi-faceted network of influences not just environmental but also, economic and social (Dunphy et al., 2007). The goal of any sustainable organization guided by adaptive management principals must be to engage in active learning to direct change towards sustainability (Verine, 2008). This ‘learning to manage by managing to learn’ will be at the core of a sustainable business strategy (Bormann et al., 1993).

Sustainable community development requires recognition of the relationship between environment, economics and social instruments within the community. An adaptive management approach to create sustainable community policy and practice also emphasizes the connection and confluence of those elements. Looking into the cultural mechanisms which contribute to a community value system often highlights the parallel to adaptive management practices, ‘with [an] emphasis on feedback learning, and its treatment of uncertainty and unpredictability’ (Berkes et al., 2000). Often this is the result of indigenous knowledge and historical decisions of societies deeply rooted in ecological practices.
(Berkes et al., 2000). By applying an adaptive management approach to community development the resulting systems can develop built in sustainable practice as explained by the Environmental Advisory Council: “active adaptive management views policy as a set of experiments designed to reveal processes that build or sustain resilience”. It requires, and facilitates, a social context with flexible and open institutions and multi-level governance systems that allow for learning and increase adaptive capacity without foreclosing future development options.

ADAPTIVE MANAGEMENT IN FLOOD MANAGEMENT AND WATER ENGINEERING

Till 1927, the main flood policy of U.S. Army Corps of Engineers was ‘levees only’. After the great flood of 1927, flood management by reservoirs was also included. The concept of non-structural measures (NSM) was first used in the context of flood control some 50 years ago, as a means to reduce the ever increasing damages, without unduly expanding the costly infrastructure. In that sense, NSMs were perceived rather as complementary additions to the essentially structural solutions to flood control, in order to reduce costs and enhance efficiency (WG-AFM). This concept has been changed in the last few decades by introduction of new approaches as shown in Figure 2:

- development of the new Swiss safety concept for dams in 1985 (Biedermann, 1997), (Biedermann, 1985);
- publication of the Manual on non-structural approaches to flood management by the International Commission on Irrigation and Drainage (ICID) in 1999 (ICID, 1999);
- publication of the International Commission on Large Dams (ICOLD), Non-structural risk reduction measures; benefits and costs for Dams in 2001 (ICOLD, 2001);
- UNESCO (IHP-V) Workshop on Non-structural measures for water management problems in 2001 (Simonovic, 2002);
- publication of U.S. Army Corps of Engineers manual on Adaptive management for water resources project planning in 2004 (U.S. Army Corps of Engineers, 2004);
- Publication of the proceedings of Question 53 of ICID congress on Harmonic coexistence with floods in Beijing in 2005.

Now in the second decade of the 21st century, it has become obvious, that the approach to flood management...
is increasingly shifting toward adaptive and non-structural measures: structural, engineering solutions appear as indispensable complements to the essentially non-structural, integrated water resources management, of which flood damage reduction is but an integral part.

ADAPTIVE MANAGEMENT CONCEPTS AND RATIONALE

During the 20th century, scientists like Bohr and Heisenberg challenged traditional paradigms with discoveries and theorems that emphasized uncertainties, complexities, and the limits of scientific knowledge (Peat, 2002). These contrasting paradigms are today reflected in distinctly different scientific schools of thought. On one hand, a Newtonian vision of the world is based on stability and predictability of natural systems. On the other, the vision promoted by Bohr and Heisenberg recognizes that change and surprises are the essence of natural systems. Newtonian principles are appropriate when working in stable systems and for designing civil engineering structures, for example, but are not fully adequate when applied to complex, dynamic ecosystems.

Adaptive management applications

As the world changes, or as unanticipated consequences are being revealed, organizations should adjust plans and operations to deal with the new conditions and to incorporate improved understanding.

Adaptive management is a common sense strategy for addressing the reality of a changing and uncertain environment. Recognition of the need to adjust management strategies can derive from at least three broad sources. First, scientific advances can provide better understanding of the complex linkages between human activities and environmental impacts. The U.S. Army Corps has experienced such paradigm shifts, one of the most famous being the abandonment of its ‘levees only’ strategy in the early 20th century (Barry, 1997). Through much of the 19th century and the early 20th century, the Corps of Engineers based its flood control program on the notion that levees were, by themselves, adequate for controlling all floods and that other measures (e.g., upstream reservoirs) were not necessary. Devastating floods along the lower Mississippi River in 1927 proved the inadequacy of this policy and ultimately resulted in the Corps moving toward a broader approach to manage flood risks.

Second, environmental changes and variability affect the
operations and impacts of Corps projects. For example, climatic variability may affect precipitation patterns, which in turn may affect the parameters of dam and reservoir operations. Thirdly, "shifts in social objectives and preferences" may challenge conventional operations schemes. In the United States, for example, the 1960s and 1970s marked a period of increasing concern over environmental issues.

**Adaptive management theories, frameworks, and practices**

Adaptive management seeks insights into the behaviour of ecosystems that are utilized by humans, and it draws upon theories from ecosystem sciences, economics and social sciences, engineering, and other disciplines. Adaptive management incorporates and integrates concepts such as social learning, operations research, economic values, and political differences with ecosystem monitoring, models, and science.

