Climatic, geomorphic and anthropogenic drivers of the 2014 extreme flooding in the Jhelum basin of Kashmir, India

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ABSTRACT
The 2014 extreme flooding in Kashmir, with the peak discharge exceeding 115,000 cfs and the Jhelum River overflowing its banks, was triggered by the complex interplay of atmospheric disturbances causing widespread extreme rainfall for 7 days preceding the event. We used multisource data in GIS environment; satellites, hydro-meteorological, socioeconomic and field data, to assess the role of various factors in the flooding. The event was aggravated by the geomorphic setup of the Valley. Tributaries in the south, characterized by high gradient, decreased time of runoff concentration and increased flood peakedness with short lag, almost simultaneously discharge enormous volumes of floodwaters into the Jhelum around Sangam. Owing to the flat gradient of the Jhelum from Sangam downstream (<5°), floods historically inundate vast areas in the stretch. The situation was exacerbated by the anthropogenic drivers, such as extensive urbanization of the floodplain, loss of wetlands, and decreased channel capacity due to the siltation from the deforested mountainous landscapes. The dilapidated flood control infrastructure and the institutional inability to manage the enormity of the event made the situation worst causing unprecedented damage to the infrastructure in the basin with the capital city Srinagar inundated up to ~30ft for more than a week.

1. Introduction
The inter-montane Kashmir valley, India is characterized by the high mountain ranges, undulating mountainous slopes, unconsolidated Karewa sediments, high-altitude side valleys and a considerably flat alluvial plain in the middle of the basin (Dar et al. 2014). The river Jhelum forms the master stream and occupies the lowest furrow in the alluvial flat of Kashmir valley forming the destination of the streams draining the bordering mountain slopes. Due to its geographic, climatic and geological setup, the Kashmir Valley is vulnerable to all types of the hazards (Meraj et al. 2015; Ray et al. 2009; Romshoo et al. 2012; Ganju and Dimri 2004; Bilham et al. 2010; Maqsood and Schwarz 2010). The historical records reveal that the Kashmir Himalayan region has suffered heavy causalities and loss of property due to the recurrent floods, earthquakes, avalanches and other hydro-meteorological disasters (Lawrence 1895; Mulvey et al. 2008; Kumar et al. 2006; Mohammed et al. 2015). The hydrographic features of the Jhelum river system establish that the frequency of floods has been very high ever since the valley assumed its present form after draining out of the primeval Karewa Lake, the Satisar (Raza et al. 1975; Dar et al. 2014). There have been almost 30 major floods in the archived history of Kashmir valley (Table 1). The magnitude of 2014 flood (~115,000 cfs) was...
almost as high as 1903 and 1959 floods recorded in the recent flood history and the living memory of the people in Kashmir (Bhatt et al. 2016; Lawrence 1895), making it a 50-year return period flood.

Although flooding is a major hazard to lives and infrastructure the world over, but mechanism and trends in flood hazards are poorly understood (Baker 1994; Slater et al. 2015). Normally, the prolonged and high-intensity rainfall is the trigger for floods; however, the geomorphic setup and nature of the socioeconomic development in the river basin would either ameliorate or exacerbate the flooding under various scenarios (Konrad and Booth 2002; Turowski et al. 2009). Recently, the frequency of extreme rainfall events and floods has increased worldwide (Kundzewicz et al. 2010; Lal et al. 2001) including the NW Himalayas (Mishra and Srinivasan 2013; Valdiya 2011). The extreme rainfall event, as evident from the 7-day antecedent rainfall data observed in the Jhelum basin, turned into one of the worst disasters in the flood history of the Jhelum compounded by the existence of the injudicious socioeconomic structures (Hassan et al. 2015) and massive land system changes (Rather et al. 2016; Oza 2003) in the floodplains that interfered with the hydraulic and hydrological processes during the flooding (Negi 2001). The scenario was further worsened due to the dilapidated flood control structures and the institutional failure on managing the enormity of the extreme flooding. The 2014 flood was very devastating killing more than 100 people and causing colossal loss to the infrastructure to the tune of INR 1 trillion (World Bank 2015). The Jhelum waters, that used to be the provider of life and sustenance, suddenly became a monstrously destructive force against the human life and the infrastructure that cohabit its backyards since millennia. The high discharge levels of the Jhelum persisted for more than a week, flooding the vast low-lying areas of the valley. The scene was frightening making the people fear for a high human loss and total destruction of the capital city, Srinagar. Even though there is tremendous advancement in the flood hazard prediction globally during the last few decades (Knebl et al. 2005; Romanowicz and Beven 1998), but there is insignificant progress in translating the benefits of the scientific advancements for the flood risk reduction of the society as was evident from the high loss of life and property during the 2014 Kashmir flooding.

Dilapidated flood control infrastructure, shrinking of the wetlands, deforestation, high rate of the urbanization of Jhelum floodplains and siltation of the watercourses witnessed in the Kashmir valley during the last few decades has degraded the ability of the environment to absorb the excess rainwater in Jhelum basin (Romshoo et al. 2011) and thus, increased the vulnerability of the basin to flooding (Meraj et al. 2015) which is manifest in the frequent flash floods and recurrent water logging observed in the floodplains of Jhelum including the Central Business District of Srinagar just after a few centimetres of rainfall.

We investigated the combined role played by the high-intensity extreme rainfall event, geomorphic setup of the valley and anthropogenic drivers in causing the widespread inundation and high infrastructure loss in the Jhelum basin during the 2014 floods. It is hoped that the integrated analyses of the casual factors would provide valuable knowledge for developing a strategy for reducing the risks in the eventuality of future flood hazards in the Kashmir Valley.

2. Study area: the Jhelum river basin

Figure 1 shows the location of the Jhelum river basin with the Jhelum River originating from the karstic mountainous terrain, characterized by a number of high discharge springs, in the South of
Figure 1. Location of study area (Kashmir valley).
the Kashmir valley. Jhelum river, one of the major tributaries of the Indus river system, is a lifeline of the Kashmir valley and comprises of 24 watersheds with almost half of them on the left bank draining from the Pir Panjal range and the other half from the right bank draining from the Greater Himalayan range. The details about the geomorphic, climatic, demographic and land system characteristics of the basin are provided in the following sections.

