



Impact assessment of coal mining on river water and groundwater and its interaction through hydrological, isotopic characteristics, and simulation flow modeling

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Abstract

Impact assessment of coal mining of Gare IV/6 Coal Block (GCB) on river water (Kelo River) and groundwater and the interaction between them were studied through hydrological studies like water-level monitoring, short and long-term river flow measurements, isotopic characteristics, and groundwater flow modeling. The hydrological study reveals that the groundwater flow is towards the Kelo River and the river is acting as effluent in nature. The flow direction is parallel to Kelo River in the downstream of the GCB. The isotopic study suggests that the Kelo River water is enriched with $\delta^{18}\text{O}/^{16}\text{O}$ ratio as compared to watershed samples. Flow modeling suggests that the Kelo River, which is adjacent to the boundary of GCB, may contribute 88.38 m³/day of groundwater. The groundwater effluence forms a meager component of the total groundwater effluence estimated for the entire length of the Kelo River passing through the study area. Based on the groundwater flow model results it is suggested that the proposed mining operation in GCB will not have any impact on the Kelo River water flow. The suspected seepage from the Kelo River flooding on the GCB is unlikely as the hydraulic gradient is towards the Kelo River. It is suggested to have a buffer zone and an embankment between Kelo River and GCB to prevent flooding from river water breaching. The present study provides an overall understanding of the hydrogeological conditions in and around mining area which will help in safe mining operations so that any hazard or threat to the local community may be prevented.

Keywords Groundwater (GW) · Surface water (SW) · Coal mining · Isotope studies · And groundwater flow modeling

Introduction

Mining industry plays a key role in development of any nation. But at the same time, it contributes towards the deterioration of the environment concerning air, water, and land pollution. Majority of mines in India are opencast. Land degradation from the open cast mining operations, e.g., excavation, dumping of overburden material or waste rock, and other allied operations, is a significant factor (Tiwary et al. 2005). Disposal of solid waste which includes overburden, waste rock, sub-grade ore, and rejected material generated during

mining operations deteriorates the surface and groundwater quality during run-off processes. Leachate water and surface run-off generated from these materials will contaminate nearby water bodies. The quality of the mine water depends upon various factors including physical characteristics of the ore, back fill practice, mining practice, the age of mine, and aquifer characteristics. Mine water can frequently have quality problems, primarily due to the alteration of equilibrium in underground water (Dhakate et al. 2008). Therefore, impact assessment before the commencement of mining activities will be helpful to mining authorities to prevent any hazard or threat in the close vicinity of the mining operation.

Groundwater may be polluted directly or indirectly as a result of both surface and underground mining activities. Both active and abandoned coal mines may have an impact on the environment, particularly on the groundwater and surface water. This results in yielding water having hardness; low pH; and high iron, aluminum, and trace elements, with a concentration of the said elements in more than that of the sample

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from the undisturbed areas. This fact has been noticed in similar studies conducted areas in the mine area of Monongalia Country, West Virginia; South of Bochum, Germany; Tozaklı coal field, Kirklareli, Northeast of Thrace, Turkey, and Sydney, Australia (Robert 1977; Mohammad and Wohnlich 2014; Arkoc et al. 2016; Ali et al. 2017). The impact of open cast coal mining in New South Wales on groundwater quality in surrounding areas during active and post-mining phases was assessed (Zhao et al. 2017). They further modeled the mine pit for predicting groundwater inflows. Similarly, issues related to coal mining on groundwater/surface water, water quality degradation, and health issues around opencast mines in different coalfields of India, viz., Korba coal field, Gondwana coal field of Raniganj, Bokaro coalfield, Jharia coalfield, Basundhara Grajanbahal area of Sundergarh, and Talchir coalfield area, were studied by various researchers (Singh et al. 2017; Adhikari et al. 2013; Singh et al. 2018; Kumar and Singh 2016; Das 2018; Tiwary et al. 2009; Dhakate and Rao 2010).

Natural hydrological processes are prone to be vulnerable due to mining activities, which inevitably produces surface cracks and subsidence. The most vulnerable impact of mining is the deterioration of groundwater and surface water. Groundwater and surface water bodies are considered as two different hydrological systems, and interaction between them is a complex process. In many cases surface water bodies are hydraulically connected to groundwater and this forms an integral part of the groundwater flow system (Li et al. 2016). In some cases the surface water body is separated from the groundwater system by an unsaturated zone, and the seepages from the surface water body may recharge to groundwater. The exchange between surface water and groundwater hydrologic framework will be useful for the advancement of groundwater assets, and relocation of defilement between them will impact each other (Jankowski and Spies 2007). The interaction between them is commonly controlled by many factors, viz., physiography, geology, climatic conditions, precipitation, and evapotranspiration (Thomas and Thomas 1995; Kalbus et al. 2006; Fleckenstein et al. 2010).

During mining processes, the surface water-groundwater interaction increases due to enhanced fracture porosity and permeability (Booth 2006; Reid 1996). This can alter hydraulic gradients close to the surface water-groundwater interface, causing leakage between hydrogeological units, which can result in aquifers changing from unconfined to confined or vice versa (Booth 2007). Mining-induced development of joints and fractures can occur from various factors such as vertical displacement of a single fracture or multiple fractures, the horizontal displacement of a single horizontal shear or complex shear, vertical slips, compression- and tension-related subsidence, and complex deformations on bedding planes (Jankowski et al. 2008; Cravotta III et al. 2014). Geologically, newly developed fractures and joints, bedding planes, and mine subsidence produce a horizontal pathway for groundwater flow between

surface water and groundwater (Jankowski 2007). Several researchers have studied the interaction between surface water-groundwater in different geological environments using different techniques (Nield 1994; Devitoo et al. 1996; Morrice et al. 1997; Scibek et al. 2007; Witthüser and Holland 2008; Brunner et al. 2010; Ryan et al. 2010; Abiye et al. 2011).

The present aim of the study is to characterize the connectivity between river water-groundwater and impact of mining from GCB on Kelo River by using hydrological studies, river flow measurements, isotopic characteristics, and groundwater flow modeling in the watershed covering GCB of Kelo River catchment, Raigarh District, Chattisgarh, India. The steady-state groundwater flow model has been constructed in the watershed covering GCB and adjacent Kelo River course for assessing river water-groundwater interaction. The groundwater flow model has been calibrated for groundwater conditions in the watershed, and impact of mining on Kelo River has been studied and illustrated in the article. The study will help the mining authorities in conducting safe mining activities and preventing any hazard or threat to the community close to the vicinity of Kelo River and using river water for their domestic use.