Adaptive management aims to create policies that can help organizations, managers, and other stakeholders respond to, and even take advantage of, unanticipated events (Holling, 1978), (Walters, 1986). Instead of seeking precise predictions of future conditions, adaptive management recognizes the uncertainties associated with forecasting future outcomes, and calls for consideration of a range of possible future outcomes (Walters, 1986). Management policies are designed to be flexible and are subject to adjustment in an iterative, social learning process (Lee, 1999).

Adaptive management is intended to increase the ability to fashion timely responses in the face of new information and in a setting of varied stakeholder objectives and preferences. It encourages stakeholders to bound disputes and discusses them in an orderly fashion, while environmental uncertainties are being investigated and better understood.

Adaptive management can help reduce decision making gridlock by making it clear that decisions are provisional, that there is often no "right" or "wrong" management decision, and that modifications are expected. Adaptive management should help stakeholders, managers, and elected officials and other decision makers recognize the limits of knowledge and the need to act on imperfect information.

Adaptive management is not simply a "trial and error" process, but rather represents a more systematic "learning while doing" process (Lee, 1999).

Some degree of learning is inevitable in almost any management approach; adaptive management is structured to make that learning more systematic and efficient.

A distinction is often made between adaptive management approaches that are "passive" and those that are "active." Within "passive" adaptive management, a single, preferred course of action, based on existing information and understanding, is selected. Outcomes of management actions are monitored, and subsequent decisions are adjusted based on the outcomes. This approach contributes to learning and to more effective management, but it is limited in its ability to enhance scientific and management capabilities for conditions that go beyond the course of action selected. By contrast, an "active" adaptive management approach reviews information before management actions are taken. A range of competing, alternative system models of ecosystems and related responses (e.g. demographic changes; recreational uses), rather than a single model, is then developed. Management options are then chosen based upon evaluations of these alternative models. All modes of adaptive management require outcomes of management actions to be monitored.

Elements of adaptive management that have been identified in theories and practice are:

- management objectives that are regularly revisited and accordingly revised;
- a model(s) of the system being managed;
- a range of management choices;
- monitoring and evaluation of outcomes;
- a mechanism(s) for incorporating learning into future decisions;
- a collaborative structure for stakeholder participation and learning.

Table I summarizes practices that were fairly standard as of a generation ago, as well as ways in which those practices are evolving.

An important aspect of evolving concepts of engineering practice is the way uncertainty is recognized and addressed. It is today widely appreciated that many consequences of civil engineering investments cannot be precisely forecasted. Whether the objective is to take advantage of new opportunities or to insure against bad outcomes, the goal is to create the capacity to respond appropriately as new situations which may include unforeseen surprises develop. Flexibility over the life of the project is essential to effective development and functioning of civil engineering systems.

| Table I. Trends in the evolution of civil engineering design practice |
| --- | --- | --- |
| Design element | From traditional | Broadening to |
| **Scope** | Project | System of projects |
| **Purpose** | Single purpose | Multiple and sometimes conflicting objectives |
| **Means** | Structural | Non-structural |
| **Focus** | Construction | Long-term management |
| **Risk Recognition** | Little | Extensive |

Adaptive management concepts and practices represent innovative, current thinking on resolving conflicting demands and adjusting to changing social preferences and priorities.

Many of adaptive management’s benefits come in the form of better knowledge of ecosystem response to management actions. This improved knowledge reduces uncertainties and should therefore improve management decisions. Benefits of better future management decisions will be realized in the future. These benefits, however, are difficult to measure and translated into dollars, the standard metric of economic analysis. The intangible nature of these benefits stands in contrast to the direct, up-front costs of adaptive management programs, such as ecosystem monitoring programs, scientific staff, and institutional support.

The strategies of adaptive flood management (AFM) are shown in Figure 3 (ICID, in preparation).

HOLISTIC DESIGN OF ADAPTIVE HYDRAULIC STRUCTURES

A doctoral dissertation entitled Holistic design of adaptive hydraulic structures was presented in 1998 (Emami, 1998b), (Emami, 2005a), (Emami, 2005b), (Emami, 2005e). The main strategies of the holistic design are as follows:

- Ensure a flexible and adaptive design in view of hydrosystems’ changes and the inherent uncertainties of water engineering;
- Establish the interdependence of hardware (structures), software (monitoring system, management) and brainware (experts, management and knowledge) in design;
- Adapt to the stochastic nature of river flow by integration of seasonal characteristics and river forecasting;
- Learn while doing;
- Recognize the uncertainties of risks of project and design hydraulic structures to adapt to extreme events far larger than the design parameters and remain inherently safe (structural ductility and resilience (American Society of Civil Engineers (ASCE) Task Committee, 1995), (Hansen, 1992), (Emami, 1998a), (Emami, 1998b), (Emami, 2005c), (Emami et al., 2002), (Emami, et al., 2005);
- Base the design on comprehensive management and flexibility;
- Enhance safety by ‘designing’ crisis management preceding the events and in real time for the structure and downstream population centres;
- Comprehensive monitoring of hydro systems and structures.

Using the function analysis system technique (FAST), which is one of the main features of the value engineering methodology, the holistic design strategies are shown in Figure 4. FAST diagram interconnects the functions by How-Why logic.