2.1. Geomorphic setup of the basin

The Kashmir valley forms a composite basin with fairly well developed drainage system and Jhelum forming the main channel of the drainage. The bordering mountain ranges remain snow covered almost throughout the year and provide ground for the development of a number of streams which have more or less established their own entities within valley. These tributary drainage basins together with the river Jhelum constitutes the drainage system of the Kashmir valley. The valley is filled with ~4265 ft thick Plio-Pleistocene fluvo-glacio-lacustrine sediments which are generally known as the ‘Karewas’ (Kotlia 1985; Dar et al.2013). Recent studies in the basin demonstrated the spatial variation of tectonic activity along the Pir Panjal and Great Himalayan mountain ranges, pointing to a general trend of higher degree of tectonic activity towards the Pir Panjal flank of the basin (Dar et al. 2014). The tectonic activity has tilted the Kashmir basin towards northeast with the result the Jhelum has an asymmetrical position in the valley floor lying close to the Great Himalayan flank than to the Pir Panjal flank. The altitudinal variation, between 3543 ft and a maximum of 17,520 ft, implies a great variation in the geomorphic characteristics of the valley. Besides imparting potential energy to the drainage systems, the relief also induces variations in temperature, precipitation and vegetation cover over the basin.

2.2. Climate of the basin

Jhelum basin, encompassing the Kashmir valley, has cold moist winters and mild temperature in summers (Drew 1875). The valley receives most of its precipitation during winters brought in by the western disturbances (WDs) (Bhutiyani et al. 2010). The WDs are most active during winter and spring and decrease significantly as summer progresses (Dar et al. 2015). In almost every season, dry air masses, mainly WD pass over the Mediterranean and Caspian Sea and gather moisture. A part of the WD hot moisture-laden air masses attains the height to cross over the Pir Panjal mountain range and precipitate in the valley, which monsoonal winds usually fail to do except during the late summer. During the late summers, the Kashmir valley is under the influence of SW monsoons, but its magnitude and intensity is usually low (Sen et al. 2017). On the basis of temperature and precipitation, the Kashmir valley experiences four seasons; winter (Dec–Feb), spring (Mar–May), summer (Jun–Aug) and autumn (Sep–Nov) (Bagnolus and Meher-Homji 1959). The maximum precipitation (30–40% of total annual) occurs during spring season when WD strikes the northern face of the Pir Panjal. Winter precipitation, mostly in the form of snow, is fairly widespread. July is the hottest month. June to September is period of summer monsoon in the sub-continent of India, but the valley of Kashmir receives less rains during this season. Autumn is characterized by the least disturbed weather when sky generally remains clear, sunshine duration is longer with very little precipitation. Overall, the Kashmir valley has highly dreary and monotonous winter with very little sunshine, pleasant spring and warm summers.

2.3. Demography and land system changes

As per the Census of India (2011), the total population of Kashmir valley has gone up by 26% from 5.48 million in 2001 to 6.89 million in 2011 with the consequent increase in the population density. A significant increase in the area under settlements has been observed during the last four decades (~40%). The pristine aquatic ecosystems, which perform important hydrological functions in the
basin, are consistently degrading due to the urbanization in their vicinity (Khan et al. 2004; Romshoo et al. 2011; Pandit 1991) wherein untreated sewage and effluents find their way into lake waters and wetlands altering their biogeochemistry (Khanday et al. 2017; Rashid et al. 2017). Increased population has also exert pressure on the arable agricultural land for its conversion to settlements.

Over the last few decades, the landscape in the Jhelum basin has significantly transformed as the land is being converted to other uses without any regard to its congenital land use suitability. A significant shift in the cultivation patterns from agricultural to horticultural land use has occurred in the basin mainly driven by economic considerations but partly attributed to the depleting water resources (Romshoo et al. 2015; Showqi et al. 2014). The area under the water intensive paddy cultivation has decreased significantly by about 700 km² during the last about 40 years only (Rather et al. 2016) and the same has been either transformed into horticulture or built-up land. This has significantly reduced the demand for irrigation in the basin. Large-scale deforestation, dwindling grasslands, depleting glaciers and water bodies and denuded landscapes have transformed the land surface processes linked to hydrology, erosion and weather patterns in the Jhelum basin that are manifest by the decreasing streamflows (Romshoo et al. 2015; Showqi et al. 2014), increasing sediment and nutrient load (Zaz and Romshoo 2012; Badar et al. 2013), shrinking fish habitat and degrading water quality (Rashid and Romshoo 2013). The land system changes observed in the Jhelum basin have serious implications for the catchment scale hydrological processes, not in the basin alone but also in the downstream part of the Indus (Rather et al. 2016). Extensive deforestation of the natural forests in the upland catchment area of Jhelum for timber and fuel wood has reduced the water-retention capacity of the forest ecosystems (Badar et al. 2013). The rapid expansion of human settlements and major infrastructure development projects like railways and expansion of highways in the Jhelum basin serves to divert or constrain the natural pathways of the Jhelum and its tributaries.

3. Materials and methods

3.1. Data used

In this study, we utilized datasets from various sources; ASTER DEM 30-m resolution, Landsat MSS, Landsat TM, OLI Imagery (30-m resolution), meteorological data from Indian Meteorological Department (IMD), land use and land cover (LULC) data, census data, discharge data, flood inundation data and other field data. The ground photography of flood markers was used as reference data to validate the flood area maps derived from the satellite data. Table 2 provides the details of the data used in this research.

