Hydrogeochemical Processes Governing Uranium Mobility: Inferences from the Anthropogenically Disturbed, Semi-arid Region of India

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Received: 26 April 2021 / Accepted: 27 July 2021 / Published online: 4 August 2021
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Abstract
Khetri Copper Belt, Rajasthan, is anthropogenically active and geologically belongs to the Delhi super-group. A study was designed to understand the geochemical processes controlling the elemental mobility in the groundwater. Sampling sites were divided into three zones, i.e. copper, quartzite and granite mine zones depending on the type of mineral excavated. A total of 32 representative groundwater samples were collected and analysed for heavy metals and radionuclide (U) using ICP–MS. A maximum U concentration (average 87 µgL−1) is observed in the quartzite mine zone, and minimum (average 13 µgL −1) is found in the copper mine zone samples. A high concentration of U (maximum of 430 µgL−1) in groundwater is attributed to mineral dissolution due to geogenic and anthropogenic activities. Despite the presence of Jaspura and Gothra granitoid in the copper mine zone, the abundance of U is low suggesting the scavenging of U by sulphides or iron oxides. Additionally, at the confluence of two geological groups, Fe concentration is found high with a low concentration of U which further confirms scavenging of U. It is evident from the results that in the absence of iron-bearing sulphides, U concentration in groundwater would be very high compared to the current concentration. It also indicates low concentration of U in the copper mine zone is due to dissolution of Fe sulphide-rich waste. The present study recommends further research to understand the feasibility of mining waste for the removal of U contamination from groundwater.

Uranium (U) is a carcinogenic radionuclide, and excessive consumption poses a potential health risk to humans (Blantz et al. 1985). U accumulates in organs and tissues of the human body and causes various health hazards (Russell and Kathren 2004; Wei et al. 2019). It leads to chronic disorders of the liver, kidney and bones (Craft et al. 2004; Brugge and Buchner 2011; Katz 2014). The most important route of U entry is through drinking water. World Health Organisation (WHO) recommends 30 µg L−1 as the permissible limit for drinking water (WHO 2011); exceeding this permissible limit could cause chronic health impacts on human beings.

Sources of elements in groundwater are being controlled by both anthropogenic and geogenic processes (Li et al. 2016a, b, 2017, 2018; Ren et al. 2021). Quartz mine containing U minerals in Pinhal do Souto, Portugal, is a source of surface and groundwater contamination, and the concentration of U exceeds in wet season due to dissolution of minerals (Neiva et al. 2014). In Korea, the concentration of U exceeds WHO limit in 160 wells out of 4140 located in the plutonic region governing by desorption and re-dissolution processes. The concentration is above 200 µg L−1 in 24 wells which could cause chemical toxicity in humans on long-term exposure (Shin et al. 2016). In the state of Baden-Württemberg, Germany, the fertilisers and geogenic factors are attributed to rise in U concentration in groundwater exceeding the German legal limit for drinking water (Liesch et al. 2015). Similarly, U contamination in groundwater is also reported in different countries such as Poland (Kozak et al. 2013), France (Cuvier et al. 2015), Spain (Villa et al. 2011), Serbia (Momčilović et al. 2013), USA (Burow et al. 2017), Switzerland (Stalder et al. 2012) and China (Wu et al. 2014).

Groundwater contains a high concentration of U in the different parts of India (Sharma et al. 2019, 2017; Rani et al. 2013a, b; Patra et al. 2013; Duggal et al. 2016; Coyte et al. 2019; Selvi et al. 2016) posing a probable health risk to the community. In the northern part of Rajasthan,
the concentration of U crosses the WHO permissible limit for drinking water and the consumption of groundwater is unsafe for human health (Rani et al. 2013a, b). U is harmful to human health due to its chemical and radioactive toxic nature. The long-term consumption of groundwater with high concentration of U could lead to kidney and bone problems. Hence, it is important to understand the geochemical processes governing U mobility in natural conditions.

