Journal of Indian Geomorphology
Volume 4, 2016 ♦ ISSN 2320-0731
Indian Institute of Geomorphologists (IGI)

Flooding in the Confluence Zone of the Ajay and the Kunur Rivers, West Bengal: A Hydrogeomorphological Assessment

Suvendu Roy[1] and Biswaranjan Mistri[2]
[1]*Department of Geography, University of Kalyani, Kalyani-741235*
[2]*Department of Geography, University of Burdwan, Bardhaman-713104*
E-mail: suvenduroy7@gmail.com *(Corresponding author)*

Abstract: *The study investigates the major causes behind frequent flooding in the confluence zone of the Ajay and the Kunur rivers. Channel cross and long profiles are obtained from remote sensing and field survey. Hydrological parameters are calculated from channel geometry using empirical equations. Sub-basin level runoff analysis using Soil Conservation Service Curve Number method is applied to estimate discharge characteristics. Finally, subsurface basinal flow characteristics are also analysed. The results show that the flood here occurs because of an adverse combination of parameters. These include downstream narrowing of channels, sedimentation at the confluence, absence of dykes near it as well as sub-basinal landuse characteristics and subsurface flow conditions.*

Introduction

In this study, the term hydrogeomorphology, a combined term of hydromorphology and geomorphology, has been used for their potential approach to proper explanations of flood condition in any area. According to Vogel (2011), Hydromorphology is a sub-field of hydrology and it deals with the structure and evolution of Earth's water resources. It also addresses the origin and dynamics of water resource systems influenced by both natural and anthropogenic factors. Fluvial Geomorphology is also an integrated part of this discipline, because fluvial system is a component of hydrologic systems, and hydromorphology encompasses the field of geomorphology (Vogel, 2011). Hydrological regime indicates the quantity and dynamics of water flow, with connection to the groundwater bodies (Balestrini *et al*., 2004) and can be correlate them with flood events. Attributes like channel dimensions, planform, hydraulic gradient, carrying capacity etc. are other important parameters for analysing flood behaviour. Dynamic interactions between surface and sub-surface hydrology are the current focus areas of the hydrogeologists and geomorphologists for investigating flood events (Steiger *et al.* 2005). Channel confluences are critical components of drainage system geometry, and are points at which river morphology and hydrology can change drastically (Stevens *et al*., 1975). Study related to flood characteristics and their causes for any particular confluence zone of major flood prone rivers get less attention from researchers for its extremely complex behaviour (Mosley, 1976). The present paper reports a hydrogeomorphic study of flood characteristics in the confluences of the Ajay and the Kunur. Its main objective is to investigate main causes of flood generation in the confluence zone of the Ajay and the Kunur rivers.

Study area

In the present study, the confluence zone of the Ajay river and its tributary — the Kunur — have been selected for studying flooding characteristics (Fig. 1). The east flowing Ajay emanates from Sarwan block of Deoghar district in the Chhotanagpur plateau and meets the river Bhagirathi at Katwa (Jain *et al*., 2007). The river traverses some 299 km over three different lithological zones. In the upstream region, it passes through the Archaean gneissic complex for about 195 km, over the patches of Gondwana sedimentary rocks for the subsequent 32 km and over the quaternary sediments for the rest of its course (Bhattacharya, 1972). The catchment area of the river is long and narrow. The slope of the main river is flatter than that of the tributaries and the slope in the plain of West Bengal in much flatter than that in its upper reaches. The river is a meandering one with variable widths ranging from ~1,200 to 125 m. The average discharge of the river is about 10,000 cusecs during the rainy season (Bhattacharya, 1972). The Ajay covers about 253 km of its total length up to the confluence point with the Kunur. The 5th order Kunur is one of the important right bank tributaries of the Ajay, which covers 33% area of total lower Ajay basin between 131 and 20 m. Landsat 8 OLI image of 26 April, 2013 (path 139, row 44) indicates that the landuse/landcover of the basin includes farmlands (41.74%), forests (31.35%), water bodies (10.35%), settlements (13.82%) and of barren land or unsuitable areas for agriculture (2.73%).

