A Case Study of Heavy Rainfall Events and Resultant Flooding during the Summer Monsoon Season 2020 over the River Catchments of North Bihar, India

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ABSTRACT

The state of Bihar experienced three spells of heavy to very heavy rainfall in July 2020, leading to large-scale flooding and inundation of low-lying areas along the Gandak, Bagmati/Adhawara, and Kosi catchments. Since this flooding came amidst the peak of the COVID-19 pandemic, it created a scary situation for relief and rehabilitation agencies. The analysis of the synoptic situation preceding and during rainfall spells on (i) 3rd-4th July 2020 (ii) 8th-12th July & (iii) 20th-23rd July indicated an essential role in the oscillatory nature of the Monsoon Trough, which is traditionally associated with enhanced rainfall activities along the foothills of the Himalaya, which is the main catchment area of all the major river systems of Bihar. The analysis of realised Areal Averaged Precipitation (AAP) leads to another important finding regarding the strong correlation and time lag between rain and the corresponding rise in the river level. The proposed statistical models simply provide impacts of AAP over rising in the water level at River Gauge stations with the lag time of 24/48/72 depending upon the locations of River Gauge stations.

Keywords: *Areal Averaged Precipitation, Quantitative Precipitation Forecast, Sea Level Pressure and Outgoing Longwave Radiation.*

1. Introduction

The Indian subcontinent's physical and riverine structure makes various parts of the country vulnerable to floods. Flooding is one of the most damaging and recurring phenomena in India. Intense rainfall, dam breaches, unplanned urbanization, and land use/land cover (LU/LC) changes are the main causes of floods, which often result in the loss of lives and property. The frequency of floods has been increasing over the last three decades (Sparks 2018). So, flood mapping and the use of flood inundation models have grown in importance for monitoring and assessing flood impacts. Despite several attempts, an effective flood monitoring and forecasting system has been missing in densely populated countries like India (Wu et al. 2012). Bihar is one of India's worst-affected states, according to the National Disaster Management Authority (NDMA), due to periodic floods (NDMG 2008). According to reports, floods affected 16.6 percent of the country's flood-prone areas, which lie in the state, affecting 22.1 percent of the population. It was reported that 76 percent of the population in North Bihar was affected by floods. Floods in Bihar are a periodic tragedy that occurs on an annual basis, claiming the lives of thousands of people as well as livestock and other valuables.

The flood is caused by all five major river systems flowing through the state, i.e., the Ganga, Kosi, Gandak, Bagmati, Adhawara, etc. The topography of Bihar is also marked by several seasonal and non-perennial rivers originating from Nepal and Tibet and carrying high sediment loads, which are subsequently deposited in the plains of Bihar. As it is a continuously evolving process, the river system's course also keeps changing on a year-to-year basis, thus making any long-term management plan very difficult. The cases of frequent flooding in the state have been extensively studied both in terms of meteorological and geological factors. One of the most extensive studies of the flooding of the river Kosi was done in the aftermath of a flash flood in August 2008, which permanently altered the river's course (Reddy et al. 2008). Moreover, the rain is fed to river systems through many tributaries along a huge area with a very complex orography, and a meteorological system ranging from synoptic-scale to local scale contributes to the process (Pandit 2009; Reddy et al. 2008; Kumar et al. 2021; Ranalkar et al. 2016; Prasad et al. 2021). As a combined effect of all these factors, whenever the river Ganga's catchment (usually in the north of Bihar) received heavy rainfall during the summer monsoon season, the state experienced floods caused by the overspill of river water into floodplains or breaches of embankments. River floods occur when a large amount of rainfall is received during wet spells of the summer monsoon season (JJAS). In this context, researchers have examined the observed rainfall events over different periods, and locations (Davis et al. 2006; Prasad et al. 2021; Tripathi et al. 2019; Ranalkar et al. 2016; Deo et al. 2016; Rakhecha and Soman 1994; Kumar et al. 2021; Singh et al. 2011) and found an increased risk of flood conditions (Guhathakurta et al. 2011; Gupta and Nair 2017; Deo et al. 2016). The observed heavy rainfall events and their synoptic features were studied by India Meteorological Department (Pai et al. 2015), (Mohapatra et al. 2009) examined the heavy rainfall events during 2001-2005 and compared the early 1970s, and shows that the probability of detecting heavy Rainfall is 64% over Bihar and suggested a slight improvement in the forecast skill during 2001-2005 (Mohapatra et al. 2009). Heavy rainfall studies in Bihar (Singh et al. 2011; Tripathi et al. 2020; Kumar et al. 2021) made the diagnostic study of some flood-producing rainfall events. A similar study for Bangladesh was carried out by (Prasad et al. 2021). The synoptic conditions associated with the heavy rainfall events (2001-05) as an early warning system need improvement through synoptic charts. Monsoon-Trough's position lies to the north of its normal position in July and August (Mohapatra 2008; Ranalkar et al. 2016; Sharma 2012). During the summer monsoon season, the air over Bihar and the adjoining area becomes hot and humid with sufficient latent instability. The convective type of clouds formed, leading to the disastrous rainfall in Bihar and the adjoining Nepal region (Tripathi et al. 2019; Pattanaik and Rajeevan 2010). It has been observed over the years that such intense rainfall activity (64.4 mm/day as per criteria by the India Meteorological Department (IMD)) causes river floods, especially in north Bihar. As per the criterion, rainfall >114.5 mm/day is classified as a very heavy rainfall event. As it has been analyzed by (Pattanaik and Rajeevan 2010) such extreme rainfall events have preferred regions of occurrence over the west coast, central parts, and northeast India. Such intense rainfall events have preferred regions of occurrence over the west coast, central parts, and northeast India, and their overall contribution to JJAS rainfall is showing an increasing trend. Such events are contributed mainly by synoptic-scale systems having a periodicity between 3 and 7 days, which broadly fits into the present case pattern. With the advancement of radar and satellite technology, it is relatively easier to identify and track such high-impact weather events once they reach the detection threshold.