The high content of uranium is found in the forms of carbonates (andersonite, bayleyite and grimselite), phosphates (autunite and torbernite), oxides (metaschoepite, metastuhtite and uraninite) and silicates (uraninite and swamboite) (Deditius et al. 2008; Gorman-Lewis et al. 2007; Gorman-Lewis et al. 2008a, b; O’Brien and Williams 1983; Ray et al. 2011; Locock and Burns 2003; Gorman-Lewis et al. 2009). Uraninite is insoluble and is readily oxidised through rock-water interactions to soluble uranyl ions (U(VI) O2−(s)) through dissolution, complex formation and desorption-sorption (Tricca et al. 2000). Under anoxic conditions reduced sulphur and iron species may reduce U(VI) to U3O8/UO2 (Gong et al. 2016) (Eqs. 1–4).

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\begin{align*}
\text{UO}_2^{2+} + \equiv \text{FeS} & \iff \equiv \text{S}^{2−} - \text{UO}_2^{2+} + \text{Fe}^{2+} \quad (1) \\
\equiv \text{S}^{2−} - \text{UO}_2^{2+} & \iff \equiv \text{S}^0(s) - \equiv \text{UO}_2(s) \quad (2) \\
\text{FeS}(s) + \text{H}_2\text{O} & \iff \equiv \text{Fe}^{2+} + \equiv \text{HS}^{−} + \equiv \text{OH}^{−} \quad (3) \\
\text{UO}_2^{2+} + \equiv \text{HS}^{−} & \iff \equiv \text{UO}_2(s) - \equiv \text{S}^0(s) + \equiv \text{H}^{+} \quad (4)
\end{align*}
\]

Geological features such as fractures and faults also create oxidising conditions. Under oxic conditions, dissolution of Fe-rich minerals increases and thus in groundwater (Smith and Roychoudhury 2013). Groundwater present in the fracture zone is more prone to contamination. Fracture zones yield most of the water and are also helpful in locating the available water resources (Banks et al., 1992). The iron-bearing minerals adsorb and immobilise the U(VI)-bearing species at circumneutral pH under oxidising conditions (Li and Kaplan 2012). U gets mobilised in the presence of oxygen and nitrate in groundwater (Watson et al. 2013).

Due to the complex behaviour of U, geochemical processes governing the U mobility in groundwater are difficult to understand. Considering this, the region active for mining for different types of minerals such as granite, quartzite and copper is selected. The selected study area would be helpful in better understanding the perspectives of U mobility under the influence of different types of anthropogenic and geogenic factors. The main aim is to understand (1) the impact of mining on the concentration of Fe, Mn and U and (2) understanding the perspectives of U mobility under the influence of different types of anthropogenic and geogenic processes.

### Study Area

The study area is well known for copper mines, and it is located in the Jhunjhunu district of the Indian state Rajasthan (Fig. 1a). It is located at an altitude of approximately 370 m above the mean sea level with N 28° 04.070’ latitudes and E 75° 49.294’ longitudes. The region is covered by the Thar desert in the western direction and Aravalli ranges in the eastern direction. Scattered sand dunes and Aravalli hills are present in the region. The region is famous for copper mines since historical times, and the region is explored for mining at scattered locations extending from Singhana (north) to Raghunathgarh (South). Mines for quartzite (Ishakpura) and granites (Papurana) are also active in the area.

Rocks of Khetri complex are characterised by magmatism metasomatism and comprise metasedimentary and igneous intruded by granitoids (Sarkar and Dasgupta 1980; Gupta et al. 1998). The study area falls in the Aravalli–Delhi fold belt and is physically divided into northern (North Delhi fold belt) and southern (South Delhi fold belt) parts by Kantli fault (NW–SE transverse) (Gupta et al. 1998). Rocks of the Delhi super-group undergo many folding and polyphase metamorphisms (Kaur et al. 2012). The Khetri belt falls in the Northern Delhi fold belt. The metasedimentary rocks are majorly made up of two groups based on age, i.e. an older Alwar (dominate in psammite) and a younger Ajbaghar group (dominate in pelites) (Heron 1923; Das Gupta 1968). Most of the region is covered by the Ajbaghar (metamorphosed argillites and calcareous) and Alwar group (arenaceous). The rocks of Ajbaghar group are composed of schists and phyllites and intruded by basic rocks such as granites and amphibolites. The rock composition of Alwar group varies from pure ortho-quartzites to arkose with bands of magnetite, hematite and amphibole. At the confluence of different lithological units (Ajbaghar and Alwar), major faults and fractures are observed (Roy Chowdhury and Das Gupta 1965). The juncture of Alwar and Ajbaghar is also enriched in iron oxide-copper–gold deposits (Knight et al. 2002). The metasomatic alternation of granites in the region is enriched in U and rare-earth elements mineralisation (Kaur et al. 2014).