Obviously the holistic design of adaptive hydraulic structures closely corresponded with AFM. In the last two
decades, the strategies of AFM were successfully applied to a few large water projects in Iran. A summary of these cases studies are presented below.

Case study #1: Sistan flood management project

The history of floods and droughts in the Sistan Plain extends to hundreds of years ago. During the past fifty years, major floods have occurred in 1957, 1982 and 1991 with tens of million dollars in total damage and unimaginable human suffering. The droughts for their part have prevented the development of this impoverished province of Iran. For example, the notable drought of 1971 was so severe that 70% of the population was forced to migrate to other provinces. Chahnime off-channel reservoirs, constructed in 1980 and shown in Figure 5, effectively prevented a similar disaster during 1984–1986 droughts.

After the floods of 1991, two alternatives were proposed for flood mitigation of the Sistan Plain. The first one was an option of flood control through huge dike construction. The alternative scheme was based on a holistic approach and called for addressing drought and flood problems by construction of more reservoirs and diverting the flood peak into the reservoirs by using non-structural approaches. The scheme would have resulted in enormous saving and reduced construction time. In practice, financed by the World Bank, the flood control dikes were constructed after 7 years in 1999. When the unprecedented drought in the history of the region began in 2000 and extended for 3 years, it became apparent what the region needed most were more reservoirs and holistic thinking. The Sistan River with an average volume of 2300 MCM (million cubic metres) dried up for 3 years. The drought was so severe that the irrigation area decreased from 100,000 to less than 10,000 ha.

Case study #2: Early impoundment of Marun dam

In view of water crisis in the world and economic considerations, impoundment of reservoirs during construction can be very important especially for large dams in developing countries. Using seasonal characteristics and forecasting models, the first filling can be achieved after the flood season. But the spillway should be in service before the next flood season. In the course of a research on early impoundment of 165 m high Marun Dam in Iran, application of holistic design strategies resulted in an innovation that would enhance the safety and flexibility of the first impoundment, which is the most dangerous period in the life cycle of a dam (Emami, 1998a), (Emami, 2001). A thin concrete shell was proposed for plugging of the diversion tunnel, which could readily be exploded if required to reverse the impoundment. The concrete shell was appropriately called fuse shell. The fuse shell would enhance the flexibility of the design especially in view of common uncertainties of water engineering. Unfortunately the fuse shell idea was not implemented for the first filling of Marun Dam in March 1996. So when unexpected leakage of more than 7 m³/s occurred during the filling (Figure 6), the 10 m long concrete
plug lacked the desired flexibility. The fuse shell could have saved the day. It could have ended the crisis in 2 or 3 days instead of 6 months. The probability of piping in the core, the delay in construction activities and the environmental damages to the fishes after the explosion of the gates could have been avoided. In practice, the first application of the fuse shell was in another Iranian dam, Godalandar on Karun River for the first impoundment in December 2000 (Emami, 2001). Unlike the Marun Project, there was no need for explosion of the plug in the first impoundment of the Godalandar Dam in December 2000. However, the existence of the fuse shell gave the owner and the consultants the assurance required for a safe and flexible impounding scheme (Emami, 2005d).
Case study #3: Value engineering of Vanyar spillway

In a value engineering study undertaken in 2003 on the spillway of Vanyar Dam in North-West of Iran, the Kurit expert system guidelines on selection initial reservoir elevation in routing of the design flood and season characteristics resulted in considerable reduction of spillway length. The length of the side channel spillway, which was 110 m in the base case (Figure 7), was reduced to 40 m when a lower initial reservoir elevation for routing of the design floods in spring for wet years was proposed in the creative phase of the value engineering studies. The water resources modelling of the system demonstrated that if the decision for reservoir drawdown were based on the forecasting model, the drawdown would not reduce the regulated flow of the reservoir. The intelligent operation proposed not only decreased the spillway cost by 40% and solved the geological problems at some part of the spillway, but also considerably would reduce the outflows of different floods in Tabriz, which is located just 5 km downstream of the dam. Finally the damages of flood inundation on the reservoir rim would be reduced substantially. It is interesting to note that a comprehensive flood forecasting and warning system (FFWS), emergency action plan (EAP) and decision supporting system (DSS) have been designed for this project (Figure 8). Based on the results of forecasting models for spring volume of Ajichay River in three consecutive years, a drastic improvement of the models and learning has been observed.

Furthermore, in the context of the restoration of Urmia Lake, which is the largest salt lake in the Middle East, it was decided to change the main objective of Ajichay Dam from agriculture to lake restoration in 2015. In this context the non-structural approaches adopted for hydrological safety of the dam is much more adaptive than the structural alternative and consequently billions of rials would be saved.

Case study # 4: Early impoundment of Karkheh dam

The Karkheh Dam is a large multi-purpose earthen embankment dam built in Iran on the Karkheh River in 2001. The
The Karkheh Dam is on the Karkheh River in the Northwestern Province of Khūzestān, the closest city being Andimeshk to the East. It is 127 m high and has a reservoir capacity of 5.9 BCM (billion cubic metres) (Figure 9). The Karkheh Dam is designed to irrigate 320,000 ha of land, produce 520 MW of hydroelectricity and to prevent downstream floods. In 1956, studies began on the Karkheh Dam by the American company Development and Resources Corporation, which was headed by David E. Lilienthal, the former Chairman of the Tennessee Valley Authority. In 1990, the final studies were completed by MahabGhods Consulting Engineers. The construction of the Karkheh Dam started in 1992 and the dam was completed in 2001. During construction, 120 contractual and over eight consultative companies worked on the dam.