There are no such comprehensive studies available in the North Bihar that discussed the cascading impacts of floods and the reoccurrence of shorter periods such as few days of intervals. So in this study, we try to fill the gap as well as make an attempt to correlate the oscillatory pattern of Monsoon Troughing, Impacts of Pressure gradients, and other Synoptic Conditions for the extreme spells of rainfall over river Catchments of Gandak, Bagmati/Adhawara and Kosi/Mahannada of North Bihar along with the impacts of AAP over the River Gauge stations for the specific lag times.

The statistical finding of lag times may be used for the mitigation and planning of Floods in the said studied areas. The method used was simple, but still suitable for use by the community involved in flood risk(hazard) management, not necessarily experts in hydrological modeling. In July 2020 floods in river catchments (Gandak, Bagmati/Adhawara, and Kosi/Mahannada) impacts approximately 96,08,31 population residing in 122 (Fully) and 407 (partially) affected Panchayats of 74 blocks of 10 districts (Source: Disaster Management Department, Govt. of Bihar). In the first event, 140 to 250 mm of rain was recorded in two days on the 3rd and 4th of July, while in the second event, which was a prolonged one lasting for four days, 120 to 260 mm of rain was realized. In the third

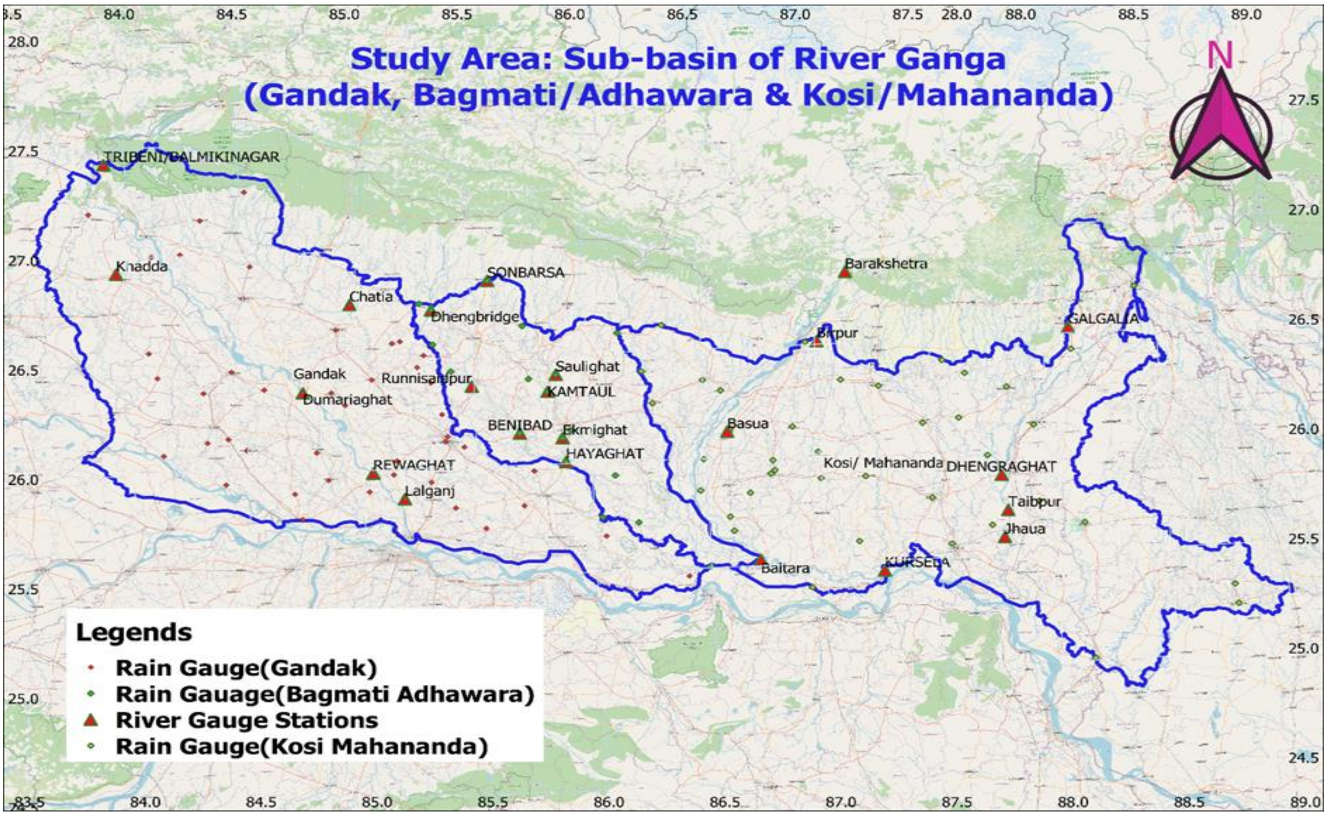

Figure 1: Study Area along with the Rain Gauge and River Level Gauge Station.

event, which was most intense, 140 to 280 mm of rain was recorded in four days spell between 20th and 23rd July 2020. As the rivers were already flowing above their danger levels by the second third and third events, Rainfall's Impact were incremental on the river level. Thus, the last flood spell was most destructive and most challenging for the authorities to manage the situation was further aggravated due to the prevailing lockdown and associated restrictions imposed for the Covid pandemic containment.

The methodology discussed in Section 3 and synoptic meteorological conditions associated with the intense rainfall spell and its associated impact on the flood situation, as well as proposed statistical models for the impacts of AAP over river gauge stations, have been discussed in the different subsections of Section 4 and the conclusion arrived in Section 5.

