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Evaluation of Flood Forecasting, Early WarningSystem and Iits Role in Flood Management in Indus basin, Pakistan

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ABSTRACT

This paper evaluates the effectiveness of Flood Forecasting and Early Warning (FF&EWS) in the Indus basin, Pakistan. It is non-structural measures, used extensively. It forecast and disseminate of flood warning to the people that are exposed to flood. The aim of this paper to evaluates the effectiveness of early warning. The Indus basin were selected as the study to achieve the objectives. Data were collected from primary as well as secondary sources. The Indus basin was affected by numerous floods, however, the flood of 2010 and 2022 were the century worst flood. The analysis reveals that in Indus basin, flood warning is one of the non-structural mitigation measures. It is the sole responsibility of Pakistan Meteorological Department, which predict through an established weather radar stations covering the Indus basin. After flood forecasting, an important stage is disseminations of flood forecasting to the vulnerable communities. It share through a network of telemetric, fax and email with the related federal, provincial and concerned district government as early warning to minimize the risk in the flood prone areas in Indus basin. The major findings of the study highlights that, improper flood forecasting in the remote areas of Indus basin, limited coverage by radar network, terrain and human encroachment has aggravated the consequences of floods. By strengthening local level risk reduction capacity focus, need to be made at the union council and tehsil level to minimize the damages of flood. The study concludes that the study area is out of the range of existing flood forecasting. The effectiveness can be improved by addressing the challenges faced by the flood management line agencies. On the basis of analysis, suggestions and recommendations are formulated to improve flood forecasting and early warning system in Indus basin, Pakistan

1. Introduction

Globally flood forecasting is very important for monitoring of flood hazard to minimize the impacts of flood (Cammerer et al., 2013). Flood Forecasting and Early warning (FF&EW) is one of the important pre-disaster measure, that minimize the damages caused by floods, saves human lives and other properties (Ali, 2018). The concept of flood forecasting and early warning is applied to highlight the timely dissemination of forecasted flood information (Allaire, 2018). FF&EWS play an important role for mitigating the impacts of floods on communities and infrastructure, which can reduce the loss of life and property by enabling communities to take necessary precautions (UNDRR, 2019). Effective FF&EWS rely on advanced technologies to provide accurate and timely predictions about weather (Basha et al., 2018). The importance of FF&EWS is underscored by the devastating impacts of floods worldwide. Floods are among the most frequent and destructive natural disasters, causing significant economic losses and displacement of people (World Bank, 2020). By providing early warnings, these systems can help save lives, reduce economic losses, and promote resilience in flood-prone communities (Hallegatte et al., 2013).

Early warning system has been developed to communicate information to authorities to take emergency measures in communities that should be affected by flood (Pappenberger, et al., 2008). Flood early warning helps to minimize the losses of human lives and loss of economy (Krzhizhanovskaya, et al., 2011). Nevertheless, the frequency and intensity of floods are increasing (Rahman and Khan, 2013). (FF&EW) form a key part of preparedness strategies for disastrous flood events by providing (EW) several days ahead (De-Roo, 2006). Many (FF) rely on precipitation inputs, which come initially from observation networks (rain gauges) and RADAR system (Sanders, 2007). Presently, used of advance technologies in (FF&EW) have made a significant impact in minimizing flood damages (Bashir et al., 2010). However, the effectiveness of FF&EWS varies from region to region due to existing RADAR coverage that limits the effectiveness of FF&EWS (WMO, 2022).

Indus basin, Pakistan were hit by 23 worse floods that affected Indus basin on large scale (NDMA, 2022). In Indus basin, flash floods are mostly occurs in upper Indus basin mountainous regions, however the riverine floods are occurs in the lower Indus basin flood plains regions (PMD, 2022). In the Indus basin, the devastating floods of 2010 has killed nearly two thousand people, injured over one thousand persons, and displaced millions of people as well as destroyed livelihoods and properties (Mustafa and Wrathall, 2011). Similarly, 2022 flood is one of the worst flood in history, which affected more than 33 million people, 1,355 people were died and 12,700 were injured (GoP and NDMA, 2022). To mitigate flood in Indus basin both structural and non-structural mitigation strategies are applied (Rahman, 2015). Flood Forecasting Division (FFD) Lahore is the main stakeholder for timely (FF) and issuance of (EW) to the flood prone communities in Indus basin, Pakistan (PMD, 2022). One of the significant challenge for FF&EWS and its role in flood management in the Indus basin, Pakistan, is the accuracy and reliability of flood data (PMD, 2022). However, gaps in data collection, particularly in remote areas, compromise the effectiveness of leading to less reliable predictions and potentially inadequate warning to the affected communities (NDMA and PDMA, 2022). The lack of sufficient data can be attributed to various factors, including limited infrastructure, inadequate funding, monitoring system in Indus basin, which affects the ability of existing early warning system.

This paper is an important attempt to evaluate the effectiveness of (FF&EW) and its role in flood management in Indus Basin, Pakistan. Evaluation is particularly important for (FF&EW) in the Indus Basin, Pakistan, due to its vulnerability to flooding. The Indus basin is one of the most flood prone region, in which the frequency and severity of floods are day by day, increasing due to climate change and human encroachment (Ali et al., 2018). An effective and well developed (FF&EW) system, can save lives and reducing the economic impacts of floods in the Indus basin, Pakistan (GoP, 2022). The effectiveness of (FF&EW) varies from region to region depending on the existing meteorological RADAR coverage and the effectiveness of communication and dissemination process. The existing FF&EWS and its role in flood management in the Indus basin, Pakistan, lies in its ability to support decision-makers to develop effective flood management strategies. However, despite the existing FF&EWS, significant gaps in FF&EWS, that includes limited spatial and temporal coverage by weather radars, inconsistencies in data quality, and lack of standardization, which limits FF&EWS in Indus basin. By addressing data gaps through improved monitoring networks, investment in infrastructure FF&EWS can be make more effective Therefore, this research is an important attempt to evaluate the effectiveness of (FF&EW) and its role in flood management in Indus basin, Pakistan. This research paper is divided into five sections. The first section deals with the detail introduction of the study, the second section is given to the methods and material used to carry out the study, whereas the third section is given to the analysis and results, while section four were given to

discussion. On the basis of the analysis result and discussion this research paper is concluded and recommendations are proposed to make flood forecasting and early warning system more effective in Indus basin, Pakistan.