Based on the worldwide experiences of dam failures, the first filling of a dam is the most dangerous period in the life cycle of dams. In this context, a comprehensive study for first filling was undertaken in the last 20 months of construction. In the context of this study, the strategies of AFM were applied in an integrated approach (Emami, 2005e). A day to day monitoring of the Karkheh Basin was undertaken and climate forecasting models based on El Niño southern oscillations (ENSO) were utilized along with hydrological forecasting models. When the models predicted below average inflow in next spring in February 2000, the impoundment of the reservoir started while the dam was still under construction and the embankment crest was below the spillway crest (Emami, 2005a). The following spring was one of the driest seasons in the history of the river but a volume of 400 MCM of water stored in the reservoir in the previous winter saved the day!

Case study # 5: ENSO based seasonal flood warning in Iran (2015)

In August of 2015, a very strong El Niño was forecasted and a study undertaken for six selected basin in Iran (Figure 10), indicated a good teleconnection of Strong ENSO events and precipitations in autumn. The historical finding supported the teleconnection observed. These forecasts were used for enhanced real time management of extreme floods observed in the south-west basins (Such as Marzi Gharb and Karkheh). In fact, the Iranian power ministry issued a warning on large floods forecasted for November and December 2015 one months in advance. The mentioned ENSO based forecasts and warning matched closely with the observed

Figure 9. A general View of Karkheh Dam. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 10. Basins used for climate forecasting and flood warning in 2015–2016 in Iran. [Colour figure can be viewed at wileyonlinelibrary.com]
The most important challenge of the flood engineers in the 21st century is to design and construct safe and low cost environment-friendly hydraulic structures with uncertain design parameters. Solution of this problem will above all require adopting a holistic and adaptive approach. The main strategies of the holistic design are to:

- ensure a flexible and adaptive design in view of hydrosystems’ changes and the inherent uncertainties of water engineering;
- establish the interdependence of structural and non-structural approaches in design. In this context ‘management of hydraulic structures’ would have to be designed too;
- adapt to the stochastic nature of river flow by integration of seasonal characteristics and river forecasting;
- learn while doing;
- recognize the uncertainties of risks of project and design hydraulic structures to adapt to extreme events far larger than design parameters and remain inherently safe (structural ductility and resilience);
- base the design on comprehensive management and flexibility;
- Enhance safety by ‘designing’ emergency and crisis management preceding the events and in real time for the structure and downstream population centres.

In the past decade the holistic design has been used for several water projects including dam construction, flood management and value engineering studies. In all the cases the holistic design has resulted in enhanced safety and reduced cost and construction time. The experiences of application AFM in the above mentioned projects are as follows:

- the large projects are inherently unique; consequently the adaptation of holistic design for each case varies greatly from one to another project. In some cases one or two strategies have more effect on the proposed alternative;
- value engineering is an effective tool for achieving a unique solution for a unique project. The creativity phase and job plan of Value Engineering (VE) provide a good base for non-structural proposal. The participation of operation personnel in VE workshops would help the holistic approach of the team;
- for most cases, the clients and consultants readily accept the holistic approach for early impoundment of reservoirs. In this case, the non-structural approach can be very effective;
- in view of inherent uncertainties associated with determination of design floods, structural ductility has crucial importance in hydrological safety of cofferdams. In this context, it should be pointed out that in the last 15 years, 4 large cofferdams were overtopped and failed in Iran;
- implementation of AFM can result in innovations in hydraulic structures such as ‘fuse shell’ for early impoundment of reservoir;
- information technology can greatly help implementing AFM measures;
- the tragic experiences of great tsunamis of December 2004 and March 2011 vividly indicated the crucial role of non-structural measures especially emergency and crisis management and the need for robustness and resilience of hydraulic structures.

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PAST FLOOD DISASTER DAMAGES AND PAST–FUTURE FLOOD COUNTERMEASURES IN JAPAN

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Abstract

In this report, we first describe Japan's geographical and climate features, then discuss the historical changes in flood damage since 1949, provide details of some major flooding events, then describe the government's current efforts to mitigate damage from flooding disasters, and finally present our research results. We explain that lowland areas are socio-economically important in Japan; that heavy rainfall is becoming more frequent due to the effects of climate change; that flood damage has decreased considerably since 1960, showing the effects of infrastructure; and that although damage to crops has decreased, floods still cause significant damage to agricultural infrastructure. We describe some past heavy rainfall events that resulted in significant human casualties. We explain that, to reduce flood damage further, the government has started a system of "basin flood countermeasures" whereby all concerned parties upstream and downstream of the river basin (central government, local government, municipalities, companies, residents, etc.) work together on flood control measures and the importance of individual decision-making in this system. In terms of our research results, we introduce a program to predict the water level of drainage pumping stations and drainage channels in low-lying areas in real time, based on weather information, etc.