2. Study Area

The study area spans 19 districts of North Bihar and adjoining some parts of East Uttar Pradesh and North West Bengal in India. It spans the longitudes of 83.5^0E and 89.0^0E, as well as the latitudes of 24.5^0N and 27.0^0N. The Upper Ganga basin is made up of various rivers that run through North Bihar. The Gandak river basin (58800sq km), Bagmati/Adhawara river (18845 sq km), and the Kosi/Mahananda river basin (95552sq. km) are shown in Figure 1. There are several tributaries/dhars there, including the Kamla Balan, Bhutahi Balan river, Dhemama dhar, and others, which drain water to the basin's major rivers. Floods in Bihar are often caused by a breach of embankments along the Kosi River due to heavy rainfall during the monsoon season. Several remedial measures have been taken by the governments of Bihar (India) and Nepal to regularly monitor floods and protect the low-lying areas of North Bihar (Sinha et al. 2008). Intense rainfall during the monsoon season typically results in the greater runoff, which drains into the river basin's lower catchment areas. As a result, the low-lying parts of north Bihar are particularly vulnerable to flooding and waterlogging and the rise of Ganga River water also causes the long waterlogging in the lower reaches of North Bihar. According to historical hydrographic data, floods were recorded in 1987, 1998, 2000, 2001, 2003, 2004, 2008, 2010, 2013, 2017, 2019, 2020 and 2021.

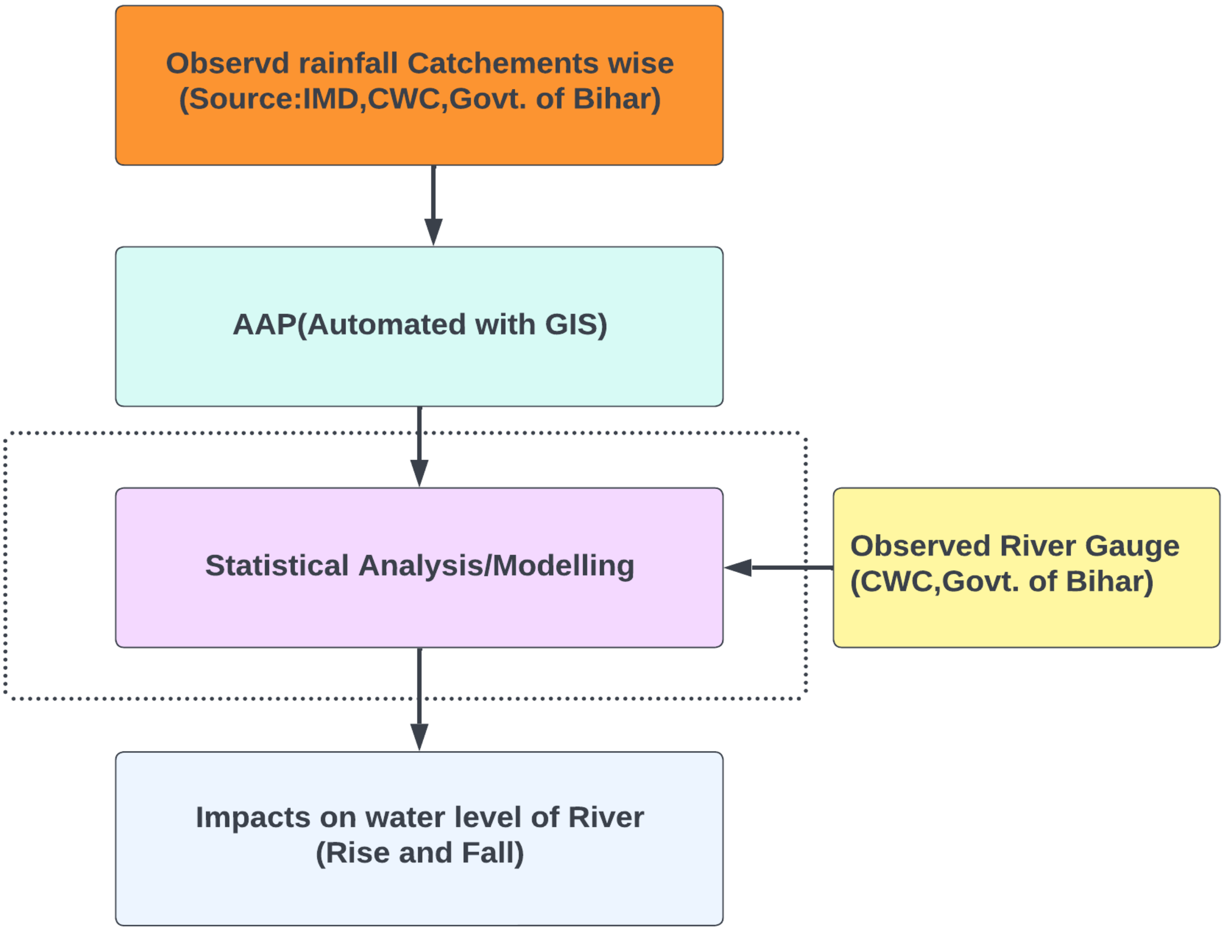

Figure 2: The detailed methodology adopted for this study.

The floods in Bihar in 2013 affected about 5.9 million people across 20 districts. The flood of 2017 was one of the greatest flood occurrences in North Bihar, affecting 19 districts. The 2017 floods were caused by a sudden rise in water output due to excessive rain in the Himalayan foothills near Nepal and adjoining areas. Between August 12 and August 30, 2017, the tributaries of these rivers were inundated.

