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True cost of coal: coal mining industry and its associated environmental impacts on water resource development

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Keywords

Coal mining; Coal energy; Groundwater quality; Environmental impacts; Sustainable development

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True cost of coal: Coal mining industry and its associated environmental impacts on water resource development

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Abstract

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1. Introduction

The development of an economy is linked with a country's natural resource potential. These natural resources and environment are the primary factors influencing sustainable development. For decades, mining and sustainable development have been the focus of significant research for academic and public policy institutes worldwide [1,2]. Coal, being the cheapest fuel, is the strategic resource in development, energy security. Its economical pricing and its geographical distribution patterns render it one of the most favored and dominant energy source for both developing and developed countries (e.g., Australia, China, Germany, India, Japan, South Africa and the US) [3]. Among the natural resources, coal is one of the three main energy resourcesand used to generate 40% of the world's electricity [4]. This coal consumption seems to be amplified to 50% by 2030. Since 1961 coal and coal based power plants have brought prosperity toglobalpower and energy sectorsand soonseveral hundred millions people will get coal-generated for the very first time in thehistory [3]. However, the mining and processing of coal has had significant negative impacts on the environment, human health, and climate change. In 2012, for example, the global extraction of 7.8 billion tons of coal [5] contributed to 39% of global CO_2 and-methane production and to the deaths of millions of miners [6−8]. The air quality of coal mining areas around Jharkand, India from 2010 to 2011 greatly exceeded recommended concentrations of

NO$_2$, SO$_2$ and total suspended particles (TSPs) [9]. Undergroundcoal mining has converted the Appalachian mountains of West Virginia into valleys and turned its streams orange with acidic water [3].

Coal and water are two interrelated resources. Water is the most crucial component in mining industry that is consumed at all stages of a mine's life [10]. The hydrological consequences of coal mining are significant and complex, as mining can lower water tables, disturbing natural drainage patterns, and can cause surfaceand sub-surface aqueous contamination. The effects of exploration and mining activities on both water quantity and quality have been documented in a variety of studies [2,11–13]. Water table instability, potential flooding, uncontrolled disposal and collapse of waste dumps are significant challenges to the sustainable mining of coal. Despite the fact that coal mining is globally a relatively small water consumer, 7 to 9 BCM (billion cubic meter) of water are consumed annually [14]. In China, annually 120 billion-m^3 water (i.e. 20% of total national consumption) is used in the underground and surface coal mining. Whereas on average extraction of one coal produced 4m^3 wastewater [15]. In the Angul-Talcher region of Odisha (India) 86.26 million-m^3 of water is extracted from river systems for the coal industry [16]. The legacy of mining activity due to poor extraction practices, improper water disposal, and mine tailingscan also negatively impact the water cycle [17,18]. In China, for example, the extraction of one ton coal depletes water resources by 1.32 m^3, and causes the contamination of 0.88 m^3 of water bodies and damage to 0.17 m^{3}of ecological environments with a consequent economic loss of about 50.61 Yuan [19]. The utilization of one ton of coal in thermal power sectors costs 86.61 Yuan and depletes water resources by 26.35 m^3 [19]. The coal industry does paycompensation costs. In China this industry pays asewage discharge fee of 1.4 Yuan per

equivalent to the soil erosion fee, water resource fee of 0.1–1.6 Yuan/m^3, anda compensation fee against soil erosion and soil conservation of 0.5–1.5 Yuan/t [19]. Yet it requires the revision in real terms to establish a true coal-related water resource cost. Overall, more than 50% of the world's largest coal producers or consumers face water stress in their region. For example, major coal producers such as Japan, Indonesiaand South Korea have drastically increased water consumption due to coal mining, and are designated as highly water stressed countries [20]. Agricultural, fishery and tourism industries are also affected by coal mining [21–25]. For instance, Acid mine drainage (AMD) from abandoned coal mines in Pennsylvania degrade 8800 km of streams and rivers, resulting in annual loss of 653 million Yuansfromthe fishery industry [26].

The aim of this review article is to determine the trends and impacts of coal mining on water resource development (i.e., the inherent cost of coal). The information presented will highlight the causes and processes that contaminate waters and cause fracturing and subsidence of overlying strata, disrupting hydrological pathways. This review will help to formulate environmentally sustainable coal mining operations.

1.1. Coal mining effects on water quality

Coal mining can pose serious threats to surface and sub-surface waterquality, and it can also impact on drinking water availability in many mining areas. It affects watersboth physically and chemically. Physically it causes silting and decline of water quantity. Chemically coal mining can cause AMD and cause the release of metallic and (metal(loid)) compounds to receiving waters (Fig. 1).

Coal resources are extracted by surface and underground mining. Both of these activities can disrupt aquifers, resulting in increased rates of
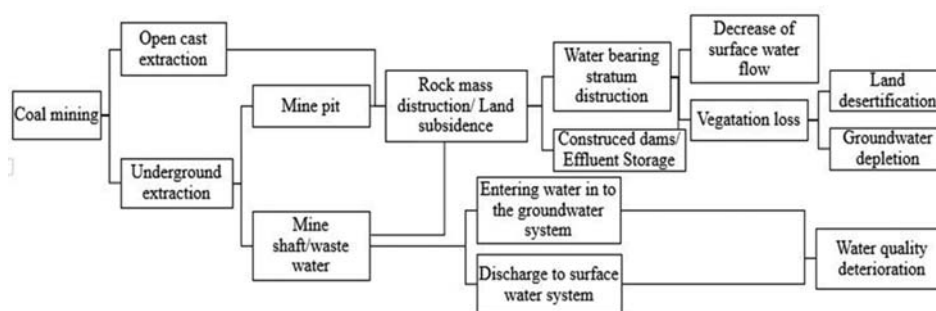

Fig. 1. Impacts of coal mining activities on water resource development (modified from Ref. [19]).

evaporation, permeability and contamination [27]. A highly complex interaction exists between coal extraction and water resources, leading to potential impacts on both hydrology and water quality at each stage of a mine's life.