Central Ground Water Board (2014) stated that the majority part of the Kunur basin is covered by laterite aquifer (58%), which is concentrated in the upper part of the basin with least yield capacity of 20–60 m^3 day^{-1}. The lower portion of the basin is covered by alluvial aquifer (38%) with high yield. The upper edge of the basin consists of patches of sandstone, shale and fine-grained siltstone with coal seams. The report has also mapped an eastward subsurface flow in this region with electric conductivity of 500–2000 μS cm^{-1}. For the present work, channel characteristics of the Ajay from Pandaveswar to its confluence with Kunur is also taken into consideration besides the Kunur Basin (Fig. 1)

Previous works

There are several studies on the topic of flood and its characteristics in the lower Ajay Basin (AB). Mukherjee (1985) stated that the confluence zone of the Ajay and the Kunur in the lower AB have experienced nine to ten major floods in 17 years (1959–1975). Choudhuri (1995) indicated that the lower reaches of the Ajay and the Kunur are frequently inundated during the rainy season for their incapability to accommodate

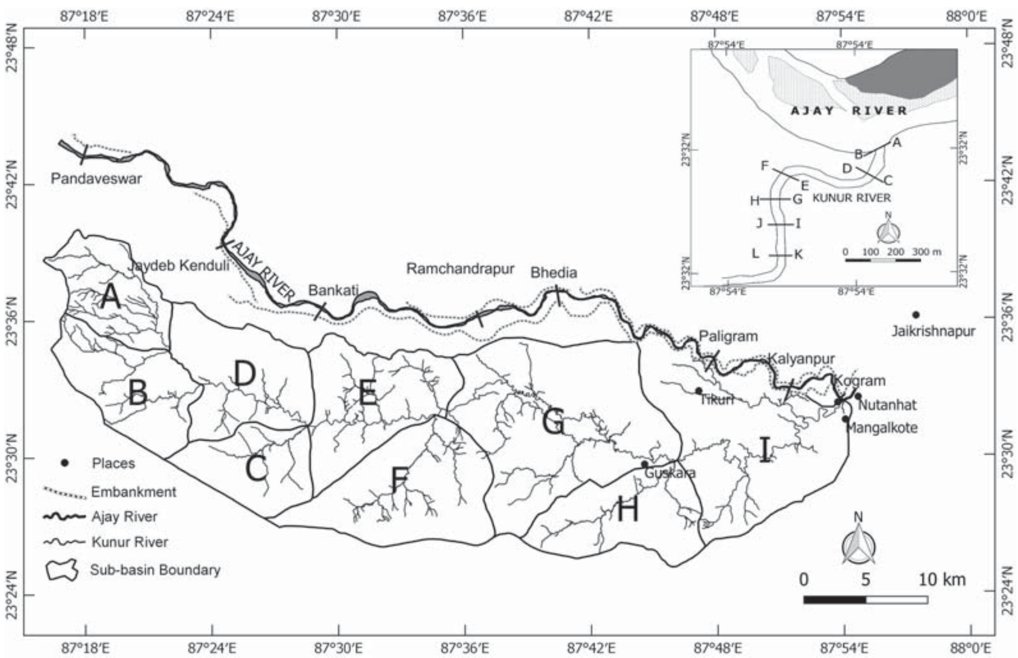

Figure 1. Location map of the study area showing Kunur sub-basins and location of profiles across the Ajay. The inset shows the position of cross profiles close to the outfall of the Kunur.

discharge due to sedimentation in the riverbed. Mukhopadhyay (2010) reported flood dynamics and related problems in the lower AB and pointed that embankments on both the banks of lower Ajay is one of the major factors for flood generation in the area. During 18th and 19th century normal floodwater used to remain within the embankments because the channel of Ajay was deeper than the present. Mukherjee (2002) and Mukhopadhyay (2010) discussed spatial and temporal variations of flood in the area under review. The present study area within the lower AB falls under high or severe flood prone area (Mukhopadhyay, 2010; Molla, 2010). Other important causes of flood in the study area are breaching of embankment (Mukhopadhyay, 2009 and 2010), discontinuous embankment (Molla, 2011; Roy and Dutta, 2012) and topographical depression in the right bank of the Ajay (Roy, 2012). All the previous studies have mainly focused on spatial and temporal scale analyses of floods and its impact on the local riverine landscape. Fundamental causes of the flood in the lower AB are less studied. The factors such as the role of groundwater flow, depth of groundwater table, land use pattern and runoff characteristics of catchment areas are significant factors of flood generation, which need detailed investigation.

Methods and materials

For fluvio-geomorphological analysis, channel dimension based calculations are used. Fourteen cross-sections have been obtained for both the rivers (Ajay: 8, Kunur: 6). 30-m ASTER DEM in conjugation with 15-m Landsat 8 OLI Band 8 data of 26 April 2013 (path 139, row 44) have been used for obtaining the cross-sections of the Ajay. In case of the Kunur, field measurements have been carried out for cross-sections and longitudinal profile with the help of Auto Level.

