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TECHNICAL ARTICLE

Alteration of Surface Water Hydrology by Opencast Mining in the Raniganj Coalfield Area, India

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Abstract Surface excavation and overburden dumping in the Raniganj Coalfield have defaced the natural topography and impacted the hydrology. Excavation and dumping of overburden within the channels has obstructed streamflow and altered water availability in the lower parts of small catchment basins. The surface drainage paths of ephemeral channels and flow accumulation by channel networks was estimated from digital elevation remote sensing images using Arc Hydro Tools of Arc GIS software. The runoff from small basins was estimated using the US Soil Conservation Service Curve Number method and initial abstractions (depression storage) were estimated from CARTOSAT DEM satellite images using GIS techniques. In the studied area, 129 depressions (abandoned and working mines) were identified within 53 small basins over an area of more than 24 km^2. The excavated areas arrest surface runoff, leading to degradation of downstream channels.

Keywords Initial abstraction · River obstruction · Runoff contributing area · Runoff discharge · Small catchment basin

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Introduction

In India, 60 % of the total mineral production is from surface mines, hereinafter referred to as opencast mines. The Raniganj Coalfield has been one of the most important sources of coal in India for more than 200 years. Opencast mines in the Raniganj Coalfield began production where coal seams cropped out, much earlier than underground mines (Melnikov and Chesnokov 1969). During India's pre-nationalization period (before 1972–1973), numerous small mines were excavated and left unreclaimed. Opencast mining has increased since then. In the Raniganj Coalfield, most (76.1 %) of the coal is still produced by opencast mining [Eastern Coalfield Limited (ECL) 2011]. In comparison to underground coal mining, opencast mining has the advantages of full-scale mechanization, high output per man-shift, low unit cost, etc. Twenty-four opencast mines currently operate in the Raniganj Coalfield (Eastern Coalfield Limited 2013).

In the Raniganj Coalfield, 2.54 million m^3 of overburden is removed for every million t of coal produced by opencast mining (Eastern Coalfield Limited 2011). In addition, according to Ghosh (1990), every million t of coal extracted in India by opencast mining damages a surface area of about 0.04 km^2. The altered topography affects surface hydrology through initial abstraction, or retention, of surface runoff, obstruction of small channels and reducing discharge to lower catchments. As the water moves towards lower elevations within a catchment, some water remains within open pits and blocked channels in the basin area, while the rest is discharged.

Younger and Wolkersdorfer (2004) aptly mentioned catchment-scale management of mine surface water as a way to reduce impacts from mining. Earlier studies widely used the US Soil Conservation Service (SCS) model (US

Soil Conservation Service 1972) for runoff prediction, storm water accounting, water resources management, and planning at the catchment scale (Hawkins 1993; Lewis et al. 2000; Ragan and Jackson 1980; Slack and Welch 1980). The relationship between rainfall and runoff from a catchment is very complicated, involving a number of interconnected variables. The SCS (1972) curve number (CN) is a popular method to estimate runoff depths from storm rainfall (Bhadra et al. 2006). Remote sensing data is now used as the basic information input for computing runoff using the runoff curve number (RCN) model, correlating generalized land cover with hydrologic soil groups and data derived from the SCS table (Chandra et al. 1984; Kumar et al. 1991; Ragan and Jackson 1980).

In India, Chandra and Sharma (1978) estimated flood discharge empirically in the Ramganga basin using LANDSAT remote sensing data. The RCN model was also used to estimate runoff from overburden mine spoil and over a reclaimed opencast mine surface (Ritter and Gardner 1991; Taylor et al. 2009). The model is attractive because the major input parameters are defined in terms of land use and soil type, which allows a user to experiment with alternate forms of land development and assess the impact that changes might have (Ragan and Jackson 1980). These models were originally developed to predict runoff volumes from agricultural fields and small watersheds. In this study, we have attempted to assess the alteration of surface hydrology by retention and diversion of surface runoff by excavations, and the reduction of water availability to the lower catchment caused by changes in the land surface in the Raniganj Coalfield.

Study Area

The Raniganj Coalfield is one of the richest coal deposits in India. The coalfield is bounded by the latitudes 23°22′ to 23°52′N and longitudes 86°36′ to 87°30′E. Most of the coalfield is sandwiched between the Ajay and the Damodar River, while small portions lie north of the Ajay River, south of the Damodar, and west of the Barakar River (Fig. 1). The coalfield extends over 1530 km^2 in the states of West Bengal and Jharkhand. More than 90 % of the Coalfield is mined by ECL; only a small area is mined by the Bharat Coking Coal Limited and the Indian Iron and Steel Company.

The area between the Ajay and Damodar Rivers was selected for the present study because intensive opencast coal exploitation is confined to this area (Fig. 1). To better understand the magnitude of the surface water alteration, the entire interfluve was divided into 53 micro-watersheds.

Materials and Methods

Selection of Micro-basins

For the convenience of analysis, the Ajay-Damodar interfluve was divided into 53 micro basins, based on the presence of opencast mines (working, abandoned or both). At first, micro-scale ephemeral channels were extracted (by calculating flow accumulation) from a digital elevation image (Carto-DEM 2008) using Arc Hydro Tool, an extension of Arc GIS Software (Fig. 2a). Small-scale catchment polygons (basin boundaries) were also processed in this way (Fig. 2b). Abandoned and working mines were identified and marked from Survey of India (SOI) Toposheets (1:50000, 1975-76), multiband Landsat thematic mapper (TM) images of 1990, 2000, 2005, and 2010, and multi-temporal Google Earth images from 2003 to 2013 (Manna and Maiti 2014). To estimate streamflow, Koltun and Whitehead (2002), classified rural unregulated basin characteristics into five categories: physical characteristics, location characteristics, hydrologic characteristics, land cover, and climate.

