of different components and removal of residual gas from the IVC whatever small it is to further lower the temperature. As a diagnostic tool for operation we have measured molar flow rate and temperature of still and mixing chamber under different still heater power.

Development of the dilution refrigerator happens to be an important development of technology in the field of low temperature research. However, it appears that there is scope for further improvement of the system. The cryogen-free dilution refrigerator has been formed more popular to research community for its simple operation and requires no liquid helium. We can think of making a cryogen-free system in the near future.

1. Pradhan, J., Das, N. Kr. and Chakraborty, A., Thermo-dynamical process simulation of dilution refrigerator. *Cryogenics*, 2013, **57**, 158.
2. Das, N. K., Pradhan, J., Naser, Z. A., Roy, A., Mandal, B. C. Mallik, C. and Bhandari, R. K., Design and performance of a ^{4}He–evaporator at <1.0 K. *Cryogenics*, 2012, **52**, 679–684.
3. Pradhan, J., Das, N. Kr. and Chakraborty, A., Transient phenomena initiating phase transition in dilution refrigerator. *Cryogenics*, 2014, **63**, 69–76.
4. Wheatley, J. C., Rapp, R. E. and Johnson, R. T., Principles and methods of dilution refrigeration. *J. Low Temp. Phys.*, 1971, **4**(1), 1–39.

ACKNOWLEDGEMENTS. We thank Dr D. K. Srivastava and Dr. Alok Chakrabarti of VECC, for their support and encouragement.

Received 21 August 2015; revised accepted 8 September 2016

doi: 10.18520/cs/v112/i05/1023-1028

Flash flood disaster threat to Indian rail bridges: a spatial simulation study of Machak River flood, Madhya Pradesh

K. H. V. Durga Rao*, A. Shravya, V. Venkateshwar Rao, V. K. Dadhwal and P. G. Diwakar

National Remote Sensing Centre, Indian Space Research Organisation, Balanagar 500 037, India

The recent flood in Machak River, Madhya Pradesh, India is a distinctive paradigm of flash floods that washed off rail tracks and killed a number of passengers besides incredible damage to Indian Railways and to the surrounding villages. This shows the vulnerability of bridges/culverts to flash floods in the country. Flash floods devastated the Machak River during the midnight of 4 August 2015 due to heavy rainfall in the catchment. The duration of flooding was small with less lead-time. Narrow river sections could not accommodate the peak discharge causing severe flooding in floodplains. Hydrological and hydro dynamic simulation was studied in the Machak River using space-based inputs to quantify the causes of flash floods and its impact. Satellite-based rainfall (GPM and IMD's WRF merged product) was used in hydrological modelling in the absence of field rainfall and discharge data. Flood inundation simulations were done using CARTO digital elevation model of 10 m resolution. Inundation extent, depth of inundation, and velocity of flow at different reaches were examined. As the slopes were steep in the upstream catchment area, the lag-time of the peak flood was found to be less and washed off the Machak rail culvert without any alert. The study reveals that quantitative parameters of the disaster are due to high intensity of rainfall, drainage congestion and sudden change of slopes across the catchment.

Keywords: Hydrological simulation, hydrodynamic modeling, Machak River, rail accident.

IN India, thousands of rail bridges/culverts are more than 100 years old, and many of them are prone to floods due to change in hydrological conditions and river regime. During the last decade, many bridges are affected by flash floods in the country causing damage to lives and property. A flash flood is caused by heavy or excessive rainfall in a short period of time, generally less than 6 h (ref. 1). When it rains rapidly on saturated or dry soil with very low absorption ability, the run-off that is caused gains tremendous force and becomes a gushing river which takes down almost everything in its path. It can sweep all kinds of debris downstream in just a few hours. Sometimes these run-offs could also join with other low lying water or streams causing even more devastating impact[2]. Quantitative assessment of flood hydrograph associated with flash floods is a challenging task. Anticipating the magnitude of the event and its time of occurrence is a difficult job. A given rainfall event's chances to produce a flash flood are dramatically affected by such factors as antecedent precipitation, the size of drainage basin, the topography of the basin, channel characteristics, and so on. Thus, a flash flood event is the concatenation of a meteorological event with a particular hydrological situation[3]. Development of flash flood forecast models in conjunction with flood inundation simulation models using hydrological and hydrodynamic modelling can give flood alarm in the floodplains which is an effective non-structural method of flood damage mitigation[4].