The aquifers in the region are found in quartzite and alluvium (Central Groundwater Board, 2008). The alluvium aquifer (30 to 70 m) is thicker compared to quartzite (10 to 15 m). However, due to overexploitation of groundwater resources and lack of precipitation the water table is declining rapidly from last few decades. Many wells are already dried off in the region, and at some locations, the water for domestic purposes is being transported from other places.
The groundwater is present in fractures and joints in the quartzite aquifer. Most of the study area falls in the quartzite aquifer zone. The alluvium aquifer covers the northern part of the study area near the Singhana. The groundwater flow is fast in quartzite aquifer compared to alluvium due to steep gradient in the earlier. The groundwater flows from the hills at Khetri Nagar (stretching south-west–north-east) to low-land areas in the eastern and northern directions.

**Methodology**

**Sampling and Elemental Analysis**

The sampling locations were categorised into 3 zones, i.e. copper mine zone (CMZ), quartzite mine zone (QMZ) and granite mine zone (GMZ) depending on the type of mine. Considering each mine as a centre point, the sampling locations were distributed systematically in north, east, south and west directions. From each direction, a total of approximately 3 samples were collected after the interval of 2–3 km depending on the availability of hand pump. The main constraint of sampling was the non-availability of functional hand-pumps. To avoid contamination due to the pipeline, the groundwater was pumped for 5 min before sampling.

The groundwater samples were collected in May 2019. A total of 32 groundwater samples, i.e. 7, 13 and 12, were collected from QMZ, CMZ and GMZ, respectively. For the perseveration of water samples, pH is maintained below 2 by adding few drops of concentrated Supra-pure HNO₃ (Radojevic and Bashkin 1999). After the addition of HNO₃, the samples were filtered using standard pore size 0.45-μm syringe filters at the sampling site. Preservation and filtration were done at the field to prevent the chemical changes in the collected samples. Narrow-mouth polypropylene bottles were used for the sample collection. Before the sampling, the sample bottles were washed with Milli-Q ultrapure and the sample itself to avoid contamination. Parameters such as pH, EC and temperature of the samples were measured in situ using a portable pH meter (Hanna instrument, H196107). The quantitative estimation of Fe, Mn and radionuclide (²³⁸U) concentration was done at Inter-University Accelerator Centre (IUAC), New Delhi, using inductively coupled plasma mass spectrometry (ICP–MS). The ICP–MS was...
calibrated using standard solutions of 1, 20, 50 and 100 µg/L prepared from 1000 µg L⁻¹ multi-element stock solution (1000 µg L⁻¹) via dilution process. For QA/QC, standards, namely DGH, MBH, JB-1a and AMH, were used (Rathi et al. 1994; Imai et al. 1995; Saini et al. 2013). To assess the precision and accuracy during the analysis, elemental concentration in the blank (Milli Q prepared from 18.2 MΩ·cm Ultrapure, Sigma-Aldrich) and standards were measured after every 10 samples. The elemental detection limit varies from 0.1–1000 µg/L for Fe, Mn and radionuclide. In the present study, ICP–MS was used for the analysis; however, other instruments such as fluorimetry, flame atomic absorption spectrometry and inductively coupled plasma optical emission spectrometry are also widely used for the estimation of concentration of U in water, rock and soil, and the modifications suggested by Pradhan et al. (2020a, b), Pradhan and Ambade (2020a, b) and Pradhan and Ambade (2019) are recommended.