Estimation of Runoff Contributing Area of Excavations and Obstructed Channel Length in the Upper Catchment

Each excavated depression has a separate rainfall collection zone within its own small catchment basin. To calculate the volume of rain water that may be retained within each excavated depression, the runoff contributing area (RCA) of depressions was calculated. A total of 129 excavations were demarcated using the topographic contour (with 2 m intervals derived by interpolation from digital elevation CARTOSAT images) orientation (Fig. 3). Flow length of channel runoff in the upper catchment area that had been obstructed by the depression also was calculated and stored in an attribute table of channel length in the GIS platform (Fig. 3).

Calculation of Volume of Excavations

Satellite-based digital elevation data and co-registered ortho-images (Carto-DEM 2008), available at 1 arc-sec (i.e. 30 m) of resolution was used to analyse the magnitude of defaced topography. This image is able to provide elevation information of each pixel in Arc GIS software. Surface topography is represented by contouring (at 4 m intervals through interpolation) from the digital elevation image using surface analysis in GIS Spatial Analyst tools and Arc GIS software. The grid method (also known as the borrow pit method) was used with GIS software to plot a

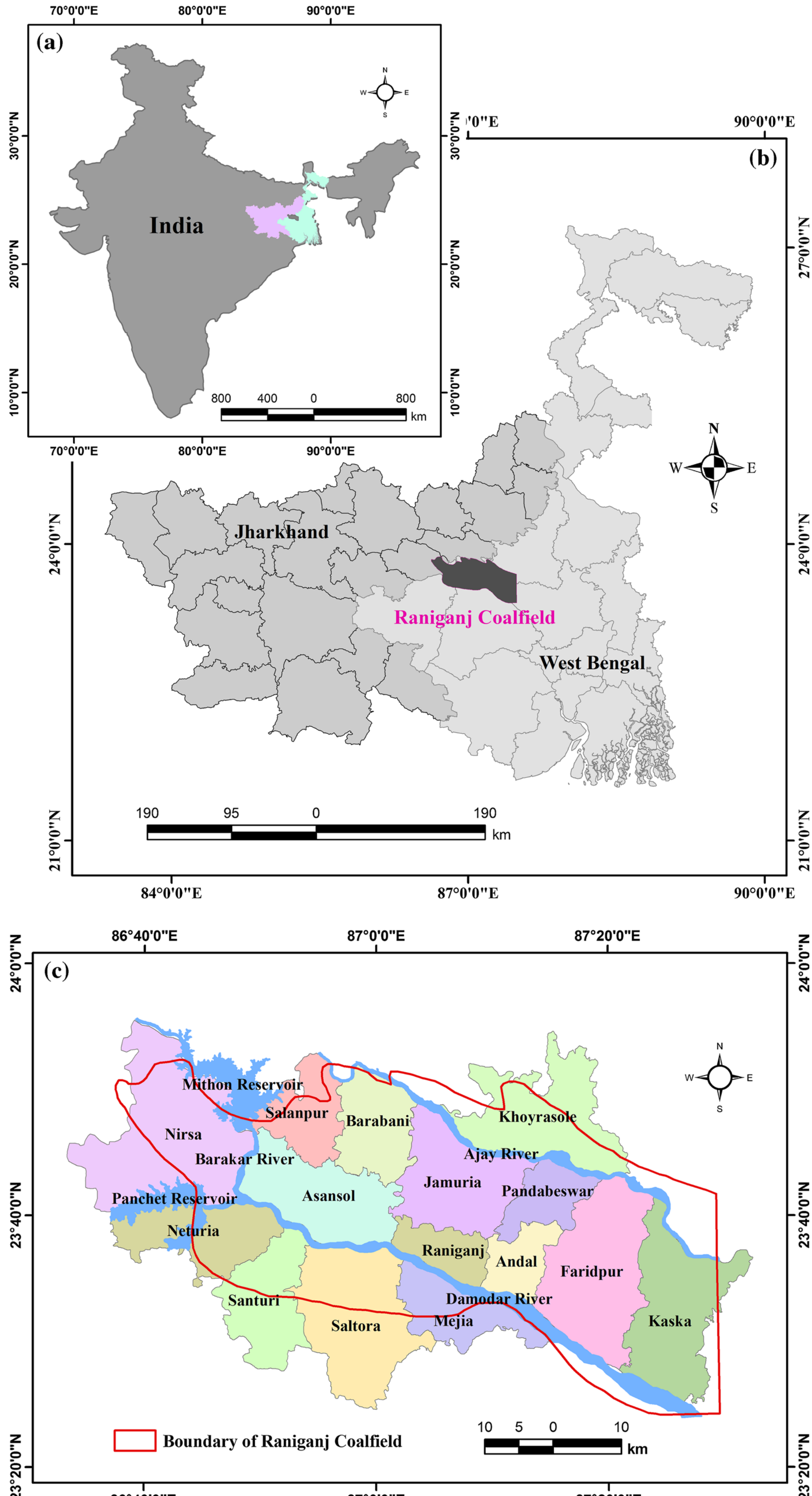


Fig. 1 Location of the study area; **a** India; **b** RCF in West Bengal and Jharkhand; **c** RCF in blocks of West Bengal and Jharkhand