3. Materials and Method

In this study, data from the network of rain gauges (both manual and automatic) maintained by the India Meteorological Department (IMD), the Government of Bihar, the Central Water Commission (CWC), etc. have been used for the estimation of averaged areal precipitation (AAP) and other rainfall information. The study area and the rain gauge station, as well as the river level gauge station, are shown in Figure 1. For the synoptic situation relevant to the catchment, the Flood Meteorological Office's operational bulletin has been referred to, and NWP guidance has been taken from the Global Forecasting System (GFS global) and Weather Research and Forecasting (WRF) model run by IMD. The river level gauge information is collected from the message exchange with the CWC and the Bihar State Flood Monitoring Agency under the Water Resource Department (Govt. of Bihar). As per the operational procedure, FMO Patna issues an accurate catchment-wise Quantitative Precipitation Forecast (QPF) for each of the three (studied) catchment areas responsible for flooding in Bihar in the said duration. As the purpose of the study was to analyse the synoptic situation leading to three specific heavy/very heavy rainfall spells and their consequential effects on the river level, atmospheric condition, and synoptic situation before and during the rainfall, the spell has been taken into account.

Since the actual precipitation measurement using different types of Rain gauges is a point measurement that cannot give the full picture of precipitation over a catchment area, so for operational purposes, Averaged Areal Precipitation is estimated. There are different methods for computing the AAP, like the arithmetic mean, isohytal analysis, Thiessen polygon, and distance gridded average. In IMD, isohytal analysis and gridded analysis are used for arriving at averaged areal precipitation, and in the present study, we have used isohytal analysis to calculate the AAP value. To find the link between observed rainfall and subsequent flooding and get the statistical modeling, the approach used is shown in Figure 2.

4. Results and Discussion

The Himalayas' foothills' topography enhances the heavy rainfall events during July and August since the monsoon trough's position remains north of its average position over the Gangetic plain during this period (Talchabhadel et al. 2018; Varikoden and Revadekar 2020). The trough's position is conducive to convection and rainfall over the foothills of the Himalayas. Three consecutive rainfall spells over Bihar between July 2 and July 23, 2020, resulted in flooding in the rivers of North Bihar's catchments.

4.1 Rainfall episodes from 2nd to 4th July

During the first event, the heaviest rainfall occurred on July 4 (which was the result of a synoptic situation prevalent on July 3 as per the NWP guidance). All three catchment areas got very significant average areal precipitation. Out of the three, Kosi Mahananda got the heaviest AAP of 37.90, followed by Bagmati at 26.24 and Gandak at 16.53, indicating the presence of a weather system in the eastern part of the state on July 2nd and 3rd, 2020. These rainfall spells were essentially due to a trough in the westerly wind and the oscillation of the monsoon trough.

The monsoon trough passes through Daltonganj, and an associated cyclonic circulation over East Uttar Pradesh up to 3.1 km was noticed; however, as per the radar analysis, there was a significant diurnal movement in the monsoon trough, and it shifted towards the foothill in the late evening and night hours, resulting in heavy to very heavy rainfall. Both synoptic conditions and prevailing westerly winds produced widespread rainfall activity, and heavy to very heavy rainfall was realised on July 3 and isolated extremely heavy rainfall on July 4 over the Gandak river catchments. The gradients of mean sea level pressure (MSLP) (1002–996 hPa) played an influential role in the convergence of the winds for the necessary uplifting. The daily Ongoing Longwave Radiation (OLR) reached a minimum of 150 Watt/m2 (the range is 150-220). During the period, OLR<150 watts/m^2 was noticed at most places in the western parts of Bihar. The cloud top or vertical extension of clouds varied between 11 and 16 km during the entire enhanced activity period.

4.2 Rainfall episodes during 8th-13th July

The monsoon trough is again shifted towards northern India and passes over Bihar from July 8 onwards, then subsequently propagates closer to the foothills (As per the NWP guidance and observed datasets). The cyclonic circulation has now turned over Southeast Bihar and extended up to 3.6 km vertically. On July 11, a North-South trough formed over east Uttar Pradesh to Chatishgarh due to the continued strengthening of the monsoon wind's easterly regime and the Cyclonic Circulation's influence over Odisha.

As a result of the strengthening of the westerly regime, the North-South troughs weakened and cyclonic circulation developed over south-east Bihar. Because of the influence of the aforementioned system, widespread rainfall activity was observed across the state. Under the influence of these systems, heavy to very heavy rainfalls occurred on four consecutive days, and extremely heavy rainfall occurred on the fifth day.

4.3 Rainfall episodes from 19th -23nd July

During these periods, the first monsoon break was observed for the summer monsoon season 2020. The monsoon trough again moves closer to the Himalayas' foothills from July 19 onward. It will oscillate over North Bihar for the next three days before splitting into eastern and western ends on

July 22. Under the influence of a strong gradient of MSLP (less than 1000 hPa), a strong south-westerly wind in the region leads to intense convection over the area. The oscillation of the monsoon trough during these periods resulted in widespread rainfall activity and isolated extremely heavy rainfalls on the 19th, with subsequent heavy to very heavy falls occurring at the isolated locations. The highest rainfall reported from Ramnagar in West Champaran is 28.7 cm. As per the INSAT 3D and INSAT 3DR products like OLR, the values of OLR are lowest on July 19 (100 watts/m²). During the spell, daily OLR is less than 200 watts/m². Also, the cloud top brightness temperature was less than -80 °C at the time of intense rain on July 19, 2020. Doppler weather radar-derived products show that the cloud top varies from 11 to 14 kilometres vertically in the atmosphere.

As highlighted in the present study, rainfall does play the most important role, but other factors also have a bearing on the resultant flood and its duration. In the present case, cumulative rainfall in the pre-monsoon period of March, April, and May 2020 was 182.2 mm. This was the highest cumulative rainfall realised in pre-monsoon months since 1936. As a result of this bountiful rainfall, the water table in most parts of the state's flood-prone areas was already saturated before the southwest monsoon season's commencement, and a near-frequent, intense spell of rainfall in July resulted in heavy inundation.