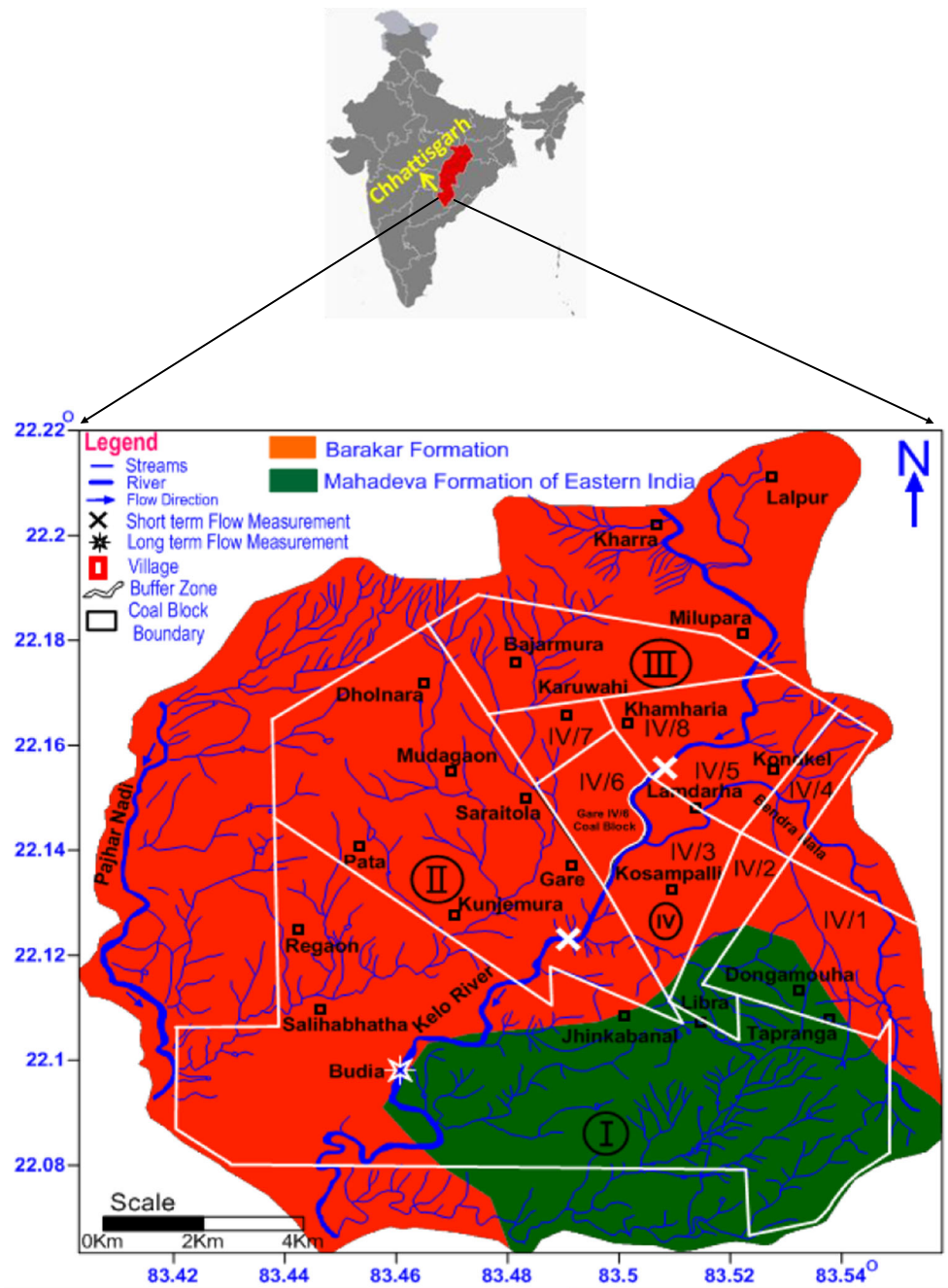
Study area

Gare Coal Block in Raigarh district consists of four units (Gare I–IV), and Gare IV unit is further sub-divided into eight sub-units (I–VIII) (Fig. 1). The Gare IV/6 Coal Block encompasses an area of 381.42 ha with latitude 22° 08' 04" to 22° 09' 48" N and longitude 83° 29' 07" to 83° 30' 24" E and falls in Survey of India Toposheet 64° N/8. Gare IV/6 Coal Block is located in Gare village about 50 km from Raigarh. Mainly due to the lithology, the overall drainage in the catchment area is sub-parallel to dendritic (Chakraborty et al. 1992). Kelo River flows from the north towards the southwest and forms the eastern boundary of the Gare IV/6 Coal Block (Fig. 1). The average annual rainfall of the area recorded at Raigarh for the year 2012 and 2013 was 1647.72 mm/year and 1625.70 mm/year. The average annual rainfall for the year 2016 recorded in the area was 1252.3 mm/year (Rainfall Statistics of India 2016). The area forms a part of Kelo River watershed which flows southeasterly over northern portions of the study area and takes a southwesterly trend near Milupara village. Bendra and Pajhar Nala (streams) are the main tributaries of Kelo River. The Kelo River though seasonal receives water from groundwater throughout the year indicating its effluent nature and ultimately it joins Mahanadi River in the south.

Geology and hydrology of study area

The formation belonging to Permian to Triassic period under a thin alluvial cover of the Quaternary period is present in the

Fig. 1 Key map of the Gare Coal Block watershed showing geology, different sub-units of Gare coal blocks, flow measurement locations, and buffer zone (After Das et al. 1992)



area. Pre-Cambrian formation of Chhattisgarh group forms the basement. The geological sequence of the Mand-Raigarh coalfield has been studied (Das et al. 1992, 2001; Acharyya 1997; Dutta 1998; Murti 1987; Naqvi and Rogers 1987). The Archaean rocks occur along the northern as well as southern boundaries of the coalfield and are represented by garnetiferous granite, gneiss, mica, schists, and pegmatites. They are mostly found in juxtaposition with the sedimentary formations. In the northern part, they are present as inliers in the Talcher north of Kurumkela village as well as in the Barakars near Pelma village. The stratigraphy sequence of the area is given in Table 1.

The Gare IV/6 Coal Block is underlain mainly by Barakar and Mahadeva formation of Gondwana system under a thin alluvial cover (Table 1). Based on the lithology, the Barakar formation of Gare Coal Block is sub-divided into two groups, viz., upper and lower Barakar. The upper Barakar ore is fine-grained mica and sandstone, siltstone, and shale, while the lower group is made up of medium- to very coarse-grained sandstone. Gare IV/6 Coal Block comprises the only upper member of Barakar formation. The stratigraphic sequence of the formation in the area has been established based on sub-surface data obtained through exploratory drilling wells which

Table 1 Generalized stratigraphic sequence of Gare Coalfield area (After Das et al. 1992)

Age	Formation	Lithology
Quaternary		Alluvium soil, laterite, gravel, and conglomerates
-----Unconformity-----		
Upper Cretaceous to Eocene	Deccan trap volcanics/-intrusives	Basaltic flows and dolerite dikes
-----Unconformity-----		
Lower to Middle Traissic	Kamthi formation	Coarse to medium grained sandstone, frequently ferruginous red sandstone and shale
Upper Permian	Raniganj formation	Fine to medium grained sandstone, sandy shale, carbonaceous shale, and minor coal horizon
Middle Permian	Barren measures	Gray shale, sandy shale, fine-grained sandstone with ripple marks and with ferruginous alternate bands
Lower Permian	Barakar formation	Alternate units of fine-grained sandstone and shale, carbonaceous shale and coal seams, medium to coarse grained frequently very coarse grained arkosic sandstone, carbonaceous shale and coal seams
Upper Carboniferous to Basal Permian	Talchir formation	Mostly fine grained sandstone, khaki green to cement gray shale and siltstone diamictites and rhythmites
-----Unconformity-----		
Protozoic	Chattisgarh	Quartzite, sandstone, phyllite
	Cuddapah	Quartzites and red hard fine-grained sandstone and limestone
Archaean		Granites, gneisses, mica schist, quartzites, intruded by pegmatite and quartz veins

is confined to coal bearing upper Barakar formation, constituted mainly of sandstone, shale, and coal seams associated with carbonaceous shale exposed over a larger part of the area and overlain by the younger Barren measure in the north along strike fault trending in ESE-WNW direction. Altogether nine coal seams have been identified within the block with thickness varying between 0.85 and 7.60 m (Das et al. 1992).