3.2. Flood inundation mapping

3.2.1. Flood extent maps

Multi-date satellite data were used to map the flood inundation in the Jhelum basin. Due to the cloudy conditions, a large set of satellite images was used to map the flood inundated areas in the basin (Table 2). The data were pre-processed using standard image processing procedures (Lillesand and Kiefer 1987). All the satellite and GPS field data were co-registered with respect to each other in order to ensure the precise delineation of the inundation boundaries. The tie-points were taken all across the satellite image to ensure better geometric correction of the data, achieving a root mean square (RMS) error of less than 1.00. On-screen visual interpretation of the satellite data was employed (Romshoo et al. 2011; Rashid and Romshoo 2013) to map inundation areas in the basin at 1:40,000 scale as it is suitable and preferred over the digital image analysis in the mountainous terrain (Rashid et al. 2016). The flood inundation extent maps generated from the satellite data on different dates were then integrated to generate the overall maximum flood inundation extent of the 2014 flood in the Jhelum basin (Figure 2).
3.2.2. Flood depth maps

Immediately after the 2014 floods, the water levels were recorded with the help of GPS at 1483 locations across the Jhelum basin using the flood markers on trees and buildings etc. as the precursor for the maximum flood depth. Subsequently, the flood depth map was generated from the GPS-recorded flood depth point data using the nearest neighbour (NN) interpolation algorithm (Sibson 1981; Ledoux and Gold 2005). NN interpolation method finds the closest subset of input samples to a query point and applies weights to them based on proportionate areas in order to interpolate a value. To determine the value of an attribute at location \( x \), values of the points which are natural neighbours of \( x \) and their relative weights are used. The weight of each neighbour is equal to the NN coordinate of \( x \) with respect to the neighbour. If we assume that each data point in a set has a scalar attribute \( a_i \), then the NN interpolation is described as

\[
f(x) = \sum_{i=1}^{n} w_i(x)a_i, \tag{1}\]

where \( f(x) \) is the interpolated function value at the location \( x \).

3.3. Flood infrastructure damage mapping

The damage to the infrastructure, mainly embankments along the banks of Jhelum in the vicinity of the capital city, Srinagar, was recorded in the field during the GPS-supported field surveys and the

| S. no. | Datasets Source | Purpose | Scene ID |
|-------|----------------|---------|----------|
| 1     | ASTER DEM 30-m resolution | Topographic evaluation longitudinal river profiles | ID:ASTGDEM03V2_034E074 |
| 2     | Landsat MSS (17 November, 1972) | Built-up, wetland mapping | ID:EMP149R36...1M19721117 |
| 3     | Landsat Thematic Mapper (TM) (26 July, 1987*; 13 September 1992**) | Flood plain mapping | *ID:ETP149R36..ST19870726 **ID:ETP149R36..ST19920913 |
| 4     | Landsat TM (15 Oct 1992*; 17 Oct 2010**) | Srinagar imperviousness mapping | *ID:ETP149R36..ST19921015 **ID:LT05..L1TP..149 036..20101 017..20161 012..01..T1 036..20140 910..20170 419..01..T1 |
| 5     | Landsat 8 Operational Land Image (OLI) (10 September 2014) | 2014 flood mapping | ID:LC08..L1TP..149 036..20140 910..20170 419..01..T1 |
| 6     | GeoEye | Mapping- Built-up, wetland, Jhelum width profile, National highway, Railway line | – |
| 7     | GPM (IMERG) | NASA | Precipitation | – |
| 8     | INSAT3D | Indian National Satellite System | Precipitation | – |
| 9     | Meteorological data | Indian Meteorological Department (IMD) | Precipitation | – |
| 10    | Discharge data | Flood and Irrigation Department, Srinagar | Jhelum stream flow data | – |
| 11    | Demographic data | Census of India (2011) | Demographic change | – |
| 12    | Ground control points (GPS) | Field survey | Flood depth | – |
data were plotted on the satellite images immediately after the floods. The data about the length, depth and location of the breaches along the river embankments in the city, where the maximum damage was reported, were recorded in the field.

3.4. Tributary river profiles of Jhelum

Using ASTER DEM, longitudinal river profiles of various tributaries of Jhelum in the south of the basin were generated in order to determine the gradient patterns of the channel profiles. The slope angle directly influences the behaviour of the river during flooding. The tributaries in the south, characterized by high basin relief and high stream gradients, almost simultaneously discharge enormous volumes of floodwaters into the Jhelum at Sangam.

3.5. Hydro-meteorological data analysis

Rainfall data from 12 IMD stations in the Jhelum basin, recorded during the first week of September 2014 coinciding with the floods, were analysed. The meteorological stations are located all across the length and breadth of the Jhelum basin. We also used high-resolution satellite precipitation products (0.1°) from the Integrated Multi-SatelliteE Retrievals for GPM (IMERG) provided by National Aeronautical Space Administration (NASA), Global Precipitation Measurement (NASA GPM) and INSAT3D data from Indian National Satellite System to generate information about the
spatial distribution of the rainfall during the period. The satellite products were validated with the observed precipitation data from the ground stations.

The hourly flood discharge gauge data before, during and after the flooding at Sangam, Srinagar and Asham stations along the main trunk of the Jhelum river from 3 to 15 September 2014 was analysed to understand the behaviour of the hydrograph at these three locations.

3.6. Assessment of the anthropogenic influences

Though extreme rainfall or Glacial Lake Outburst Flooding (GLOF) is most often the main trigger for a flood event but the anthropogenic influences have the potential to significantly ameliorate or exacerbate the flooding scenario. The census of India data was used to determine the changes in the total population, population density, households and other relevant socio-economic factors in the floodplains of Jhelum basin between 1981 and 2011. Siltation (Khan et al. 2004) and loss of wetlands and water courses (Kumar 2016) and urbanization of the Jhelum floodplains (Kumar and Acharya 2016) exacerbated the flooding in a basin. The urbanization and loss of wetlands in the floodplain of the Jhelum basin was assessed from 1972 to 2013 using the change detection analysis of the Landsat MSS and Landsat ETM satellite data. The satellite data were pre-processed using the standard image processing procedures as described in Section 3.2.1. The wetland and built-up areas in the basin were delineated from the satellite data using the on-screen digitization (Romshoo et al. 2011; Rashid et al. 2016). The change detection analysis provides the estimate of the changes in the built up and wetland area in the basin during the last 41 years.