A five year intensive study conducted in Pennsylvania showedthat about 9% of the total water supplies were directly affected by the coal mining-induced subsidence in the region [24]. Various natural features and ways by which mining operations contaminate water sources comprised of types of aquifers and rocks, geochemistry of the coal seam its stratum and adjunct aquifers, the topography of the area.

Hydro-geochemical processes including; cation exchange reactions, water−rock interaction, and water flow also affects geochemistry and evolution of these aquifers [28]. Coal extraction can enhance the salinity (conductivity) of runoff and watersheds [29,30], runoff and base flow [30,31], sediment, metals, sulfate water and pH as a result of acid neutralizing processes [32,33] and seam bed erosion [34]. Approximately 40% of the groundwater of Northern Province of China is affected by coal mining activities [28]. In comparison, water contamination rateof coal mining region of South China is 2.4 fold than the average national level, whereas it is 3.5 times than the northern regions of Inner Mongolia, Ningxia, Shaanxi, and Gansu [19].

Another important environmental concern of coal mining is the drainage water [35]. Coal mining in the entire Appalachian mountain range of West Virginia has been shown to make its streams run orange with acidic water [3]. Abandoned coal mines in Scotland are considered to be the second most significant surface water quality threat [36]. Elevated concentrations of Hg and other physicochemical parameters (TDS, Na^+, F^-, SO_4^2, and trace elements) were also reported in the Thar coal aquifers of Sindh (Pakistan) [37]. Acid mine drainage can also affect agricultural yield; for instance, fields of the Barapukuria coal mining area (Bangladesh) irrigated with coal mine drainage had low yield of rice [17].

The produced mine water can have significant environmental impacts. In China, coal and iron producing mines produce 1.2 billion tons/year of waste water [38]. This mine water undergoes inorganic and microbial oxidation when comes in contact with water and atmospheric oxygen, and produces ferric hydroxide and S-rich acid known as acid mine drainage (AMD). It affects the water quality in term of lowering its pH, and increasing its total solids contents (TDS), trace elements and sulfate concentrations [39−41]. The volumes produced can also be large: 41 coal mines in Korea, for example, produce 141,000 m^3/day AMD [42]. The abandoned mines of Young Dong and Young Jin mine (Gangneung coalfield, Korea) discharge 5000 m^3d^{-1} mine water that severely deteriorate water quality [43]. Around 76486 ha of land and 4989 km of streams covering 44 counties of Pennsylvania are also affected by AMD [44]. In the USA, abandoned coal mines polluted over 14,484 km of streams and 0.44 million hectares of land with mine water [44].

The coal mining industry also produces tons of solid waste [45]. It is one of the biggest source of solid waste and accounted for 40% of the total solid waste generated in China [44]. These coal wastes cover an area of 15,000 ha [46]. Coal waste rock dumps generally contain sulfideand iron minerals e.g. pyrite(FeS_2), chalcopyrite($CuFeS_2$), sphalerite $(Zn,Fe)S$, galena (PbS), troilite (FeS), and pyrrhotite (FeS), siderite $(FeCO_3)$, illite(K,H_3O) $(Al,Mg,Fe)_2(-Si,Al)_4O_{10}[(OH)_2(H_2O)$, ankerite $(Ca(Fe,Mg,Mn)(CO_3)_2)$ [47,48]. Under oxidizing conditions, these sulfide minerals break down followed the following acid forming equation (Eq. (1)).

$$FeS_2 + 3.75O_2 + 3.5H_2O = Fe\,(OH)_3 + 2SO_4^{2-} + 4H^+ \qquad \text{(Eq. 1)}$$
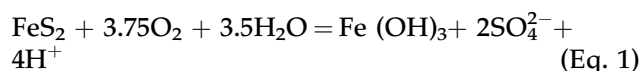
Acid mine drainage acidifies nearby water and soil bodies (Table 1). For instance, low pH and high TDS of the Olifants River (South Africa) and groundwater contamination of salt range of Chakwal (Pakistan) are the result of such reactions, which in turn were attributed to intensive coal mining [63,64]. Coal mining-derived AMD can also have relatively high concentrations of metal(loids) such as Ag, As, Cd, Cu, Cr, Hg, Mn, Mo, Ni, Pb, Sb, Se, Zn, U and V [41]. Significant correlations of sulfur with these elementssuggests that the degradation of other sulfide minerals, which are the constituents of coal, likely occurs [48]. For example, groundwater in the Indian Coal Basin is highlycontaminated with such metalloids as a result of AMD, mine tailings and leachate [59]. The aqueous pH, temperature, content of Fe and O_2, water saturation rate, chemical activation energy and rate of biological degradation were shown to be the primary controls on AMD generation [65].