4.4 Analysis of monsoon trough

Except during the first spell of rainfall between July 2 and 4, which was associated with a trough in the westerly wind, the remaining spells were essentially associated with a monsoon break-like situation, i.e., the location of the monsoon trough was north of its mean position and a northwesterly wind prevailed over the surface. The monsoon trough, which is part of the global equatorial trough of low pressure in the northern summer season, has the most profound influence on monsoon rainfall, and its impact on heavy rainfall over Bihar is also established in the present studys north of its mean position and a northwesterly wind prevailed over the surface. The monsoon trough, which is part of the global equatorial trough of low pressure in the northern summer season, has the most profound influence on monsoon rainfall, and its impact on heavy rainfall over Bihar is also established in the present study. In their classic study of the Indian summer monsoon (Krishnamurti and Ardanuy 1980), they identified a salient pressure oscillation in the trough region having a periodicity between 5 and 12 days during which the variation in pressure may range between 5 and 12 millibars; however, this feature was not identifiable in the present case.

4.5 Analysis of satellite data

Satellite data for the corresponding period was also analysed to see the cloud characteristics. The brightness temperature as measured by the onboard radiometer is an excellent measure of the microwave radiance travelling upwards from the top of the atmosphere. The daily mean value of water vapour BT varied from 235-230 on 22 July to 225-210 on 19 July. Any large variation in value would indicate a significant change in the vapour profile. Still, in the instant case, it is seen that there was deep convection in the moist layer, and very high convective clouds with a height reaching between 9 and 16 Km were present throughout the period. The value of OLR is lowest on July 19 (100 watts/m²). During the spell, daily OLR remained less than 200 watts/m². The cloudiness pattern is found to be consistent with the relative location of the monsoon trough over the area.

4.6 Precipitation characteristics of different catchment

Analysis of averaged areal precipitation (AAP) reveals that the first spell of heavy rain affected all three catchment areas, and afterward, there was a noticeable periodicity in the rainfall epoch. The Bagmati and Gandak groups of rivers received almost similar rainfall throughout the study, with five distinct peaks. The precipitation pattern in the Kosi group was somewhat steady, with only two noticeable peaks. However, the three river groups received the most rain on July 20 and 21. On the 20th of July, Gandak received 119.06 mm of AAP, followed by the Kosi group, which received

Table 1. Average Arial Precipitation (AAP) of the studied river catchments for the flooding events (1st to 3rd).

Event	Catchment/Rainfall	Kosi/ Mahananda	Bagmati/Adhawara	Gandak
1st Flooding event	3 July	2.03	4.09	21.65
	4 July	8.36	8.77	3.29
	5 July	37.90	26.24	16.53
	6 July	6.00	4.84	18.968
2nd Flooding event	8 July	5.06	2.01	8.25
	9 July	28.60	26.90	22.14
	10th July	12.50	5.75	20.98
	11 July	41.00	44.4	40.73
	12 July	47.09	15.44	17.16
	13 July	44.04	49.83	37.97
3rd Flooding event	19 July	9.49	2.52	21.74
	20 July	68.81	105.51	119.06
	21 July	21.99	43.14	34.97
	22 July	6.34	23.71	26.88
	23 July	16.82	2.52	30.4

68.81 mm of areal averaged precipitation (AAP). The Bagmati catchment AAP received 34.97 mm of rain on July 21. This simultaneous peaking of AAP worsened the flood situation across the state. During the entire period, the highest AAP of 120 mm was received in the Gandak catchment. The lowest AAP of 70 mm was realised under the Kosi catchment, while Adhwara and Bagmati received 105 mm of AAP (Table 1).

4.7 Impacts on the river level at different gauge stations

Gandak: Analysis of the change in gauge level and AAP leads to some very significant findings. Under the Gandak catchment area, the river gauge at Chatia has the smoothest response to AAP, and during the entire period, it remained below the danger level. While the river gauge at Triveni has the sharpest response, followed by Khadda, and the danger level was breached in response to the third spell of rain, with a lag of about 48 hours between the realisation of the AAP and the breach of the danger level, The river behaved uniformly and in unison at Dumariaghat, Lalganj, and Rewaghat. All rain gauge locations except Triveni and Khadda showed a rising trend between July 13 and July 16, despite a rain cessation (shown in Figure 3.

Bagmati: Out of four river gauge stations, Runnisaidpur and Dhenbridge showed a decreasing trend with a decrease in AAP, Benibad was steady, and Hayaghat showed an increasing tendency with decreasing precipitation (shown in Figure 4).

Adhawara: Like Gandak, the river gauges in the Adhwara basin showed that the water level was going up from July 10 to July 17, 2020, even