Figure 3. Flood inundation level (depth) in the flood plains of Jhelum basin.
4. Results

4.1. Flood inundation extent and depth

Out of the 1074 km\(^2\) of the Jhelum floodplains, 843.74 km\(^2\) (78.56\%) were flooded during the 2014 flooding as determined from the analysis of the time series of the satellite data dating from 5 to 15 September 2016 supported with the ground truth and field observations (Figure 3). The flood depth map generated from the point flood depth marker data all across the Jhelum floodplain (Figure 2) indicated inundation levels in the basin up to 30.9 ft (Figure 3) in the South Kashmir.

4.1.1. Extreme rainfall event

During 1–7 September 2014, the Kashmir Valley received widespread and abnormally high rainfall (Figure 4) resulting in the unprecedented flooding in Jhelum basin. The analysis of precipitation data from the IMD observatories located across Kashmir valley indicated that the South Kashmir received the maximum amount of rainfall. Seven-day antecedent rainfall recorded at certain places in the south Kashmir like Qazigund crossed 617 mm. An average of precipitation data recorded over meteorological stations showed that the south received on an average 433 mm of rainfall during the first week of September. North Kashmir received low precipitation averaging about 162 mm during the same period. The summer capital of the state, Srinagar recorded about 173 mm of rainfall in the first week of September, crossing its 25 year high of 151.9 mm preceding the 1992 floods. The high-resolution precipitation information from the globally available products – IMERG and INSAT3D – was also analysed and compared with the IMD data. The analysis revealed that the

Figure 4. Observed precipitation from meteorological observatories in Kashmir valley in the first week of September (1) Anantnag AWS-A084C98C, (2) Kokernag OBSY-42 046, (3) Pahalgam OBSY-42 028, (4) Srinagar Agro AWS- A0A8C15C, (5) Baramullah AWS-A0B4D428 (6) Gulmarg AWS-A0B4DAFA, (7) Gund-ORG, (8) Qazigund OBSY-42 044, (9) Kupwara OBSY-42 031, (10) Awantipora-IAF, (11) Shopian AWS-A0AAF244 and (12) Srinagar OBSY-42 027.
IMERG product is very close to the observation data with a correlation coefficient of 0.78 as compared to the INSAT3D data which showed lower correlation coefficient of 0.47 (Figure 5).

4.1.2. Flood discharge
The Jhelum waters overflew the embankments for major part of its stretch from South Kashmir to the Srinagar city during the floods. The gauge reading at Sangam crossed 35.4 ft on 5 September 2014 with the floodwaters measuring about 1,15,000 cfs and overflowing 3–6 ft above the banks. Similarly, the gauge reading at Srinagar crossed 30 ft on 7 September 2014 much above the danger mark of 22 ft discharging more than 70,000 cfs of floodwaters against the drainage capacity of about 35,000 cfs. The floodwaters entered the Srinagar city through several breaches along the weaker sections of its embankments and due to the overflowing of the Jhelum 5 ft above its banks. The 2014 flood hydrograph at Sangam, Srinagar and Asham stations is shown in Figure 6. However, because of the high magnitude of the floodwaters at Sangam and Srinagar stations, the gauge came under the floodwaters several times during the flood event and therefore the gauge data were not available for certain time intervals during the flooding.

Figure 5. Comparison between IMERG, INSAT3D and IMD data.

Figure 6. Flood hydrograph at Sangam, Srinagar and Asham station.
4.1.3. Geomorphic influences

High-intensity rainfall can trigger rapid hydrologic and geomorphic responses and may cause flooding over large areas (Arnaud-Fassetta et al. 2009). Longitudinal river profile analysis provides useful data to make relevant conclusions about the geomorphic influences on the flooding. The longitudinal river profile analyses revealed that most of the tributaries of Jhelum, particularly in the south, are characterized by steeper gradients, rapids, waterfalls and knick-points (Figure 7).

The Jhelum drains through the valley floor and is characterized by gentler gradient and meanders across a broad flat valley floor over its own deposited sediments (Figure 8). The average width of the Jhelum reach from Sangam to Wular Lake is ~311.7 ft, but the river narrows to ~200 ft at Srinagar. As evident from Figure 9 also, the active channel width of Jhelum in the Sangam stretch varies from 384.45 ft to 293.14 ft and near Srinagar the width decrease up to 164 ft. Similarly, near the Wular Lake, the width of the river varies 311.68 ft to 216.54 ft.

4.1.4. Floodplain urbanization

The built-up area within the floodplains of Jhelum (1074 km²) has increased by ~4 times from 55.47 km² in 1972–203.30 km² in 2013 (Figure 10). Also, the population within the flood plain has increased from 11,29,947 in 1981 to 30,21,335 in 2011 (Census 1981, 2011). Furthermore, two important transport and communication projects in the form of railways and roadways have come up in the midst of the Jhelum floodplains (Figure 11). Similarly, the length of the macadamized
roads within the Jhelum floodplains has increased from approximately 745.64 km to 1698.23 km between 1962 and 2016 (Figure 12). Moreover, the presence of recently constructed railways and four-lane national highway which runs through the floodplains, have made a difference in the inundation levels and patterns observed in the basin during the 2014 flood.

4.1.5. Wetland loss
The total area of the major wetlands with area >25 ha has decreased from 288.96 km² in 1972–266.45 km² in 2013 (Figure 13 and Table 3). It has been observed that in and around Srinagar city only, we have lost 20 wetlands to urban colonies during the last five decades, particularly in the South of the Srinagar. As a result, the impervious concrete surfaces in the south of the city, due to the urban sprawl have increased from 34% in 1992 to more than 65% in 2010 severally affecting the hydrological processes in the basin (Figure 14). Also, the Wular on the Jhelum River, the largest natural floodwater storage in the basin has significantly shrunk during the last 100 years (Wetland International 2007) (Figure 15 and Table 4). The open water surface has shrunk from 89.59 km² in 1911 to 15.73 km² in 2013.