Coal mining-derived AMDcan be neutralized [66] by either a) inhibiting the acid generation reactionsexposure of oxygen and water to pyrite and other sulfide minerals or b) reactions with carbonates (aragonite, calcite, dolomite, and siderite), silicates, aluminosilicates, and hydroxides of Fe and Al (Eq. (2)) [45]. Such alkaline mine waters are produced, for example, by neutralization and coal mining-dervied AMD in Scotland [33].

Table 1. *Examples of coal mining impacts on water and soil contamination.*

Country	Region	Source of pollution	Water chemistry	Remarks	Reference
Australia	New South Wales, Southern Coalfields	Land subsidence induced by long wall mining	Water became more saline and had high concentrations of Fe, Mn, Sr, and Ba	Connectivity of ground and surface water accelerated water–rock interactions and dissolution of minerals	[49]
Bangladesh	Barapukuria Coal Mining Area	Dewatering	pH, EC, Temperature, HCO_3^-, NO_3^-, SO_4^{2-}, Cl^-, Na^+, K^+, Mg^{2+}, Ca^{2+} and Fe (total) werewithin the tolerable limits of WHO water quality guidelines.	Shallow groundwater in the Barapukuria coal mining area was almost unavailable in summer seasons. Reduction of rice production by 40–50% was also observed.	[17]
		Mine Drainage Water (MDW)	Acidic pH, high EC, K^+, Mg^{2+}, Ca^{2+} Fe, Cl^- and NO_3^- and high metallic element content	Affected soil fertility and retarded plant growth	[50]
	Dinajpur, northwestern Bangladesh	Drainage water and groundwater contamination	Mn, Cu, Co, Zn, Pb, Sr and Ni released from mine effluent contaminated the water reservoir in the irrigation zone	55% of the mine drainage/irrigation waters and 50% of the groundwater were moderately to highly contaminated	[51]
Brazil	Figueira region, Paraná,	Acid mine drainage (AMD)	Acidic pH, elevated levels of SO_4^{2-}, As, Fe, Mn and Zn	AMD generated in the bituminous coal mining activities was a potential source of metals and As to water systems.	[52]
	Morozini River basin	abandoned coal mines	lakes showed high concentrations of SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, K^+, Fe, Al, Ba, Si, Zn, Ni, Sr, B, Cd, Cr, Pb and Cu.	Lakes becomes unfit for recreational activities	[53]
China	Jinci Spring area in Shanxi Province	Mining impacts on water systems	High SO_4^{2-}, TDS, NO_3, Ca^{2+}	Coal mining changed runoff, recharge and discharge paths	[13]
	Wuhai City	Leaching of coal piles/ solid waste	As, Co, Mn, Mo, and B were highly enriched in the soils. Underground and surface waters had high As and Ni	Soils and waters were highly threatened due to the leaching of solid waste	[54]
	Shandong Province	Coal mining	Water is oxic in nature and had high SO_4^{2-} content	Groundwater quality deteriorated	[55]
Germany	Kahnsdorf	Coal spoil dumps	Acidification to pH 2.6	Pit lake of the area caused acidity of surface water	[56]
Greece	Ptolemais and Meliti opencast lignite mines	Flooding	High content of As, SO_4^{2-} and trace elements (Cd, Cr, Hg, Ni, Zn, and Pb) was observed	Water quality (subsurface and streams) deteriorated	[57]
India	Makum Coalfield, Tinsukia district, Assam	Acid mine discharge	Water was highly enriched with Fe, Al, Mn, Ni, Pb and Cd	Tikak, Tirap andTipong collieries were highly contaminated with AMD and generated low pH and metal enriched discharge	[59]
		Neutral acid mine drainage (NAMD)	Alkaline pH with low metal content	Ledo and Baragolaicollieries were producing alkaline drainage with low metal loading	[60]
	Northeastern coalfields (Ledo and Tirap)	Coal mine drainage	Highly acidic with high values of EC, TDS, SO_4^{2-}, Ca, Mg, Fe	Water was deemed unsafe for drinking purposes	[60]
Pakistan	Thar coal fields, Sindh	Water aquifers contamination	Low pH, SO_4^{2-} with High Hg, F-, TDS, Na^+ and other trace elements concentrations	Groundwater was highly contaminated with Hg and other physiochemical parameters were affected	[37]
South Africa	Johannesburg	Groundwater contamination	Highly acidified and contaminated groundwater	Pyrite oxidation in Mine tailings was the source of metallic elements	[61]
	Pretoria area	Acid mine drainage	120Mega L/day of AMD generated	Affected daily potable water	[62]
UK	—	Mine water	Low pH, high Fe, and Mn were principal contaminants	Fresh to hypersaline water affected	[57]
USA	Pennsylvania	Coal mining discharge	Drainage had high concentrations of EC, TDS, SO_4^{2-} and trace elements (Fe, Mn, Al, Zn)	Untreated mine discharge had high dissolved ions	[26]

Table 2. Types and magnitude of land subsidence in coal mining regions.