The shape of the open channel (rectangular, circular, semi-circular, trapezoidal, and triangular) is an important dimension for the channel morphological analysis. The channel of the Kunur is trapezoidal. A trapezoidal open channel cross section is shown in the Fig. 2a along with the parameters used to specify its size and shape. These parameters are b, the bottom width; B, the width of the water surface; l, the wetted length measured along the sloped side; y, the water depth; and α, the angle of the side slope from the vertical.

The hydraulic radius for the trapezoidal cross-section is often expressed in terms of water depth, bottom width, and side slope (y, b, and z) as follows.

Area of the trapezoid = Cross-sectional area (A) = y(b+B) /2=(y/2)(b+B). ...... Eq. 1

The wetted perimeter (P) for the trapezoidal cross-section has been calculated using the equation (P = b + 2l), and hydraulic radius (Rh) of a trapezoidal cross-section is calculated with the equation (Rh = A/P). In order to estimate bankfull discharge of the Kunur, Manning's equation has been applied. According to Chow (1964), Barnes (1967), Benson and Dalrymple (1967), Limerinous (1970), Jarrett (1985) and Summerfield (1991), Manning's method is an accurate and reliable method of discharge estimation for any river, where there is limited scope for field measurement and data availability. The velocity of stream flow is influenced by the gradient, roughness and cross-sectional form of the channel (Knighton, 1984). Manning's equation defines the mean flow velocity (v) as;

$v=k(R^{2/3}h \times s^{1/2}) /n$ Eq.2

where, k is a dimensionless constant (=1 in metric units and 1.46 in English units), Rh is the hydraulic radius (defined as the cross-sectional area divided by the wetted perimeter, but commonly approximated by mean channel depth), s is the longitudinal slope, and n is Manning's roughness coefficient, which is a dimensionless number that defines the flow resistance of a unit area of bed surface (Manning, 1891; Bloom, 2009). The Manning's roughness coefficient (n) is usually estimated from a table given by Chow (1964) or by comparing photographs illustrating channels of known roughness (Simons and Richardson, 1963) (Fig. 2b).

For hydromorphological assessment, several literatures based on hydrogeology, maps, groundwater flow diagram and borehole data have been collected. Runoff characteristic of any basin is an important parameter for basin-scale flood analysis. To estimate the spatial variation of runoff in the Kunur Basin, Soil Conservation Service (SCS) curve number method has been applied here individually for the nine sub-basins (A-I) (Fig. 1). The SCS curve number method is a simple, widely used and efficient method for determining the approximate amount of runoff from a rainfall event over a particular area. For drainage basins where no runoff has been measured, the Curve Number Method can be used to estimate the depth of direct runoff from the rainfall depth (USDA, 1999). The SCS Curve Number Method is originally developed by the Soil Conservation Service (1964, 1972) for conditions prevailing in the United States (Chow, 1964). The following equation is used to calculate the direct runoff from any ungauged basin:

$Q=(P-0.2S)^2 / (P+0.8S)$ Eq.3

where, Q is estimated direct runoff (mm), P is maximum storm rainfall within a day

Figure 2. (a) Trapezoidal channel cross-section of the Kunur. (b) Bed-forms of the Kunur.

(mm) and S is the potential maximum retention. S is calculated from CN value by the relationship:

$$S = (25400/CN) - 254) \text{.........Eq.4}$$

here, CN value can be computed from Chow (1964). This method requires one-day storm rainfall data, hydrological soil characteristics and land use/land cover pattern of the studied region. In the present work, daily rainfall data of September 2000 (a major flooding year in the lower AB) have been collected from River Research Institute of Kolkata, for Ilambazar gauge station (five kilometres upstream from the study area). For hydrological soil characteristic of the Kunur basin, soil texture map (2001) of Bardhaman district is collected from National Bureau of Soil Survey and Land Use Planning, Kolkata, and for the land use/land cover information, Landsat 8 OLI image of 26 April, 2013 (path 139, row 44), has been processed by ArcGIS v.9.3.

Results and discussion

For proper understanding of the dynamics of flood in the confluence zone, both the rivers must be taken into consideration (Stevens *et al.* 1975). The channels of the Ajay and the Kunur have been taken separately for analysing the role of their channel geometry on flood generation in the confluence zone. The hydromorphological characteristics of the surrounding area of the confluence zone have also been taken into consideration.