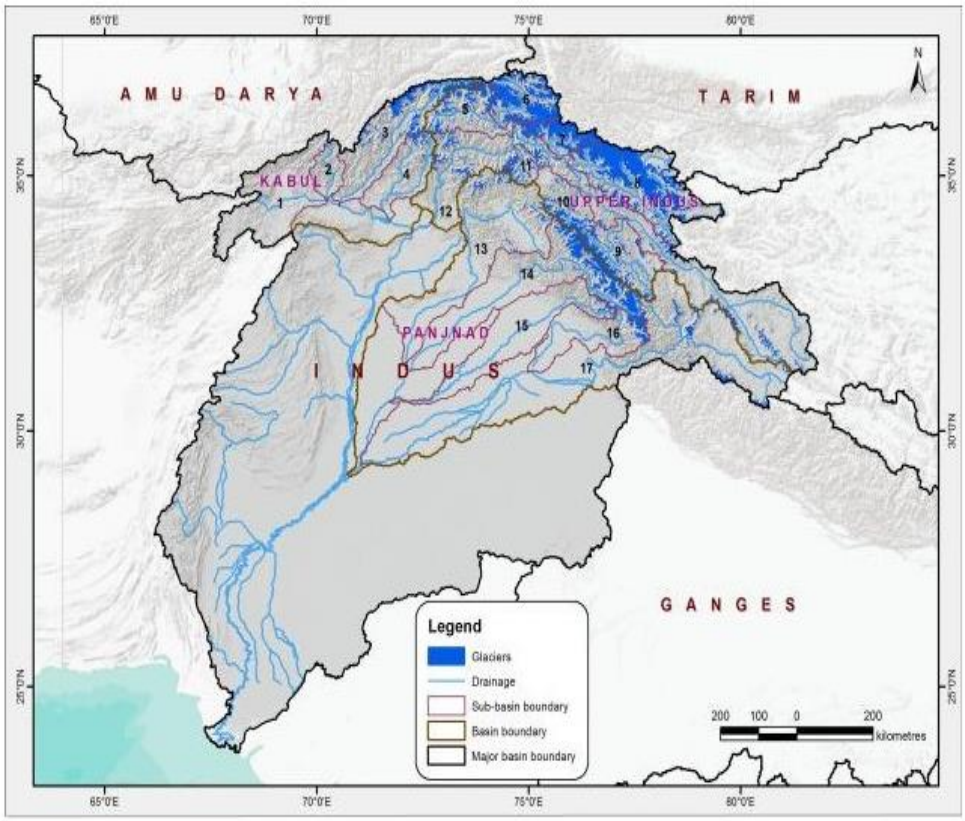


Figure. 1. Location map of the study area

2. The study area

2.1 Profile of the Study Area

The Indus basin extends between 24.14° to 34.46° North latitude and 67.41° to 74.68° East longitude in Pakistan (Figure. 1). About 520,000 square kilometers area is covered by Indus basin in Pakistan, which is 65% of the land area and 80% of the total population (Yu et al., 2013). The total length of the Indus river is 3,180 km (Nepal and Shrestha, 2015). Based on physiography Indus basin is divided into the Upper and Lower Indus (Zafar, 2016). The Upper Indus basin (UIB) consist of the mountains of Himalaya, Karakoram, and Hindukush, while the Lower Indus basin (LIB) is consist of plains of Punjab and Sindh province (Shrestha et al., 2019). The Indus passes through gigantic gorges 4,500-5,200 metres (15,000 17,000 feet) deep near the Nanga Parbat (WAPDA, 2022). The Indus basin is largely fed by the snow and glaciers of the Himalaya, Karakoram and Hindu Kush ranges (Hashmi, 2012). The Indus basin comprises the main Indus and its major tributaries that include Kabul river and Kurram, Swat, Jhelum, Chenab, Ravi, Beas and Sutlej river (IRSA, 2022). Indus basin, receives an overall rainfall of less than 15 inches, however Himalayan foothills, which receive significant rainfall (PMD, 2022). Indus basin is prone to geophysical, hydrological and meteorological phenomenon (Rahman and Shaw, 2015). The 2010 floods in upper and later on in lower Indus basin affected more than 18 million people, caused 1985 deaths and destroyed 1.7 million houses in the flood affected areas (Hayat, 2019). Similarly, 2022 flood also affected more than 33 million people in lower Indus basin (LIB) that leads 1,355 people deaths and 12,700 people were injured (NDMA, 2022).

In order to minimize the damages of flood disasters in Pakistan, structural and non-structural mitigation measures are applied (Rahman, 2015). In the present set-up, (FFEW) is one of the non-structural measures implemented to reduce

the flood risk. In the changing climate scenario, the role of (FF) is significant due to increasing people exposure of flood events. This paper evaluates (FFEW) in Indus basin. Indus basin were selected as the study area due to many that includes, most of the population are living in this basin, all the rivers and tributaries of Indus are passes through this region which effect human lives and properties. This research work were conducted in the Indus river basin, which experiences high magnitudes of floods that causes huge economic damages and human losses. The important strategy is Flood Forecasting and Early Warning System. The effectiveness of FF&EWS varies from region to region due to existing RADAR coverage. It is therefore, this research is an important attempt to evaluate the effectiveness of (FFEW) in Indus basin, Pakistan.

2.2 Data collection and Analysis

The focus of this research work is on the effectiveness of (FFEW) in Indus basin, Pakistan. The data were collected through primary as well as secondary sources. Data were collected directly from the study area through Personal Observation, Interviews, field survey and Questionnaires. An interview schedule were framed in Indus basin, which covering different aspects. In order to get basic information, interviews were conducted from the local authorities and (Expert, notables and elder people) about the effectiveness of (FFEW) in Indus basin, Pakistan. Questionnaire were arrange for individual, for Focused Group Discussions (FGDs) and questionnaire for the line agencies and Government departments also that concerned with flood management and early warning in Indus basin, Pakistan. In the study area, total 75 questionnaires were filled with different line agencies local administrations and flood affected communities (Table, 1). In order to analyze data about flood forecasting and early warning in Indus basin, out of 75 questionnaires, 30 were filled at federal level from PMD Islamabad, FFD Lahore, FFC Islamabad, NDMA and WAPDA at federal level. Similarly, at regional level PDMA, DDMA and Provincial irrigation department in the study area to know about the effectiveness of flood forecasting and early warning. Similarly, 45 questionnaires were filled at community level from Effected Community members to flood early warning dissemination in time. Five FGDs meeting were conducted with line agencies, stakeholders and effected communities to validate the data and information, which were collected during field visit in Indus basin. After data collection, data were analyzed by using different statistical tools to evaluate the effectiveness and expected outcomes to make (FFEW) in Indus basin more effective to minimize the flood risks.

Table 1, Line agencies and Stackholders

Ser No	Name of Line agencies and Stackholders	Number of Respondents	Percentage of respondents
1.	PMD Islamabad	7	9
2.	FFD Lahore	5	7
3.	NDMA	5	7
4.	PDMA	6	8
5.	DDMA	7	9
6.	Effected communities in the sample districts	45	60

3. Analysis and Results

For analysis data representation is very important. The collected data was processed through different software, which are SPSS, MS Excel and GIS. The (FFEW) in the Indus basin, Pakistan is a key component of disaster management. The Indus basin has a network of hydrometeorological stations, which provide rainfall, river flows and discharge data. The early warning dissemination system in the Indus basin is robust and effective, with warning disseminated through various channels, including mobile phones and media applications. However, the (FFEW) in the Indus basin covered vast area, which limits its effectiveness. The existing (FFEW) in the Indus basin is inadequate, due limited hydrometeorological stations, communication and dissemination system. The stakeholders, line agencies and local communities, have insufficient access to (FFEW). Similarly, inadequate flood infrastructure, insufficient reservoir capacity, inaccurate flood risk assessment, limited flood forecasting which limits their ability to effectively respond to flood in Indus basin.