Country/Region	Year	Area	Subsidence rate (mm)	Type of subsidence	Reference
Australia	−	New South Wales, Southern Coalfields	25	Horizontal	[49,68]
Belgium	1992−2010	Winterslag and Zwartberg	200	Vertical	[69]
Bangladesh	2014	Barapukuria, Dinajpur	100−890	Trough	[70]
Canada	2004−2007	Frank Slide area, Alberta	3.1	−	[71]
China	2012	Guqiao	158	−	[72]
	−	Huainan	7800	−	[73]
	1998−2008	Wujiabao and Xiayuan	798.37−763.18	−	[13]
Colombia	−	Venecia and Bolombolo Regions, Antioquia	730	−	[74]
Czech Republic	2007	DoubravaVrchovec	450	Horizontal	[75]
England	1983−2005	DoubravaUjala	34	Horizontal	[76]
Germany	Early 19th century	Ruhr district	20,000−24,000	−	[77]
	1998−2015	Wurm valley	51	−	[78]
India	2007	Jharia	0−27.8	−	[79]
Indonesia	2005−2006	East Kalimantan	400	Vertical	[80]
Korea	1992−1998	Samchuck	220	Vertical	[81]
South Korea	2013	−	3900	sink-hole & trough subsidence	[82]
Taiwan	1972−2012	Changhua, Yunlin, Chiayi, and Pingdong in Central and Southern Taiwan	12−34	−	[83]

$$CaCO_3 + H^+ = Ca^{2+} + HCO_3^- \qquad \text{(Eq. 2)}$$

Carbonate-AMD reactions such as those in Eq. (2) are associated with the release of high content of Fe, Mn, Ca^{2+}, and Mg^{2+} [67]. Coal mining associated impacts that deteriorate groundwater quality are enlisted in Table 1.

1.2. Effects of land subsidence on regional water systems

Neotectonic movements of underground masses can result in subsidence, sinkholes and uplifting of infrastructures. During surface and/or underground mining operations, 100s of meters of overlaying layers of soil or rock referred to as 'mine spoil' are removed. The propagation of deformed and displaced waste rocks induces pressures on larger surface subsidence, changes the permeability, porosity and hydraulic gradient of strata, and water table levels. Coal mining induced land subsidence incidents in different regions are reported in Table 2.

Land subsidence due to coal mining operations is one of the important factors affecting surface structures and water resources. Subsidence is a surface and subsurface, horizontal and/or vertical sliding of the ground surface into mine voids that can be small or large scale, generalized or localized in nature (Table 1). Land sliding and subsidence are mainly induced by in situ pressure, underground water regime, topography, rate and method of extraction [84]. Long wall mining either in active

way or by passive way (due to residual subsidence) have more severe magnitude of subsidence as compared to open pit mining method [85,86].

In China 92% of the total coal is extracted by underground caving mining methods. This intensive subsurface coal mining in densely populated coal basins has caused severe land subsidence, resulting in ecological, economic and environmental concerns [46,87]. It has been estimated that production of 10,000 tons of coal in China leads towards an estimated land subsidence of 0.2−33 ha [44]. It has been predicted that over-extraction of coal in China will expand the land subsidence impacts by 2×10^4 ha/year [88]. In Shanxi Province, China, it has been reported that out of 20,000 km^2 of coal mining affected land, around 650 km^2 of the area experienced land subsidence [89]. An area of 2000 km^2 in Taiwan also experienced subsidence of 1.2−3.2 m [83]. In the case of India, highly volatile and bituminous coal at the Barapukuria Mine occurs stratigraphically beneath the DupiTila (water-bearing) Formation, which is declared as naturally vulnerable, due to sinking and subsidence incidents in the area.

The magnitude of subsidence is much more severe in karst areas. For example, an area of 500 ha in Fankou mines (Guangdong), 2000 ha of Enkou mining area (Hunan), 294,000 ha of Shanxi province were experiencedland sinking [90]. Furthermore, Shanxi Province in China the land slinkingdue to coal mining increase by 9400 ha each year [90].

In South Korea, 548 subsidence cases with an average rate of 3.9 m were reported for 349 coal

Table 3. Water depletion status of different coal mining regions around the globe.

Country	Date year	Area	Water table depletion (m)	Reference
Bangladesh	2001–2011	Barapukuria, Dinajpur	>5	[17]
India	2013	Jharia, Jharkhand	1.29–6.9	[99]
	–	Ranigang, Barddhaman, West Bangal	7–18	–
	2014	Angul-Talcher belt, Odisha	7–9	[100]
China	2013	North China	0.02–0.028	[40]
	2000–2014	Shenmu-Fugu	>10	[96]
		Yulin-Shenmu	2–6	
	1952–1993	Jiaozuo, Henan province	34	[44]
	–	Yongcheng mining area	5–10	[101]
	1994–2005	Jinci spring area	18.45	[13]
Colombia	2020	Plan Bonito	14.8	[4]
	2014	Cesar	10	
England	1980–2006	Oxton Bogs	2	[18]
	1980–2006	Dover Beck catchment	4	

mines [82]. The subsidence is due to the steep slope (at an angle of 40°) of mining site and the slant chute block caving excavation method. Similarly, long wall coal mining since the 1982 in Australia region has caused infrastructure damagedue to landslides. The fracturing and sinking of overlaying strata generally increases water conductivity and water–rock interaction. In the Rivulet Catchment in Sydney, Australia, for example, high concentrations of metallic elements in water were proposed to bedue to the increased water–rock interactions as a result of fractures and faults [91]. Land subsidence also changes the slope of the surface that affect drainage pattern by disturbing its water flow channel [70]. It can also reduce the thickness of aquifers, modify the natural retention period, and create a permanent water logging situation. In the Ruhr district, annual subsidence of 4.7–8.5 mm affects water channels of the EmscherRiver catchment area [77]. Subsidence also increased the silt-trapping efficiency of the floodplains of Wurm River (Western Germany) [78].