1. Background: A recent situation

1.1. Geological feature

Japan is an island country located in the Pacific Ring of Fire at the eastern end of the Eurasian Continent, and three-quarters of its land area is mountainous. Lowland areas play a significant social and economic role in Japan. The residential demography of Japan categorized by heights above mean sea-level is shown in Fig. 1, based on Sugimoto 2017. Approximately 64 million people, 50% of the population, live in areas that are less than 25 m above mean sea-level elevation. The Ministry of Agriculture, Forestry and Fisheries (MAFF) reports that approximately 32% of agricultural communities live in areas below 30 m mean sea-level elevation (Fig. 2, MAFF, 2016a). The land area below 30 m mean sea-level elevation is less than 12% of the total inhabited land (Fig. 3, Japan Statistic Association, 2007).

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1.2. Climate of Japan

Japan, excluding Hokkaido Island, located in Monsoon Asia, receives relatively high rainfall owing to seasonal rain fronts and typhoons. The annual rainfall received throughout the country is approximately 1,670 mm (MILT, 2019). Therefore, flood control and protection work have been important issues for a long time. Accordingly, various types of infrastructure, such as river path changes, river embankments, reservoirs, and discharges have been installed.

The frequency of short-term heavy rainfall of ≥50 mm/h (precipitation in the previous hour at every hour) is increasing (Fig. 4, JMA, 2019). The average number of short-term heavy rainfall between 1976 and 1985 was approximately 226 per 1,300 observation points per year; this number increased to approximately 327—about 1.4 times—between 2009 and 2018. In contrast, the number of days with daily precipitation of ≥1.0 mm decreased by 9.3 days per 100 years to approximately 120 days in 2020, considering the statistical period from 1901 to 2020. Thus, the study of climate in Japan has shown an increase in the frequency of heavy rainfall with decreasing number of precipitation days, including days of light rainfall.

![Fig. 4. Annual frequency of over 50 mm/h precipitation in Japan](image)

2. Past flood disasters

Until the 1960s, the casualties from flood and typhoon disasters were extremely high, exceeding 1.66 person per 100,000 people each year*. In particular, the 15th typhoon in 1959 (commonly known as Isewan Typhoon) caused enormous devastation with more than 5,000 dead and missing, thus triggering disaster prevention efforts by the government. In 1961, the Basic Act on Disaster Management was enacted, in which the government decided to actively implement disaster prevention measures and promote comprehensive and systematic disaster prevention policies to protect people’s lives and property. The act has contributed to the maintenance of social order, securing of public welfare, and declining of annual disaster casualties to around 100 people.

* Total population: Ministry of Internal Affairs and Communications, 2021.

![Toll of dead and missing (count)](image)
Fig. 5. Annual toll of dead and missing because of flood and typhoon disasters since 1949 in Japan. The toll of dead and missing was calculated with reference to Ushiyama (2017), National Police Agency (1968-2019) and Ministry of Land, Infrastructure, Transport and Tourism (2021).

The agricultural damage caused by flood and typhoon disasters in the last 40 years based on the website of the Ministry of Agriculture, Forestry and Fisheries concerning disasters (MAFF, 2021) is shown in fig. 6. The flood-based damages to agriculture have been increasing, especially in the last four years. Annual agricultural damage caused by flood disasters has mostly exceeded approximately 200 billion JPY (equivalent to 1,893 million US dollars at the exchange rate of 105.6 JPY per USD as on February 20, 2021), and in 2018 and 2019, it was over 400 billion JPY. While economic damage to agricultural crop production, which used to be high, has decreased, the damage to agricultural infrastructure, such as ponds, headworks, irrigation-drainage canals, and farm roads, is still high. Such infrastructure play a key role in water circulation and contribute to disaster risk reduction. Therefore, policies and research and development pertaining to disaster risk management must be strengthened.

The solid line with square markers in fig. 6 shows the annual number of deaths and missing persons due to flood and typhoon disasters. In the last 40 years, disasters with death toll exceeding 200 people have been rare. In 2004, several medium-level disasters occurred, leading to a high overall toll of dead and missing. The details of the 1983 and 2018 disasters are presented as follows.

3. Past heavy rainfall events causing major damage

3.1. Isewan Typhoon, 1959 (Showa 34)
The 15th typhoon (commonly known as Isewan Typhoon) made landfall at Shionomisaki shortly after 6 pm on September 26, 1959, with a pressure of 929 hPa. A maximum instantaneous wind speed of 45.7 m/s and a maximum tide level of 5.31 m (Nagoya port) were recorded in Nagoya city. The typhoon caused major storm surge damage from Nagoya city to the coast of Mie prefecture. The daily rainfall from September 26 to 27 was approximately 160 mm in Tsu city, Mie prefecture, equivalent to once in 80 years. Of the 5,098 people reported dead or missing, over 90% were in the three prefectures of Aichi, Mie, and Gifu around the Ise Bay, and 70% of these casualties were due to the storm surge. Over 5,000 people were reported dead or missing, approximately 149,000 homes were destroyed, 158,000 homes flooded, and 5760 levees breached, making it Japan’s largest flood disaster of the 20th century. The damage to agricultural land in Aichi prefecture included approximately 1,800 ha of rice paddies covered in debris, approximately 35,000 ha of rice paddies flooded, approximately 1,300 ha of crop fields covered in debris, and approximately 7,700 ha of crop fields flooded (Yamauchi, 1959). The enormous destruction caused by this typhoon prompted the Japanese government to legislate the Disaster Countermeasures Basic Act. Hence, this typhoon is said to be the disaster that shaped Japan’s disaster prevention policy.