Fluvio-geomorphological aspects and flood

CHANNEL CHARACTERISTIC OF THE AJAY RIVER: From the numerical data of eight cross-sections of the Ajay in the upstream direction up to Pandaveswar from the confluence point, an important anomaly of channel geometry is found. In general, width of any natural river increases downstream for containing increasing discharge (Leopold and Maddock, 1953; Knighton, 1987). However, in the case of the Ajay, channel width decreases in the downstream direction (Table 1). Depth of the Ajay channel is also in a complex situation, because it has no clear relationship with channel width ($r = 0.14$). Ideally, there should be a negative relation between them (Leopold *et al.*, 1964). Channel bed is incised at some places below Pandaveswar, because of insufficient channel area to contain huge floodwater due to placement of embankments.

Most monsoon floods have the ability to alter floodplain and channel morphology in a significant way (Kale, 2003). Several breaching points are also developed during these floods because of low channel width and high unit stream power. Baker and Costa (1987), in their worldwide empirical work related to estimation of average unit stream power at a cross-section (alluvial), pointed out that channel width is inversely related to the power per unit area. As a result, in the Ajay, decreasing downstream width escalated chance of bank erosion and embankment breaching. In the confluence zone near Kogram, the width of the Ajay is just 221 metres. This makes the site most vulnerable in the lower AB. Normally, there should be a negative correlation between 'distance from confluence' and 'channel width' (Leopold and Maddock, 1953; Knighton, 1987). However, in the study area there is a strong positive correlation between them ($r = 0.91$) and there is no relation between 'distance from confluence' and 'channel depth' ($r = -0.06$). High value of width-depth ratio indicates presence of large floodplain area (Rosgen, 1994). In the study area, it is very low as compared to upstream cross-section sites. As a result, the study area is prone to floods.

The major cause behind the above anomalies is the existence of embankments on both banks of the Ajay for a long period of time. The total length of the embankments is about 136.16 km, out of which the right bank accounts for about 80.97 km and left bank comprises about 55.19 km (Mukhopadhyay, 2010; Molla, 2010). Due existence of these embankments, riverwater cannot spill over during flood event and consequently suspended sediment gets silted on the river bed after fall in floodwater velocity. Gradually, the river bed is raised and fails to contain the flood volume, thereby increasing flood frequency and magnitude.

In the confluence zone of the Ajay and the Kunur, river bed sedimentation problem is clearly identified from the temporal increase in floodwater level at Natunhat gauge station (Fig. 3). Due to discontinuity of right bank embankment (after Kogram village there is no embankment up to Jaikrishnapur village), huge volume of entrapped floodwater suddenly gets released through the gap and quickly spread over the confluence point and its surroundings area in Mangalkote block of Bardhaman district. Major source of this sediment is eroded material from the Kunur basin, with an average erosion rate of 47.61 kg ha^{-1} y^{-1} (Roy, 2013). Due to this, a natural barrier for the Ajay's flow is formed which restricts free flow of water and results in flooding (Fig. 4).

CHANNEL CHARACTERISTIC OF THE KUNUR RIVER: Table 2 shows the relation between of channel geometry and bankful discharge of the Kunur. Like the Ajay, there are several channel dimensional anomalies for the Kunur. Six cross sections near the confluence of the Kunur channel show that channel width (B), cross-section area (A) and carrying capacity gradually decrease towards the confluence (Table 2). As a result, the lower Kunur fails to contain the monsoon discharge and generates flood in the confluence zone. The longitudinal profile of the Kunur also shows that the rise in channel bed near the confluence creates an obstruction for the flow, which is more than 150 m^3s^{-1} during peak discharge (Roy and Mistri, 2013). In addition, flood water of the Ajay enters into the Kunur channel and accentuates flooding in the confluence zone (Fig. 4).

Connection with groundwater flow

Hydrogeologically the study area is

Table 1. Channel dimensions of the Ajay from Pandaveswar to Kogram

Cross-section Site	**Elevation** (m)	**Distance from confluence** (km)	**Channel width (w)** (m)	**Maximum depth (d)** (m)	**Width-depth ratio** (w/d)
Pandaveswar	65	130.28	1026	11.89	86.29
Jaydeb Kenduli	59	111	719	10.51	68.41
Bankati	58	106.27	518	9.39	55.17
Ramchandrapur	50	85.12	345	8.58	40.21
Bhedia	44	77.08	473	7.02	67.38
Paligram	36	59.42	273	11.48	23.78
Kalyanpur	29	50.31	316	10.68	29.59
Kogram	27	44.34	221	11.78	18.76

Note: 1. Cross section at the outlet of the Kunur; 2. Cross section at Natunhat–Guskara road bridge