3.1 Floods in Indus basin, Pakistan

Like other South Asian countries, Pakistan is exposed to floods. Floods in the Indus basin of Pakistan are a recurring and devastating issue due to its geography, steep topography and dense river network makes it prone to flooding,

especially during the monsoon season. In recent years, climate change has exacerbated the problem, leading to more frequent floods in Indus basin. Flood events that hit the Indus basin are flood of 1950, 1955, 1956, 1957, 1959, 1973, 1976, 1988, 1992, 1997, 2001, 2003, 2010, 2012, 2014, 2015 and 2022. In 2007, Khyber Pakhtunkhwa, Sindh and Baluchistan were also affected by flood. At least 130 people were died and 2,000 were displaced only in Khyber-Pakhtunkhwa in July and 22 people died in the month of August. But the 2010 and 2022 floods caused huge human and financial losses in (Figure, 2). The Indus basin in Pakistan is prone to severe flooding, particularly during the monsoon season from June to September. These floods are caused by intense and widespread rainfall, combined with the melting of glaciers and snow in Upper Indus basin (UIB). The Indus basin has unique geography, steep slopes from north to south, with its large network of rivers, canals, and irrigation systems, makes it vulnerable to flooding, which cause riverine floods in Lower Indus basin (LIB).

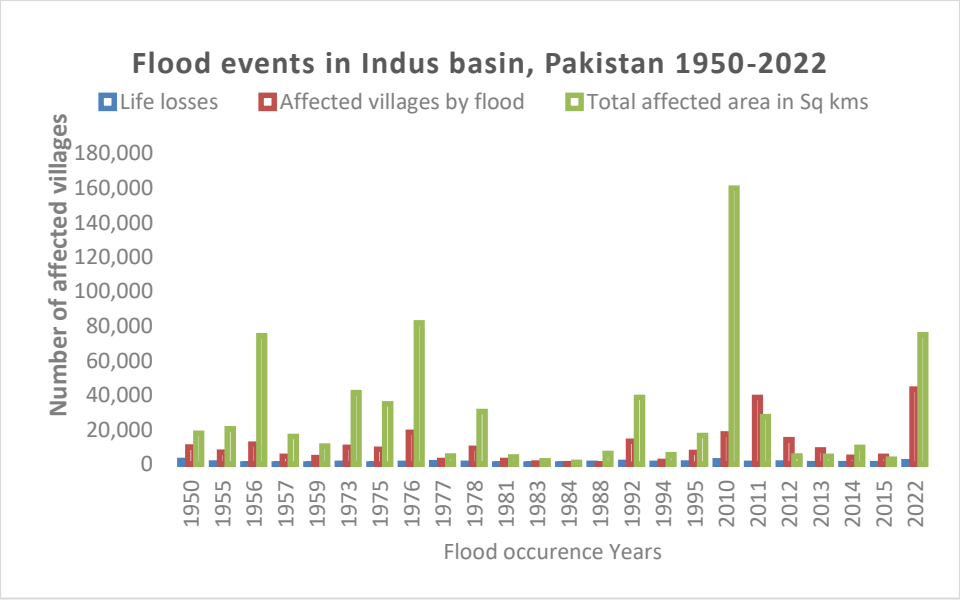


Figure 2, Flood events in Indus basin, Pakistan, 1950-2022

3.2 Existing FF and EWS in Indus basin, Pakistan

PMD is responsible for providing meteorological service in Indus basin, Pakistan. The major functions of PMD are to provide information on meteorological matters with the objective of disaster mitigation to predict weather forecast information. FF services to public through electronic and print news media. Doppler radars are installed in different regions, which detect precipitation and predicting weather in Indus basin. In Indus basin flood is one of the most destructive natural disaster, that cause human losses and damages to properties. The (EW) is applied to provide advance warning to line agencies and communities in order to protect the people and properties. Effective FFEWS depends on risk knowledge, hazard assessment, forecasting mechanism, early warning and dissemination of FEW to communities to save lives and other properties. (EW) is one of the key elements of (DRR) which play an important role in disaster preparedness by sharing timely information with vulnerable communities in Indus basin.

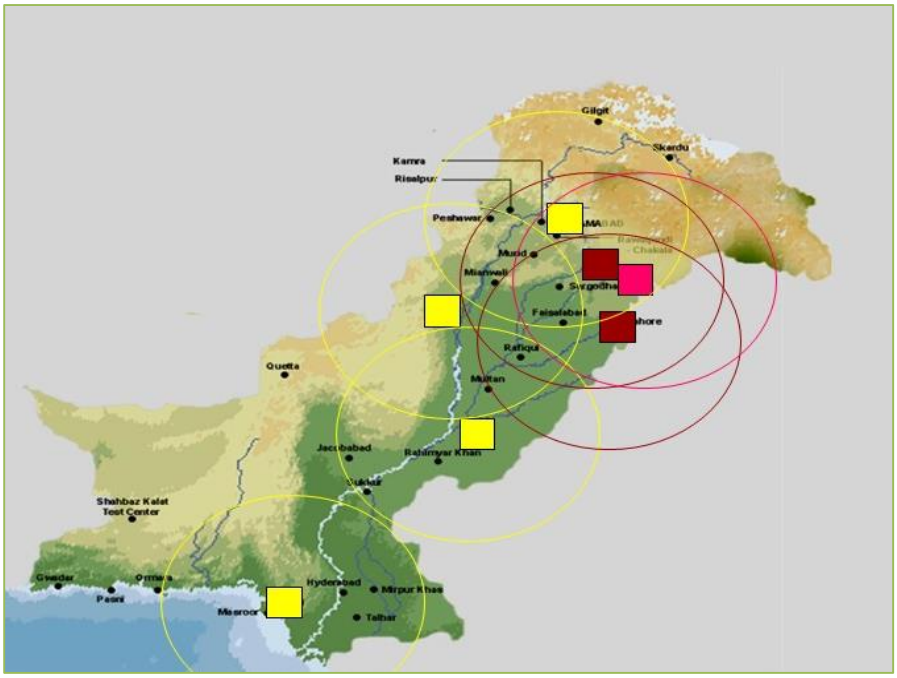
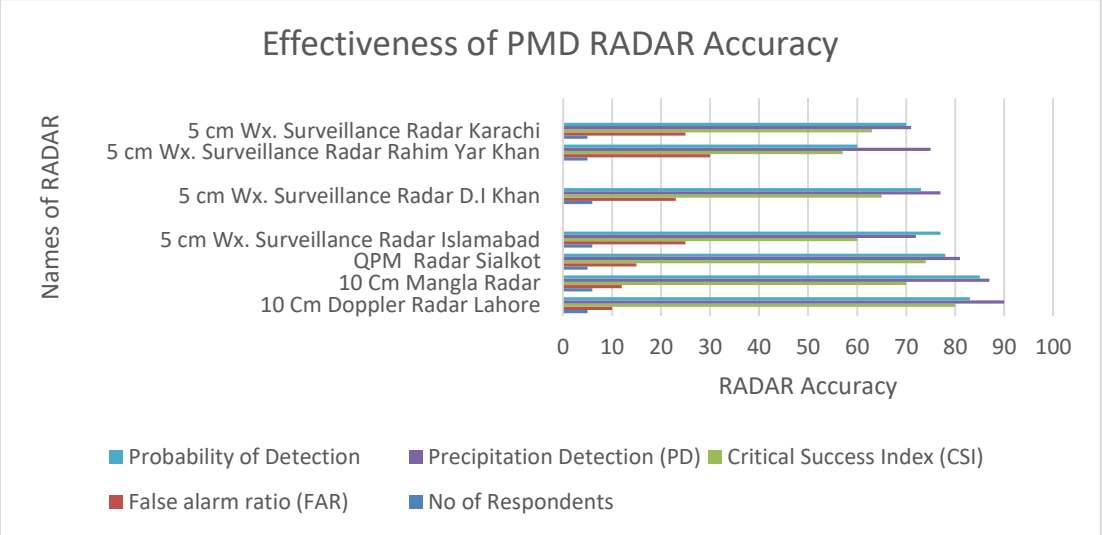