Groundwater occurs within the primary porosity of alluvial material at shallow depth and within the secondary porosity of Gondwana sandstone which occurs at deeper depth in the Gare Coal Block. The groundwater occurs under unconfined conditions in the shallow aquifer, whereas it occurs under the confined condition in the deep sandstone aquifer. Prevailing geomorphological features control the occurrence and movement of groundwater in alluvial formation.

Materials and method

Groundwater monitoring in 24 selected bore wells/dug wells in the watershed, spread over 190.2 km² covering the Gare Coal Block, was carried out for pre-monsoon and post-monsoon season (Table 2). The topographic elevations of these wells were varying from 258 m (amsl) at well no. G10 to 301 m (amsl) at well no. G8, whereas Kelo River reach adjacent to the Gare block IV/6 was found to be at 257 m (amsl) and 261 m (amsl) (Fig. 2a). The depth to groundwater level during June 2014 varies from 249.76 m (amsl) at well no. G2 to 296.56 m (amsl) at well no. G21 (Fig. 2b). Twenty groundwater and two surface water (on Kelo river—one at

upstream and the other at downstream of Gare IV/6 coal block) samples were collected in the watershed area covering Gare Coal Block during June 2014. The samples were analyzed for $\delta^{18}\text{O}/^{16}\text{O}$ ratio and δ deuterium ratios in the laboratory of CSIR-National Geophysical Research Institute, Hyderabad, using Isotope Ratio Mass Spectrometer, Isoprime Company, Germany, following standard procedures to investigate a hydraulic connection between groundwater and surface water (Kelo River) (Fig. 3a, b). Similarly, long-term and short-term flow measurement of the Kelo River was carried out during pre- and post-monsoon periods in the upstream and downstream reaches concerning Gare IV/6 Coal Block to assess the impact of proposed coal mining on the river flows. The flow measurement was carried out using LYNX Cup type Water Current Meter. The flow measurement experiments were repeated several times and average results were taken.

Groundwater flow modeling

The groundwater flow model in the watershed covering Gare IV/6 Coal Block has been conceptualized as a two-layered weathered and fractured aquifer system in the upper Barakar formation based on the hydrogeological data collected during field investigations by using Visual MODFLOW Software for Windows v.3.1 (Guiger and Franz 1996). Essentially, mathematical modeling of a system implies obtaining solutions to one or more partial differential equations describing groundwater regime (Konikow and Bredhoeft 1978). In the present case, it

Table 2 Observation well details, reduced level, and depth to groundwater level in the watershed covering Gare Coal Block for post- and pre-monsoon periods during November 2013 and June 2014

Well no.	Well type	Latitude (°N)	Longitude (°E)	Topographic level (m) (amsl)	Depth to water (m) (bgl) post-monsoon (November 2013)	Groundwater level (m) (amsl) post-monsoon (November 2013)	Depth to water (m) (bgl) pre-monsoon (June 2014)	Groundwater level (m) (amsl) pre-monsoon (June 2014)	Aquifer type
G1	SW	22.13364	83.49509	257	—	—	—	—	—
G2	BW	22.12706	83.48186	266	13.29	252.71	16.24	249.76	Shale and coal bed
G3	DW	22.20247	83.50514	276	4.33	271.67	6.4	269.6	Sandstone
G4	SW	22.15128	83.50050	261	—	—	—	—	—
G5	DW	22.11092	83.50028	287	3.82	283.18	4.3	282.7	Sandstone
G6	DW	22.10828	83.51031	276	2.30	273.7	2.83	273.17	Sandstone
G7	DW	22.13283	83.50819	280	6.09	273.91	6.28	273.72	Sandstone
G8	DW	22.13061	83.53233	301	6.89	294.11	8.29	292.71	Sandstone
G9	DW	22.10725	83.53678	300	4	296	4.2	295.8	Shally Sandstone
G10	DW	22.11211	83.44722	258	6.37	251.63	6.47	251.53	Sand
G11	DW	22.19814	83.52983	281	10.26	270.74	9.91	271.09	Sandstone
G12	DW	22.19164	83.52317	282	5.02	276.98	7.15	274.85	Sandstone
G13	DW	22.16064	83.52756	280	8.46	271.54	Dry	—	Clay
G14	DW	22.14931	83.51136	276	9.05	266.95	11.2	264.8	Clay
G15	BW	22.15867	83.49747	277	10.06	266.94	12.16	264.84	Sandstone
G16	DW	22.12836	83.44794	264	2.5	261.5	3.04	260.96	Coal bed
G17	DW	22.13781	83.46411	277	8.08	268.92	9.69	267.31	Sandstone
G18	DW	22.13033	83.46725	268	5.87	262.13	6.95	261.05	Coal bed
G19	DW	22.13856	83.48939	271	5.11	265.89	7.7	263.3	Shale and coal bed
G20	DW	22.16731	83.49236	294	5.55	288.45	7.65	286.35	Sandstone
G21	DW	22.17706	83.47944	299	3.18	295.82	2.44	296.56	Sandstone
G22	DW	22.17264	83.46053	299	3.3	295.7	4	295	Shally sandstone
G23	DW	22.15189	83.47947	284	5.35	278.65	Dry	—	Shally sandstone
G24	DW	22.15697	83.46842	281	5.79	275.21	6.18	274.82	Shally sandstone

SW surface water (Kelo River), BW bore well, DW dug well, DW dug well, bgl below ground level, amsl above mean sea level

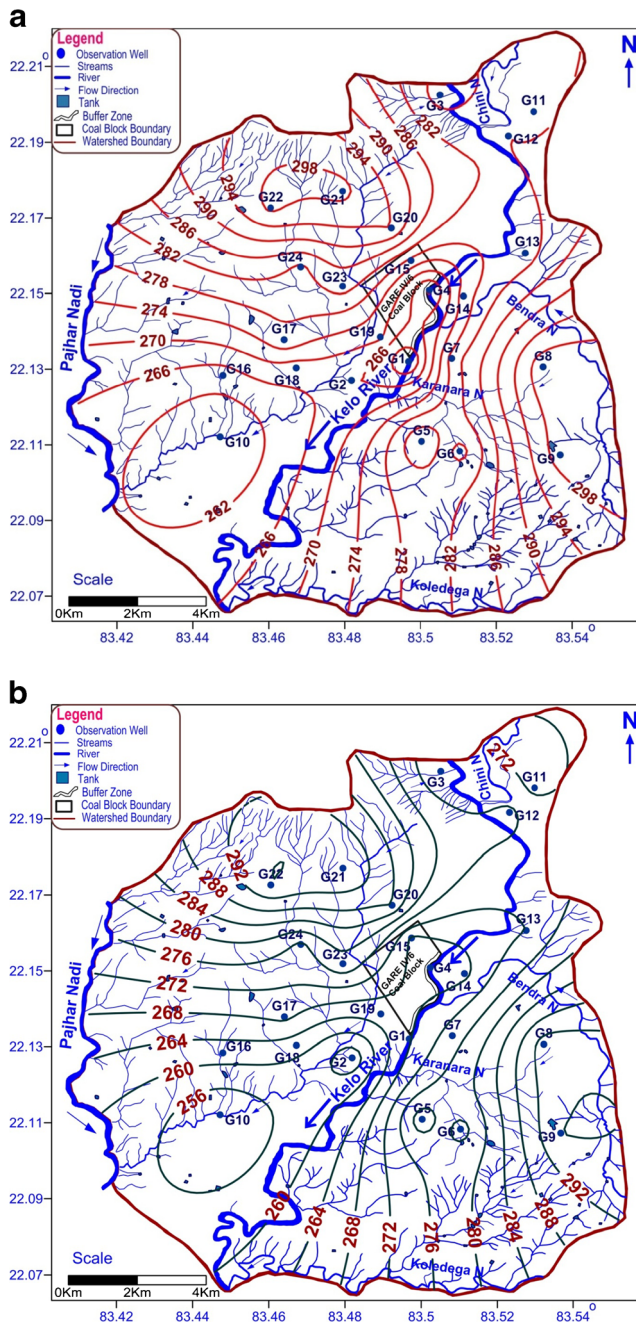


Fig. 2 **a** Topographic contours in m (amsl) in the water covering Gare IV/6 Coal Block. **b** Groundwater level m (amsl) for the post-monsoon (June 2014) in the watershed covering Gare IV/6 Coal Block