![Fig. 6. Damage caused by flood and typhoon disasters](image-url)
3.2. Nagasaki Flood, July 1982 (Showa 57)
On July 23, 1982, torrential rainfall exceeding 100 mm/h fell for approximately three hours in Nagasaki, causing flooding, landslides, and avalanches of rocks and earth. The daily rainfall in Nagasaki city was 448 mm, equivalent to once in 200 years (Ota, 1983). Nagasaki is a hilly city, and approximately 90% of the 299 casualties died in landslides due to the collapse of slopes. The damage to agriculture and forestry land in Nagasaki prefecture included approximately 2700 ha of agricultural land flooded, buried, or covered in debris; and approximately 20,000 agricultural and forestry facilities damaged. The cost of damage to agricultural facilities, produce, and livestock was approximately 8.4 billion yen (Tanaka et al. 1983).

3.3. Kagoshima Heavy Rain, 1993 (Heisei 5)
In the afternoon of August 6, 1993, heavy rainfall of up to 99.5 mm/h fell for several hours in the area around Kagoshima city. The banks of three rivers flowing through Kagoshima city burst, flooding approximately 11,000 buildings. The daily rainfall in Kagoshima city was 259 mm, equivalent to once in 200 years (Iwamatsu, 1994). Cliffs alongside the national highway collapsed at 22 points along a 4 km stretch. Approximately 3,000 people were stranded, including drivers of 1,200 vehicles, train passengers, and local residents. In addition, 49 people were reported dead or missing. The soil in this area is known as Shirasu, which is made up of fine volcanic rock and ash; hence, it is susceptible to erosion by rainfall. This is believed to have resulted in the collapse of several slopes. Approximately 800 locations of agricultural land and 1500 agricultural facilities were damaged in Kagoshima prefecture (Yasuda et al. 1994).
3.4. July 2018 flood

We report the details of the July 2018 flood (Western Japan flood), which was the worst disaster in the past 30 years, with more than 230 casualties. Two years since the disaster, several findings have been reported from various viewpoints.

3.4.1. Climate condition

Tokyo Climate Center, Japan Meteorological Agency (2018) reported the following:

Various parts of Japan experienced significant rainfall during the heavy rain event of July 2018 (28th June–8th July), with unprecedented precipitation recorded at some Automated Meteorological Data Acquisition System (AMeDAS) stations of the Japan Meteorological Agency (JMA). During this period, stations in the Shikoku and Tokai regions recorded more than 1,800 and 1,200 mm, respectively (Fig. 7). Some areas experienced two to four times the precipitation of the monthly climatological normal for July (Fig. 10). The overall precipitation reported by 966 selected AMeDAS stations throughout Japan for early July 2018 was the highest for any 10-day period since 1982, highlighting the nationwide significance of this event.

The primary synoptic/meso-scale atmospheric circulation-related factors contributing to the heavy rainfall event detailed in Section 1.1 are as follows (Fig. 11):

(A) ongoing concentrations of two massively moist air streams over western Japan;
(B) persistence of upward flow associated with the activation of the stationary Baiu front;
(C) characteristics of line-shaped precipitation systems.

Factors (A) and (B) dominated the event as a whole, while (C) played a significant role in certain areas.
3.4.2. Alert system
From August 30, 2013, JMA begun operating an emergency warning system that calls for the highest level of caution (JMA, 2013). JMA announces emergency warnings when heavy rains and tsunamis that far exceed the warning announcement standards are predicted and when the risk of serious disasters is significant. Some examples of past phenomena targeted by this special warning system are the great tsunami triggered by the Great East Japan earthquake, which resulted in more than 18,000 casualties. Another incident is the Isewan typhoon, which resulted in more than 5,000 casualties and recorded the highest tide level in Japan's observation history. During the heavy rains of July 2018, eleven prefectures (Gifu, Kyoto, Hyogo, Okayama, Tottori, Hiroshima, Ehime, Kochi, Fukuoka, Saga, and Nagasaki) announced an emergency warning at 17:00 on July 6, calling for the maximum caution. The number of municipalities subject to emergency warnings peaked at 157—the highest since the system started in 2013.