Table 2. Channel dimensions of the Kunur from confluence point (A-B) to upstream direction (source: field survey, 2012)

Cross-section Site	**Elevation** (m)	**Distance from confluence** (km)	**Channel width (w)** (m)	**Maximum depth (d)** (m)	**Width-depth ratio** (w/d)
Pandaveswar	65	130.28	1026	11.89	86.29
Jaydeb Kenduli	59	111	719	10.51	68.41
Bankati	58	106.27	518	9.39	55.17
Ramchandrapur	50	85.12	345	8.58	40.21
Bhedia	44	77.08	473	7.02	67.38
Paligram	36	59.42	273	11.48	23.78
Kalyanpur	29	50.31	316	10.68	29.59
Kogram	27	44.34	221	11.78	18.76

characterised by unconsolidated materials (85% granular materials within the 185 metres borehole depth at Tikuria, Mangalkote, Fig. 5a) and high groundwater potentiality. The average fluctuation of groundwater table between pre-monsoon and post-monsoon is 6 m, as per State Water Investigation Directorate (SWID) data of 2004. Niyogi (1985) had prepared a groundwater flow direction map of the study area for pre-monsoon and post-monsoon seasons with two cross sections (Fig. 5b). These cross profiles clearly indicate that the Ajay plays an important role for subsurface discharge scenario with development of a deep groundwater 'trough'. As a result, the Kunur behaves like an influent stream and gets recharged by subsurface flow from the Ajay basin. Therefore, channel bed of the Kunur remains saturated all through monsoons and aid flooding. During the winter 'boro' paddy cultivation, farmers draw water from a number of wells dug in its channel (Fig. 5c), which increases hydraulic gradient (Todd and Mays, 2005; Raghunath, 2013) towards the Kunur and helps to direct more subsurface flow into it.

SCS curve number method and direct runoff estimation (sub-basin wise)

Nature of water loss due to infiltration and rate of runoff generation are the prime controllers of basin hydrology (Wagener *et*

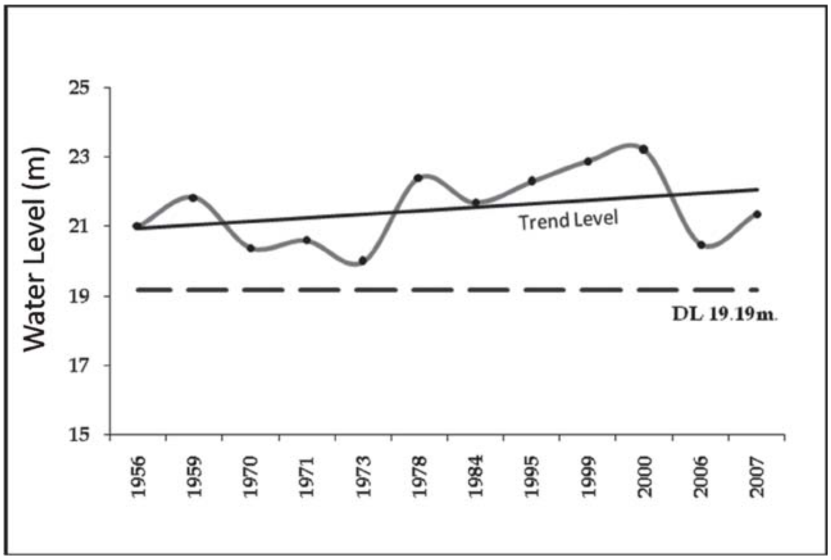

Figure 3. Water level of the Ajay at Natunhat gauge station during past major floods. DL: Danger Level. Source: Irrigation and Waterways Directorate, Mayurakshi South Canal Division, Govt. of West Bengal, 2010

al., 2004). To analyse the flood characteristics of any basin, it is very important to know how the basin surface responds to rainfall event. Rate of infiltration, surface water retention capacity, direct runoff amount, etc are the vital indicators of basin flood analysis (Grayson and Moore, 2005). For the Kunur basin, SCS curve number method has been used to quantitatively estimate the influence of these indicators and their spatial variation. It has been observed that in the confluence zone (Sub-basin I of Fig. 1), maximum retention capacity (S) is lower (25.12 mm) and the amount of direct runoff is higher (133.36 mm) than the other sub-basins (Table 3). The sub-basin I is also entirely under agricultural use with very high CN value (91). These factors support to generate a high overland flow of