was assumed that the groundwater system is a two-dimensional one, wherein the Dupuit-Forchheimer condition is valid. The partial differential equation describing two-dimensional groundwater flows for a homogeneous aquifer may be as

$$\frac{\partial}{\partial y} \left(T_x \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial x} \left(T_y \frac{\partial h}{\partial x} \right) = S \frac{\partial h}{\partial t} \pm W \quad (1)$$

where T_x and T_y are the transmissivity values along x and y directions, respectively; h is the hydraulic head; S is the storativity; W is the groundwater volume flux per unit area (+ve for outflow and -ve for inflow); and x and y are the Cartesian coordinates.

Usually, it is difficult to find the exact solution of Eq. (1). One has to resort to numerical techniques for obtaining their approximate solutions. In the present case, the finite difference method was used to solve the above equation. The partial differential equation was replaced by a set of simultaneous algebraic equations valid at different node points. After that, using standard methods of matrix inversion, these equations were solved for the water level.

Physical framework for groundwater modeling

The groundwater flow model has 53 rows and 52 columns with 300×300 -m grid, and for Gare IV/6 Coal Block fine grid of 100×100 m was made (Fig. 4). The entire watershed was divided into grids of size 300×300 m, and again, the Gare IV/6 Coal Block was divided into smaller grids of size 100×100 m. The highest hydraulic conductivity of saturated upper Barakar formation was found in the Gare IV/6 Coal Block and its surroundings, and accordingly, maximum hydraulic conductivity of 3 m/day was assigned based on the pumping test results carried out in a watershed (Dhakate et al. 2013). The open-cut sections in Gare IV/6 Coal Block adjacent to the Kelo River contained sandstone underlain with shale. Thus, a slightly lower hydraulic conductivity of 2.4 m/day was assigned to the cells adjacent to the Kelo River course and hydraulic conductivity varying between 1 and 1.2 m/day was assigned in the rest of the area (Fig. 5). The second layer was assigned a hydraulic conductivity of 1 m/day uniformly over the entire watershed (Dhakate et al. 2013). The hydraulic conductivity in the vertical direction was assumed as one tenth of that in the horizontal direction. Constant head boundary condition was assigned to one cell in the outflow region of the Kelo River with a groundwater head of 250 m (amsl). The later inflows enter into the river from the watershed along the southern side of the river. The groundwater level was observed as 250 m (amsl) in the southern side of the river. Therefore, the same constant head was simulated in the entire flow model. Kelo River course was appropriately simulated with a river head boundary condition.

The low hydraulic conductance of exposed shale was assigned as 10 m/day between the riverbed and aquifer. River stage elevations, varying from 269 to 267 m (amsl), were appropriately assigned to the cells of Kelo River reach adjacent to the Gare IV/6 block (Fig. 6). The rainfall during monsoon season generates mostly surface water runoff and escapes into the Kelo River as top Barakar formations do not allow good infiltration due to low hydraulic conductivity. The upper Barakar does not allow good infiltration and hence

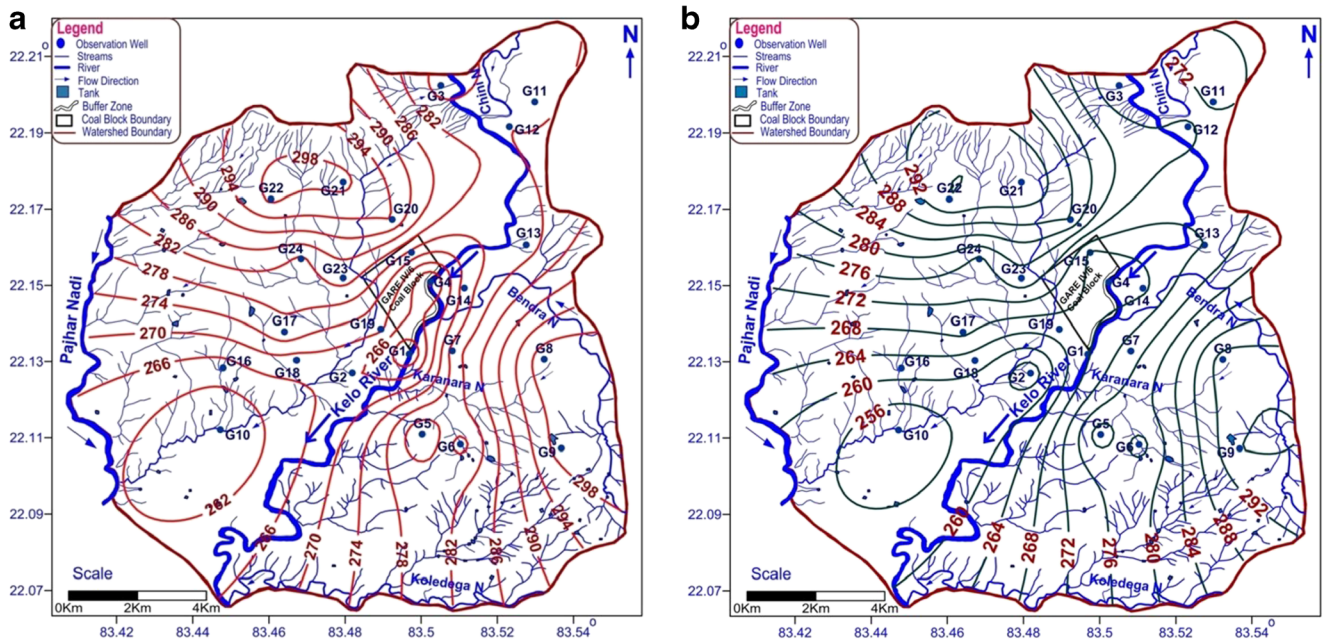


Fig. 3 **a** The $\delta^{18}\text{O}/^{16}\text{O}$ ratio of groundwater and surface water in the watershed covering Gare IV/6 Coal Block. **b** δ deuterium of groundwater and surface water in the watershed covering Gare IV/6 Coal Block