3.4.3. Disaster damage
Cabinet Office Japan (2019) reported the following:
The heavy rain event of July 2018 caused river flooding, inundation, sediment, and other disasters, which rendered 237 people dead, 8 persons missing, and 466 people injured. Damage to houses included complete destruction, partial destruction, and flooding of 6,767, 15,447, and 28,510 houses (information from the Fire and Disaster Management Agency, as of January 9, 2019. Reference: https://www.fdma.go.jp/disaster/info/items/h30-7_59.pdf).
Debris flows occurred concurrently at several locations. A massive flooding disaster occurred because of the breach of levees that occurred because of a “backwater phenomenon,” wherein the water level remains high over a long period at the point where the tributary meets the main stream. River flooding occurred owing to heavy rainfall exceeding the capacity of the river control facilities. Nationally, heavy rainfall caused damage to 346 points. Inland inundation occurred at 88 municipalities in 19 prefectures. Furthermore, 2,581 sediment disasters—791 debris flows, 56 landslides, and 1,734 cliff failures—occurred in 32 prefectures (information from the Ministry of Land, Infrastructure, Transport, and Tourism, as of January 9, 2019. Reference: http://www.bousai.go.jp/updates/h30typhoon7/index.html).
Damage to utilities included power outages, affecting a maximum of approximately 80,000 households. The power supply for residential areas was restored on July 13, 2018. Gas supply was also disrupted, affecting approximately 290 households; this was restored on July 8, 2018 (information from the Ministry of Economy, Trade, and Industry as of January 9, 2019. Reference: http://www.bousai.go.jp/updates/h30typhoon7/index.html). Water outages occurred at 80 municipalities in 18 prefectures, affecting a maximum of approximately 260,000 households; it was subsequently restored in all areas by August 13, 2018 (information from the Ministry of Health, Labor, and Welfare, as of January 9, 2019. Reference: http://www.bousai.go.jp/updates/h30typhoon7/index.html).
A total of 3,779 shelters were built in all the prefectures. The maximum number of evacuees was approximately 28,000. All the general shelters were closed by December of the same year (some welfare shelters remained open until March 2019).

The agriculture sector suffered the following damages: 30 billion JPY for crop production, 56.5 billion JPY for damage to farmland at 26,000 locations, and 85.4 billion JPY for damage to agricultural facilities including 32 collapsed irrigation ponds. The total damage amounted to 340.9 billion JPY (MAFF, 2019).

3.4.4. Disaster response
Cabinet Office Japan (2019) reported the following:
From July 2, 2018, the government held a series of inter-agency disaster alert meetings to prepare for emergencies. The government established the Major Disaster Management Headquarters, headed by the Minister of State for Disaster Management at 8:00 a.m. on July 8. The headquarters held 23 meetings until September 6. The prime minister attended most of the meetings and led activities to grasp the extent of the damage, the overall coordination of response measures, and the prevention of secondary disasters.
The government immediately began rescue operations in early July. Organizations, such as the local police, Fire and Disaster Management Agency, Self-Defense Force, and Ministry of Land,
Infrastructure, Transport and Tourism, dispatched rescue units from across Japan to the affected areas to conduct rescue and search operations as well as secondary damage prevention activities and life support activities.

The government established the Heavy Rain Event of July 2018 Initial Response Review Team to analyze and review the initial response measures taken by government officials and utilize the lessons learned from this disaster for future disaster response initiatives. In the aftermath of the disaster, many government officials carried out various support activities at the affected local governments. The review team held discussions based on reports on measures taken by individual ministries and agencies as well as reports submitted by 79 government officials, including senior officials from the cabinet office, who were in charge of on-site coordination (Deputy Director-Generals and Directors) and other senior officials from ministries and agencies (Director-General/Director-level officials) dispatched to the affected areas. The Review Team outlined items that should be appreciated and those that require some improvement with respect to the following five areas, where the most initial response efforts were focused: (1) ascertainment of the shelter situation, (2) debris disposal and sediment removal, (3) water supply support and restoration of water service, (4) securing of housing, and (5) support for local governments.

Since personal and social damage was tremendously huge, several local governments, such as Hiroshima, Okayama, Ehime, and Gifu Prefectures, have verified and reported on the disaster emergency response. In addition, Okayama Prefecture and Hiroshima City published disaster records to make citizens and local residents aware of the scale of the disaster. Many universities and research institutes, such as Ehime University, Okayama University, and the Disaster Prevention Research Institute of Kyoto University, have also published disaster investigation reports.

4. Past-Future Countermeasure

4.1. Basin flood countermeasures
In order to prepare for the increase in flood risk due to climate change, it is necessary to build a system with the collaboration of all concerned parties (central government office, local government, municipalities, companies, residents, etc.). This system is called “basin flood countermeasures,” which aims to ensure that all parties voluntarily and initiative tackle the flood with embankments, protection facilities, appropriate operation of drainage gates and pumps, land-use plans, evacuation plans etc. For example, the following two flood countermeasures are being considered in rural areas. The first one is dam reservoir operation for flood control. Most dam reservoirs for irrigation equip the spillway at the top, and water flows over the spillway during floods to avoid holding excess water. Thus, most dam reservoirs contribute little to flood control. However, we now consider that the reservoirs can drain stored water in advance of flood and hence maintain their high storage capacity (Fig. 12, MLIT, 2020).

Fig. 12. Flood control operation of an irrigation dam reservoir (left: water drained to increase vacant storage in advance of a typhoon, right: typhoon runoff water was held in the dam, MLIT, 2020)

The other flood countermeasure involves improving the drainage facilities, such as repairing and replacing aging facilities (especially those close to city areas) such as pumps, gates, and waterways. This is because the transformation of paddy fields into residential areas reduces the rain storing capacity, increases flood risk and human and economic damage during inundation.