4.1.6. Flood control infrastructure
Jhelum main breached its banks at more than 26 places and 16 of these breaches were observed in and around the Srinagar city only (Figure 16). The breaches of the river embankments and overflowing of the riverbanks on 6–7 September led to the quick inundation of the city submerging its vast areas.
Vast areas in Kashmir valley were inundated during 2014 floods, as can be seen from Figure 2. Many of these areas remained under floodwaters for more than a week. Some low-lying areas in the Srinagar city remained under floodwaters for more than 4 weeks. In south Kashmir, several villages and cultivated lands were washed away by the floodwaters of the turbulent mountainous tributaries of the Jhelum like Rembiara, Vishav and Romshi. The flood inundation levels recorded in the

### Table 3. Wetland* loss in the Jhelum flood plains between the years 1972 and 2013.

| S. no. | Name                        | 1972 (km²) | 2013 (km²) | Change  |
|-------|-----------------------------|-----------|-----------|---------|
| 1     | Chak-i-Wazir Subaram       | 2.151     | 1.885     | −0.27   |
| 2     | Near Dangarpur             | 1.339     | 0.803     | −0.54   |
| 3     | Near Phashakuri            | 0.478     | 0.455     | −0.02   |
| 4     | Bodsar                     | 1.711     | 1.184     | −0.53   |
| 5     | Near Dandapokhan           | 0.532     | 0.399     | −0.13   |
| 6     | Danda Pokhan               | 2.228     | 2.044     | −0.18   |
| 7     | Near Gund- i- Chandal      | 1.505     | 0.846     | −0.66   |
| 8     | Nambal i narakur           | 4.653     | 4.592     | −0.06   |
| 9     | Hokersar                   | 14.670    | 13.984    | −0.69   |
| 10    | Rakh arat                  | 5.150     | 3.342     | −1.81   |
| 11    | Near Shah Hamdan           | 0.746     | 0.344     | −0.40   |
| 12    | Dal lake                   | 27.53     | 24.21     | −3.32   |
| 13    | Khushal sar                | 1.140     | 0.945     | −0.20   |
| 14    | Anchar Lake                | 48.082    | 45.337    | −2.74   |
| 15    | Miragund Jhil              | 3.026     | 2.162     | −0.86   |
| 16    | Near Miragund              | 0.432     | 0.402     | −0.03   |
| 17    | Near Panznor               | 0.285     | 0.005     | −0.28   |
| 18    | Near Yakmanpur             | 2.471     | 2.147     | −0.32   |
| 19    | Near Shalapur              | 0.454     | 0.207     | −0.25   |
| 20    | Near Batapur               | 0.465     | 0.367     | −0.10   |
| 21    | Rakh-i-Rabitar             | 2.155     | 1.592     | −0.56   |
| 22    | Rakh Salura                | 3.416     | 1.606     | −1.81   |
| 23    | Near Magripura             | 9.288     | 9.089     | −0.20   |
| 24    | Walvanpur                  | 0.807     | 0.525     | −0.28   |
| 25    | Manasbal Lake              | 1.876     | 1.827     | −0.05   |
| 26    | Near Asham                 | 0.570     | 0.509     | −0.06   |
| 27    | Rakh Maigom                | 5.306     | 4.900     | −0.41   |
| 28    | Near Sadhunara Hasti Khan  | 0.525     | 0.363     | −0.16   |
| 29    | Near Wular lake            | 0.297     | 0.255     | −0.04   |
| 30    | Near Wular lake            | 0.418     | 0.284     | −0.13   |
| 31    | Near Hakbara               | 0.347     | 0.204     | −0.14   |
| 32    | Near Gund Ramzan           | 0.932     | 0.275     | −0.66   |
| 33    | Near pumping station       | 0.446     | 0.425     | −0.02   |
| 34    | Wular lake                 | 136.595   | 132.828   | −3.77   |
| 35    | Haigam Jhil                | 6.491     | 5.894     | −0.60   |
|       |                              | 288.962   | 266.454   |          |

*Wetlands with area > 25 ha.

### Table 4. Open water area changes of the Wular Lake between 1911 and 2013.

| S. no. | Year | Open water area (km²) |
|-------|------|-----------------------|
| 1     | 1911 | 89.59                 |
| 2     | 1954 | 97.42                 |
| 3     | 1962 | 76.16                 |
| 4     | 1979 | 26.60                 |
| 5     | 1992 | 52.46                 |
| 6     | 2001 | 14.29                 |
| 7     | 2013 | 15.73                 |

5. Discussions

5.1. Drivers of flooding

Vast areas in Kashmir valley were inundated during 2014 floods, as can be seen from Figure 2. Many of these areas remained under floodwaters for more than a week. Some low-lying areas in the Srinagar city remained under floodwaters for more than 4 weeks. In south Kashmir, several villages and cultivated lands were washed away by the floodwaters of the turbulent mountainous tributaries of the Jhelum like Rembiara, Vishav and Romshi. The flood inundation levels recorded in the
floodplains of the Jhelum were one of the highest in the archived hydrological history of Kashmir with several habitations in Srinagar city inundated up to 20 ft. The Jhelum was flowing 3–6 ft above its embankments in the stretch from Sangam to Kakapora for a distance of about 20 km on 6–7 September 2014. The storage of water in this stretch was around 40 million m³ at any point of time on 6–7 September 2014. The Jhelum River swelled attaining a width of more than 2 km at certain places in the South Kashmir.