India seems to lurch from one major natural disaster to another. We experienced major earthquakes, tsunami,

*For correspondence. (e-mail: khvdurgarao@yahoo.com)

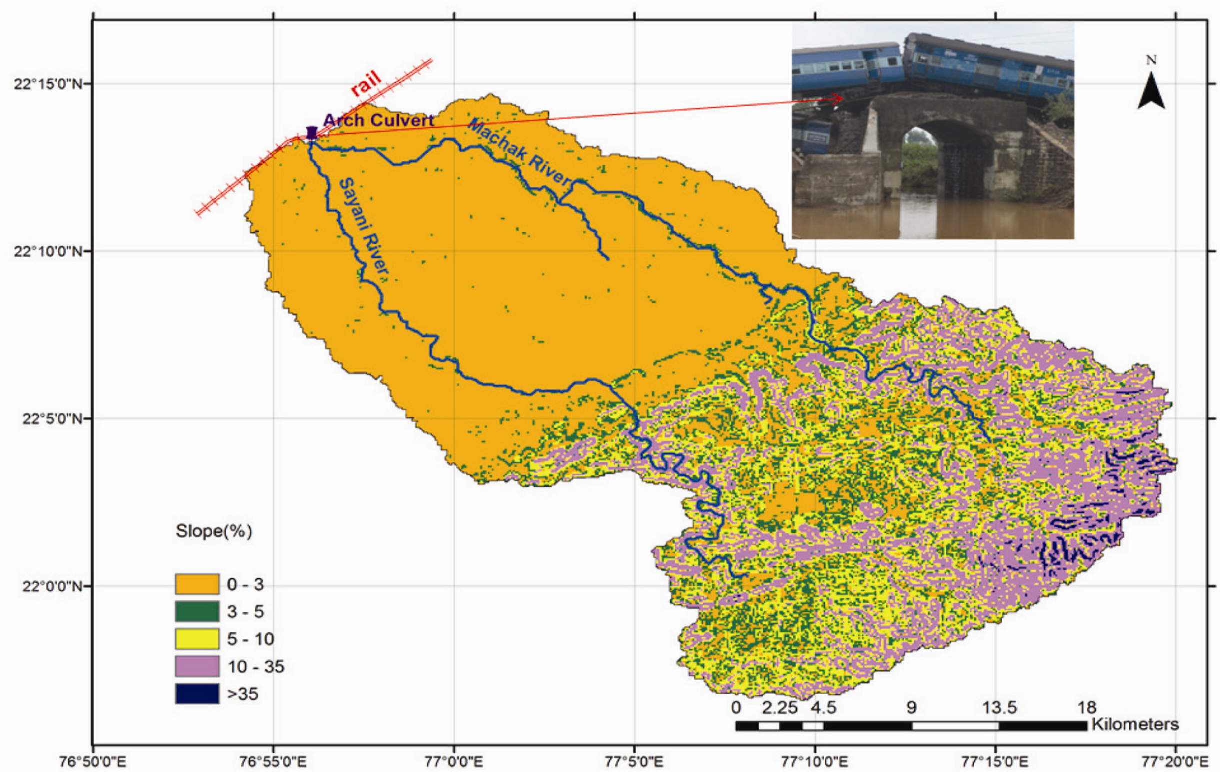

Figure 1. Topography of the Machak River catchment and the arch culvert.

floods and droughts during the last decade. Our ability to predict and minimize the impact of these disasters has not improved much[5]. Flash floods struck the rail bridge on Machak River, the river level was abnormally high, and gradually washed away the track bed, resulting in sinking of the track. The Kamayani Express, which was headed to Varanasi on the down line, derailed as flash floods (caused by cyclonic storm Komen) dislodged an old culvert on the Machak river near Mandla village, causing track misalignment[6]. Many people died and over 100 injured in the accident during the midnight of 4 August 2015 (ref. 6).