Fig. 4 Groundwater flow model domain of watershed covering Gare IV/6 Coal Block

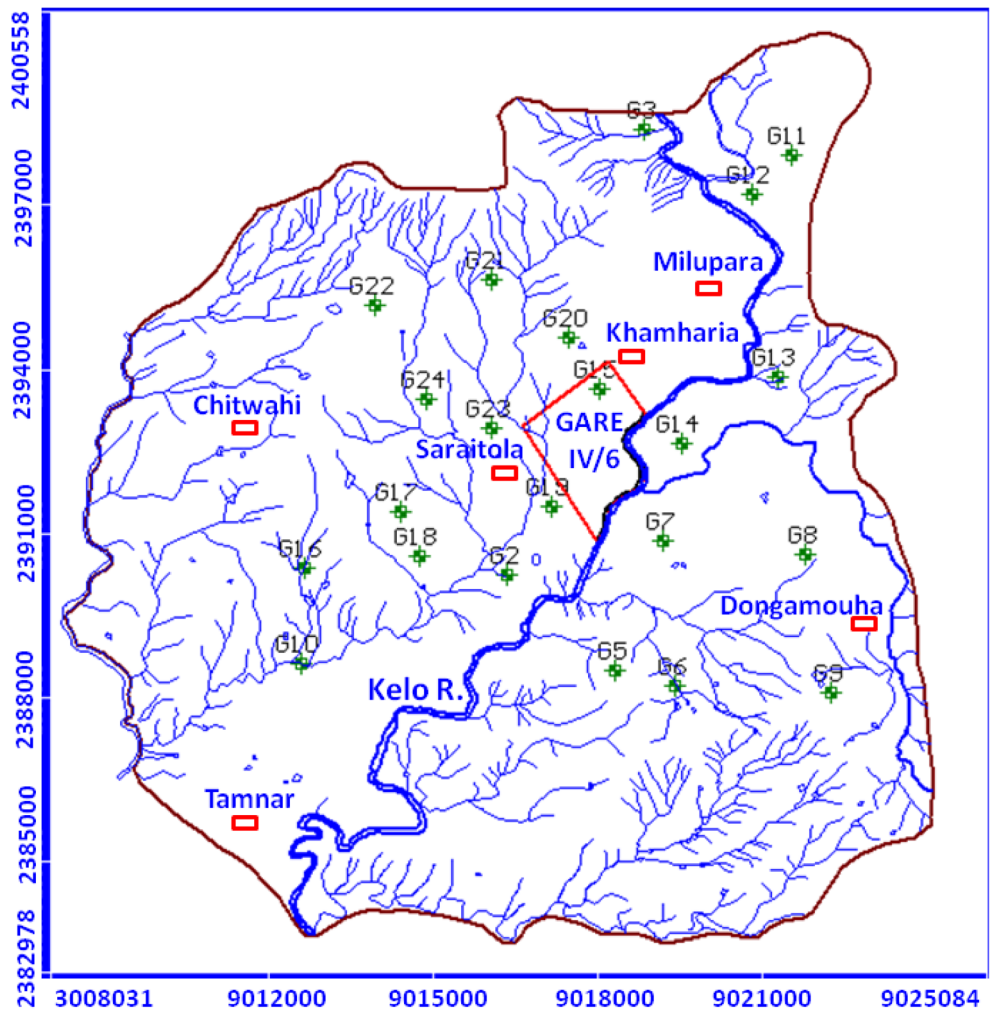
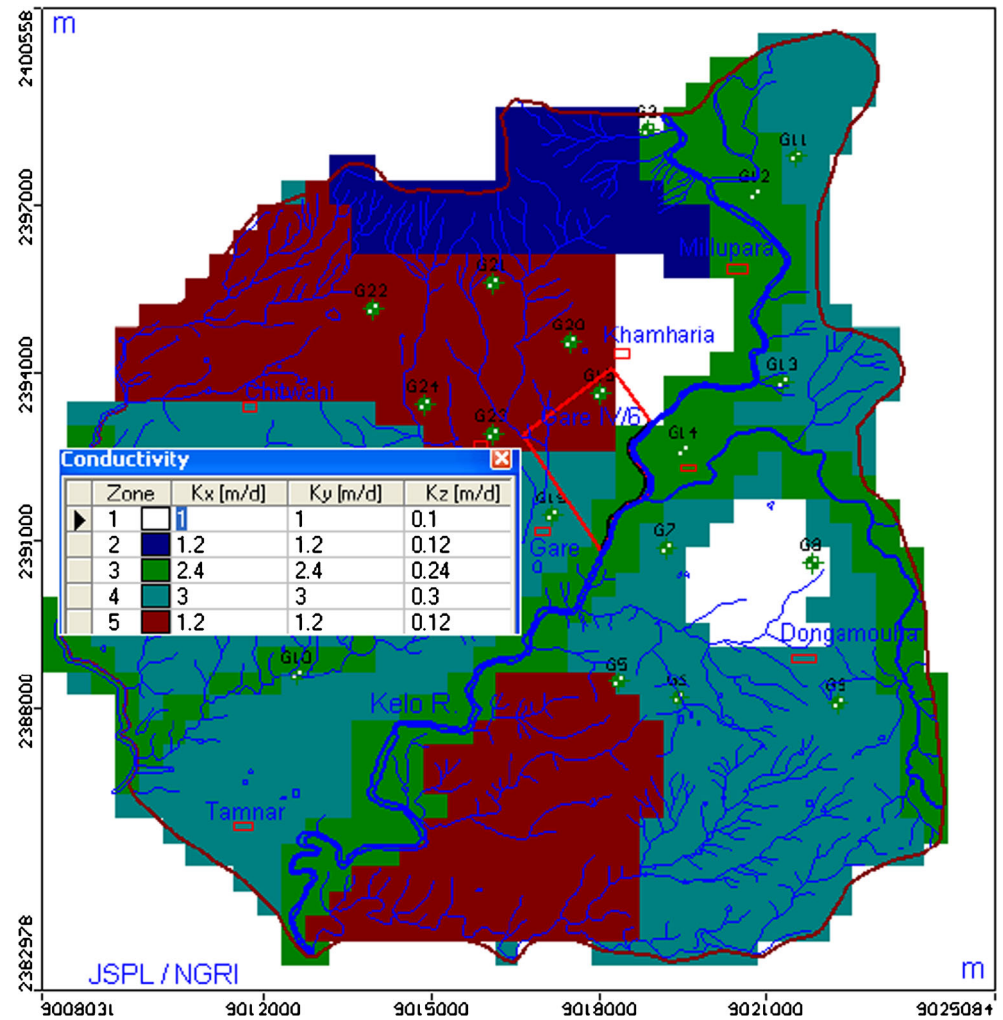


Fig. 5 Hydraulic conductivity (m/day) distribution pattern in the groundwater flow model of watershed covering Gare IV/6 Coal Block



results in low groundwater recharge in the area. Accordingly, the recharge boundary condition was assigned in the top layer with the recharge rate of 33 mm/year uniformly in the entire study area (Fig. 6). (While assigning pumping rate to different cells in the model, care was taken for the groundwater pumping centers in and around the habitations as well as the active coal mine pumping in the adjacent areas to the Gare IV/6 Coal Block (Fig. 6).) The average pumping rate assigned at each pumping center was 80m³/day.