Statistical Analysis

The statistical parameters such as average, standard deviation and median were calculated for the interpretation of data. ArcGIS 10.6.1 was used for locating the sampling locations on the geological map using GPS locations. The inverse distance weighting (IDW) method was used for the multivariate interpolation of U concentration. Graphs were plotted using the Grapher software (version 10).

Risk Assessment

Drinking water containing excessive U for a longer duration adversely affects kidneys and bones (Zamora et al. 1998; Kurttio et al. 2005). The risk caused by excessive intake of U is calculated in terms of average daily dose (ADD) via Eq. 5 (WHO 2011; Li et al. 2019; Wu et al. 2020; He et al. 2020; Ji et al. 2020):

$$\text{ADD} = \frac{U \times DWI \times EF \times ED}{LE \times BW}$$

The full form of the used abbreviation is as follows: $U =$ uranium concentration (mg/L), $DWI =$ daily intake of water (4.05 L per day) (Saini et al. 2016), $EF =$ exposure frequency (350 days per year) (USEPA 1999), $ED =$ exposure duration (65 years) (WHO, 2011), $LE =$ life expectancy (65 years with 365 days per year, i.e. 23,725 days) and $BW =$ body weight (53 kg of an adult Indian standard person) (Sharma et al. 2017).

Hazard quotient (HQ) indicates the probable health risk caused by the ingestion of uranium on the consumption of contaminated water. HQ values less than 1 suggest no adverse health effects due to the consumption of uranium contaminated water (AERB 2004), and it was calculated using Eq. 6 (He and Li 2020; He et al. 2021; Wei et al. 2021).

$$\text{HQ} = \frac{\text{ADD}}{\text{RD}}$$

where RD indicates the reference dose.

Results and Discussion

Variation in Concentration of Heavy Metals and U

U concentration varies from 0.03 to 430 µg L⁻¹ with an average of 37 µg L⁻¹ indicating high contamination in the region. U concentration exceeds or near the WHO permissible limit (30 µg L⁻¹) at some of locations. It is observed high at all the sites falling in quartzites mine zone with an average concentration of 87 µg L⁻¹. Fe concentration is also observed very high with an average concentration of 2.48 ± 3.31 ppm. Fe exceeds BIS permissible limit (0.3 ppm) at all the sites except two locations.

High concentration of Mn (133 µg L⁻¹) and Fe (6.56 mg L⁻¹) in the copper mine zone compared to quartzite and granite mine zone is attributed to the dissolution of sulphides. The average U concentration is observed lowest (13 µg L⁻¹) in the copper mine zone. Baidya and Pal (2020) reported mineralisation of uraninite near the Kolihan and Chandmari Cu deposits confirming the abundance of U in the copper mine zone. Uraninite is the probable source for U in the groundwater. The low concentration of U in groundwater of copper mine zone is attributed to the scavenging capacity of sulphides such as Mackinawite (FeS₀.₉) or Fe-oxyhydroxides (Leermakers et al. 2016; Abdelouas et al. 1999). It also suggests immobilisation of U in groundwater by sulphide dissolution. Thus, the present study confirms that sulphide mines have a buffering capacity to control the U mobilisation in groundwater.

Source of U

The presence of U-rich granites and albetised quartzite rocks (GSI 2011) is a major source of U in groundwater of the north-eastern part of Rajasthan. Statistical variation of U concentration is classified into three classes (Fig. 2). The highest value of the first class is 30 µg L⁻¹ which is a WHO permissible limit, and the rest are further classified into two classes, i.e. high (31–120 µg L⁻¹) and severe (above 120 µg L⁻¹). In the copper mine zone, U (90 µg L⁻¹) concentration is observed high at CE2 located near to the confluence of two geological groups (Ajabgarh and Alwar) compared to other locations. Fractures at the confluence of geological groups create oxic conditions which lead to the dissolution of minerals and permits U mobilisation into
groundwater (Abdelouas et al. 1999). Adithya et al. (2019) observed that groundwater in the oxidising conditions contains a higher concentration of dissolved U. Faults that occur at the juncture of Ajabgarh and Alwar groups are attributed to the high mobility of U in groundwater. The current study is preliminary in nature, and further detailed study is needed with more number of samples from the confluence of geological groups. High contamination at ME3 (80 µgL−1 U) is due to its closeness to albitite line. The albitite line is enriched in uraninite (Ray, 1990), a potential source of U in the groundwater. ME3 is located in close proximity of Dabla granitoid, and illegal small scale mining is also observed in its surroundings. The high concentration of U in the groundwater is also attributed to mining activities.