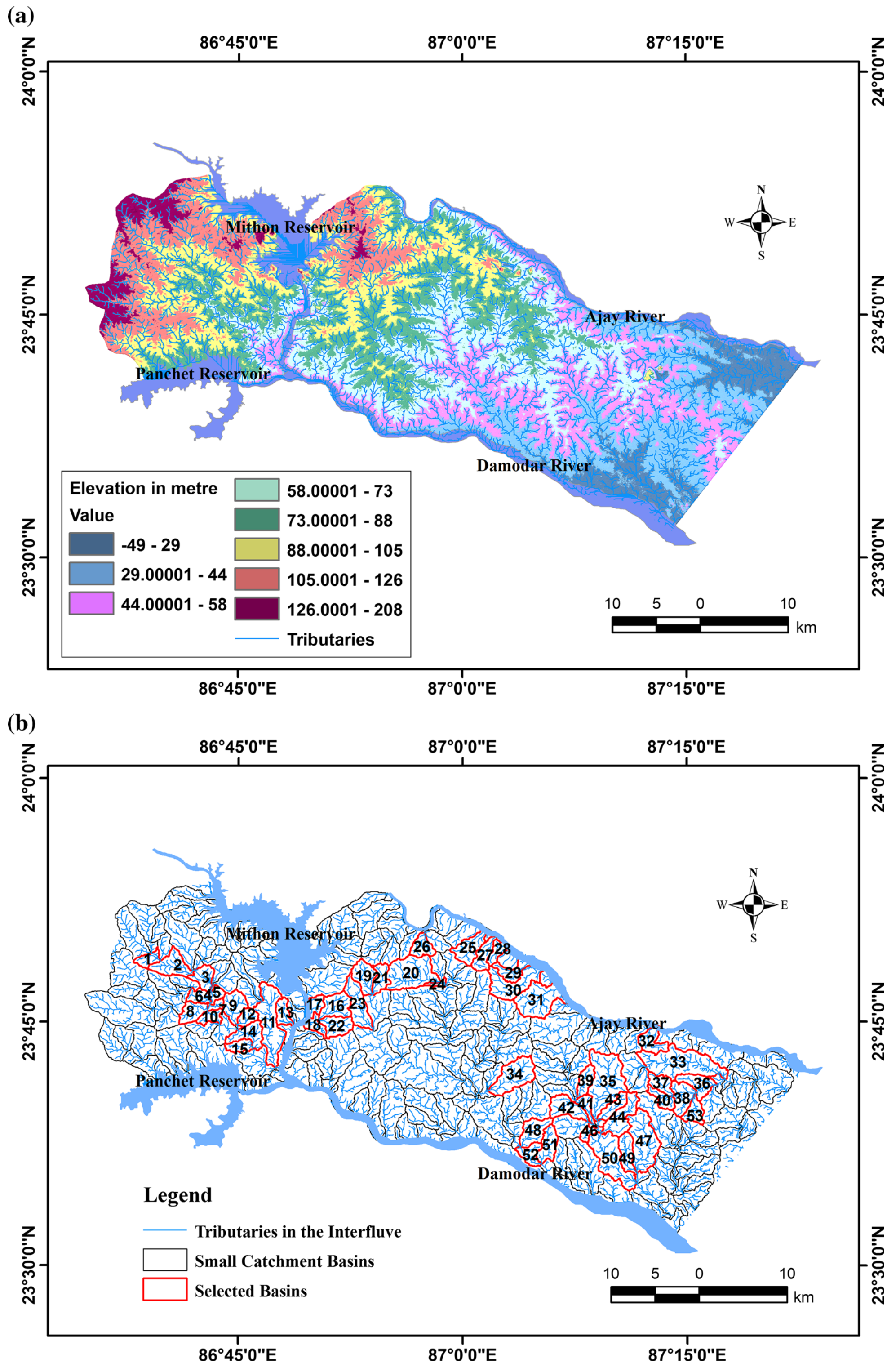


Fig. 2 **a** River channels derived from DEM image; **b** Small catchment basins derived from DEM image and Selected basins

100 m grid net and calculate the excavation volume by applying a grid to the excavation area.

$$V = [(D1 + D2 + D3 + D4 + Dn)/n)]A$$

where V is = volume (m^3), A is area (m^2 calculated from the grid), and D is depth of cut (m).

The Runoff Curve Number (RCN)

The RCN is a quantitative descriptor of the land and soil complex and is commonly assigned based on information acquired from field surveys and interpretation of aerial photograph or satellite imageries (Slack and Welch 1980).

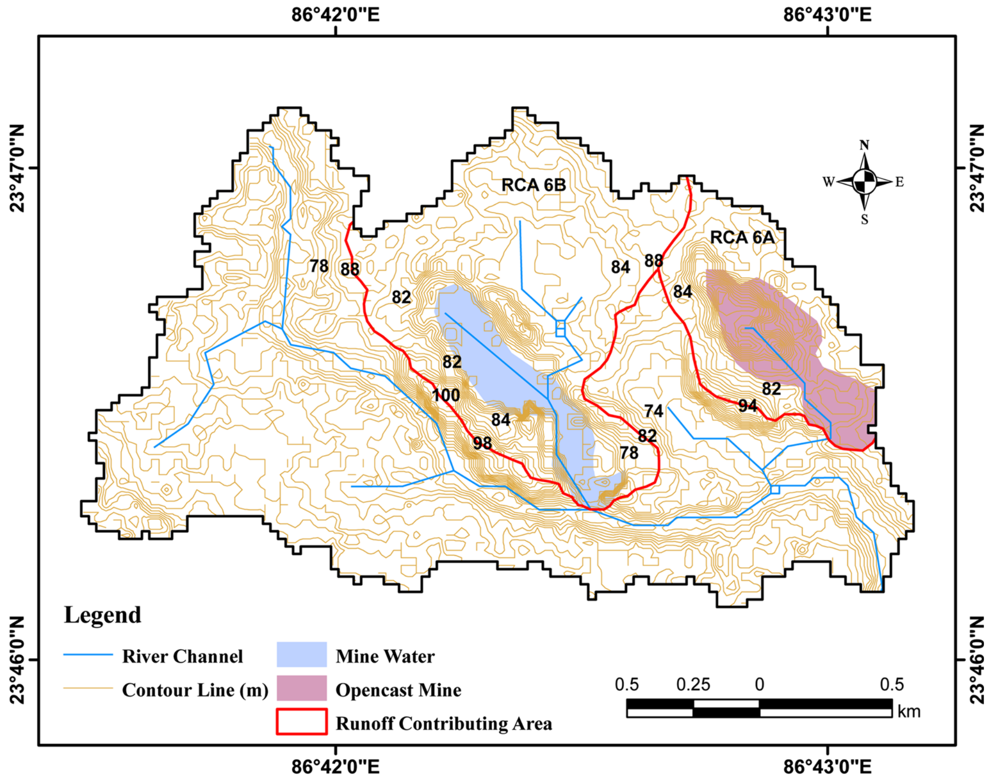


Fig. 3 Demarcation of Runoff Contributing Area (RCA) based on contour values and obstructed flow length of ephemeral channels