Floods are primarily triggered by extreme and widespread rainfall events and GLOFs. As per the analysis of the archived meteorological data for Srinagar during the last 125 years, September is normally the least rainy month for the valley with the mean rainfall of 26.6 mm. The widespread and intense rains observed in the state during 1–7 September 2014 are mainly attributed to the rare combined effect of the WD over J&K and its interaction with monsoons (Ray et al. 2015; Kumar and Acharya 2016), which seem to have intensified in its last phase over the valley that predominately receives the precipitation from WD (Kumar and Acharya 2016). The high rainfall observed in the south Kashmir along both flanks of the Pir Panjal Mountain gives credence to the influence of the monsoons in the observed extreme rainfall (Figure 4). Katra meteorological station on the southern flank of the Pir Panjal recorded more than 625.4 mm of the rainfall during the week preceding the floods in Kashmir. There are also unverified reports of cloudbursts in the upper reaches of the Jhelum basin during the period, which might have suddenly and drastically increased the water levels in the Jhelum basin. However, there is no instrumental evidence of these reported cloudbursts in the basin. Analysis of the hourly satellite-based precipitation data also did not show any evidence of a cloudburst in the basin as the maximum satellite-based hourly rainfall was <30 mm during the period.

The morphology of the southern tributaries of the Jhelum is governed by a number of drivers including climate, lithology and tectonic processes. Studies carried out in the Kashmir Valley suggest
Figure 10. Urbanization in the floodplains of Jhelum (a) 1972 and (b) 2013.
that the drainage patterns have undergone significant changes due to the differential tectonic activities on the Pir Panjal and Great Himalayan sides of the Kashmir Valley (Dar et al. 2014). The relief is most pronounced in tributaries draining the upper reaches of the Pir Panjal and Himalayan side. However, at lower elevations (below \(~7874\) ft), the tributaries attain low relief because they drain through the loose unconsolidated Karewa Group of sediments (Burbank and Johnson 1983). Most of the Karewas have been dissected by fluvial networks and the amount of fluvial deepening varies between the interfluvies. The proximity of sediment sources derived from erosion of the Karewa deposits, anthropogenic-triggered landslides and the reworking of inherited sedimentary formations leads to large sediment fluxes into the tributary channels. Due to abrupt change in the tributary gradient, an increase in the size and volume of water with the consequent increase in the sediment load is observed as the tributaries join at lowlands. The high-intensity extreme rainfall in combination with other factors such as sediment load, high stream gradient, snowmelt and landslides brought about quick flooding in the tributary catchments, discharging huge volume of floodwaters into the Jhelum valley floor.

The average width of the Jhelum reach from Sangam to Wular Lake is \(~311.7\) ft, but the river narrows to \(~200\) ft at Srinagar increasing the flood vulnerability of the city (Figure 8). The banks of the river Jhelum are fragile composed of the sediments. Besides, the ongoing Himalayan tectonic activity is slowly deforming the valley floor, thus affecting the stability of the river banks. This tectonic activity has also resulted in the formation and migration of the river meanders especially in the Srinagar reach of the Jhelum where it is affected by numerous lineaments/faults (Ganju and Khar 1984). The sideways migration of meanders and river bank breaching occurred because the high-velocity waters during the flooding shifted towards the outside of the meanders, causing erosion of the riverbanks. Therefore as seen in Figure 9, the active-channel width has decreased over the time due to the encroachment and growth of vegetation on the river banks. Besides, the siltation

Figure 11. Extent of flood inundation and physical flood barriers in Jhelum basin as mapped from Landsat 8 satellite image of 10 September 2014.
Figure 12. Road network in the floodplain of River Jhelum (a) 1972 and (b) 2013.
Figure 13. Wetlands in the floodplain of River Jhelum (a) 1972 and (b) 2013.
has also decreased the active channel capacity of the river Jhelum to about 35,000 cfs. As pointed out by Slater et al. (2015), a reduction in channel capacity can amplify flood hazards even if the flow frequency distribution does not change. Moreover, the inadequate drainage system in the Srinagar city further compounded the flooding problem, thereby impeding the dewatering of the floodwaters from the low-lying areas.

Figure 14. Built-up expansion in the South of Srinagar City. (a, b) Land use land cover of 1992 and 2010. (c, d) Pervious and Impervious surfaces in 1992 and 2010.

Figure 15. Open water extent of Wular Lake at different points in time: (a) 1911, (b) 1954, (c) 1962, (d) 1979, (e) 1992, (f) 2001 and (g) 2013.
Growth of the human population, the horizontal expansion of settlements, encroachments of the watercourses and floodplains, the reclamation of low-lying floodplains of Jhelum for agriculture (Rather et al. 2016; Rashid et al. 2016), loss of wetlands and the siltation of rivers (Zaz and Romshoo 2012; Romshoo and Rashid 2014; Pandit 1988), have worsened the flood risk in the Jhelum basin. With the urbanized and mismanaged floodplains of Jhelum lending impetus, the 2014 flooding attained disastrous dimensions due to the prolonged steady precipitation observed over the entire Kashmir valley during the first week of the September. It also needs to be kept in mind that Kashmir Valley has been receiving a good amount of snowfall since 2010, which is responsible for the higher snowmelt runoff in the Jhelum tributaries even in the month of September (Murtaza and Romshoo 2017). Moreover, the man-made barriers are responsible for the higher levels of inundation observed in some areas of floodplains particularly around the Srinagar city. The presence of the prominent physical barriers in the midst of the floodplain restricted the spread of the floodwaters in certain areas of the floodplain, thereby increasing the inundation levels in Srinagar city. A few of the traditionally flood-hit areas in the Jhelum floodplains did not receive the floodwaters during 2014 floods because of the presence of the railway embankment (Figure 11). The influence of these man-made infrastructure development projects in the basin needs to be researched in order to quantify their impacts on 2014 flooding in order to initiate corrective measures in future.