4.2. Efforts to reduce the number of victims further
As mentioned earlier, the death toll from flooding has decreased significantly in Japan due to the construction of river and coastal defenses. Such structures are usually designed to withstand a maximum of once-in-100-years rainfall; hence, the defenses function sufficiently for rainfall less than this scale, indicating that damage is unlikely. However, due to the effects of climate change, rainfall events exceeding the scale of once in 100 years are becoming more likely. Therefore, minimizing the
number of victims in the event of rainfall exceeding assumed levels is an important issue in Japan. In addition to improving existing flood defenses and weather forecasting, individuals evacuating on their own initiative in the event of a disaster is a suggested solution. It has been observed that a certain number of residents do not evacuate in the event of a disaster. According to psychological analysis, this is believed to be due to normalcy bias and conformity bias. Normalcy bias is a psychological bias referring to the mental state where “when humans confront an unexpected abnormality, they believe that a certain degree of abnormality is within the normal range,” which is essential for humans to survive. However, in the event of a disaster, excessive normalcy bias makes people unable to recognize the danger accurately. Conformity bias is a psychological bias referring to the mental state where humans “do not want to stand out by acting differently from other people,” which causes them to prioritize behaving the same as others around them over their own free will.

In a survey of people affected by the heavy rain of July 2018, the most common reason given by people who did not evacuate was “I did not think I would be harmed.” Several people also responded: “because the area in which I live has never been damaged in the past” and “because my neighbors did not evacuate.” All these responses involve normalcy bias and conformity bias (Taniyama, 2019). Therefore, to reduce the number of victims, each individual should understand that “disasters that exceed expectations will occur, and if that happens, I will need to make the decision myself to evacuate to save my own life” and evacuate as appropriate.

4.3. Introduction of research results: System to predict water levels in real time during flooding, to support decisions about the operation of drainage pumps

Two programs were developed to predict the water levels of drainage pumping stations and drainage channels in low-lying areas in real time, based on weather information, etc (Kimura et al. 2019 and Azechi et al. 2021). Both these programs can predict water levels several hours ahead in real time, based on the most up-to-date measurements and weather forecast data.

The program to predict the water levels of drainage pumping stations is a long short-term memory (LSTM) program, which is an improved version of a recurrent neural network (RNN) that identifies the characteristics of a temporal sequence of data. By learning sufficient past rainfall and water level information, this program can perform prediction calculations with a high accuracy at high speed (Fig. 13). This program can be applied to any location where there are sufficient past observation data; hence, it can predict water levels at water level observation points, not just at drainage pumping stations.

The program to predict the water levels of drainage channels is a one-dimensional unsteady flow analysis. It can make stable prediction calculations by applying an implicit method to the rainfall runoff and a non-equidistant third-order finite difference method (quickest method) to reproduce the water level (Fig. 14). It can calculate the water level of a network of drainage channels and examine the process of water overflowing around these channels. Prediction results for an entire area can be output at arbitrary time intervals. To perform these calculations, local information such as the cross-section of channels must be established and entered in advance.

These two programs form the main elements of the local wastewater management and disaster mitigation information system that we have developed (Fig. 15). This system can present users with prediction results from the two programs to support the efficient operation of drainage pumps, or to help users make decisions about the appropriate operation of facilities, such as sluice gates.

![Image of water level prediction at pumping station (LSTM program)](image1)

![Image of rainfall runoff and overflow calculation (Hydraulic program)](image2)
5. Conclusion

In Japan, damage from flooding is on the decline, owing to the construction of flood defenses. However, due to the effects of climate change, rainfall exceeding expected levels is becoming more likely; hence, there is an increasing risk of severe rainfall events. This indicates that there is a possibility that existing flood defenses may not function. Thus, it is necessary for all organizations, people, and institutions related to the river basin to work together to minimize damage from flooding in the event of a disaster. In particular, to reduce human casualties, it is important for individuals to make their own decisions to evacuate; hence, it is necessary to take action to raise awareness in this regard.

References


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Fig. 15. Display results and usage of the two programs in the local wastewater management and disaster mitigation information system

Note 1: For the pumping station calculation, the system learns from 8 years’ data.

Note 2: For the drainage channel calculation, the latest water level measurement cannot be obtained; hence, it displays the difference from the set initial water level.

System provides real-time prediction information to support decisions by

Displays drainage channel water level prediction results. Information provides trends for an area.

Displays pumping station water level prediction results. Instantly provides pinpointed information.

Target pumping station. 25 m pool, can be drained in approx. 8 s

Instantly provides pinpointed information.


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11th N.D. Gulhati Memorial Lecture for International Cooperation in Irrigation and Drainage on “Putting People at the Heart of What We Do” Presented at 24th International Congress on Irrigation and Drainage, 2022 and delivered by

Hon Karlene Maywald, DUNIV, FTSE, GAICD South Australian Water Ambassador

The Hon Karlene Maywald is currently the South Australian Water Ambassador. Her previous roles include South Australian Minister for Water Security and the River Murray, Murray Darling Basin Ministerial Council Member and Chair of the Australian National Water Commission.

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Putting People at the Heart of What We Do

Hon. Karlene Maywald
South Australian Water Ambassador and Chair of the Australian National Water Commission (Australia)