MC and MS1 with a U concentration of 216 and 31 µgL−1 are located close to active granite mines. Sedimentary rocks derived from granites are enriched in uranium concentration (Hobday and Galloway 1999). Almost all the locations in the quartzite mine zone are contaminated with U indicating its geogenic origin in the groundwater.

Classifying the samples according to geological groups, the concentration of Fe and Mn is observed high at the confluence of the Ajabgarh and Alwar groups (Fig. 3). Natural recharge leads to the dissolution of minerals in the fracture zones. The elemental concentration is observed high in the fracture zone due to the presence of the oxic condition. Fractures and faults at the confluence of two geological groups create oxic conditions which enhance the dissolution of Fe-rich minerals. The dissolved Fe minerals act as a scavenger for U, thus reducing the U concentration, which is supposed to be high. At the Alwar group, Fe and Mn concentration are lowest among all the geological setups and U concentration is the highest. It indicates that in natural conditions sulphide mines acts as a buffer and control the dissolution of U in groundwater. In the Khetri region, despite uranium-rich minerals, U concentration is observed low in CMZ compared to its neighbouring locations, which is due to the buffering capacity of sulphide mines.

In the KBC region, the abundance of uraninite is observed in close vicinity to quartzite and copper mines (Ray 1990; Baidya and Pal 2020). However, a high concentration of U is observed in the groundwater of the quartzite mine zone comparative to the copper mine zone. In the copper mine zone, a high concentration of Fe is observed and it is well known that the Fe is a scavenger for U in natural conditions.
A strong correlation between Fe and U suggests that Fe scavenges U from the groundwater in the copper mine zone.

**Processes Affecting U Concentration in Groundwater**

High U content in groundwater is due to weathering or anthropogenic dissolution of U-bearing minerals. The origin of U in groundwater is geogenic, but it is also significantly influenced by anthropogenic activities. Both geogenic and anthropogenic factors will be discussed in detail in the following sections.

**Geogenic Processes**

The primary source in the region is U-bearing silicate minerals such as granite and uraninite. The region is known for Cu mineralisation along with the occurrences of Au±Fe±Co±Ag±REE±U±P (Baidya et al. 2017). The geology of the region is very diverse and made up of different types of parent rocks. Fractures and faults are common features found at the boundary of two-parent rocks. Penetration of oxygen through fractures and faults create oxidising conditions. Percolation of oxidised water into the fractured granite (Garralón et al. 2006) and redox reactions dissolves U-rich minerals releasing U through rock water interaction (Devaraj et al. 2021). High EC up to 5350 μs/cm in the region further confirms a high rate of mineral dissolution (Punia and Siddaiah 2017). Thus, a high concentration of U in groundwater is attributed to mineral dissolution, faults or fractures in the region.

U does not show a significant correlation with Fe except at the confluence of Ajabgarh and Alwar group. At the confluence of Ajabgarh and Alwar group, fractures and faults promote the dissolution of sulphides and U-enriched silicates. U and Fe have a significant correlation coefficient ($R^2 = 0.97$) at the confluence of Ajabgarh and Alwar group which indicates a strong association between U and Fe. Additionally, fractures and faults create oxic conditions which are responsible for the desorption of U from clay minerals, metal oxides and oxyhydroxides (Zhou and Gu 2005; Yang et al. 2014).