Flash flood triggered in the Machak River on 4 August 2015 due to unprecedented rainfall in the catchment. The disaster was not captured by any satellite as the flood took place in the night and receded within a short period. The river catchment is un-gauged and does not have any first-hand information to understand the flood situation. A hydrological and hydrodynamic modelling study was carried out on the Machak river flash floods for approximate quantification of flood discharges and its inundation extent in the river. This will help in understanding what might have happened during that flood event and to take care of such events in future. Thorough field work was carried out to examine the hydrology of the Machak River and its flood impact. The complete scenario was simulated in the Geographic Information System (GIS) environment using space-based inputs through hydrological modelling approach and discussed in the following sections.

Machak River has a catchment area of 743 sq. km (up to the rail bridge) and flows directly to the Indira Sagar Reservoir constructed on River Narmada in Madhya Pradesh. Sayani, a tributary to Machak River, joins Machak just before the rail bridge. Machak river profile is narrow with an approximate width of 100 m at the main Machak River rail bridge. The catchment has steep slopes in the upstream area and very flat floodplains in the downstream area. The rail accident happened at an arch rail culvert (having single went) which is more than 140 years old and located approximately 300 m from the main rail bridge. A small drain passes through the culvert and joins the Machak River in the downstream side. Catchment boundary up to rail bridge was delineated in GIS environment. The river profile and arch bridge are shown in Figure 1. Black soils, clay loam, and sandy clay loam are the predominant soils in the study area[7], these soils exhibit the property of expansion and shrinking[8]. Slopes in the catchment area were computed using the CARTOSAT Digital Elevation Model (DEM). Slopes in the upstream part of the catchment are very steep, whereas in the slopes in the downstream floodplains are very mild (less than 3%) as shown in Figure 1.

The average annual rainfall in the Harda District of Madhya Pradesh is approximately 1125 mm (ref. 6). During the flood event, there was a cyclone named Komen[6]

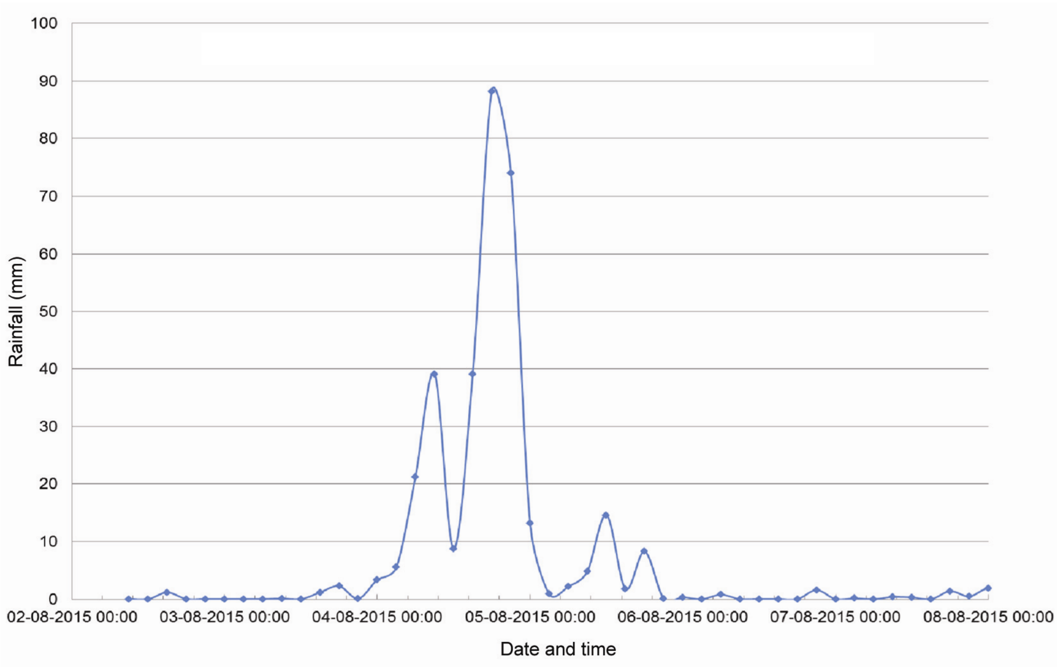

Figure 2. Temporal rainfall (3 h) in the catchment during the flood event.