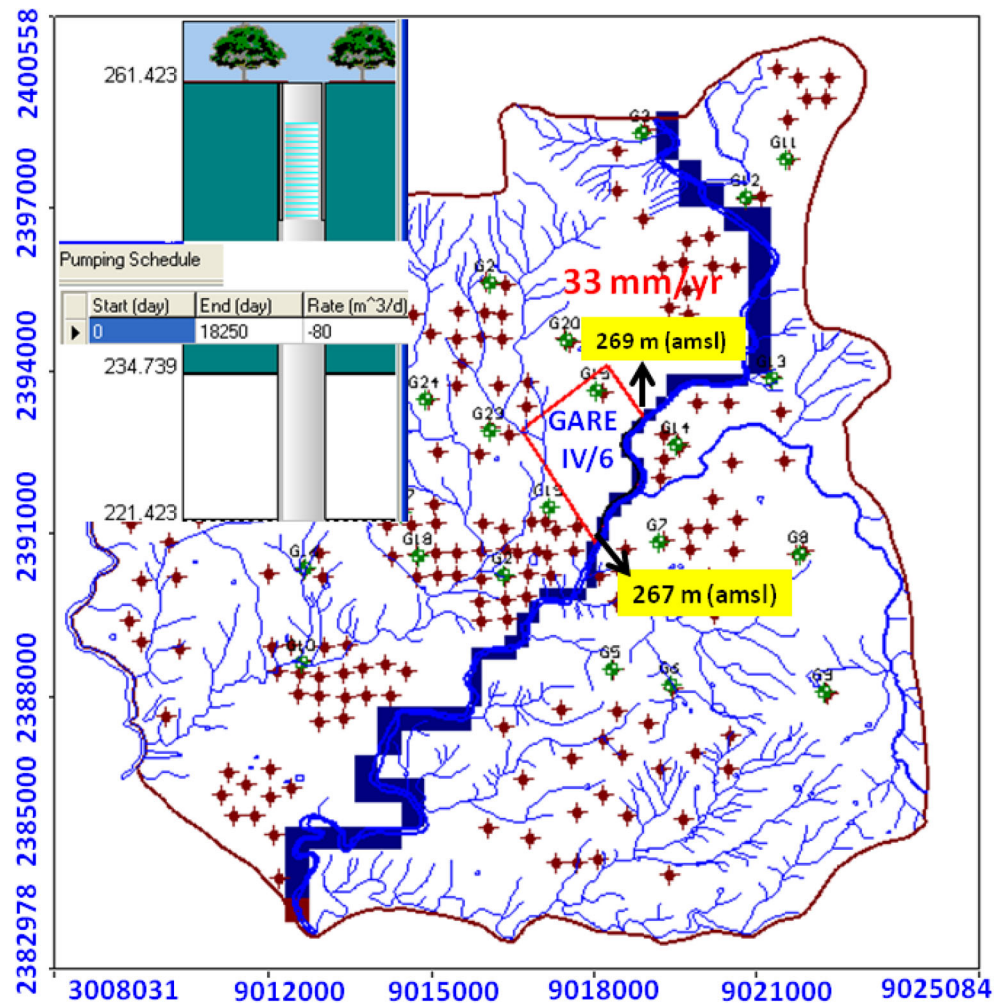
Results and discussion

An integrated approach, viz., hydrogeological, isotopic analyses, river flow measurement, and groundwater flow modeling, was carried out in the watershed covering Gare Coal Block to assess the groundwater and surface water (Kelo River) interaction in the Gare IV/6 Coal Block. Geologically, the Gare IV/6 Coal Block is underlain mainly by Barakar and Mahadeva formation of Gondwana system with thin alluvial cover. Barakar formation of Gare block is divided into upper and lower groups. The upper

Barakar is fine-grained, while lower one consists of medium to very coarse-grained sandstone. Gare IV/6 Coal Block comprises the only upper member of Barakar formation.

The depth to groundwater was ranging from 2.3 to 13.29 m (bgl) during post-monsoon period of November 2013 and 2.44 to 16.24 m (bgl) during pre-monsoon period of 2014 (Table 2). The minimum depth was noticed as 2.3 m (bgl) (well no. G6), whereas the maximum depth was found as 13.78 m (bgl) (well no. G2) during pre-monsoon season. The groundwater level contours for the pre-monsoon 2014 season indicate that predominant groundwater flow direction is from watershed boundary towards the Kelo River, and significant steep hydraulic gradient occurs adjacent to Gare Coal Block (Fig. 2b). Groundwater flow was parallel to Kelo River in the downstream of Gare Coal Block and was acting as an effluent in nature. It is significant to note that steep hydraulic gradient occurs in the upper Barakar formation near the Gare IV/6 Coal Block adjacent to the Kelo River (Dhakate et al. 2013). Groundwater flows parallel to the Kelo River in the downstream of Gare Coal Block. The hydraulic gradient indicates the occurrence of groundwater effluence to the Kelo

Fig. 6 Map showing the pumping wells, observation wells, constant head, recharge, and river boundary conditions in the groundwater flow model of watershed covering Gare IV/6 Coal Block



River from Gare Coal Block and its adjacent area. Field observations also confirm about little seepage from the upstream in the open-cut sections adjacent to the Kelo River. There is no river water contribution to the seepage in the open pits. The groundwater-level contours indicate that the effluent nature of Kelo River is particularly because of receiving groundwater effluence from the Gare Coal Block.

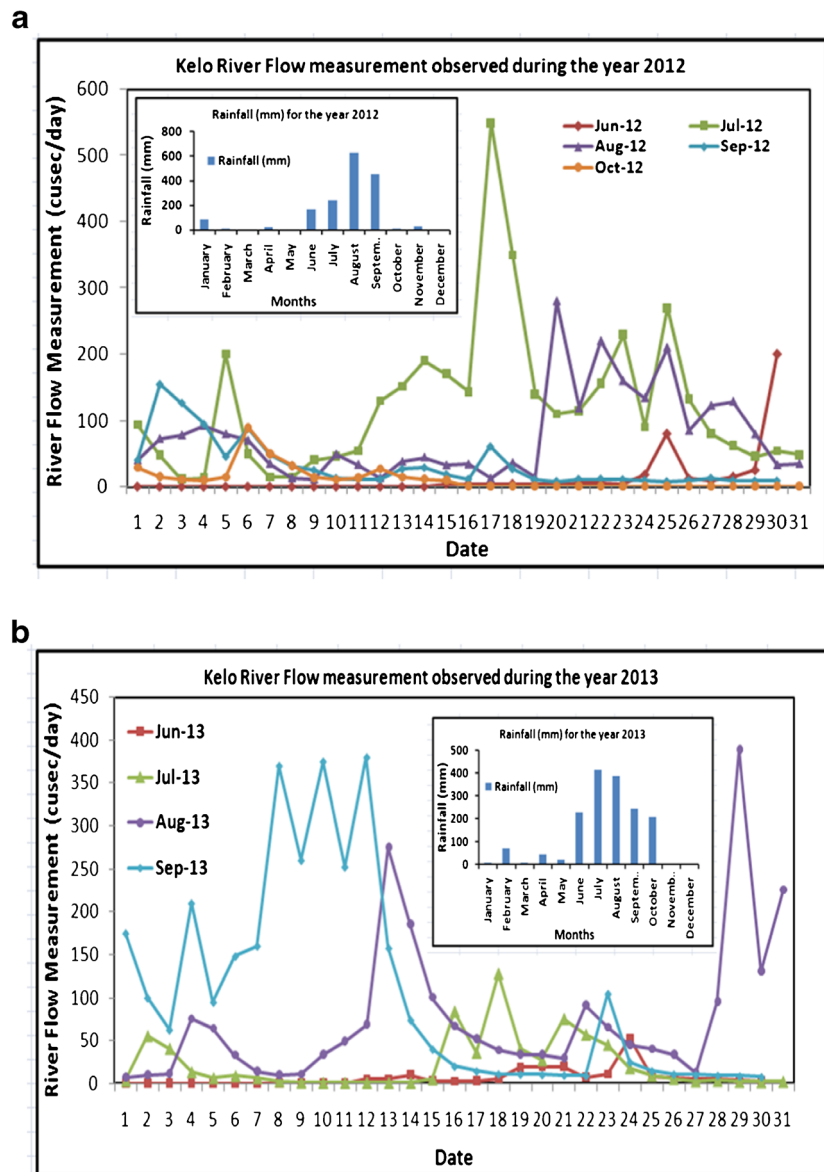
The long-term daily flow measurement pattern of Kelo River for the years of 2012 and 2013 was available with mining authorities. The long-term flow measurement of Kelo River was observed at Budia village (Fig. 1). Similarly, rainfall pattern for the particular year was also analyzed. The rainfall station is situated at Raigarh, which is about 50 km away from the Gare village. The maximum flow in Kelo River of 550 cusecs/day was observed during July for the year 2012, and during this period, an average annual rainfall of 1647.72 mm, which is considered as a good amount of rainfall, was recorded in the watershed (Fig. 7a). Similarly, during 2013, maximum flow of 388.88 cusecs/day was observed in the Kelo River. During this period, an average annual rainfall of 1625.70 mm was recorded in the watershed (Fig. 7b). Thus,

from the above figures, it is observed that during the rainy season, the good amount of flow is generated in Kelo River.