U concentration is observed very high, i.e. approximately three times of WHO permissible at QW3 (430 µgL$^{-1}$), MC (216 µgL$^{-1}$), CE2 (90 µgL$^{-1}$) and ME3 (80 µgL$^{-1}$). The Fe concentration is comparatively low at all the sites, i.e. QW3 (1 mgL$^{-1}$), MC (0.3 mgL$^{-1}$) and ME3 (1.9 mgL$^{-1}$) except at CE2 (32 mgL$^{-1}$). At CE2, both U and Fe concentrations are high compared to other locations indicates low U sequestration by Fe. Mn concentration is also high (278 µgL$^{-1}$) at CE2 indicating Mn reducing condition mobilises U in the groundwater. Mn reducing conditions mobilise U concentration in groundwater (Riedel and Kübeck 2018). It also indicates U mobilisation capacity of Mn exceeds the sequestration capacity of Fe at CE2.

** Anthropogenic Activities**

Anthropogenic activities (industries or mining) lead to overexploitation or pollution of resources. Granite, quartzite and copper mines are major anthropogenic activities in the region. The concentration of U is found high near quartzite and granite mines due to the abundance of granite minerals. Neighbouring quartzite mines groundwater resources are overexploited, and groundwater resources are completely depleted at some locations. Most of wells are dried up in the region, and water is being imported from neighbouring locations for domestic purposes (Punia and Siddaiah 2017). Overexploitation is a situation where the rate of groundwater extraction exceeds the average rate of aquifer recharge (Foster and Loucks 2006). U mobilisation is also attributed to overexploitation or decline of groundwater resources in India, specifically in state of Rajasthan and
Gujarat (Coyte et al. 2018). The groundwater fluctuations also release U in the groundwater (Devaraj et al. 2021) and withdrawal of huge quantity of groundwater during mining fluctuate groundwater level. Quartzite mines lie in the Alwar group comprised of quartzite marble, schist and gneiss in addition to Gothra granitoid that enhances the dissolution of U-enriched mineral resulting in high concentration of U at QW3 (430 µgL⁻¹). Due to depletion of groundwater resources, the agricultural activities are reduced significantly in the region since last decades. The role of fertilisers and irrigation practices in the mobilisation of U (Riedel and Kübeck 2018) is ruled out. The anthropogenic factors such as overexploitation of groundwater resources and mining activities disturb the redox reactions or rock–water interaction affecting the dissolution of U in the groundwater.

**Risk Assessment**

Results show that at some of the locations HQ value lies near 1 and at four locations (QW3, CE2, MC and ME3); it is above 1 indicating the probable adverse health impacts (Fig. 4). The reference dose value is taken as 4.53 mg kg⁻¹ day⁻¹ (AERB 2004). HQ varies from 0 to 7 with an average of 0.61 ± 1.33. Consumption of U-contaminated water leads to nephrotoxicity, genotoxicity and developmental defects in humans (Brugge and Buchner 2011; Lariviere et al. 2007). Maximum HQ values ~ 7 at QW3 demands further studies to assess the health impact of U in the region. The long-term consumption of the groundwater could cause cancer in the community. However, the estimation of HQ suggests only the probability of risk and actual adverse impacts on human health needs to access at ground level. The field investigations and surveys are needed to track the health record of the community. The natural U concentration is observed elevated and exceeds the WHO permissible limits in many parts of world, and available data are not enough to confirm water-related disease among community because of lack of diagnostic facilities (Waseem et al. 2015).

The elevated concentration of U (0.83 ± 0.64 µgL⁻¹) observed in cow milk in the U mining and exploration region of Zambia (Haakonde et al. 2021) indicates the bio-accumulation of U in the domestic animals. A maximum concentration of U (430 µgL⁻¹) with HQ value of 7 recommends further research considering its impact on fauna and flora. The groundwater is being used for agricultural and domestic purposes in the region depending on its availability. The bio-accumulation of U in agricultural fields (Galhardi et al. 2020) and domestic animal’s increases cancer risk among the community. Monitoring and assessment of groundwater prior human consumption is recommended.
Future Research Scope

In the present study, U concentration is observed less in copper mining zone compared to other locations despite the abundance of uraninite or granite, a source of U. It indicates that Fe-hydroxides or FeS are potential scavenger of U from the groundwater. Mine waste enriched in iron sulphides is generated in huge amount across the globe (Thom et al. 2013; Eurostat, 2017). Thus, the present study purposes the application of mining waste (tailings and overburden rocks) for the treatment of U concentration from groundwater. The natural attenuation of U from groundwater using mining waste needs further research, as mining waste is also a source of heavy metal contamination.