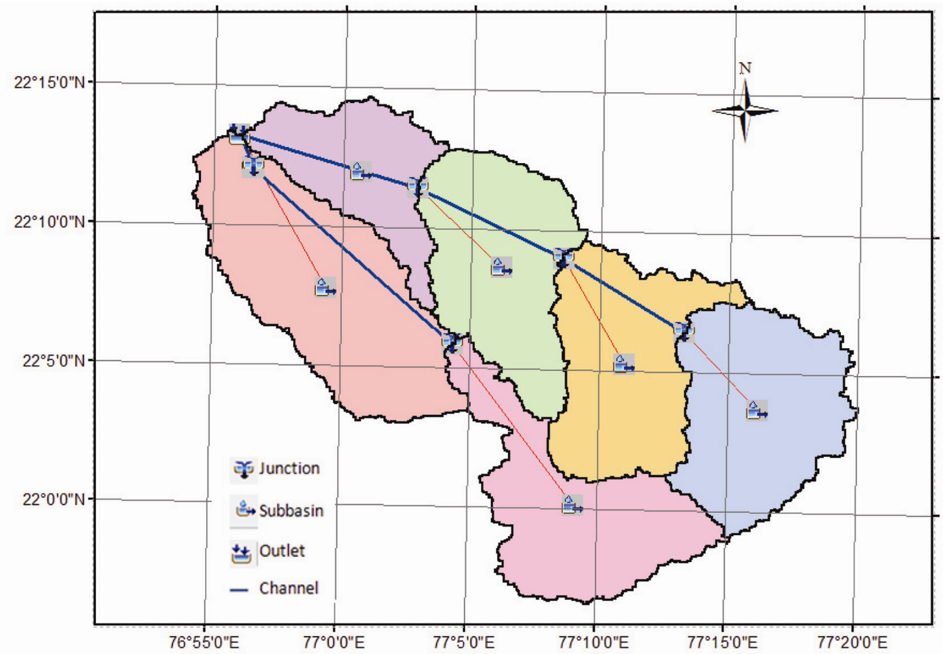

Figure 3. Hydrological model set-up of the study catchment.

which caused high intensity rainfall in the surrounding region. Local people claim that heavy rainfall led to the flood event; unfortunately neither a single rain-gauge nor a discharge measuring gauge was available in the entire catchment to have a quantitative estimate of the event. Due to non-availability of field measurements, satellite-based rainfall data was used in the study. IMD's WRF rainfall product and global precipitation measurement (GPM) 3 h rainfall data of 0.25 × 0.25 degree spatial resolution images were used in the study for the period of 2 to 8 August 2015 covering the catchment area. A very high intensity of rainfall of 265 mm (catchment average) occurred on 5 August 2015 (8 a.m. of 4 August to 8 a.m. of 5 August 2015), of which 65% of rainfall occurred in just 6 h (3 p.m. to 9 p.m. of 4 August 2015). Rainfall recorded by Climatic Prediction Centre data (CPC;

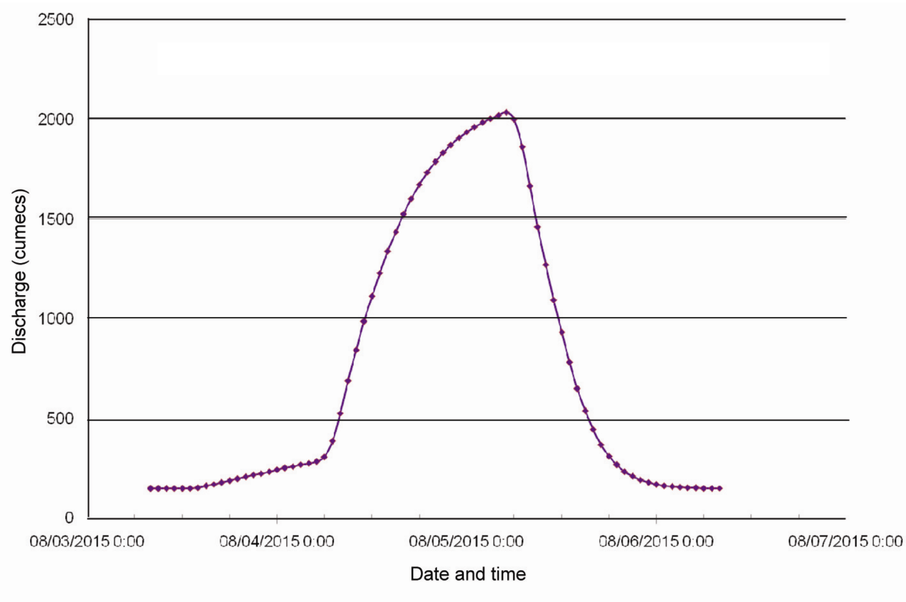

Figure 4. Computed flood hydrograph at rail bridge during the flood event.