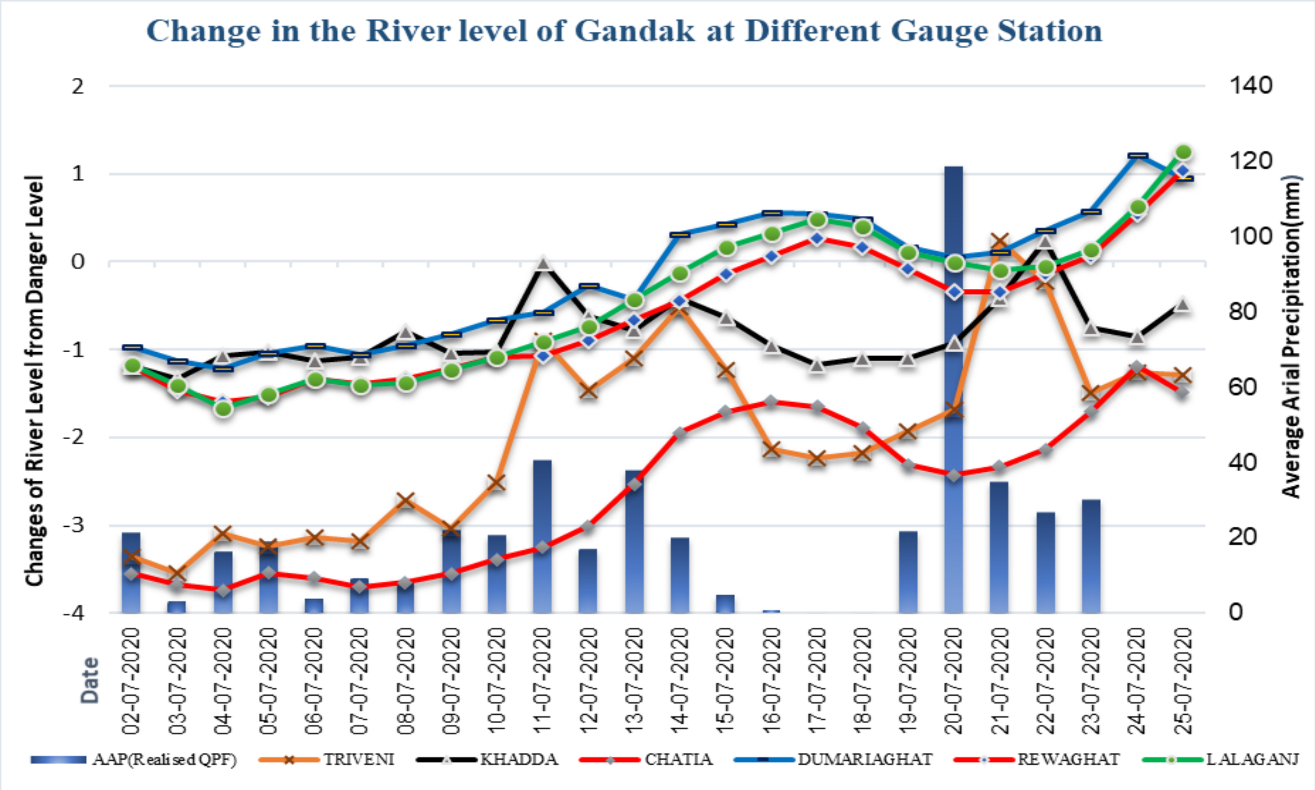

Figure 3: The Response of River Gauge Levels to Average Arial Precipitation in River Catchments (Gandak).

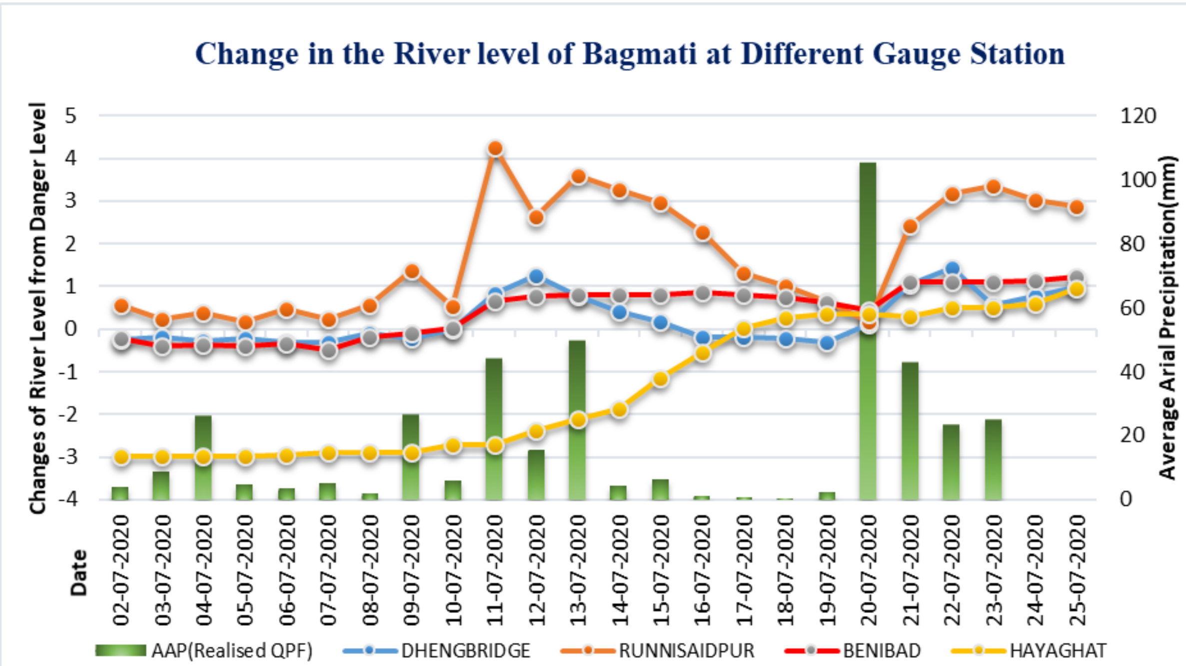

Figure 4: Shows the response of river gauge levels to the average areal precipitation of the river catchments (Bagmati).

though it had stopped raining as of July 13. However, the river gauge at Sonbarsa behaved oppositely, i.e., showing an abrupt decreasing trend with the rainfall decrease (shown in Figure 5).