The RCN of a given soil—vegetation—land (SVL) complex in a specific antecedent moisture condition (AMC) takes on values from 0 to 100 (Table 1). This number is derived from the character of the soil and vegetation, including crops, and the land use of that soil as well as the intensity of land use. The unit of S (potential maximum retention) is inches or mm. When CN tends to 100, S tends to zero (in water-logged areas or in wet paddy fields).

Determination of Curve Number

The CN value is derived on the basis of the SVL and AMC complex. Determination of CN values requires the following data input: (A) land use land cover (LULC) class; (B) hydrologic soil groups; (C) hydrologic (draining) condition; and (D) AMC.

Land Use Land Cover

Land use, soil, and slope together give rise to surface runoff. In the SCS model (US Soil Conservation Service (1969, 1972), slope is ignored. The present study includes 17 types of land uses which can be categorized in nine broad groupings: vegetative cover, water bodies, agriculture, settlement, factory zone, mine pits, dumps, sand deposits and wasteland. Vegetative cover comprises dense, sparse, and scrub vegetation. Water bodies include small village ponds and flooded mine pits. Settlements include concentrated and sparsely settled areas. Dumps include spoil dumps and coal waste dumps. Mine pits are working opencast mines and areas of clay extraction for brick manufacturing. The detailed land use analysis was done on a plot to plot level for each micro-basin from the Google earth image, considering minute variations in land use practices along with analysing the IRS LISS-III satellite imagery and ground truthing from field verification (Fig. 4).

Hydrologic Soil Groups

Soil properties play an important role in estimating runoff. The four hydrological soil groups are hydrologic soil cover categories, which are used to estimate runoff from rainfall (US Soil Conservation Service 1969). The more that soil groups are compared with their land use categories, the better the result, but considering more soil groups and distributing land uses to those groups complicates the process. The influence of ground cover is treated independently—not in hydrologic soil groups. In this study, the basins as well as the sub-watersheds were categorized in different hydrological soil groups, based on the following criteria (Fig. 5).

- Hydrologic soil group A (low runoff potential): soils having high infiltration rates, even when thoroughly wet, consist chiefly of deep, well to excessively drained sands or gravels. The USDA soil textures normally

Table 1 Runoff curve number assigned to the land uses over hydrological soil groups (AMC II)

Landuse	Hydrological soil group with Run off curve number			
	A	B	C	D
Water bodies	100	100	100	100
Mine water	100	100	100	100
Opencast mine	0	0	0	0
Overburden Spoil dump (brush good)	30	48	65	73
Factory zone (urban industrial, 72 % impervious)	81	88	91	93
Settlement-65 % impervious	77	85	90	92
Settlement-30 % impervious	57	72	81	86
Scrub vegetation (wood–grass combination, fair)	43	65	76	82
Sparse vegetation (wood grass combination, poor)	57	73	82	86
Vegetation (wood fair, moderately dense)	36	60	73	79
Wasteland (fellow bare soil)	77	86	91	94
Agriculture poor	66	74	80	82
Extracted soil (fellow bare ground)	68	79	86	89
Brickfield (open space poor)	68	79	86	89
Sand deposition (open space good)	39	61	74	80
Coal waste dump (brush good)	30	48	65	73
Coal dump (fellow residue cover poor)	76	85	90	93

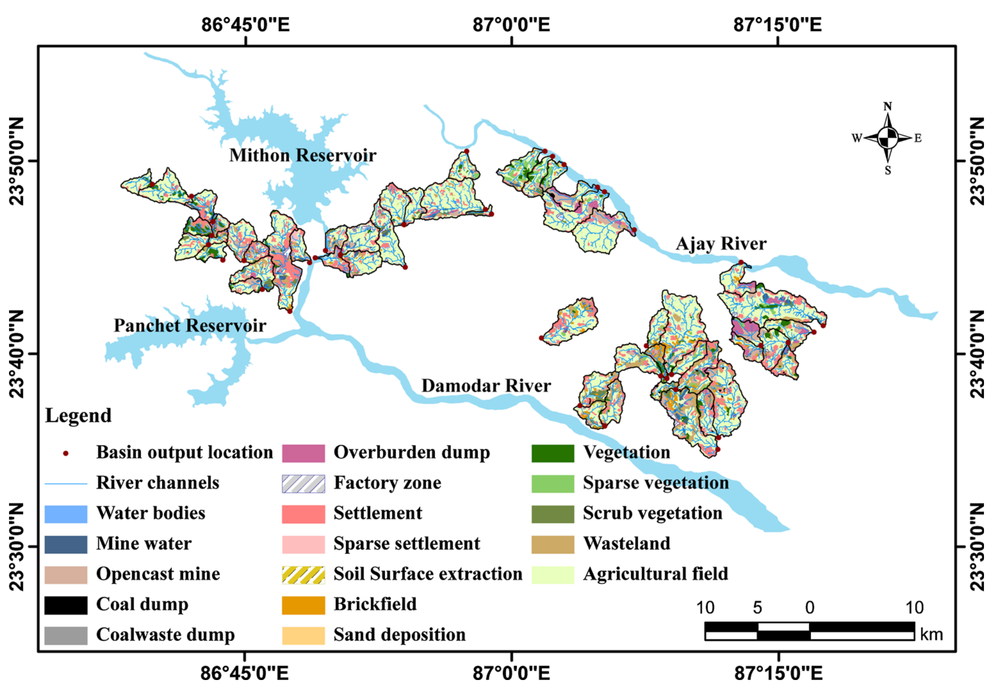


Fig. 4 Land Use Land Cover (LULC) map of the selected small catchment basins

included in this group are: sand, loamy, loamy sand, and sandy loam.