Figure 3, PMD Flood forecasting system Source: (PMD, 2022)

PMD has a network of radar systems and weather observatories, which provide data for FF&EWS in the Indus basin. Two precipitation measuring radars of wavelength 10 cm and 5 cm have been installed at Lahore and Mangla with the financial assistance of ADB. The PMD has installed 10 cm Doppler radars to enhance its weather forecasting and monitoring capabilities. This radar system provides quantitative and three-dimensional precipitation data in catchment areas of main reservoirs, enabling the PMD to better predict and manage floods. In order to collect data about flood Doppler radars questionnaires were filled from PMD Islamabad, FFD Lahore, FFC Islamabad, NDMA and WAPDA PDMA, Provincial irrigation department about the accuracy of radar data. Three FGDs meeting were conducted with line agencies, stakeholders and effected communities to validate the data for cross checking of the information and data, which were collected during field visit in the selected sample districts of Indus basin, Pakistan. To assess the integrated flood management system in the Indus basin statistical tools were used to evaluate the effectiveness and expected outcomes. The performance of the Doppler Radars was evaluated using metrics such as false alarm ratio (FAR), and critical success index (CSI), precipitation detection (PD) and probability of detection (POD) in (Figure, 3 ; 4).

During FGDs with line agencies questions were asked about the accuracy of radar system installed in different stations of Indus basin. The line agencies respondents answered that 10-cm Doppler radar installed in Lahore, with false alarm ratio (FAR) 10 %, critical success index (CSI) 80%, precipitation detection, 90% and probability of detection (POD) 83%. While 10-cm Doppler Radar installed in Mangla, having (FAR) 12 %, (CSI) 70%, PD, 87% and (POD) 85%. Quantitative Precipitation Measurement (QPM) radar in Sialkot has been installed by PMD to enhance its weather forecasting and monitoring capabilities. It detects the position of clouds and precipitation within the radius of 230 kms. (QPM) Radar at Sialkot, having (FAR) 15 %, (CSI) 74%, precipitation detection (PD), 81% and probability of detection (POD) 85%. To improve the flood forecasting and early warning in Indus basin PMD has installed a 5 cm Wx surveillance radar in Islamabad, which provide high-resolution data on precipitation, wind patterns, and other weather phenomena, enabling the PMD to predict severe weather events with greater accuracy. 5 cm Wx surveillance radar in Islamabad with (FAR) 25 %, (CSI) 60%, precipitation detection (PD),72% and probability of detection (POD) 77%. 5 cm Wx surveillance radar (D.I Khan) to enhance its weather forecasting, with this advanced radar system, the PMD aims to provide better services to the public and support decision-making for various sectors. 5 cm Wx surveillance radar in D.I Khan, with (FAR) 23 %, (CSI) 65%, precipitation detection (PD),77% and probability of detection (POD), 73%. Similarly, 5 cm Wx surveillance radar in Rahim Yar Khan with (FAR) 30 %, (CSI) 57 %, precipitation detection (PD),75% and probability of detection (POD) 60% and 5 cm Wx surveillance radar in Karachi, with (FAR) 25 %, (CSI) 63 %, precipitation detection

(PD),71 % and probability of detection (POD) 70%. The radar system has improved the accuracy and reliability of weather forecasts and warnings in the region, enabling authorities to take proactive measures to mitigate the impact of severe weather events.



e 4, Effectiveness of PMD Radar accuracy

3.3 FFEWS in the sample districts of Indus basin, Pakistan

In order to determine whether the respondents have any idea about flood in the sample districts. Questions was asked about the flood and its affects in the sample districts that include Gilgit, Swat, Charsadda, Nowshera, D.I Khan, Rajanpur, D. G. Khan, Mianwali, Muzaffargarh, Larkana, Sukkur, Khairpur, Thatta, Jhal Magsi, Lasbila on both sides of Indus river and its tributories, where they live is flood prone? The respondents agreed "Yes" prone districts, which were affected or should be affected by flood in future by flood. As per analysis it is reveal that Swat district were the most flood prone district in upper Indus basin, while in lower Indus basin the Nowshera, D.I Khan, Larkana and Sukkur were the most flood prone district. Similarly, in upper Indus basin, Gilgit district, while in lower Indus basin Lasbila and Jhal Magsi were the least affected districts. When respondents were asked about the last severe floods in their lifetime the respondents unanimously believe that flood of the 2010 and 2022 was the severe floods in history (Table, 2; Figure, 5).

Table 2, Flood prone districts in Indus basin, Pakistan **Source: (Field survey, 2022)**

S. No	Flood Prone districts	Yes %	No%
Upper Indus bain flood prone districts with flash flood characteristics			
1.	Swat	85%	15%
2.	Gilgit	80%	20%
Lower Indus basin flood prone districts with riverine flood characteristics			
3.	Charsadda	60%	40%
4.	Nowshera	64%	36%
5.	Dera Ismail Khan	66%	34%
6.	Rajanpur	73%	27%
7.	Dera Ghazi Khan	76%	24%
8.	Mianwali	44%	56%
9.	Muzaffargarh	71%	29%
10.	Larkana	71%	29%