The surface water flow measurement was carried out during 2013–2014 for the Kelo River stage of GCB. During post-monsoon in 2013, the average flow in the upstream side was 6.7413 cusecs, whereas in the downstream side, it was increased to 15.0564 cusecs. Similar flow measurements conducted during pre-monsoon of 2014 indicated that surface water flow was 1.16093 cusecs in the upstream and 11.60065 cusecs in the downstream of Kelo River. Increased flow reported in the downstream side of the Kelo River is due to joining of Bendra Nala (stream) and Pajhar Nala (stream) and contributing additional base flow to Kelo River in the downstream direction.

Isotopes are useful and helpful for understanding the characteristics of precipitation, water evaporation mechanisms, and water recharge (Qian et al. 2013, 2014). The isotopic features differ from region to region, which can be because of changing water quality as a result of human activities. Isotopes respond sensitively to the environment that can be commonly used as tracers for monitoring water balance and hydrological cycles. Stable isotopes tracers of the water

Fig.7 a Kelo river flow measurement (cusecs/day) and rainfall (mm) pattern during year 2012. **b** Kelo river flow measurement (cusecs/day) and rainfall (mm) pattern during year 2013



molecules can be used to determine the source of groundwater recharge (Athavale et al. 1983), connectivity between aquifer and surface water (Abourida et al. 2004), groundwater flow regime, recharge, discharge mechanism, pathways and subsurface residence time of water, groundwater chemistry, its ages, and renewability (Su and Lin 2004; Xue et al. 2006; Jia et al. 2009; Subyani 2004; Ben Moussa et al. 2011; Saha et al. 2013; Rochdane et al. 2015; Su et al. 2006; Yang et al. 2007). Importance of isotopic studies has been noted in arid and semi-arid areas (Gat and Garmi 1970; Gat and Dansgaard 1972; Gibson et al. 1993; Xiao 1995; Mayr et al. 2007; Kebede et al. 2009; Liu et al. 2009; Zhang et al. 2011).

Analysis of the isotope data show significantly that the river water is enriched with $\delta^{18}\text{O}/^{16}\text{O}$ ratio compared to the groundwater elsewhere in the watershed except at the location of G22 (Fig. 3a). Delta oxygen ratios further confirm that there

is the possibility of only groundwater effluence to the Kelo River. The embedded low hydraulic conductivity shale material in the Kelo Riverbed does not allow much groundwater-surface water interaction in the river reach adjacent to the Gare IV/6 Coal Block. Similar enriched δ deuterium ratios in Kelo River water have been found compared to groundwater in the watershed (Fig. 3b). These isotopic ratios also support the possibility of only groundwater effluence to the Kelo River from Gare IV/6 Coal Block.

The groundwater head solution under steady-state condition has been obtained in the groundwater flow model by using Visual MODFLOW Software v.3.1 representing groundwater conditions during November 2013 (Anderson and Woessner 1992; Konikow and Grove 1977). The groundwater level contours computed from the groundwater flow model shows that the groundwater flow direction is towards

the Kelo River and follow the trend of observed groundwater level contours for the post-monsoon period (Fig. 8a). Similarly, calibration graph of computed versus observed groundwater level for the observation well used in the groundwater flow model in the watershed covering Gare Coal Block is shown in Fig. 8b.

The groundwater budget was computed for the entire watershed as well as for the Gare IV/6 Coal Block separately in the groundwater flow model using zone budget option in the Visual MODFLOW Software (Fig. 8a). The groundwater balance mainly consists of recharge due to rainfall as 16,754 m³/day for the entire study area. The net groundwater effluence input to the Kelo River was computed from the zone budget about 3131.20 m³/day along the entire river course from either side. Groundwater seepage inside the nearby working mines as well as ongoing groundwater withdrawal for domestic and irrigation purpose was worked out as 13,301 m³/day (Table 3). Separate groundwater balance in the Gare IV/6 Coal Block area, in particular, indicated that the block was receiving a net inflow of 606.76 m³/day from the surrounding area, whereas an outflow of 335.99 m³/day was leaving from the block to the surrounding area. The local groundwater budget in the Gare IV/6 Coal Block brought out groundwater recharge in the block as 584.44 m³/day, and the Kelo River reach adjacent to the Gare IV/6 Coal Block contributed only 1.06 m³/day as input. The outflow from Gare IV/6 Coal Block was mainly due to withdrawal from two pumping wells of 226.01 m³/day and groundwater effluence leaving to the Kelo river along the river reach as 88.38 m³/day (Table 4). Significantly, Gare IV/6 Coal Block contributes a meager 88.38 m³/day to the Kelo River, which is a very insignificant flow concerning to the total groundwater effluence of 3131.20 m³/day in the Kelo River. Thus, it can be suggested that the proposed coal mine operations from Gare IV/6 Coal Block will not impact much on groundwater effluence to the adjacent Kelo River. The in situ geological formations of the river bed and immediate open-cut sections adjacent to Kelo River showing thick shale presence does not warrant the construction of a physical barrier for arresting suspected river water seepage flooding the mine workings of the Gare IV/6 coal block. The computed groundwater effluence to the river from the Gare IV/6 Coal Block assumes a very insignificant fraction of base flow in the Kelo River.

In view of the in situ hydrogeologic characteristics of the river bed with hard sandstone underlain with shale formations overlying the coal seam at depth in the reach of Kelo River adjacent to the Gare IV/6 Coal Block and meager groundwater effluence to the Kelo river from the groundwater flow model, it is suggested that construction of a barrier for protection of suspected seepage from the Kelo river towards the Gare IV/6 Coal Block is not required and hence not recommended. However, the earmarked buffer zone between the proposed mine in the Gare IV/6 Coal Block and the Kelo river has to be maintained undisturbed.