- Hydrologic soil group B (moderately low runoff potential): soils having moderate infiltration rates when thoroughly wet. The soil textures normally included in this group are silt loam and loam.
- Hydrologic soil group C (moderately high runoff potential): moderately well to well-drained soils with moderately coarse textures. The soil texture normally included in this group is sandy clay loam.
- Hydrologic soil group D (high runoff potential): soils with very slow infiltration rates when thoroughly wet, consisting chiefly of clay soils with a high swelling potential and a perched water table. The soil textures normally included in this group are clay loam, silt clay loam, sandy clay, silt clay, and clay.

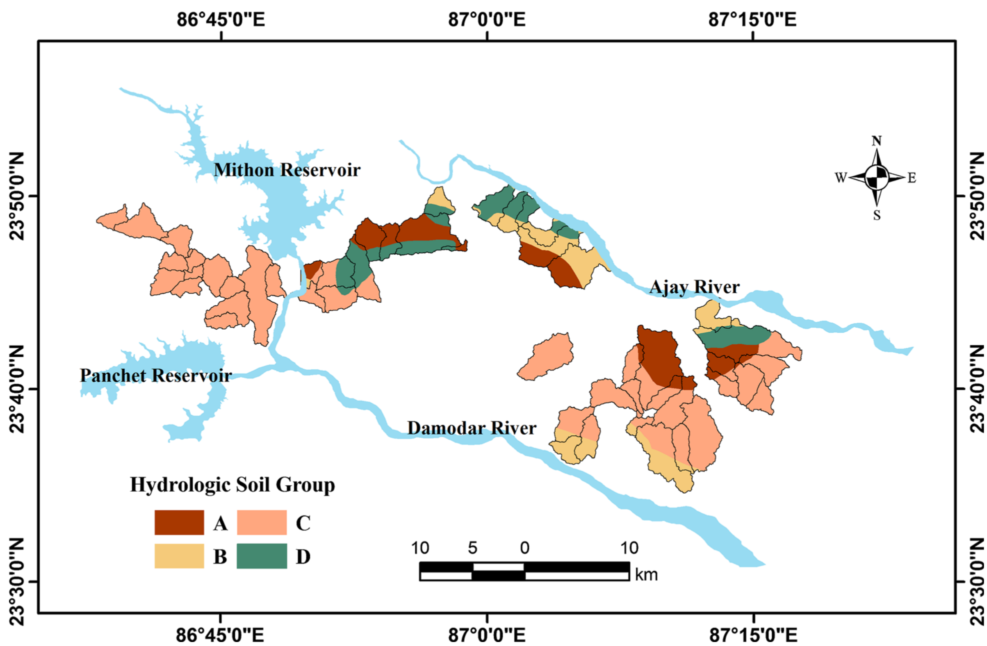


Fig. 5 Distribution of hydrological soil group over the selected small catchment basins (Modified from European Digital Archive of Soil Maps)

Hydrologic (Draining) Condition

Hydrologic condition considers the effects of cover type and treatment on infiltration and runoff. It is generally estimated from plant density and residue cover on sample areas or the amount of vegetative growth. An example of a poor hydrologic condition would be heavily grazed, sparsely vegetated pasture. A good hydrologic condition means that the soil has a low runoff potential for the given hydrologic soil group, land cover type, and treatment.

Antecedent Moisture Condition (AMC)

AMC refers to the water content in the soil at any given time. The amount of rainfall in the past few days affects the AMC and is an essential indicator of the amount of initial abstraction (Ia) and percent runoff. The SCS defined three levels of AMC:

- AMC I: Soils are dry but not to the wilting point; satisfactory cultivation has taken place.
- AMC II: Average condition.
- AMC III: Heavy rainfall and low temperature have occurred within the last 5 days; saturated soil.

In this study, AMC II was assumed, based on average antecedent moisture condition.

SCS Model

The runoff equation for a micro-basin can be written as:

$$\mathrm{Qt} = \mathrm{f}\ (\mathrm{Pt}, \mathrm{S}, \mathrm{Ia}) \tag{1}$$

where Qt is the depth of runoff over the catchment during a selective time period t, Pt is the depth of rainfall over the catchment during time period t, S is the potential maximum retention of water by the soil in equivalent depth over the catchment, and Ia is the initial abstraction during the period between the beginning of rainfall (Pt) and runoff (Qt) in equivalent depth over the catchment (Ministry of Agriculture and Co-operation 1972). Ia consists mainly of interception, infiltration, and surface storage, all of which occur before runoff begins. However, for practical purposes, Ia can be related to S, which includes Ia and the infiltration occurring after runoff begins. Both S and Ia depend on the character of the soil cover complex and the antecedent moisture condition (Hamon 1963; Singh and Dickinson 1975). Also,

$$Q = \frac{(\mathrm{P}-0.2\mathrm{S})^2}{(\mathrm{P}+0.8\mathrm{S})} \tag{2}$$

where Q is actual direct runoff (in mm), P is total rainfall (in mm), and S is potential maximum retention (in mm).

$$S = \frac{25400}{\mathrm{CN}} - 254 \tag{3}$$

where CN is the SCS runoff curve number. As indicated in Eq. 2, based on analysis of data from a large number of small watersheds, the US Soil Conservation Service (1969) found Ia to be roughly equal to 0.2S for a given storm, which means that 20 % of the potential maximum retention is the initial abstraction before runoff begins and the other 80 % (0.8S) is the runoff.