11.	Sukkur	72%	28%
12.	Khairpur	78%	22%
13.	Thatta	66%	34%
14.	Jhal Magsi	63%	37%
15.	Lasbila	60%	40%

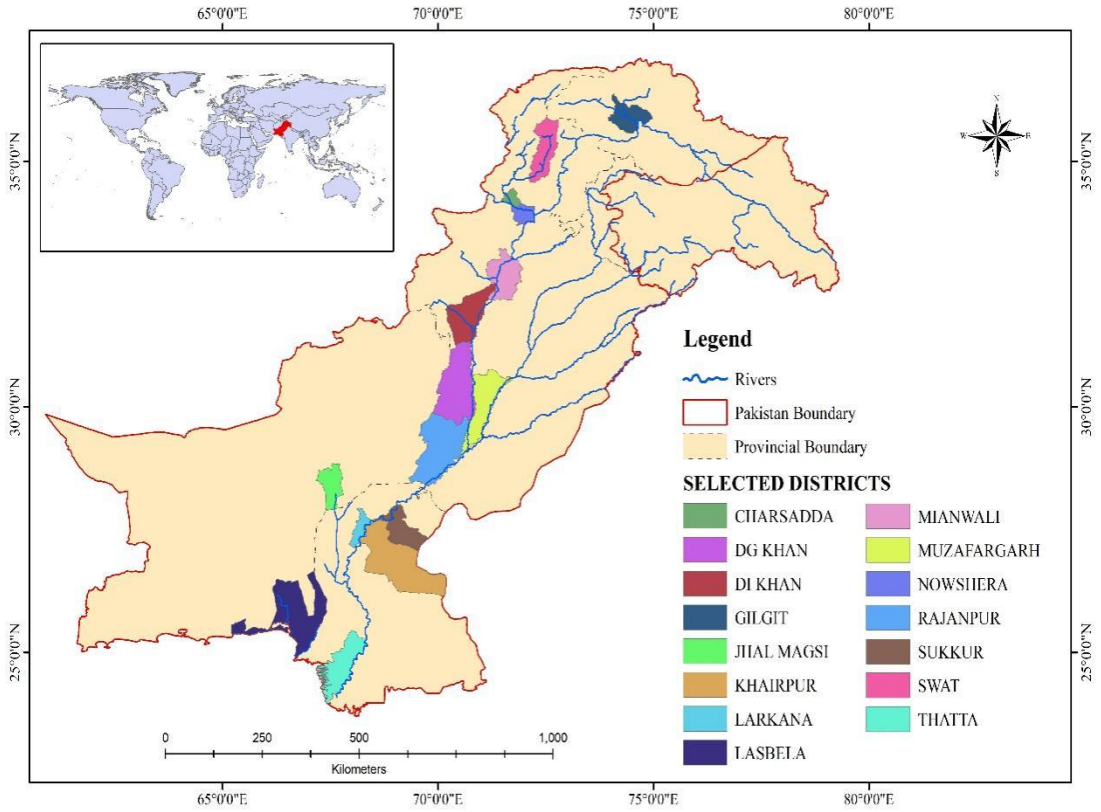


Figure. 5, Sample districts in Indus basin, Pakistan

3.4 Elements at Risk

During field survey, the questions were asked in the sample districts Gilgit, Swat, Charsadda, Nowshera, D.I Khan, Rajanpur, D. G. Khan, Mianwali, Muzaffargarh, Larkana, Sukkur, Khairpur, Thatta, Jhal Magsi, Lasbila of Indus basin, about the element at risk. These are the most affected districts in Indus basin, Pakistan. Floods in the Indus basin pose significant risks to both human life and physical infrastructure. The most vulnerable elements include residential structures, agricultural land, livestock, and essential services such as schools, hospitals, and roads. In both urban and rural areas of Indus basin, houses constructed in low-lying or unregulated floodplain areas are highly susceptible to damage or complete destruction. Agricultural fields, particularly in the Lower Indus basin, were inundated when flood occurred, leading to severe crop losses, soil degradation, and food insecurity. Additionally, livestock deaths during major floods contribute to the economic hardship of affected farming communities.

According to field survey the important elements at risk are houses and human life**.** Agriculture land and livestock were also exposed to flood. In upper Indus basin the terraces agriculture are practiced. This is also evident from the fact that most of respondents are surveyed from the area, which was flooded in 2010 and 2022 flood. The Indus basin is prone to flooding, which poses significant elements at risk. Floods in Indus basin cause loss of life, injuries, and displacement of people living in flood-prone areas, damage or destroy roads, bridges, buildings, and other infrastructure. In Lower Indus Basin (LIB) flood damaged crops, livestock, and agricultural infrastructure. It also destroyed houses, businesses,

community places like mosque, schools and colleges particularly in vulnerable communities. These elements are at risk due to floods in the Indus basin, highlighting the need for effective flood management and mitigation strategies to protect people, infrastructure, which effect by floods (Table, 3).

Table 3, Elements at risk in Indus basin, Pakistan

Ser No	Sample Districts	Human life	Houses	Agricultural land	Forests	Crops & Animals
1.	Gilgit	30	20	5	35	10
2.	Swat	40	25	15	15	5
3.	Charsadda	22	25	22	5	26
4.	Nowshera	35	25	25	7	8
5.	Dera Ismail Khan	15	44	19	7	15
6.	Rajanpur	10	50	24	6	10
7.	Dera Ghazi Khan	15	27	28	8	22
8.	Mianwali	23	35	25	4	13
9.	Muzaffargarh	8	20	30	6	37
10.	Larkana	19	25	42	0	14
11.	Sukkur	23	33	30	0	14
12.	Khairpur	29	21	35	0	15
13.	Thatta	27	28	25	0	20
14.	Jhal Magsi	13	60	17	0	10
15.	Lasbila	16	48	26	0	10

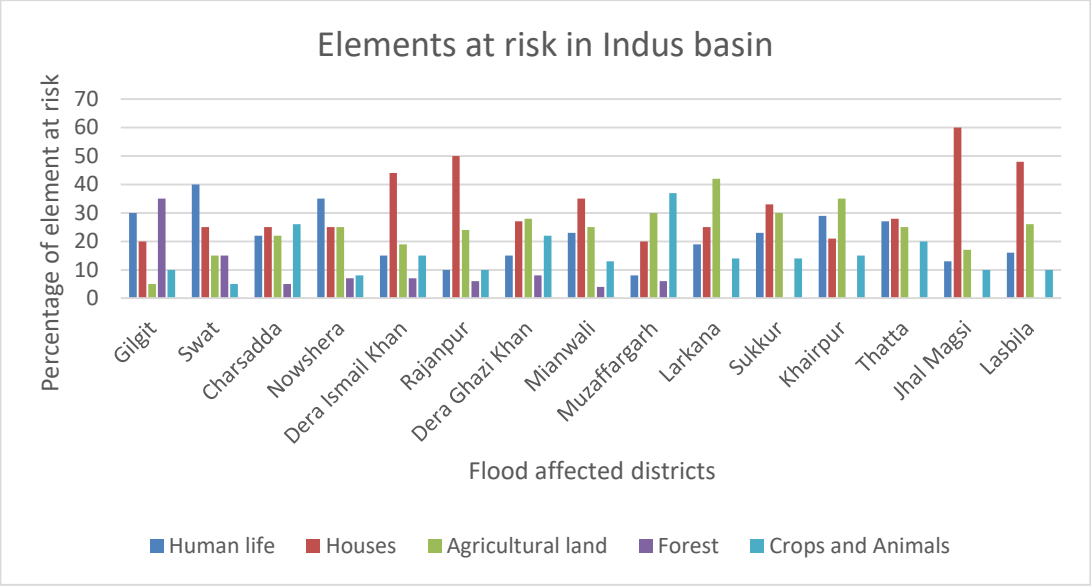


Figure 6, Elements at risk in Indus basin, Pakistan Source: (Field survey, 2022)