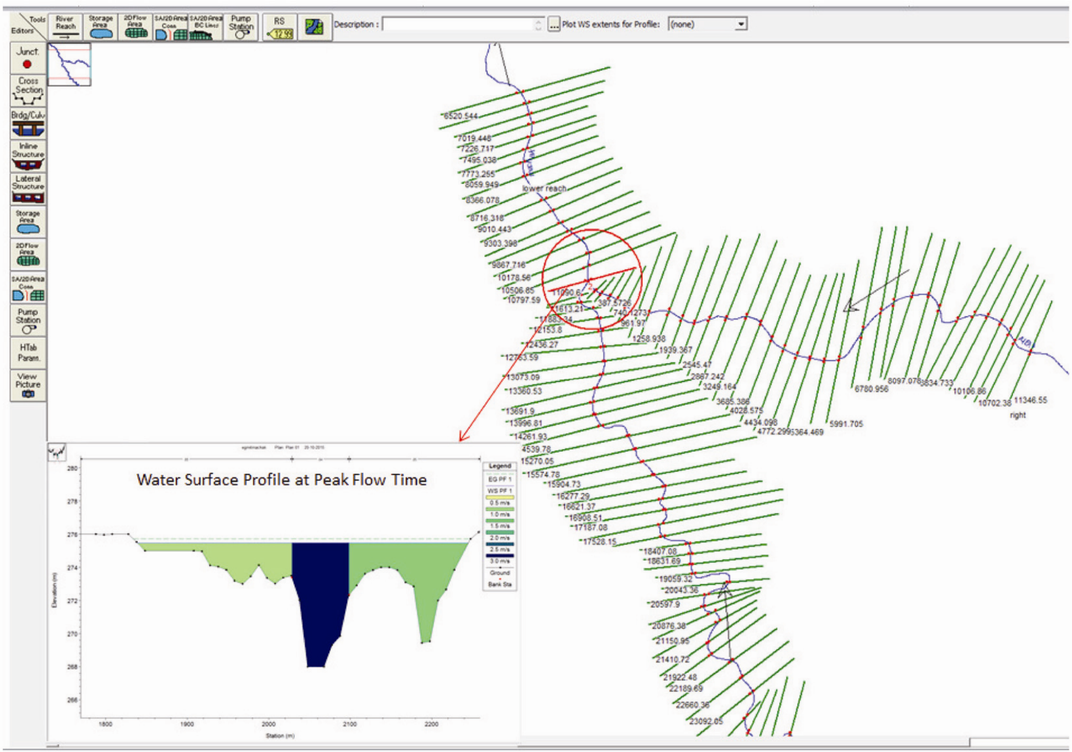

Figure 5. Computed water surface profile and the river geometry.

satellite-based rainfall product) also shows that the rainfall that day was approximately 255 mm, which is quite in agreement with IMD and GPM rainfall products. It was found that with the 35 mm rainfall recorded on 4 August, this antecedent rainfall event raised the soil moisture to saturation/semi-saturation level and the subsequent rainfall event resulted in maximum run-off in the catchment. Temporal distribution of rainfall as recorded by IMD&GPM merged product is shown in Figure 2.