Land subsidence affects surface water by disruptingand diverting river channels, fracturing riverbeds, causing flooding and ponding, decreasing runoff rates, and inducing mixing of surface and groundwaters, resulting into water quality deterioration [92]. For example, underground mining as result of surface subsidence produced subsidence water ponds in Huainan Province (China) that's are highly contaminated with Cr, Co, Ni, and As [93].

1.3. Disruption of hydrological pathways

Mining activities require smaller quantities of water than mineral processing activities (dust suppression, cooling of equipment and fire control etc.), but large-scale movement of heavy machinery and material during the development of mining operations can significantly disrupt the natural landscape and affect the water regime of an area [10]. The major factors that control water flow include the hydrogeology of the area, porosity, permeability, landscape, topography, coal depth and height, and sizes of mines. These factors further affect water recharge, discharge and its storage capacity. In case of Barapukuria (Bangladesh) less permeable soils of subsidized areas around the coal mines resulted into artificial lakes which further reduce water table and deteriorated water quality in the area [70]. Wherever, rocks deformation due to continuous mining significantly changes topography and effect transmissivity by disconnecting the local flow patterns and storage capacities of aquifers. For example, coal mine tailings that are stored in drystacks, backfilled into mines, disposed in constructed dams or in discharged to nearby surface water environments, can result in reductions in runoff [94] In China, decreases in river runoff of 5.72 million m^3have been attributed to coal mining. A study conducted in the Gujiao, China, mining areas from 1981 to 1990 showed that river runoff was reduced by 11.13 million m^3/y for each ton of coal mined. From 1990 to 2000 this figure increased to 21.77 million m^3/y, and from 2001 to 2008 it increased further to 37.99 million m^3/year [95]. Ahuge decline in Tuwei and Kuye River of China flowwas also observed during the spell of 2004–2014 [96]. Decline in water availability as a result of decrease runoff, was also observed in the Olifants River in South Africa [63]. The resultant reduction in surface runoff was linked with extensive increase in coal extraction and poor mining practices.

Groundwater in valley fills has long reaction times, resulting in higher amounts of mineral dissolution and increase TDS concentrations. This has been reported for mine inflowsand outflows of Chakwal, Pakistan [64] Similarly, prolonged coal mining in the catchments of Witbank Dam, South

Table 4. Selected coal mining incidents and their environmental impacts (2000–2016).

Date	Location	Parent company	Incident	Release	Impacts
11/01/2016	NWS, Australia	Peabody's Wambo coal mine	Collapse of dam wall	Wollombi Brook released 3 million liters of contaminated water into the Hunter River,	Black water fish were killed along 40 km of the Hunter River[a]
1/08/2015	Vietnam	QuangNinh coal mines	Flooding	Tailings and dam failure contaminated inhabited areas	Caused damage to World Heritage-listed Ha Long Bay.[b]
2/02/2014	Dan River Steam Station, Eden, North Carolina, USA	Duke Energy	Collapse of old drainage pipe	Breach of coal ash and of contaminated water	Ash flow into Dan River[c]
31/10/2013	Obed Mountain Coal Mine, northeast of Hinton, Alberta, Canada	Sherritt International	Breach of wall in containment pond	Spill of coal wastewater and muddy sediment	Coal wastewater containing fine coal particles, clay and metals discharged into Apetowun and Plate Creeks and eventually into the Athabasca River [58]
4/11/2011	Yima mining area, China	Qianqiu coal mine	4.1 magnitude rock burst occurred in the underground roadway	an earthquake of 2.9 magnitude was experienced in Yima City.	Resulted in extensive underground roadway damage, 10 deaths, 64 injuries, with an economic loss of 27.5 million yuan [101]
03/04/2010	Great Barrier Reef in Australia	—	Chinese-owned bulk coal carrier collusion	65,000 tons of coal and 300,000 gallons of engine fuel was released into the coral reef	Ecological impacts on the world's largest heritage site[b]
22/12/2008	Kingston fossil plant, Harriman, Tennessee, USA	Tennessee Valley Authority	Failure of retention wall	Release of 4.1M³ of ash slurry	The ash slurry covered 400 acres causing power lines to collapse, gas lines to rupture and damage to 12 homes[c]
22/05/2004	Partizansk, PrimorskiKrai, Russia	Dalenergo	Rupturing of a ring dike	Outburst of 160,000 m³ of ash	Release of ash into the Partizanskaya River which drains in to Nahodka Bay [117]
11/10/2000	Inez, Martin County, Kentucky, USA	Martin County Coal Corporation. Massey Coal Company, Inc.	Failure of tailing dam	950,000 m³ of coal waste sludge was released into local streams	Deterioration of drinking water facilities and 75 miles of streams, turning rivers black, and causing fish kills along the Tug Fork of the Big Sandy River and some of its tributaries.[c]

a https://www.sourcewatch.org/index.php/Coal_mining_disasters [132].
b https://ejatlas.org/conflict/master-agua-quang-ninh-mines [134].
c https://arlweb.msha.gov/MSHAINFO/FactSheets/MSHAFCT2.html. [133]

Africa has resutled in high amounts of turbidity and TDS, and decreases in the storage capacity of valley fills [63].