3.5 Dissemination of FF&EWS in the sample districts of Indus basin, Pakistan

The dissemination of (FEW) in the Indus basin is a vital component of the overall flood risk management system. It involves communicating timely and accurate information from national forecasting agencies, such as (PMD), provincial and district disaster management authorities (PDMA and DDMA) and ultimately to the at-risk communities. Various methods are employed, including television and radio broadcasts, SMS alerts, social media platforms, loudspeaker announcements by local authorities, and coordination through administrative offices such as Deputy Commissioners (DC) and Assistant Commissioners (AC). In areas with better communication infrastructure, the flow of information tends to be more efficient, enabling communities to prepare and evacuate if necessary. Fifteen affected districts were surveyed in Indus basin, Pakistan. During survey the data was collected in the selected Fifteen flood-prone districts and communities in Indus basin, Pakistan, it was found from the analysis that majority of the communities in the flood-prone districts did not receive any warning about last floods (2010 and 2022) (Figure, 5). This finding was quite interesting, which indicated that the EWS was working well for some areas and not too good for the others. This shows that a significant percentage of the population has not received early warning, which have serious implications for the flood communities in the study area in (Table, 4; Figure, 7).

Table 4, Dissemination of FF&EWS in the sample districts of Indus basin

Ser No	Sample Districts	Flood characteristics	Population 2023	Dissemination of Flood Early Warning in %	
				Warning received in % (Yes)	Warning received in % (No)
1.	Gilgit	Flash Flood	145,272	33	63
2.	Swat	Flash Flood	2,687,384	45	55
3.	Charsadda	Riverine Flood	1,835,504	47	53
4.	Nowshera	Riverine Flood	1,740,705	44	56
5.	D. I. Khan	Riverine Flood	1,829,811	40	60
6.	Rajanpur	Riverine Flood	2,381,04	44	56
7.	Dera Ghazi Khan	Riverine Flood	3,393,705	40	60
8.	Mianwali	Riverine Flood	1,798,268	48	52
9.	Muzaffargarh	Riverine Flood	5,015,325	41	59
10.	Larkana	Riverine Flood	1,784,453	38	62
11.	Sukkur	Riverine Flood	1,639,897	33	67
12.	Khairpur	Riverine Flood	2,597,535	43	57
13.	Thatta	Riverine Flood	2,597,535	32	68
14.	Jhal Magsi	Riverine Flood	203,368	41	59
15.	Lasbila	Riverine Flood	680,977	38	62

Source: (Field survey, 2022)

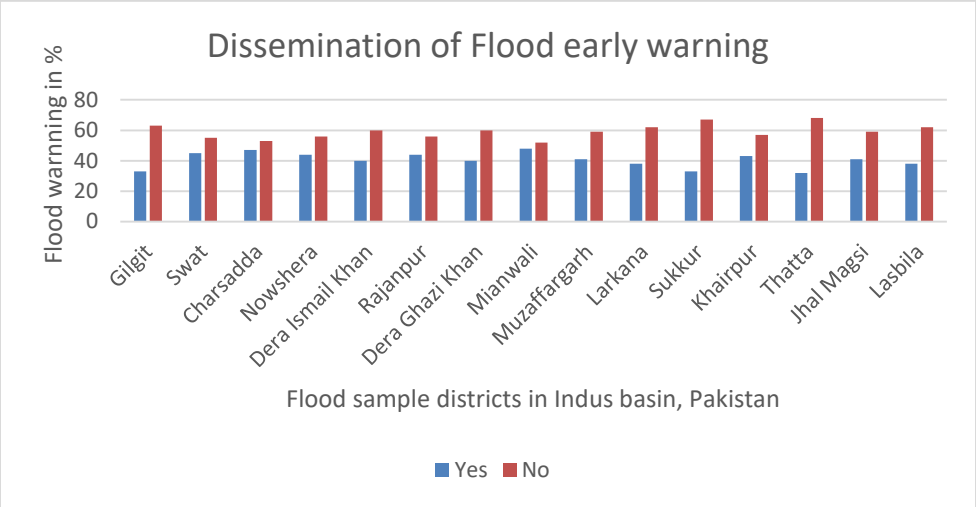


Figure 7, Dissemination of FF&EWS in the sample districts of Indus basin

3.6 Flood warning communication in sample districts in Indus basin

During survey questions was asked about flood warning communication in the affected communities at district level. The analysis shows the significant insights into the effectiveness of FEW. In Gilgit, Swat, Charsadda and Nowshera only 45 % of the population received flood warning. D. I Khan, Dera Ghazi Khan, Rajanpur, Muzaffargarh, Larkana, Lasbela, and Jail Magsi analysis showed that only 35% of respondents received flood warnings before the 2010 and 2022 floods. The primary sources of flood warnings were districts authorities 45% that include DDMA, sharing of flood warning information from AC, DC and DPO office. Sharing of flood warning information through social media 25%, and community leaders 15% and 5% by TMA in their affected tehsils in sample districts. However, in sample districts 60% of respondents reported that the warnings were not timely disseminated and communicated, while 55% stated that the warning were not clear or understandable in (Figure,8).

The analysis also highlights the challenges faced by communities in accessing and understanding flood warnings. The survey found that 70% of respondents had limited access to information, such as mobile phones or radios, which hindered their ability to receive timely warnings. Furthermore, 65% of respondents reported that they did not have a clear understanding of flood risk and evacuation procedures, which shows that there is a need for improved flood warning communication systems, including more effective dissemination of warnings, increased access to advance technology and enhanced community awareness and preparedness. The survey also shows important implications for flood risk management and disaster preparedness in the Indus basin. To improve flood-warning communication, it is essential to strengthen the capacity of local authorities, community leaders, and other stakeholders to disseminate timely and clear warnings. Additionally, efforts should be made to increase access to flood information promote community awareness and preparedness, and develop more effective flood risk communication strategies. By addressing these challenges, it is possible to reduce the vulnerability of communities to floods and enhance their resilience to these natural disasters.

Figure 8, Flood warning communication in sample districts in Indus basin

3.7 Flood Warning, preparation, communication and dissemination

In flood prone areas flood forecasting on daily basis to forecast on time to inform and communicate to the related authorities and then disseminate to people and affected community with in time. Forecasting performance is mostly appreciated in flood prone areas. Pakistan is a flood prone country that caused great damages to life, infrastructure and property. In Pakistan, the most important reasons of forecasting performances to monitor the post-flood work and on this base issued the flood forecast in general and particular in those areas that should affected by past flood or currently should be affected. Performance evaluation is therefore mostly overlooked in order to monitor flood situation throughout the country. Number of organizations are play significant role in flood hazard assessment, which includes federal Government and provincial organizations. Media play important role in personnel's awareness enhanced different aspects of (FF&EW). The organization which play role in forecasting and early warning to manage flood are the FFD, NDMA, PDMA, DDMA

and Police department on district level to communicate the flood information among each other and then disseminate to affected areas that is affected or should be affected by flood as shown in (Figure, 9).