Calculation of Discharge

The effectiveness of using remote sensing data in the CN technique for determining runoff and discharge of micro-basins for a certain rainfall was studied by the India Ministry of Agriculture and Co-operation (1972), Kumar et al. (1991), Ragan and Jackson (1980), and Schwab et al. (2002). Runoff from a single storm rainfall was successfully predicted by Hamon (1963) using this method. We estimated discharge volumes from the average 24 h storm rainfall (Supplemental Table 1), assuming AMC II. Areal distribution of rainfall was calculated based on the intersection of a gauge station's Thiessen polygon over the watersheds, as done by Fiedler (2003). Mean value of a 24 h maximum rainfall for the last 70 years was calculated for each basin using Thiessen polygons (Fig. 6). The result was compared with the field measurement (Basin 50, rainfall assigned 102.3 mm, according to Thiessen polygon) on 01.07.2014 that received an almost equal (98 mm) amount of rain in 24 h. Time of concentration is the time it takes for water to reach its maximum flow at the mouth and is obtained from Eq. (4), after Schwab et al. (2002),

$$\mathrm{Tc} = \frac{L^{0.8}\left[(1000/N)-9\right]^{0.7}}{\left[4407(Sg)^{0.5}\right]} \tag{4}$$

where T_c is time of concentration in hours, L is longest flow length in m, N is runoff curve number, and S_g is the average watershed gradient in m/m.

Concentration times for watersheds of concern range from 12 to 21 h, so 24 h of rainfall should yield a satisfactory result to predict runoff discharge. Discharge volumes (m^3) from the micro-basins, in the form of runoff, were estimated through CN. The CN in AMC II condition for each land use category was then applied in order to estimate the weighted CN for each micro-basin, following this formula from Ragan and Jackson 1980):

$$\text{Weighted CN} = \frac{CN_1A_1 + CN_2A_2 + \cdots CN_nA_n}{A_1 + A_2 + \cdots A_n} \tag{5}$$

where CN_n and A_n are the curve number and area for the different respective land uses from 1 to n. The potential maximum retention (S) in mm was calculated using Eq. 3. Runoff, in mm, was estimated by Eq. 2 (Supplemental Table 1; all supplemental files accompany the on-line version of this paper, which can be downloaded for free by all journal subscribers and IMWA members).

Results and Discussion

Flow Restrictions

Obstructed flow is a condition that occurs when the mass (water and sediment) flow rate does not increase downstream as per expectation, due either to seepage through the valley bottom or the existence of a depression or excavation, when the rainfall is lesser than the retention capacity of the void space. Here, the water loss downstream was caused by the obstruction of flow and the retention of water in numerous abandoned and working mine excavations, obstructing the water supply of numerous ephemeral channels (Supplemental Plate 1a). Excavations located near the watershed boundary (water divide zone) have little impact on surface water hydrology as they have only a small or no RCA (65 depressions are in this category out of the 129 excavations in the 53 micro-basins). The impact is greater when the excavation is located

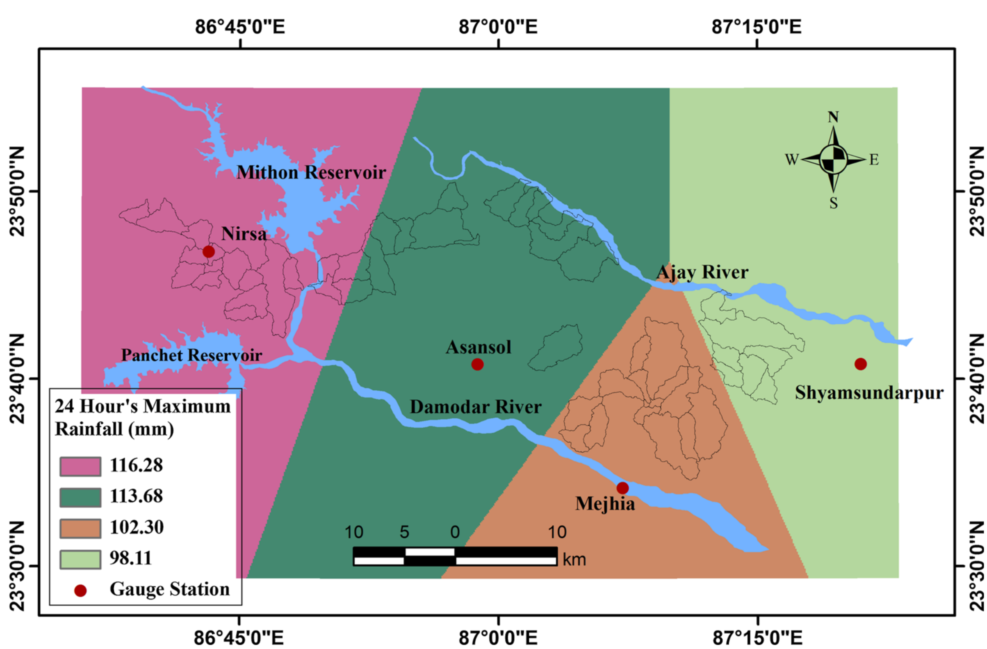
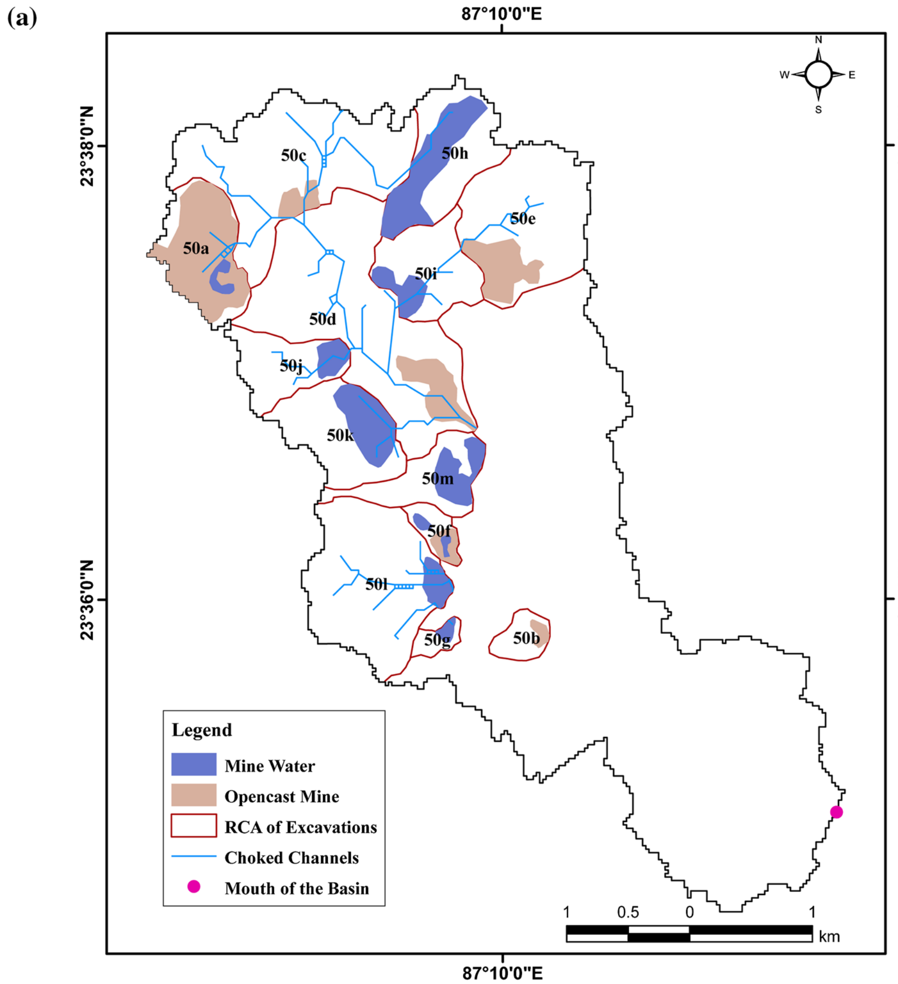