In some cases, intensive coal mining results in loss of vegetation at both mined and valley fill areas that affects the evapotranspiration rate of the hydrological cycle, as well as the storage capacity of unconsolidated aquifers.

Ground deformations as a result of surface and underground sinking may facilitate the infiltration. The combination of groundwater infiltration, rainfall and runoff can lead to substantial influx of water, resulting into flooding of open pits, the formation of pit lakes and inundation of underground mines. This has been seen in case of Barapukuria Coal Mining area (Bangladesh) [70]. Preventionof such inrushes may require active pumping, particularly when the mines are located in regions with high rainfall and low evaporation rates.

1.4. Depression of water table around the dewatered zone

Water table levelsare generally controlledby water abstraction patterns. Groundwater aquifers around coal mining areas are generally deeper and have visible declines with the passage of time. To facilitate underground coal mining, a large volume of overburden strata is often removed. Dumping of these mine tailings and heavy mechanics requires for mining operations caused soil compaction that affect porosity and permeability. These characteristic features further reduces the rate of infiltration, percolation, and leaching, thereby water table in the mining areas is decreased and causes the termination of water pathways by flooding or ponding in low lying valleys. One such example of water table lowering is Leslie County (Kentucky) where, the groundwater depletion in mining areas occurred over miles [97]. In another study in Pennsylvania, 9% of the total 2800 water supply channels within radius of 61 m of mines had reduced their water table [24]. Whereas the study of long wall mining operations of Greene (4 mines) and Washington county (3 mines) revealed that over the period of 2003—2008 affect 106 of 1214 undermined water supplies. Around 8.7% of these affected water supplies were within the 200 feet's of active mining sites [98]Similarly, another study conducted in Jharia coal mine region (India) had also shown instability in its water table [99]. Almost all of the tube wells in the mining area (Odrisha, India) dried during the summer season [100]. Additionally in case of Bangladesh, groundwater table is highly vulnerable to coal mining with a depletion rate of >5 m (Table

3). Coal mining associated water tabledepletion is much more pronounced as compared to the domestic and irrigation groundwater abstraction rate, seen in Bangladesh and India (0.1—0.5 m/year) [102,103]. It is affected either by dewatering of underground mining voids or by seepage of water from saturated grounds to the mineshafts.

The problem of water table depletion is much more severe in arid and semi-arid regions, where small-scale mining leads to the dryness of springs, termination of river channels and drought. Semi-arid regions of Anhui, Hebei, Henan, and Shandong (China) are its example, where coal extraction of last 50 years had shown severe water shortage [104].

It is relatively less severe as roadway stacks and room and pillar mining adopted in this case can reduce the drop of the water table in unconfined aquifers [96]. However, continued coal mining on large scale by longwall caving method formed the fractures that allow the rapid mine inflows following the surface subsidence and groundwater depletion. As in the case of Northern Shanxi (China) coal basin, the failure of surface strata connects the water aquifers by joining faults that cause the groundwater to drain into surface water or springs. One such example is the Janci spring of Shanxi Province (China), where continued mine pit drainage rapidly decline its groundwater table [13]. Since the year 2000, observed water decline due to extensive coal extraction in Yulin-Shenmu area was 6—9 m, whereas in the area of Shenmu-Fugu the reported drop of the water table was up to 10 m (Table 3) [96]. One ton of coal mining in China deplete water resources by 1.32 m^3 [19]. Since 1960, due to extensive coal mining, China had observed a drop of 1 m/year in its water table, in the most affected areas of Hai River basin, Liao Songhua lowland and Northwest deserts within Gansu province [105].

This over-exploitation of water resources can be a severe damage to geological conditions. The most pronounced effect is the observed phenomenon of land subsidence (Section 1.4). For example, extensive pumping (96 m^3/min) in the Ordovician limestone aquifers (Hebei province) caused a depression cone of about 10 km (radius), affecting the drinking water shortage to a population of 100,000 occupies [106]. Another example is the decline of water flow that leads towards the drought. For instance in the case of Jinci spring, China coal mining destruct the hydrological system and causes a sudden decrease in its water flow up to 0.5 m^3/s (1980s). By the time, this situation becomes more worsened with a decline inclination of 0.26 m^3/s (1990) to 0.14 m^3/s in 1992. Water of Jinci Spring area was completely dehydrated in 1994 [13]. Overall coal mining

activities disparately interrupts both local and regional groundwater Table 1 obligatory preventive measures are not taken, such interruptions can lead towards intensive imbalance of water footprint [107—109].

1.5. Backfill and dewatering: causes of flooding

In case of groundwater, large-scale mining leads to the cracks and fracturing of overlying/underlying strata, where further stress and joining of such features leads to the land subsidence, and causes a cone of depression, which seizes the water flow and enhances the infiltration and precipitation in aquifers that results into flooding also known as artificial aquifers. To provide a safe working zone this flooding/inrush require dewatering. For example, the hard coal area of Ruhr (Germany) requires a pumping rate of 48—54 Mm^3/a, which is significantly higher than the normal flow rate of <5 m^3/h [57].

For instance, extraction of coal from theZwartberg and WinterslagMines inBelgium caused an upward lift of about 10 mm/year, which resulted in flooding of ZwartbergMine. As the water level of ZwartbergMine increased, it resulted in flooding of the neighboring WinterslagMine. The overflow water was pumped at a rate of 7000 m^3/day to make Zwarting Mine operational [69].