Kosi: In the case of Kosi, the rain gauge at Barakshetra has the sharpest response between AAP and gauge level, with a lag of around twenty-four hours. The river gauge at Birpur and Kursela

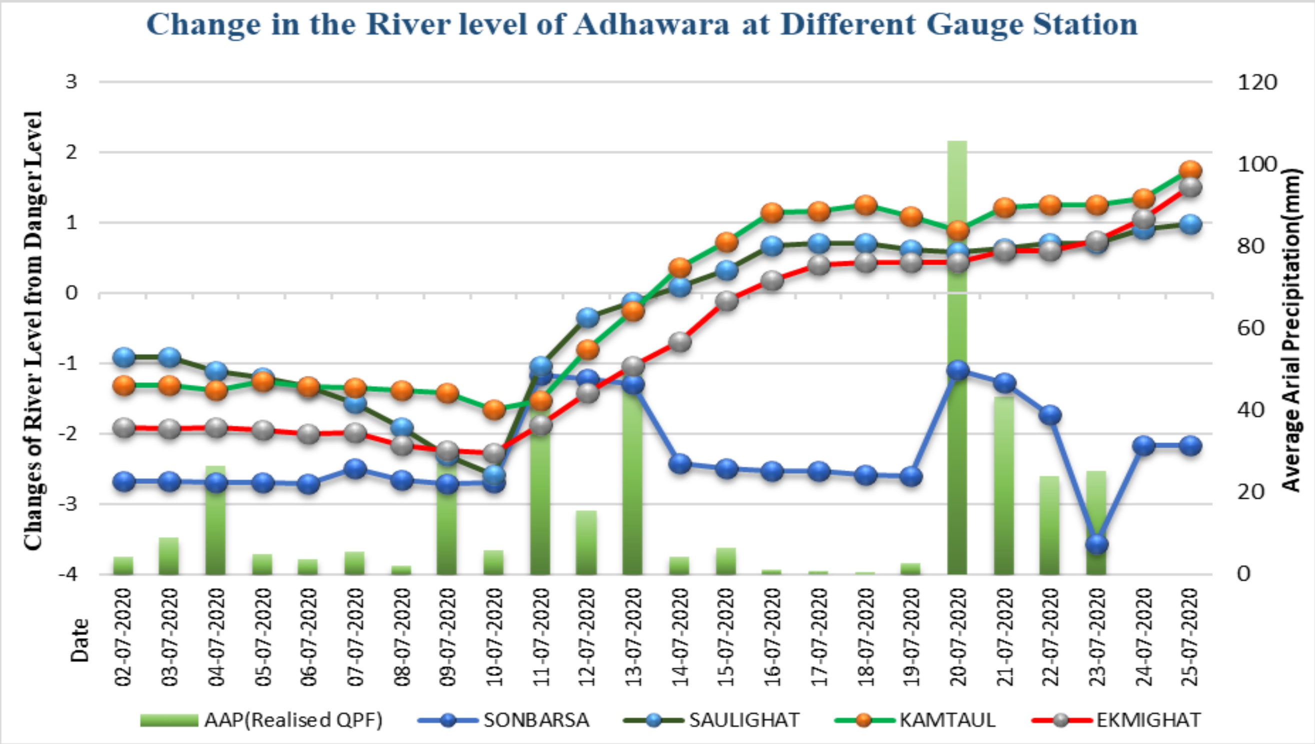

Figure 5: The Response of River Gauge Levels to Average Arial Precipitation in River Catchments (Adhawara).

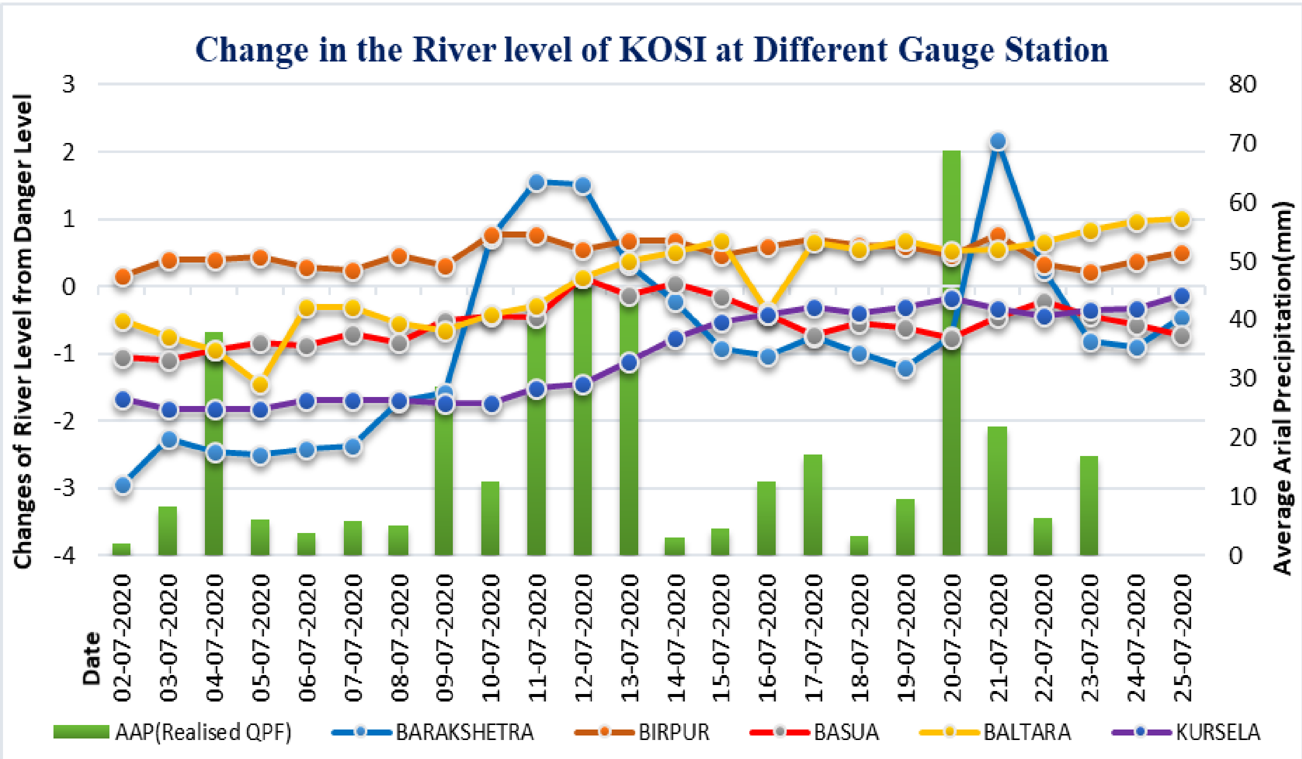

Figure 6: Depicts the response of river gauge levels to average areal precipitation in river catchments (Kosi).

steadily responded to the AAP. Notably, the river remained above the danger mark throughout the period (as shown in Figure 6).