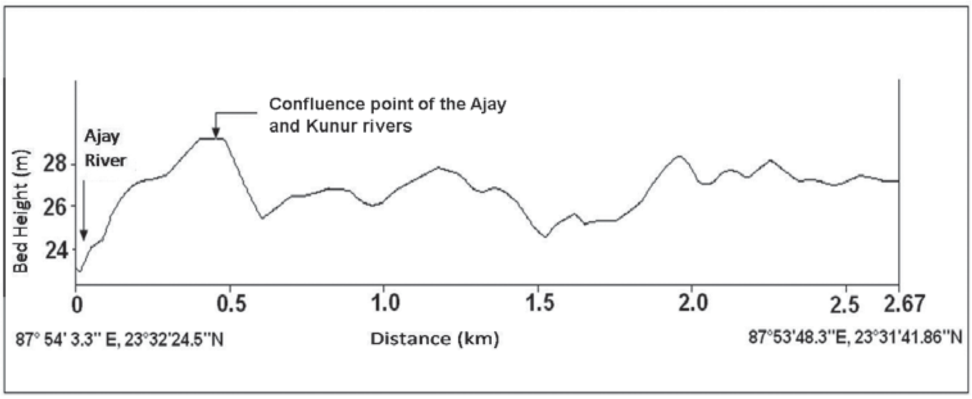

Figure 4. Longitudinal profile of the Kunur at the confluence zone. Source: field survey

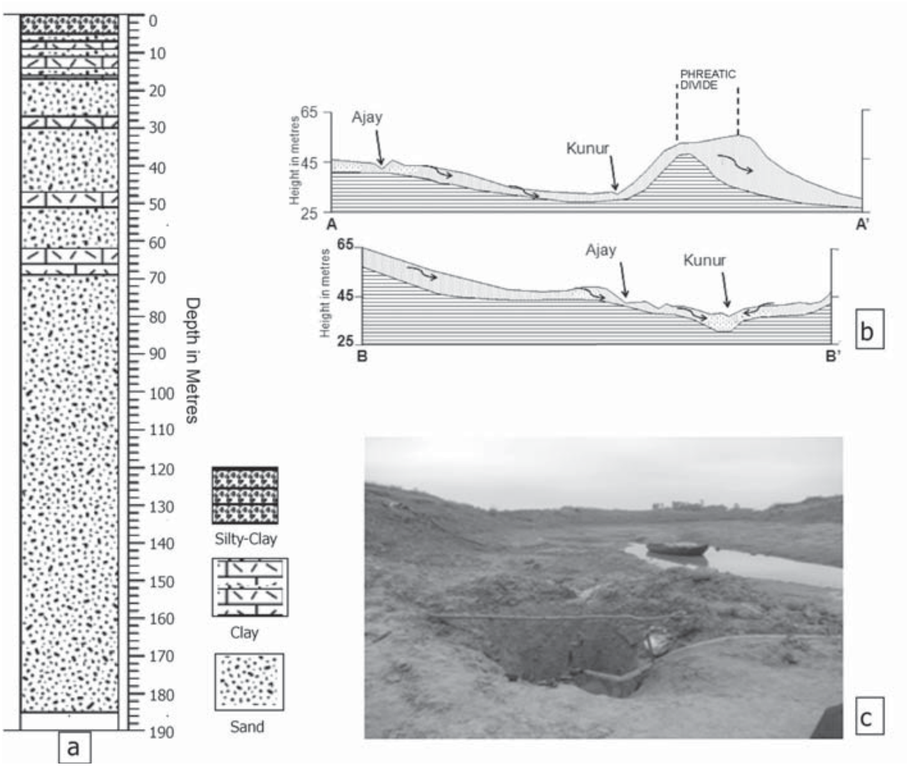

Figure 5. (a) Lithological characteristics of the study area at Tikuri. Source: State Water Investigation Directorate, 2004. (b) Subsurface profile and groundwater flow near the confluence zone. Source: Niyogi, 1985. (c) Well in the Kunur channel

Table 3. Runoff characteristic of nine sub-basin of the Kunur during a storm event on 19th September 2000, using SCS curve number method.