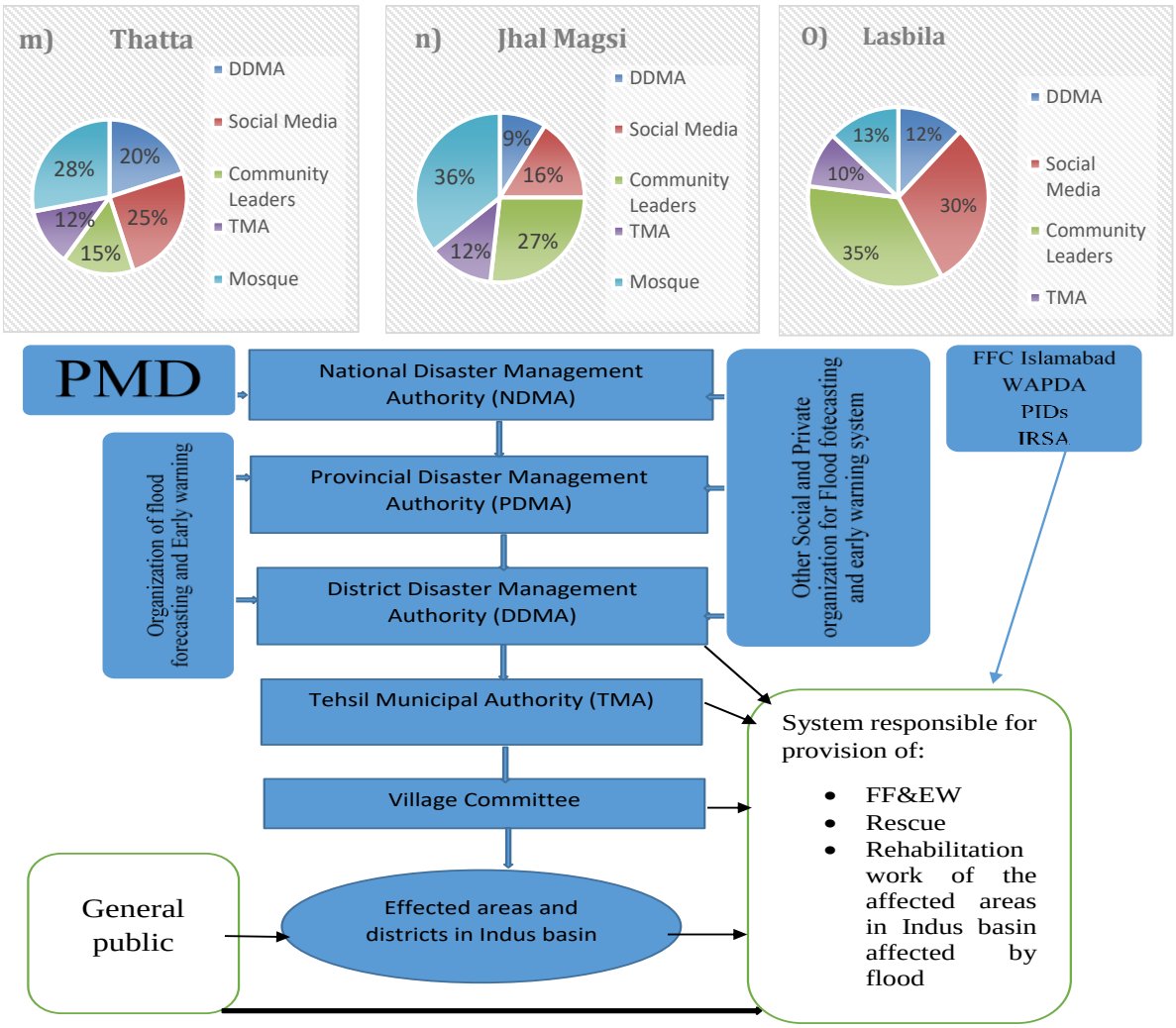


Figure 9, Process of communication and dissemination in Indus basin

3.8 Flood mitigation measures in the effected districts of Indus basin, Pakistan

The questions were asked to find out the respondent perception was whether they have any protection against flood hazards. The respondents were answered, the government is responsible for flood management to taken solid steps in order to minimize the flood risk. For this purpose different government organizations work on different projects to minimize flood in the flood prone areas of the selected districts in Indus basin. It was found from the analysis that12 % respondents answered that migration is best option from the flood affected area to safe area. 14 % respondents have the opinion that they don't have any protection against flood, but still they are ready to evacuate the area. 20% of the respondents were the opinion that, it is the responsibility of government organization to provide places for flood affected peoples, give early warning in time and restricted construction in the flood prone areas. While, 16 % of the respondents have the opinion that the embankment formation is the solution, in the most effected districts or the areas, which should be more affected by flood in future. About 12 % respondents have the opinion that they are mentally prepare if floods come again. While majority of the respondent's answers that, there should be restriction to construct houses in flood prone areas in (Table, 5).

Table 5, Protection of flood hazard in Indus basin as per (FGDs)

S. No	Sample districts	Flood Protection in sample districts
1.	Gilgit	Migration
2.	Swat	Migration
3.	Charsadda	Evacuation and given early warning with in time
4.	Nowshera	Embankment formation
5.	Dera Ismail Khan	Embankment formation
6.	Rajanpur	Mentally prepare and Evacuation
7.	Dera Ghazi Khan	To give early warning with in time
8.	Mianwali	Early warning with in time
9.	Muzaffargarh	Embankment formation
10.	Larkana	Evacuation
11.	Sukkur	Responsibility of Govt. to provide Place
12.	Khairpur	Embankment formation
13.	Thatta	Mentally prepare
14.	Jhal Magsi	Restricted houses in flood prone areas
15.	Lasbila	Proper flood management

Source: (Field survey, 2022)

4. Discussion

FF&EWS is one the effective non-structural measure applied to reduce the impacts of floods. FF and EWS strategies are widely adapted to reduce flood damages. The role of FF is to forecast the extreme weather events and to give (FEW) and timely response. FF&EWS are essential non-structural measures for minimizing flood risks, particularly in flood-prone regions. The Indus basin were selected as the study to achieve the objectives. This study aimed to evaluate the effectiveness of FF&EWS in the sample districts of Indus basin. FF&EWS is a systematic process, which disseminate warning to vulnerable communities. The objectives of this research were to evaluate FF&EWS the study area, process of communication and dissemination of FEW to the communities. To achieve the objectives of the study, data were collected both from primary and secondary sources. The study area is covered the entire Indus basin, vulnerable to frequent floods and related damages. It was found from the analysis that the entire Indus basin was hit by number of floods that includes 1973, 1992, 1993, 1994, 1995, 1996, 2001, 2005, 2010 and 2012. However, the flood of 2010 and 2022 was the mighty floods, which has caused severe damages to life, infrastructure and properties. The research revealed that major floods in 2010 and 2022 caused unprecedented devastation due to weaknesses in early warning coverage and communication gaps.