Mining waste is enriched in heavy metals (Punia et al. 2017), a source of groundwater contamination (Olias et al. 2021; Zhao et al. 2021). Mining waste highly enriched in FeS generates acid mine drainage (AMD) and contains downstream groundwater. Identification of optimum concentration of mining waste for the removal of U from groundwater is important. Achieving a balance between contamination and natural attenuation by mining waste is a topic of debate and needs further research. The dose of mining waste in groundwater after a regular interval of time would be beneficial as excessive FeS would generate AMD. A research is needed to identify the appropriate dose of mining waste and exposure duration to achieve the better removal of U from the groundwater.

The Fe-(hydr)oxides and goethite have a capacity to remove U from groundwater via complexation process (Logue et al. 2004; Gustafsson et al. 2009). Beneficiation of sulphide ore generates Fe-enriched mining tailings in abundant quantity and oxidation transforms sulphide minerals into stable goethite (Kim and Kim 2021). Iron oxyhydroxides and goethite control U mobility in the environment (Lahrouch et al. 2021). Nowadays permeable reactor barrier (PRB) is widely used technology for the treatment of groundwater. Use of mine tailings in PRB could be a probable solution for the treatment of U contamination. Further research is needed to facilitate the use mine waste as a reactive material for the manufacturing of PRB. The PRB coated with reactive material of zero-valent iron nanoparticle is found feasible for the removal and sequestration of U from groundwater (Li et al. 2015). The injection of iron nanoparticles effectively removes U contamination, but the influence of other ions such as calcium, sulphate and carbonate on the water resources needs more studies (Jing et al. 2019).

The huge quantity of mining waste is burden for environment, and its use for the treatment of groundwater would solve the problem of its disposal. The preparation of nanoparticles of Fe also increases the implementation cost at the larger scale, and the application of mining waste for the same would reduce the cost. Iron sulphide immobilises U by reduction or ion exchange processes (Gong et al. 2016; Hua and Deng 2008). Further research is needed to identify the weight% concentration of mining waste which could be used for the removal of U contamination from groundwater. As per our knowledge, no study has been carried for the removal of U contamination from groundwater using mining waste.

Conclusions

The region is active in mining, so the impact of anthropogenic activities cannot be neglected. It is observed that sulphide mine acts as a buffer and prevents the dissolution of U-rich minerals in groundwater. U concentration is found high in quartzite mine zone due to lack of buffers, i.e. sulphides or Fe-hydroxides. The study recommends immobilisation of U in groundwater using mining waste enriched in Fe sulphides and hydroxides. U concentration is observed high near to the confluence of two geological groups compared to other locations. Faults or fractures between two rocks cause oxic conditions, and oxygen leads to the dissolution of Fe-rich minerals. Source of U in groundwater is uranium mineralisation in granites, gneisses and quartzite rocks. The presence of fractures and faults significantly affects the uranium concentration in groundwater. The origin of U in the groundwater is geogenic in nature, but the influence of overexploitation of water cannot be neglected. Overexploitation of groundwater increases the ionic concentration in groundwater. The health risk assessment for cancer indicates the HQ values ~7 demand further studies to assess the health impact of U in the region.

Acknowledgements The postdoctoral fellowship of the Indian Institute of Technology Guwahati is acknowledged. The authors also acknowledge the support of IUAC for extending the ICPMS facility under the Geochronology project funded by the Ministry of Earth Sciences, Govt of India. The authors also acknowledge the help of Dr. Sumaya Prasad Dhal (Research Associate), IUAC, in the handling of the instrument.

Conflict of interest Authors declare no conflict of interest.

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