Mahananda: In the case of Mahananda, the rain gauges at Galgalia and Taibpur have the quickest response between AAP and gauge level, with a 24-

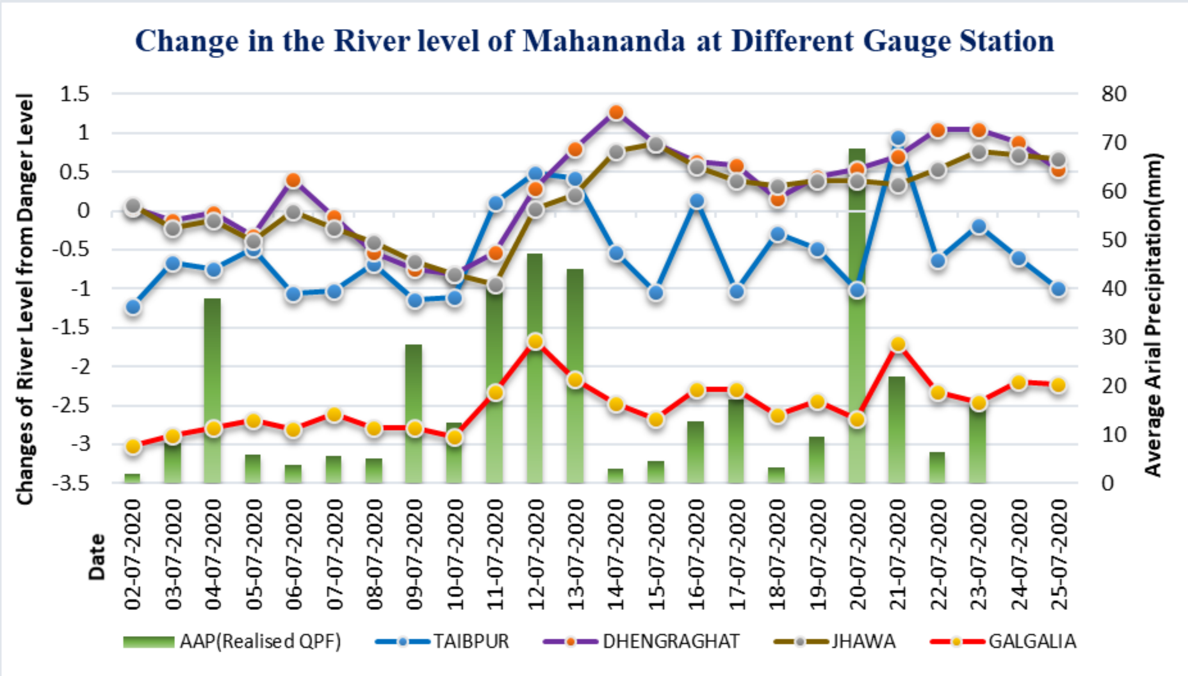

Figure 7: The Response of River Gauge Levels to Average Arial Precipitation (AAP) in River Catchments (Mahananda).

hour lag. The river gauge at Dhengraghat and Jhawa steadily responded to the AAP. Significantly, the river remained above the danger mark except for Galgalia all along the period (shown in Figure 7).

The river system under study is all medium to large rivers, with catchment areas reaching up to 10,000 square kilometres with long-distance flow propagation. Additionally, each river system is also fed by small tributaries. The flooding effect of such a system may take days to realise and make an impact in the lower reaches. As the water table in the Kosi region in the eastern part of Bihar state is very high, it may result in a long-duration flood lasting a few weeks to a month even with moderate rainfall. Thus, the flooding in the area under study is essentially due to the combined effect of infiltration and runoff that at times generates high flow in the lower reaches of rivers and low-lying topographic areas.

5. Conclusions

Although precipitation in the upper catchment area is the single most important factor for flooding, other factors like infiltration, channel carrying capacity, and a water table also play an essential role. Also, river gauge stations' behaviour has suggested that the AAP in the higher reaches of each river group has a more pronounced impact on flood situations than the rain occurring in the lower flood plain. This revealed that the analysis in this study may be used to find lag times for the mitigation and planning of floods in the studied areas. The method used was simple but st ill suitable for use by the community involved in flood risk (hazard) management, not necessarily experts in hydrological modeling. Further, after the study of several cases, dynamic models based on artificial intelligence may be developed. The study revealed that heavy to very heavy rainfall occurred over the catchments of North Bihar due to the shifting of the monsoon trough close to the foothills of the Himalayas along with upper air cyclonic circulation in the lower to middle troposphere and a trough running from this system over the region from July 11 to July 12, 2020. The flood might have been aggravated by receiving more water downstream of the catchments from the upstream rivers of the neighbouring country of Nepal. Also, the synoptic analogous model for the issuance of QPF for the rivers may be modified at specific intervals. The gauge point along the foothills has the most rapid response to the realised precipitation, while those gauge stations downstream show a lag ranging between forty-eight and seventy-two hours. To fully understand and model the relationship between realised precipitation and gauge response, a detailed study of topography, the rate of accumulation of silt, channel capacity, and the drainage condition of the catchments must be done. The gauge height information, along with river discharge concerning the runoff coefficient during a heavy rainfall period, may be needed to study for the issuance of a QPF.

Acknowledgments

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