The degree of water inrush is directly relatedto the thickness and permeability of the coal seams, their depths and head pressure. If the coal seam is fragile and its structural integrity is low than fractures can easily develop within the thick coal seam that will increase the flow of water inrush [110]. Similarly, deep mining (>1000 m) of North China plain induced greater discharge of water bearing strata through geological drains [111]. On the other hand, high-pressure groundwater can burst out due to explicit features of aquifers, geological characteristics and failure of mining strata. About 80% of water inrush cases are related to geological fault zones [112]. Because of inrush incidents of China, the maximum-recorded water inflow was 2053 m^3/min.

These water inrushes result in the elevation of water table known as groundwater rebound. This rebound is either the rise in groundwater due to cessation of pumping activities also known as passive (internal flooding) or active flooding (external flooding) in which water inrush takes place [113]. In case of France, where half of coal basins are flooded, mine water of these French mines drain into surface water bodies including rivers (95%), lakes (4%) and sea water (1%) [57]. If we take an example of China,

water inrush incidents can be divided into four major categories i.e. 1) water inundations due to limestone aquifers (92.3%), 2) surface water flooding (4.9%), 3) alluvial water flooding (1.4%) and sandstone triggered inflow (1.4%) [114]. If this rebound is not pumped out or drained through adits, the water table will raise to a level where inflow and outflow are equalized. This rebound process of groundwater also depends upon the coal stratum, size and geological features of the mining areas. For instance, observations of Ruhr (Germany) revealed that low permeable clay mineral formations in mining areas increase the speed of rebound [113].

Another example is of Northern China, where higher water pressure, thin seam strata and geological fractures and faults in Permo-Carboniferous coal seams resulted in the rise of the regional water table and accounted for massive flooding [106] About 285 of 600 coalmines of China having coal reserves of25 billion tons are under serious threat of water inrush. One hundred and twenty-two such incidents were reported during the period of 1950—1990, and it was estimated that these caused economic lossesof about 180 million US dollars [106,115]. Karst water intrusion innorthern China affected 130 mines that may halt the extraction of more than 15 billion tons of coal [116]. These intrusions cause over 50 mines to be flooded for the last 30 years. Water inrush incidence of Barakpukuria (Bangladesh) in 1996 is another example of groundwater flooding in mines.

Such intensive inrushes require dewatering of mine aquifers. For example, intensive flooding in Barakpukaria coal mine area requires continuous dewatering at the rate of 1500—1600 m^3/h [17]. Such excessive water withdrawals may affect hydrological system via land subsidence, depletion of groundwater table or reversal of groundwater flow directions, or diversion in surface water channels [96], that had a significant hydrological and ecological stress on regional water regime.

Continuous extraction and dewatering creates a cone of depression and can reduce the hydrological gradient thus requiring backfilling. Now, if the water table is towards the river, meaning that the hydraulic gradient of the aquifer is towards the stream, the groundwater will flow into the river, the stream in this case is called gaining stream. When the opposite situation is happening and the water from the river is, leaking into the aquifer the stream is considered losing stream. Once rebound is recovered to a level that surface discharges are taking place, it causes the water pollution (either of overlying aquifers or of surface watercourses) and degree of pollution is dependent to the nature of the

discharge. As reported by Ref. [113], mine water of hard coal (bituminous and anthracite coal) mines substantially oxidized sulfate minerals and in connection with drinking water resources, and increases itsFe and SO_4^{2-} concentrations.

1.6. Creation of new hydrological environments

New hydrological environments are created due to land disturbance, non-permeable or less permeable conditions, recharging and mixing of local ground and surface water [94]. For instance in case of Huanghuaihai Plains (China), due to massive subsidence surface of shallow depth coalmineswere collapsedinto water ponds. These water ponds by the influence of surface water and precipitation converted into marshlands [87]. Similarly, subsidence around Barapukuria Coal Mining area of Bangladesh transformed the trenches into artificial lakes of low quality water [70]. Furthermore, subsurface mining (mountain top removal) as result of valley fills altered the local channels of water flow. In such cases, valley fills act as headwater aquifer for local surface and groundwater and make it to flow to the underneath. The hydraulic barrier in the form of coarse overlying strata increase the storage capacity that in turn increases retention time and enhanced supplementary exposure of water rock interactions. Such phenomenon occurred in the Southern Coalfields of New South Wales, Australia, where intensive connectivity of surface and groundwater enhance water—rock interactions [60]. These water rockinteractions might include dissolution of carbonates by rock weathering and redox reaction of metals bearing oxides and hydroxides that enrich dissolved solids and metallic content. The resultant chemical modifications are more pronounced in shallow groundwater [85]. In another case, dewatering of Upper Silesian coal mines in Polandresults in the discharge of alkaline water into river tributaries of Upper Wisla (Vistula) and Upper Odra (Oder)that enrichthe tributaries withhigh concentration of Na^+, SO_4^{2-}, and Cl^- [58]. Similarly, in Spain, coal dewatering of flooded mines created a new hydrological system with high concentrations of major ions (HCO_3^{2-}, SO_4^{2-}, Ca^{2+}, and Mg^{2+}) [58].