Fig. 6 Thiessen Polygon to distribute average single day maximum rainfall over the selected small catchment basins (Database from National Climatic Data Center, NOAA)



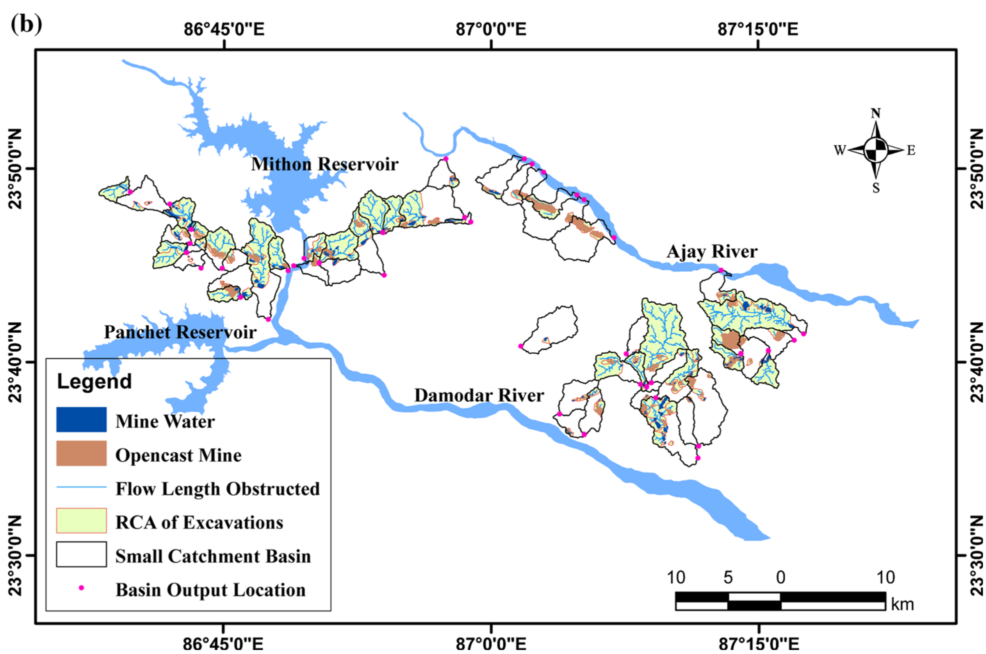


Fig. 7 Flow length of ephemeral channels choked by the excavations. **a** For example basin ID 50, **b** over the 53 selected basins