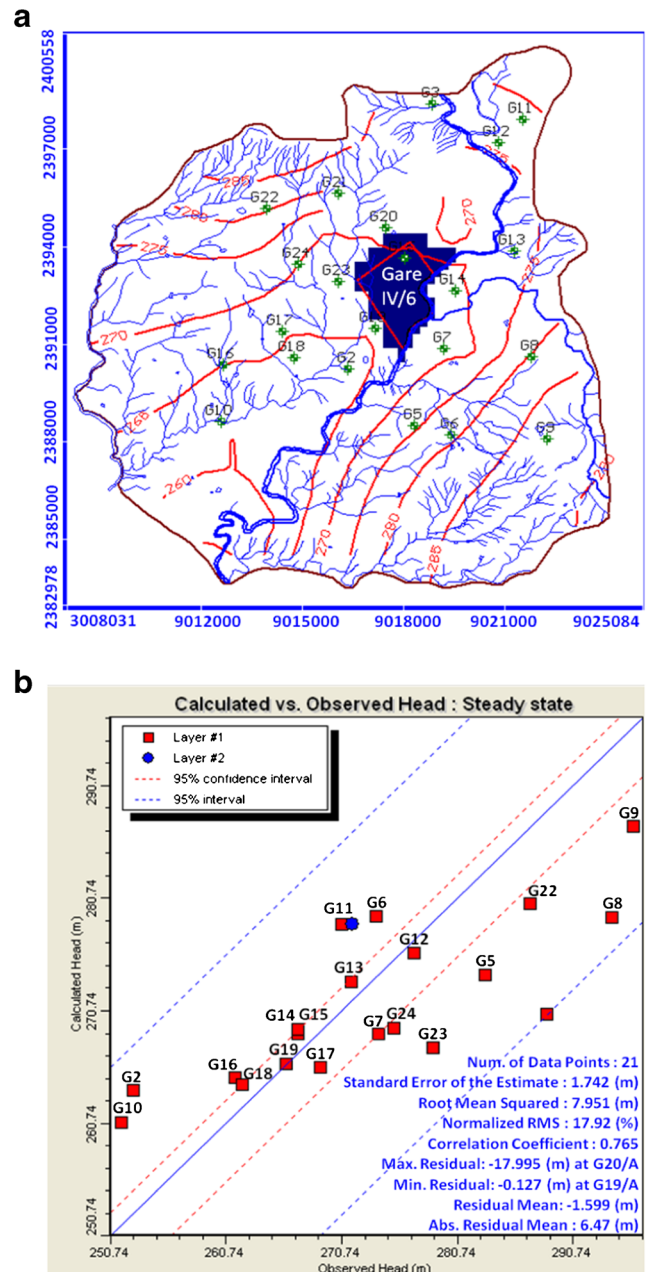


Fig. 8 **a** Zones for groundwater budget covering Gare IV/6 Coal Block, computed groundwater level m (amsl), and groundwater velocity in the groundwater flow model of watershed covering Gare Coal Block. **b** Computed versus observed groundwater level m (amsl) in the groundwater flow model of watershed covering Gare Coal Block

Impact assessment of mining on Kelo River

Kelo River flows from north to south-west direction adjacent to the Gare IV/6 Coal Block and forms the eastern boundary. It has been suggested by earlier studies that the mining authorities may leave a buffer zone of 15–20 m between the hanging wall and the Kelo River. This buffer zone should not be disturbed for mining operations. Also for protection from flooding due to flood

Table 3 Zone budget in the groundwater flow model of watershed covering Gare Coal Block

Inflow		Outflow	
Storage	0.00 m ³ /day	Storage	0.00 m ³ /day
Constant head	0.00 m ³ /day	Constant head	635.70 m ³ /day
Wells	0.00 m ³ /day	Wells	13,301.00 m ³ /day
Drains	0.00 m ³ /day	Drains	0.00 m ³ /day
Recharge	16,756.00 m ³ /day	Recharge	0.00 m ³ /day
Evapotranspiration	0.00 m ³ /day	Evapotranspiration	0.00 m ³ /day
River leakage	41.39 m ³ /day	River leakage	3131.20 m ³ /day
Stream leakage	0.00 m ³ /day	Stream leakage	0.00 m ³ /day
Surface leakage	0.00 m ³ /day	Surface leakage	0.00 m ³ /day
General head	0.00 m ³ /day	General head	0.00 m ³ /day
Zone 2 to 1	606.76 m ³ /day	Zone 1 to 2	335.99 m ³ /day
Total IN	17,404.15 m ³ /day	Total OUT	17,403.89 m ³ /day

flows in the Kelo River, an embankment should be constructed along the proposed buffer zone. Though the Kelo River is not contributing to the groundwater regime much through seepage from open-cut sections of Gare IV/6 block, the small base flow observed during the field investigations may be attributed to leakage from the shallow aquifer in upper Barakar formation, adjacent to the boundary of Gare IV/6 coal block and the Kelo River, exhibiting occurrence of very hard and compact rock which may impede groundwater-surface water (Kelo River) interaction in this reach.

Conclusions

Hydrogeological, isotopic analyses, flow measurement, and groundwater flow modeling in the Kelo River was carried out to assess the impact of coal mining on groundwater-river water and its interaction for mining of Gare IV/6 Coal Block. The base flow from Gare IV/6 Coal Block towards the Kelo River was analyzed. The

Table 4 Zone budget in the groundwater flow model for Gare IV/6 Coal Block

Inflow		Outflow	
Storage	0.00 m ³ /day	Storage	0.00 m ³ /day
Constant head	0.00 m ³ /day	Constant head	0.00 m ³ /day
Wells	0.00 m ³ /day	Wells	226.01 m ³ /day
Drains	0.00 m ³ /day	Drains	0.00 m ³ /day
Recharge	584.44 m ³ /day	Recharge	0.00 m ³ /day
Evapotranspiration	0.00 m ³ /day	Evapotranspiration	0.00 m ³ /day
River leakage	1.06 m ³ /day	River leakage	88.38 m ³ /day
Stream leakage	0.00 m ³ /day	Stream leakage	0.00 m ³ /day
Surface leakage	0.00 m ³ /day	Surface leakage	0.00 m ³ /day
General head	0.00 m ³ /day	General head	0.00 m ³ /day
Zone 1 to 2	335.99 m ³ /day	Zone 2 to 1	606.76 m ³ /day
Total IN	921.49 m ³ /day	Total OUT	921.15 m ³ /day

groundwater flow direction is from west to east towards the Kelo River. The low-permeability values were mostly reported from top Barakars formation adjacent to the Kelo River. Surface water flow measurements also indicate that Kelo River receives base flow from the adjacent upper Barakar formations. The surface water flow increases after the confluence of Bendra and Pajhar Nala in the downstream of GCB. Kelo River water has shown enriched $\delta^{18}\text{O}/^{16}\text{O}$ ratio compared to the groundwater samples except the G22 sample. Delta oxygen ratios further confirm that there is the possibility of only groundwater effluence to the Kelo River. The embedded low hydraulic conductivity shale material in the Kelo Riverbed does not allow much groundwater-surface water interaction in the river reach adjacent to the GCB. Similar enriched δ deuterium ratios in Kelo River water have been found as compared to groundwater in the watershed. These isotopic ratios also support the possibility of only groundwater effluence to the Kelo River from GCB.

Groundwater flow model was constructed for the Gare IV/6 Coal Block and adjacent Kelo River course for assessing the groundwater-surface water (Kelo River) interaction in the area. The hydrogeological data collected during the study period was utilized for construction of the groundwater flow model. The groundwater flow model was calibrated for groundwater conditions prevailing during the post-monsoon period of the watershed. The groundwater balance computed from the model indicates that the Kelo River reach adjacent to the GCB would contribute 88.38 m³/day of groundwater effluence to the river. The groundwater effluence forms a meager component of the total groundwater effluence estimated for the entire length of the Kelo River in the study area. Based on the groundwater flow model results, it is also suggested that the proposed mining operation in GCB may not impact much on the surface water flow in the Kelo River. The suspected seepage from the Kelo River flooding the GCB may not happen as the hydraulic gradient is towards the Kelo River. The proposed buffer zone may be used for the construction of embankment of the Kelo River to prevent flooding of the GCB from surface water breaching from the Kelo river bank.

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