2. Major water-related accidents in coal mining regions

Coal mining can be a complex and lethal process. Traditional and poor mining practices can cause severe accidents to, and deaths of, miners. These incidents are due to mud sliding, coal dust and gas explosions, poisoning and suffocation, roof and blastingaccidents, and flooding. The causes and different socio-economic and environmental concerns with respect to these accidentsare reported in Table 4.

Mortality rates can be very high in coal mining areas. In 2003, the global production of 5 billion tons of coal was achieved with a causality rate of 8000 miners [110]. Approximately 80% of global coal-related fatalities were reported for China, the largest global coal producer [118]. Deaths rate per million tons of coal of Turkey, China and US were 7.22, 1.27, and 0.02, respectively. During the period 2001—2010, improvements in mine safety measures made by government of China reduced the fatality rate, but it stillhad highest rate of 0.25 fatalities/million tons, 10 and 87 times the reported fatalities for India and USA [119]. Coal mining-linkedcausalities in China have been reported to includeroof collapses, gas outbursts and explosions, poisoning and suffocation, water leakages, mine flooding and fire [120—122]. Among these fatal incidents, gas explosions have been reported to be the most severe [121]. The 2015 Soma Coal Mine accident in Turkey, with 300 causalities and more than 80 injuries, was one of the worst incident reported over the last 6 years [123]. Pakistan Central mines foundation reported thatan average each year 100—200 laborers have lost their lives in coal mining accidents. Many of these accidents were the result of untrained laborers and poor mining practices. About 328 fatal accidents (with 354 deaths) were reportedsince 2008—2013 in the Salt-range Coal Mines of Punjab, Pakistan. The reported data revealed that side wall collapses accounted for 38% of these fatalities, and roof collapses, 24% [124]. The main reason behind them is the instability due to rise in water level as well as poor management.

3. Measurements and technological advancements that overcome environmental stress

Coal plays an intermediate role in urbanization, industrialization and modernization, but its mining, transportation and utilization has had serious environmental impacts in many areas. The concept of "sustainable mining capacity" [125], in which the aim is to achieve maximum economic gain with minimal ecological loss, has been introduced to this industry. The implementation of regulatory measure and technological advances can help to achieve "sustainable capacity of coal mining" [125]. The regulatory measures that can be taken include the reclamation of land, soil and water treatment facilities, use of mine water for different purposes,

construction of dams to protect the direct release of coal mine waters into surface bodies, segregation of useful metal(loid) elements and reduction of contamination by re-sing or remaining waste rocks and mine drainage. Backfilling and afforestation are two most practiced and economically viable methods of land reclamation [126,127]. Such activities reduce soil erosion and water runoff, and improve soil, water, and air quality in the mining area. One such example is Jharia coalfields (India), where afforestation via selective planation have reduced soil erosion and pollutants in the surrounding of mining areas [128]. In America under SMARCA (surface mining control and reclamation act of 1977) office of surface mines has provided $7.2 billion to reclaimed 120 ha of abandoned mine land. Following this during the term 1978—2009, SMARCA has reclaimed an area of 500,000 ha [129]. Germany has focused afforestation of former coal mining areas whereas China has favored reclamation of such areas for agriculture [129]. An example of remediation occurs in the UK, where 53 coal mine water treatment plants manage and remediate over 140, 000 m^3/day mine water by removing over 18,000 tons of iron [130]. In terms of re-use, coal mine waste rock (CMWR) from the Tiefa, China coalfields is used in brick making, power generation, subsidence rehabilitation and as fuel mixture. These bricks plants produce 1.6 billion bricks per year by using 1.377 Mt CMWR with a net profit of 49.43.5 yuan/year. This brick making facility reclaimed 2.67ha land from CMWR. The net profit for power generation is 9 yuan and of fuel admixture is 19.53 million yuan/year [131]. An example of technological advancement can also be seen in case of China, where shifting to more advanced and modern mining practices has resulted in a reduction of the death toll of coal mining accidents from 5.07 to 0.25 deaths/ton. In some cases, restoration of closed and abandoned sites to their prior mine status is not effective, but the land can be converted into recreational sites. Recycoal project, UK is one of such exemplary body that converts many of abandoned coalmines into recreational sites. The restoration of Barnburgh site, Hesley Wood site (Sheffield) Northumberland coal mining areas into public parks are such achievement [129].

Direct coal consumption carried out in 20th century halted when environmental concerns like global warming came to the forefront. Diminishing non-renewable resources and their related impacts on environment paved the way for concept of sustainable development which states efficient use of resources in environment friendly way. In this scenario, the recent hike in electricity prices and energy crises faced by Pakistani population could only be overcome if the government utilize this potential reserve of about 185 billion tons, to the country's energy mix. However, practiced traditional mining can cause the above addressed problems. The projection of technical advancement as well as environmental management measurescan advance the practiced mining activities and restore the mining industry in a sustainable way. Hence, being a late entrant Pakistan can benefit from the clean coal technologies available today.

4. Conclusions

Coal is an important global energy fuel, but the coal mining industry faces major global challenges that need to be addressed. We have presented here an overview of published data on the measurable environmental impacts of coal mining with a major focus on water resource development. Production of acid mine drainage, land subsidence, flooding, new hydrological zonations, degradation of water quality and depletion of water tables are the major challenges of coal mining. However, moves towards sustainable mining can bring improve industrial growth, protect environmental and human health and protect surface and subsurface environments.

Conflict of interest

None declared.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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