The flood vulnerability scenario in the Jhelum basin has worsened during the last few decades as a significant number of the lakes and wetlands in the basin, that used to store floodwaters and act as sponge during flooding, have been urbanized and converted into concrete landscape in the entire Kashmir Valley. Most of the wetlands and water bodies in Jhelum basin are fighting a losing battle for their survival due to the official and public apathy (Rashid and Naseem 2007; Mushtaq and Pandey 2014). The hydrological functionality of wetlands has been adversely affected due to the encroachment, siltation and depleting streamflows under the changing climate (Romshoo et al. 2015; Lal et al. 2001). As seen in Figure 15 and Table 4, the storage capacity of the Wular Lake has decreased significantly because of the massive siltation of the lake from the catchment. Due to the shrinkage of the floodwater storage capacity, the lake pushed back the floodwaters in the Jhelum main during the 2014 flooding as is evident from the flat flood hydrograph observed during 1–7
September 2014 at Asham just near the entrance of the Wular (Figure 6). The phenomenon is responsible for the increased floodwater extent and depth in the upstream stretch of the Jhelum which ultimately spilled over the embankments in the Srinagar city inundating vast areas of the city.

5.2. Flood mitigation strategy

The traditional practice of the deliberate breach of the Jhelum at Kandizal (Figure 8) before it enters Srinagar city and the opening up of the floodgates near Rammunshi bagh to divert the Jhelum waters to Dal Lake, in order to reduce the flood discharge of Jhelum in the city, was not followed this time. Based on the past experience and 2014 flood scenario, it is opined that the deliberate breach of the Jhelum at Kandizal, well in time before it naturally breached, would have substantially reduced the magnitude of inundation levels in the city as large volumes of floodwaters would have diverted to the traditional floodplain in that area, thereby appreciably reducing the discharge of the Jhelum waters entering Srinagar city. However, the act of not opening up the floodgates, meant for diverting the Jhelum floodwaters to Dal Lake, when the Jhelum was overflowing its banks, had a positive impact on the flood situation in certain parts of the city, and in fact, saved several areas in the city from getting inundated. Similarly, the deliberate breach of Jhelum ahead of Srinagar at Sonawari, well in time before the city got inundated, would have released floodwaters into the traditional floodplains and saved several areas in the city from getting flooded. Though quite a norm in the past, however, one might debate the ethicality or even merits and demerits of these decisions as it would have serious implications for a large populace that has recently settled in these traditional floodplains. Therefore, it is imperative that such important decisions are based on thorough understanding, derived from simulated scenarios, about various aspects of regulating these hydraulic structures during floods and cannot be taken on the spur of the moment as was done in the past.

The flood problem in the Kashmir valley is partly due to the inadequate carrying capacity of the river Jhelum in its length from Sangam to Khadanyar. The drainage capacity of the main Jhelum and the flood spill channel therefore proved inadequate for carrying the enormous discharge of floodwater measuring ~115,000 cfs during the 2014 floods. Just upstream of Srinagar at Padshahibagh, a flood spill channel with the original capacity of 17,000 cfs takes off to by-pass the Srinagar city. However, in spite of the flood spill channel, whose capacity is now reduced to less than 5000 cfs due to the siltation, floods are caused by the Jhelum in the city (particularly south Srinagar), if and when, the discharge of river through the city exceeds the carrying capacity of the Jhelum which is 35,000 cfs. This was evident during 2015–2017 when 6 flood alerts were officially issued as the Jhelum flows almost reached to the danger limit. Therefore, increasing the drainage capacity of the Jhelum River needs to prioritize as a long-term flood mitigation strategy.

Despite clear indications of the impending flood disaster in the valley as the drainage capacity of the Jhelum had significantly reduced due to the siltation of water courses, the authorities did not rise to the occasion to develop the adequate flood control infrastructure in the basin for enhancing the resilience of the vulnerable people in the flood-prone areas to major flood events. The fragile Jhelum embankments were found permeable at some places which allowed the floodwaters to leak through. This aided the breach and collapse of the embankments as observed at several places from Pampore down to Chathabal in the Srinagar city (Figure 16 and Table 5). Therefore, the flood control infrastructure needs to be strengthened to avoid the breaching of the embankments in future. There is need to audit the impacts of the major infrastructure development projects like railways and highways that have recently come up in the midst of the Jhelum floodplains so that the correctives are suggested to ameliorate their impacts on flooding.

Keeping in view the hydrology of the Jhelum, there is need to expeditiously start, on scientific basis, a massive dredging program of the Jhelum main and the flood spill channel to restore its cumulative drainage capacity to ~60,000 cfs. The analysis of the 2014 flood hydrograph indicates that it is imperative to start with the dredging of the Wular to increase its floodwater storage capacity, the dredging of the Jhelum Srinagar downstream, the dredging of the stretch from Sangam to Srinagar and
ultimately the dredging of the tributaries in that order. It is important to strengthen the flood control infrastructure in conjunction with other structural and non-structural measures for effective flood control in the basin. The option of an alternate flood channel from Sangam in the south to Wular in the north needs to be scientifically evaluated keeping in view the flat topography of the terrain, the water holding capacity of the Wular and feasibility of draining almost 50,000 cfs through the proposed alternate channel in the event of an extreme flood event of the magnitude witnessed in 2014. The other alternative, i.e. staggering the flood peaks of the high-gradient tributaries like Vishav, Rembiara, Romshi, Lidder, and Bringi in the south that pour huge amounts of flood waters in Jhelum around Sangam also merits consideration for providing long-term flood risk reduction in Kashmir. There is need to explore the flood control schemes that would help to store 0.75 MAF of floodwaters in the Jhelum tributaries as entitled under the Indus Water Treaty (IWT) (World Bank 1960). This alternative, if found technically feasible, would have a multiplier economic effect on flood control, agriculture, horticulture and energy production and tourism promotion.