A major challenge still remaining is the accurate prediction of catchment run-off responses to rainfall events mainly in un-gauged catchments[9]. Satellite remote sensing provides reliable, accurate and updated database on land and water that helps in simulating flood discharges

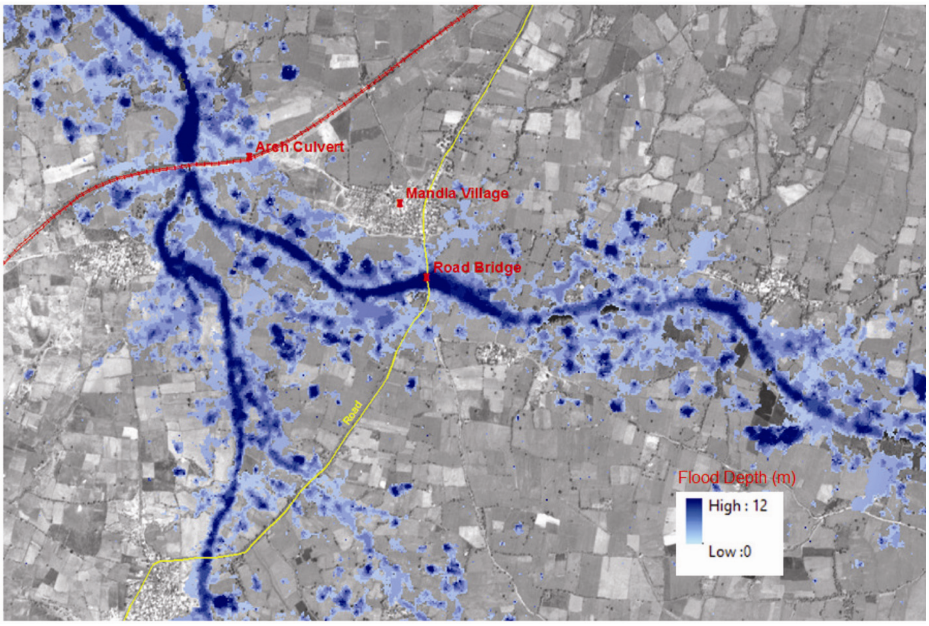

Figure 6. Approximate simulated flood inundation during peak discharge in Machak River.

more accurately[10]. Run-off was computed using space-based inputs through hydrological modelling approach. CARTO DEM of 10 m resolution, landuse land cover grid (derived from IRS P6 satellite data of 2010), and soil textural maps were used in the study. Flow direction, flow accumulation, and stream network grids were computed through an automated process. All topographic and hydraulic parameters like catchment slopes, lag-time, and channel slopes, roughness parameters were computed using the above mentioned space inputs in HEC-Geo HMS and HEC-HMS modelling environment. Rainfall during 2 and 8 August 2015 was extracted from rainfall images and fed into the hydrological model. Run-off was computed in the catchment using a semi-distributed modelling approach. Flood hydrograph was computed at the outlet (culvert location) using Muskingum method of flow routing. A basin model set-up of the study area is shown in Figure 3.

Flood hydrographs of Sayani, Machak Rivers and at its confluence were also computed. Computed flood hydrograph at outlet is shown in Figure 4. Peak flood computed at the rail bridge site was found to be 1850 m^3/s. The computed discharge could not be calibrated and validated with field discharge as there was no discharge site available; hence these simulations are approximate. However, from the Indira Sagar Project authorities (Narmada Valley Development Authority, Bhopal) it was found that the total inflow to the reservoir from all streams on the peak flood date was 4200 m^3/s (Machak River is one of the inflow streams to the reservoir).

High resolution DEMs are useful in simulating flood inundation nearest to the real world condition[11,12]. These flood inundation simulations are useful in giving information on the spatial extent of flooding in the absence of any satellite data. In this study, flood inundation simulations were done using high resolution DEM (CARTO DEM of 10 m resolution). River cross-sections profiles at regular intervals and river longitudinal profile were extracted using DEM. Manning's roughness parameters were estimated using the landuse map derived from satellite data. River banks, flow path and river centre line were delineated using satellite image acquired prior to the flood event and the river geometry was computed. Computed flood hydrographs of Machak, Sayani were fed into the model at locations where floodplain starts (less than 3% slope) and the downstream boundary conditions were defined at model outlet. Hydrographs computed were used in simulating the approximate flood inundation and in computing the dynamics of flow. Flood inundations were simulated for unsteady flow conditions using time series computed discharges. It was found that simulations matched well with field observations. It was also found that the velocity of flow varies from 1 to 3 m/s in Machak River, and 0.7 to 2.2 m/s in Sayani River. From these simulations, the approximate depth of flow at the arch bridge site was found to be 8 to 9 m. The previous highest flood level at the arch rail bridge was 272.5 m and the present flood level observed was approximately 277 m (West-Central Railway, Bhopal). Simulated flood level was found to be approximately 276 m, closely matching the field observed flood level. Water surface profile at the bridge site and the river geometry are shown in Figure 5. Simulated flood inundation during the maximum flood discharge is shown in Figure 6. From the water surface profile it can be inferred that the depth of flow at the main river bridge is deeper than the depth at arch culvert.