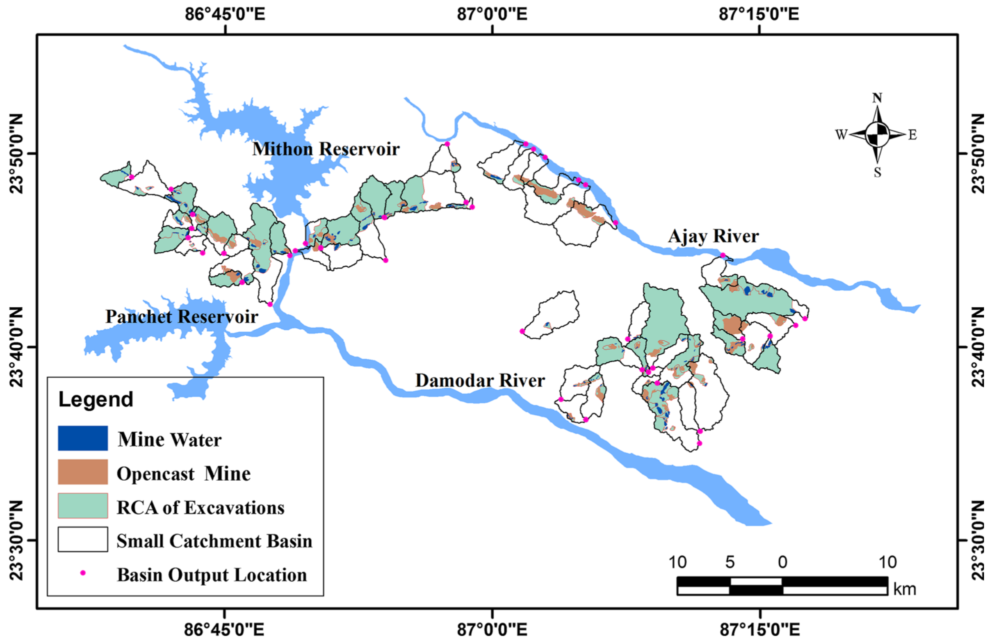


Fig. 8 RCA of the excavations over the small catchment basins

in the middle or lower catchment of the basin (Fig. 7). There were 46 such excavations that were 0–5 km from the watershed boundary and obstructed down-gradient flow in this manner, compared to 10 excavations that captured the flow from 5 to 10 km from their upper catchment, and 8 excavations that were located in the lower catchment, capturing the flow from a channel that was more than 10 km from the upper watershed boundary (Supplemental Table 2).

RCA of Excavations

The river basin itself is an RCA or rainwater collection zone for the river channel. Similarly, working or abandoned mine excavations can be a RCA within the river basin (Fig. 8). The RCA of a mine depression is controlled by the surface configuration and location of the excavation within the basin. As discussed above, a mine depression near the watershed boundary has a small RCA, one in the middle of the basin has a medium to large RCA and one in the lower reach has a large RCA. Depressions nearer to the channel have larger RCAs than depressions between two tributaries. Within the selected 53 micro-basins, 129 depressions were identified. 76 of the depressions have a RCA covering 1–10 % of the respective basin. 28 depressions have a RCA that covers 10–50 % of the respective basin, and the remaining 25 depressions have a RCA that covers 50–100 % of the respective basin (Supplemental Table 2).

Retention Capacity of the Excavations

Surface runoff from a small basin varies with the initial abstraction and the retention capacity of the depressions, especially those in the middle of a basin. The amount of water that can be retained by an excavation is directly proportional to a depression's size (Supplemental Table 2). The availability of runoff that is retained by an excavation depends on its RCA, while the availability of water depends on its position in the catchment. If an excavation is in the lower reach of a small basin, it has a comparatively large availability of surface runoff, but it does not affect the hydrology of the basin as much. Instead, its impact is conveyed downstream to the receiving parent stream. As sub-watersheds are arranged in a cascading hierarchical system, the effect of the obstructed flow anywhere within the system is conveyed downslope, thus affecting the entire system. The flow of channel water is decreased after crossing a large excavation, which results in a decay of the down-gradient channel (Supplemental Plate 1b, Supplemental Fig. 1). Some of the opencast mines are on the river bank and release overburden into the riverbed, obstructing the channel and increasing the contaminant load (Das and Chakrapani 2010; Wong 2003). Supplemental plate 1c shows an algal bloom observed in the stagnant water that exists because nutrients and other pollutants are not sufficiently diluted or washed away, threatening the river ecology.

Discharge Volume from the Basin at Maximum Daily Rainfall

Discharge volumes resulting from an average single day maximum rainfall was calculated through SCS-CN. Basins with large or numerous depressions were prone to greater retention and low discharge output (Basins 3, 5, 6, 8, 9, 11, 13, 15, 16, 17, 20, 21, 23, 24, 29, 31, 32, 35, 37, 40, 41, 44, 45, 50, and 51). Excavations in the source region of the basin do not affect the basin discharge due to less RCA (Basins 2, 10, 12, 14, 18, 22, 25, 26, 27, 28, 30, 34, 36, 38, 39, 43, 47, 48, 49, and 52). Small depressions in the lower reaches with large RCAs also impacted total discharge of the basin less due to small retention capacity (Basins 1, 4, 19, and 33). The volume of water that can be retained by depressions in a basin can sometimes exceed the total discharge of that basin (excluding the retained volume) from 24 h of maximum rainfall. Of the 53 basins, 37 had a gap between retention volume and discharge of more than 20,00,000 m^3 from the basin for a single day maximum rainfall, while 13 basins (Basins 2, 4, 7, 10, 19, 24, 43, 45, 46, 48, 49, 52, 53) showed minimal impact on the discharge, with a difference that was less than 20,00,000 m^3. Another 3 basins (Basins 34, 39, 42) had no impact on the discharge, since the discharge volume of a single day maximum rainfall was greater than the retention capacity of their depressions (Supplemental Table 2).

Conclusions

Despite certain limitations, the SCS-CN model has been widely used for estimating runoff volume. This study covered a large area and a large number of isolated small watersheds, and the SCS-CN model was successfully used to assess the magnitude of surface water hydrology alteration. Huge retention, long flow length restrictions, and low discharges were found to have altered surface water hydrology and drainage conditions. Opencast operations on river banks accelerate such alteration. Water stored in abandoned pits has changed the land use pattern of the region and affected the watershed flow pattern and river ecology of the entire downstream region. Water retention in the upper catchment could have a positive effect on groundwater recharge, but not in the study area because the ground water level in the catchment basins is shallow. Water stored in the depressions can be contaminated by metals and other contaminants and stagnation of such water can result in contaminated ponds or wetlands. Percolation of such water increases the potential of groundwater contamination. The degradation of all these channels has greatly affected the area's entire surface drainage. To restore the natural river flow, mining and dumping of spoil in channels should be regulated, and concurrent reclamation of opencast mines should be implemented. Continuous flow monitoring and quantitative assessment of the water budget would aid further investigations on the cause and effect of hydrologic disturbances and future efforts at restoring streamflow.

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