6. Conclusions

In this study, the integrated analyses of the high-intensity rainfall, geomorphic set up of the Jhelum basin together with the anthropogenic drivers such as the extensive urbanization of the floodplains, loss of wetlands and the reduced drainage capacity of Jhelum due to the siltation, was conducted to understand the 2014 flooding in the Jhelum basin. Though, the primary trigger for the extreme flood event was the high-intensity and widespread rainfall observed in the entire catchment, particularly in the south (~620 mm), during the week preceding the event, but the flooding in Jhelum is significantly influenced by the geomorphic set up of the basin exacerbated by the anthropogenic drivers. The extreme rainfall event during the first week of September which is normally a dry season is attributed to the rare combined effect of the WD and its interaction with monsoons. The tributaries in the south, such as Vishav, Rembiara, Lidder, etc., characterized by the peculiar geomorphic setup, steep gradient, decreased time of runoff concentration and the increased flood peakedness with a short lag time, almost simultaneously discharge enormous volume of floodwaters into the Jhelum at Sangam. The reach of the Jhelum from Sangam downstream up to the Wular Lake is quite flat. As a result, the floodwaters inundated large tracks of Jhelum floodplains in the stretch. The anthropogenic drivers such as the extensive urbanization of the floodplains, the siltation and loss of scores of

| S. no. | Breach site            | River bank | Latitude  | Longitude | Elevation asl (meters) | Length (feet) | Width (feet) | Height (feet) | Date of breach |
|--------|------------------------|------------|-----------|-----------|------------------------|---------------|--------------|--------------|----------------|
| 1      | Athwajan Bund          | Right      | 34° 02' 42.20'' N | 74° 52' 15.83'' E | 1559.11                | 15            | 12           | 10           | 06-09-2014     |
| 2      | Drangball Pampore      | Right      | 34° 01' 07.00'' N | 74° 54' 43.35'' E | 1567.72                | 25            | 18           | 12           | 05-09-2014     |
| 3      | Galandar               | Right      | 33° 59' 35.32'' N | 74° 55' 17.00'' E | 1565.72                | 60            | 8            | 8            | 06-09-2014     |
| 4      | Kandialz Breach I      | Left       | 33° 59' 16.05'' N | 74° 54' 42.64'' E | 1579.78                | 250           | 100          | 50           | 05-09-2014     |
| 5      | Kandialz Breach II     | Left       | 33° 59' 08.86'' N | 74° 54' 29.96'' E | 1565.32                | 150           | 50           | 20           | 06-09-2014     |
| 6      | Kandialz Breach III    | Left       | 33° 59' 05.09'' N | 74° 54' 24.63'' E | 1570.41                | 50            | 20           | 8            | 06-09-2014     |
| 7      | Lalwani Mohalla Pampore| Right      | 34° 01' 05.96'' N | 74° 54' 39.32'' E | 1562.71                | 130           | 35           | 30           | 06-09-2014     |
| 8      | Rajbagh I              | Left       | 34° 03' 59.68'' N | 74° 50' 05.70'' E | 1561.17                | 100           | 50           | 12           | 07-09-2014     |
| 9      | Rajbagh II             | Left       | 34° 03' 48.72'' N | 74° 50' 02.02'' E | 1557.04                | 40            | 20           | 12           | 07-09-2014     |
| 10     | Rajbagh III            | Left       | 34° 03' 48.16'' N | 74° 50' 00.30'' E | 1562.92                | 25            | 10           | 8            | 07-09-2014     |
| 11     | Rajbagh IV             | Left       | 34° 03' 45.30'' N | 74° 49' 46.89'' E | 1557.54                | 30            | 13           | 8            | 06-09-2014     |
| 12     | Shangrilla Hotel       | Right      | 34° 04' 00.73'' N | 74° 50' 34.84'' E | 1579.74                | 200           | 100          | 12           | 07-09-2014     |
| 13     | Shiva Pora I           | Right      | 34° 03' 24.10'' N | 74° 50' 16.85'' E | 1566.38                | 40            | 20           | 15           | 06-09-2014     |
| 14     | Shiva Pora II          | Right      | 34° 03' 31.68'' N | 74° 50' 26.09'' E | 1573.02                | 50            | 25           | 10           | 06-09-2014     |
| 15     | Shiva Pora III         | Right      | 34° 03' 30.42'' N | 74° 50' 24.27'' E | 1571.7                 | 25            | 15           | 10           | 06-09-2014     |
| 16     | Shiva Pora IV          | Right      | 34° 03' 46.83'' N | 74° 50' 12.96'' E | 1562.92                | 20            | 12           | 8            | 07-09-2014     |
| 17     | Shiva Pora V           | Right      | 34° 03' 46.04'' N | 74° 50' 12.85'' E | 1565.72                | 30            | 15           | 10           | 07-09-2014     |
| 18     | Shiva Pora VI          | Right      | 34° 03' 43.82'' N | 74° 50' 03.07'' E | 1564.29                | 35            | 30           | 10           | 07-09-2014     |
| 19     | Shiva Pora VII         | Right      | 34° 03' 34.66'' N | 74° 49' 46.92'' E | 1559.79                | 20            | 12           | 12           | 07-09-2014     |
| 20     | Shiva Pora VIII        | Right      | 34° 03' 26.84'' N | 74° 49' 44.41'' E | 1556.65                | 15            | 10           | 10           | 06-09-2014     |
| 21     | Shiva Pora IX          | Right      | 34° 03' 29.08'' N | 74° 50' 23.70'' E | 1567.54                | 20            | 12           | 12           | 06-09-2014     |
| 22     | Shiva Pora X           | Right      | 34° 03' 35.79'' N | 74° 49' 38.20'' E | 1558.27                | 35            | 12           | 10           | 06-09-2014     |
wetlands, decrease in the channel capacity due to the siltation of watercourses from the material eroded from the soft Karewa sediments and deforestation in the mountainous catchments exacerbated the flooding. The inadequate flood control structure and the lack of institutional capacity for managing the enormity of the extreme flood events increased the risk of the people to flooding. The flood risk reduction strategy suggested for the Jhelum River should help to address to build the resilience of the people to extreme flooding.

Acknowledgements

The research work was conducted as part of the Ministry of Earth Sciences, Government of India sponsored research project titled ‘Assessing the Climate Change Impacts on Hydrology of Jhelum Basin’ and the financial assistance received from the Ministry under the project to accomplish this research is thankfully acknowledged. The authors express gratitude to the anonymous reviewers for their valuable comments and suggestions on the earlier version of the manuscript that greatly improved the content and structure of this manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

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