In Pakistan, FF technology adopted by the government agencies at federal and provincial level to minimize the risk of flood in Indus basin. However, it was found from the analysis that the study area is beyond from the reach of existing RADAR network as shown in Figure, 3. The research revealed that major floods in 2010 and 2022 caused unprecedented devastation due to weaknesses in early warning coverage and communication gaps. Although Doppler radars and weather observatories exist, however their limited spatial distribution concentrated mostly in central or urban areas fails to provide effective coverage to remote and high-risk rural zones, especially in Upper Indus Basin (UIB) as shown in Figure, 4. The Indus basin in Pakistan is highly susceptible to floods due to its geographical location, terrain and climate (Figure, 1). Comparatively, this study compare with earlier works such as Ali et al. (2018), which emphasized the role of advanced technologies and institutional synergy in FF&EWS. However, the present research goes further by identifying specific quantitative performance gaps, such as false alarm ratios (FAR) and probability of detection (POD) of radar systems (PMD, 2022). While earlier reviews highlighted the importance of FF&EWS, this study provides field-based evidence of systemic issues like poor dissemination, inadequate forecasting in flash-flood prone areas, and lack of feedbacks. Successful FF&EWS depend not only on radar and satellite system, but on institutional preparedness, public

trust, and real-time action as well (Krzhizhanovskaya et al, 2011) and (Hallegatte et al, 2013).

The current flood forecasting system in Indus basin, Pakistan is well developed. The use of satellite imagery, radar technology, and hydrological models has improved the accuracy of flood predictions, but there still that require improvement, such as increasing the accuracy of prediction of weather information and lead-time for issuance of flood warning. By adapting advanced technologies, forecasting system can be enhanced to provide more accurate and timely warning to the affected communities in Indus basin. The role of (FEWS) in flood management cannot be overstated. Timely warning can significantly reduce the loss of life and properties by enabling the communities to take advance measures. In the Indus basin, where floods can be devastating, an effective (EWS) is essential for mitigating the impact of such flood events. However, it depends on several factors, which includes the accuracy of forecasting, the effectiveness of communication channels, and the preparedness of the communities at risk.

Based on these findings, different recommendations are forwarded which make FF&EWS more effective. First, there is an urgent need to expand radar and weather observation networks to ensure real-time coverage of remote and mountainous regions. Second, coordination among line agencies must be institutionalized through shared protocols, digital platforms, and standardized alert levels. Third, community engagement must be strengthened through awareness campaigns, localized flood maps, training on evacuation procedures, and integration of indigenous knowledge. Fourth, mobile-based and social media alerts should be formalized as official channels for early warning dissemination, especially in underserved districts. Moreover, efforts to enhance community awareness and preparedness helps in reducing the vulnerability of populations at risk, continuous improvement and investment in these systems are necessary to ensure the effective flood early warning. The evaluation of FF&EWS in the Indus basin highlights the importance of this system and its role in flood management. By strengthening FF&EWS the flood vulnerable communities and infrastructure can be protected from the devastating impacts of floods

5. Conclusion

The study analyzed the effectiveness of the flood forecasting and early warning system in the Indus basin, Pakistan. The flood forecasting and early warning system in the Indus basin, is well developed but still it faces challenges that limits the accuracy of FF&EW. This research also highlights the devastating consequences of the 2010 and 2022 floods. The findings of this research paper indicated that, non-meteorological factors, such as settlement in the flood-prone areas, construction of roads, lack of channel improvement, improper flood forecasting in the remote areas of Indus basin, existing RADAR network, limited coverage by RADAR network, terrain and human encroachment has aggravated the consequences of floods especially in 2010 and 2022 floods. Flood of 2010 caused deaths of 86 people, 9,800 animals were perished, more than 4,000 houses were damaged, however, 2022 flood caused more than 1,355 people were died, 12,700 people were injured. Inconsistency of historical data, limited coverage by weather radar, limited resources allocation for FFEWS can reduce the accuracy, reliability of prediction information, which ultimately affects FEWS in Indus basin reliability of early warning systems. Additionally, the lack of standardization in data collection, limited availability of real-time data, accurate FF& EW information, inaccurate warning effect the FFEWS, which make communities in Indus basin more vulnerable to flood. To enhance the effectiveness of FF&EWS, it is necessary to address the challenges faced by FF&EWS in Indus basin.

The findings of the study reveals that Pakistan has made considerable progress in establishing a forecasting and early warning infrastructure such as the deployment of Doppler radar system and the establishment of institutions like PMD, NDMA, and PDMA but still serious challenges persist, that limited FF&EWS in Indus basin. These include limited radar coverage in remote and mountainous areas, lack of real-time data transmission, inconsistent dissemination of warnings, and low public awareness of flood risks and evacuation procedures. A significant portion of the population in flood-prone areas reported either not receiving early warning or receiving them too late to take effective action. Additionally, discrepancies in the accuracy and timeliness of radar data further reduce the reliability of FF&EWS. Human encroachment, unregulated construction in floodplains, inadequate floodplain zoning, and infrastructural constraints have all exacerbated flood impacts in the Indus basin. The 2010 and 2022 floods exposed major weaknesses in the current early warning framework, underscoring the need for enhanced inter-agency coordination, greater investment in localized

meteorological infrastructure, and more inclusive community engagement strategies. The study also highlighted that while early warning systems are essential tools, their success depends on the preparedness and responsiveness of both the institutions and the communities.

In the study area, installation of flood forecasting and warning systems in the study area may help to reduce the flood losses by providing meteorological information and flood forecasting prior to flood. So that during uncertain weather events, people may be moved to safer areas before the floodwaters spread in the heavily populated parts of the area, if the warning is given in time. Real-time flood forecasting should be improved. Future research should focus on addressing the existing gaps in FF&EWS, including the development of more accurate, reliable data collection, sharing of information, enhancing community engagement and participation to make FF&EWS more effective. It is recommended that the dissemination of the flood information can be disseminated through an efficient network that include public news, media or other mean of sources by line agencies, that is easily understandable by the communities to reduce flood damages in the study area. The FF&EWS of PMD is actively involved in weather and flood management in Indus basin. It need to be further developed to serve as an effective flood forecasting, predicting heavy precipitation and flash flooding based synoptic features. It is also necessary to analyzed weather events that threaten the socio-economic development of the study area. In Indus basin, (PMD) and (NDMA) can invest in advanced techniques to improve the accuracy of flood forecasts. To address the FF&EWS challenges, it is recommended that the government invest in modern communication technologies, such as mobile apps and social media, to disseminate flood warnings more quickly and widely. Similarly, proper dissemination and communication among line agencies that include PMD, NDMA, PDMA, and DDMA with affected communities can make flood forecasting more affective in Indus basin. By addressing the challenges, Pakistan can develop more effective flood forecasting and early warning system, to reduce the impacts of flood in Indus basin, Pakistan.

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