Sub-Basin	Area (km^2)	Hydrological soil types (with area in per cent of total and land use type)	Weighted CN Value	S (mm)	P (mm)[1]	Q (mm)	Per cent of total rainfall
A	58.75	B (61.34/P),C (38.66/P)	81.71	56.86	160	107.5	67.19
B	74.77	A (30.23/I),B (13.67/P),C (56.10/P)	76.8	76.73	160	94.52	59.08
C	58.1	C (89.31/TF),D (10.69/A)	77.43	74.04	160	96.16	60.1
D	87.11	B (3.18/P),C (96.82/DF)	70.28	107.41	160	78.02	48.76
E	113.28	C (73.05/DF),D (26.95/A)	75.66	81.71	160	91.57	57.23
F	92.89	C (98.23/DF),D (1.77/A)	70.37	106.95	160	78.24	48.9
G	191.27	C (53.35/A),D (46.65/A)	89.4	30.12	160	128.78	80.49
H	79.15	C (14.80/A),D (85.20/A)	90.56	26.48	160	132.09	82.56
I	160.31	D (100/A)	91	25.12	160	133.36	83.35

Note: 1. Rainfall on 19 September 2000 (River Research Institute, Kolkata)
P: Pasture land, I-Industrial area with 72% impervious land, TF: Thin forest cover, DF: Dense forest cover, A: Agricultural land

83.35% from 160 mm rainfall, augmenting the discharge in the lower part of the Kunur. In contrast, in sub-basins D, E, and F, water retention capacity is high due to presence of forest cover.

Conclusions

This work helped to understand the relevance of channel morphology and hydromorphological parameters in flood analysis in the Kunur-Ajay confluence zone. The flood here is caused due to a combination of factors. These include downstream constriction of channels, siltation at the confluence zone, non-existence of embankments in a crucial stretch, subsurface flow conditions and landuse characteristics.

Acknowledgements

The authors would like to thank Sadhan Mallik and Subhankar Bera, ex-students of University of Burdwan, for their contribution during data collection. Department of Geography, University of Burdwan, provided the instrumental support. Helpful suggestions received from the anonymous reviewer is also acknowledged.

References

Baker, V.R. and Costa, J. E. (1987) Flood power. In: Mayer L. and Nash D. (eds), *Catastrophic Flooding*, Allen and Unwin, London: 1–21.

Balestrini, R., Cazzola, M. and Buffagni, A. (2004) Characterising hydromorphological features of selected Italian rivers: a comparative application of environmental indices. *Hydrobiologia*, 516: 365–379.

Barnes, Jr., H.H. (1967) Roughness characteristic of natural channels. *U.S. Geological Survey Water-Supply Paper* 1849.

Benson, M. A., and Dalrymple, T. (1967) General field and office procedures for indirect discharge measurements, *Techniques of Water-Resources Investigations*, U.S. Geological Survey, Book 3, Chapter A-1.

Bloom, A.L. (2009) *Geomorphology, a Systematic Analysis of Late Cenozoic Landforms*, 3rd Ed, PHI Learning Private Ltd., New Delhi: 482p.

Choudhuri, J. (1995) *The History and Culture of Barddhaman District* (in Bengali). Pustak Bipani, Kolkata: 202–209.

Chow, V.T. (1964) *Handbook of Applied Hydrology*, McGraw-Hill, New York: 588p.

Grayson, R. B. and Moore, I. D. (2005) Effect of land-surface configuration on catchment hydrology. In: Parsons, A.J. and Abrahams, A.D. (eds) *Overland flow: Hydraulics and Erosion Mechanics*, Routledge, New York: 137–163.

Jarrett, R.D. (1985) Determination of roughness coefficients for streams in Colorado. U.S. *Geological Survey Water Resources Investigations Report*: 85–400.

Kale, V.S. (2003) Geomorphic effects of monsoon floods on Indian rivers. *Natural Hazards*, 28: 65–84.

Knighton, A.D. (1984) *Fluvial Forms and Processes*, 1st Ed, Edward Arnold, Sheffield: 215p.

Knighton, A.D. (1987) River channel adjustment: The downstream dimension. *River Channels: Environment and Process*, Basil Blackwell, Oxford: 95–128

Leopold, L.B. and Maddock, T.J. (1953) Hydraulic geometry of stream channels and some physiographic implications. *U. S. Geological Survey Professional Paper*, 252: 55 p.

Leopold, L.B., Wolman, M.G. and Miller, J.P. (1964) *Fluvial Processes and Geomorphology*, 1st Ed, Freeman and Co., San Francisco: 521p.

Limerinos, J.T. (1970) Determination of the manning coefficient from measured bed roughness in natural channels. *U.S. Geological Survey Water-Supply Paper* 1898-B.

Manning, R. (1891) On the flow of water in open channels and pipes. *Transactions of the Institution of Civil Engineers of Ireland*, 20: 161–207.

Molla, H.R. (2010) Delineation and zonation of flood prone area of lower Ajoy river basin. *Practising Geographer: Journal of the Indian Geographical Foundation*, 14(2): 63–70.