Figure 7. Flood situation in Machak river during the event (source: West-Central Railway, Bhopal).

It is presumed from flood inundation simulations that rail track shrinking took place due to flood water impoundment along the approach track of the arch culvert. As these simulations were done using 10 m resolution DEM, it is approximate but can give an overall flood scenario in the absence of any satellite data during the flood event. From simulations and field reports, it was noticed that flow entered through the Mandla village due to breach in the river and travelled through the existing drain and stuck the rail arch bridge. Flood situation during the event (receding state of flood; early hours of 5 August 2015) at a road bridge near Mandla Village is shown in Figure 7 to demonstrate the severity of the flood.

Slopes in the upstream side of the Machak catchment were high compared to those in the floodplain near the rail bridge. Velocity head was converted into static head due to sudden change in slopes. It is understood that the single went arch bridge was not just sufficient enough to carry the flood discharge to the downstream side during the event. High intensity rainfall, variation in catchment slopes, and drainage congestion near rail bridge caused the floods in the study area. The role of soil properties in that area has to be examined. Proper care and measures should be taken in future to prevent such events. There should be discharge and rainfall gauges in the upstream side of the river to warn floods in advance. Proper drainage system should be provided at bridge sites (approach roads/rail lines) to minimize such events in future. Rail/road bridges having flood threat should be identified, and development of spatial flood early warning models in such areas can give flood alarm that can help in minimizing the flood damage.

1. http://www.srh.noaa.gov/mrx/hydro/flooddef.php
2. Gowda, P. R., Buddhikot, O. and Subbarao, A., *Flash Flood Research and Prediction Model*, Green Kids Now, Inc., 2014, pp. 1–36.
3. Charles, A. Doswell III, Brooks, H. E. and Maddox, R. A., Flash flood forecasting: an ingredients-based methodology. *Weather Forecasting*, 1996, **2**, 560–580.
4. Durga Rao, K. H. V., Venkateshwar Rao, V., Dadhwal, V. K. and Diwakar, P. G., Kedarnath flash floods: a hydrological and hydraulic simulation study. *Curr. Sci.*, 2014, **106**(4), 598–603.
5. Srinivasan, J., Predicting and managing extreme rainfall. *Curr. Sci.*, 2013, **105**(1), 7–8.
6. Harda twin train derailment: https://en.wikipedia.org/wiki/Harda_twin_train_derailment
7. Central Ground Water Board, http://cgwb.gov.in/District_Profile/MP/Harda.pdf
8. Taboada, M. A., Soil shrinkage characteristics in swelling soils, 2003; http://users.ictp.it/~pub_off/lectures/lns018/39Taboada1.pdf
9. Kabiri, R., Comparison of SCS and green-Ampt methods in surface run-off: flooding simulation for Klang watershed in Malaysia. *Open J. Mod. Hydrol.*, 2013, **3**, 102–114.
10. Durga Rao, K. H. V., Rao, V. V., Dadhwal, V. K., Behera, G. and Sharma, J. R., A distributed model for real-time flood forecasting in the Godavari Basin using space inputs. *J. Disaster Risk Sci.*, 2011, **2**(3), 31–40.
11. Cook, A. and Merwade, V., Effect of topographic data, geometric configuration and modeling approach on flood inundation mapping. *J. Hydrol.*, 2009, **377**, 131–142.
12. Ghimire, S., Application of a 2D hydrodynamic model for assessing flood risk from extreme storm events. *Climate*, 2013, **1**, 148–162.

ACKNOWLEDGEMENTS. The authors acknowledge the West-Central Railway (Bhopal) engineers for providing the available field information about the event. Their cooperation and data support during the field work is also acknowledged.

Received 13 November 2015; revised accepted 21 September 2016

doi: 10.18520/cs/v112/i05/1028-1033