Molla, H.R. (2011) Embankment and changing micro-topography of lower Ajoy basin in eastern India. *Ethiopian Journal of Environmental Studies and Management*, 4(4): 50–61.

Mosley, M.P. (1976) An experimental study of channel confluences. *The Journal of Geology*, 84(50): 535–562.

Mukherjee, M. (2002) *Flood of Lower Ajoy Basin: A Spatio-temporal Analysis Since Independence*. Unpublished Thesis, Department of Geography, Visva-Bharati University, Santiniketan: 250p.

Mukherjee, S. (1985) Floods in West Bengal (A Spatial and Temporal Analysis). In: Chatterjee, S. P. (ed) *Geographical Mosaic- Professor K.G. Bagchi felicitation Volume*, Manasi Press, Calcutta: 262–271.

Mukhopadhyay, S. (2009) Sand Splay as a disaster in the lower Ajay River basin of eastern India. *Eastern Geographer: Journal of Eastern Geographer Society*, 15: 51–56.

Mukhopadhyay, S. (2010) A Geo-environmental assessment of flood dynamics in lower Ajoy river including sand splay problem in eastern India. *Ethiopian Journal of Environmental Studies and Management*, 3(2): 96–110.

Niyogi, M. (1985) Ground water resource of the Ajay Basin. In: Chatterjee, S. P. (ed) *Geographical Mosaic: Professor K.G. Bagchi felicitation Volume*, Manasi Press, Calcutta: 165–182.

Raghunath, H.M. (2013) *Hydrology: Principal, Analysis, Design*, Reprint of 2nd Ed, New Age International (P) Ltd., Kolkata: 463p.

Rosgen, D. L. (1994) A classification of natural rivers. *Catena*, 22: 169–199.

Roy, S. and Mistri, B. (2013) Estimation of peak flood discharge for an ungauged river: A case study of the Kunur river, West Bengal. *Geography Journal*, 2013, Article ID 214140, 1-11. , DOI: http://dx.doi.org/10.1155/2013/214140

Roy, S. (2012) Spatial variation of floods in the lower Ajay River Basin, West Bengal: A geo-hydrological analysis. *International Journal of Remote Sensing and GIS*, 1(2):132–143.

Roy, S. (2013) Generating Iso-Erosion Rate Zones for the Kunur River Basin Using Combine Methods of Soil Erosion Estimate. *International Journal of Geology, Earth & Environmental Sciences*, 3(2): 77–89.

Roy, S. and Dutta, S. (2012) Role of embankment in Flood: A study in the confluence zone of Kunur and Ajay rivers, lower Ajay river basin, West Bengal. *Indian Streams Research Journal*, 2(9): 1–7.

Simons D. B. and Richardson, E. V. (1963) Forms of bed roughness in alluvial channels. *Transactions of the American Society of Civil Engineers*, 128: 289.

Soil Conservation Service (1964) *National Engineering Handbook*, Section 4: Hydrology, Department of Agriculture, Washington, 450p.

Soil Conservation Service (1972) *National Engineering Handbook*, Section 4: Hydrology, Department of Agriculture, Washington, 762 p.

Steiger, J., Tabacchi, E., Dufour, S., Corenblit, D. and Peiry J.L., (2005) Hydrogeomorphic processes affecting riparian habitat within alluvial channel-floodplain river systems: A review for the temperate zone. *River Research and Applications*, 21: 719–737

Stevens, M.A., Simons, D.B., and Richardson, E.V. (1975) Nonequilibrium river form. *Journal Hydraulics Division*, American Society for Civil Engineers, 101(HY5): 557–565.

Summerfield, M.A. (1991) *Global Geomorphology: An Introduction to the Study of Landform*, 1st Ed, Pearson Education, Edinburgh: 537p.

Todd, D.K. and Mays, L.W. (2005) *Groundwater Hydrology*, 3rd Ed, John Wiley & Sons, New York: 636p.

United States Department of Agriculture, Natural Resource Conservation Service, and National Employee Development Centre (1999) *SCS Runoff Equation: Module 205*. Engineering and Hydrology Training Series, 1–27.

Vogel, R.M. (2011) Hydromorphology. *Journal of Water Resources Planning and Management*, 137(2): 147–149.

Wagener, T., Wheater, H.S. and Gupta, H.V. (2004) *Rainfall-Runoff Modelling in Gauged and Ungauged Catchments*, 1st Ed, Imperial College Press, London: 306p.

Date received: 08 February 2014
Date accepted after revision: 26 December 2015