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REVIEW ARTICLE

Surface Runoff in Open Cast Mining Areas: Methods, Influential Factors, Quantifications, and Trends

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Abstract
The impact of surface mining on surface runoff was reviewed in articles published from 2009 to 2020 indexed in Science Direct, Scopus, Web of Science, and Scielo databases. Measurement methods, quantities, influencing factors and trends of surface runoff in mining areas are presented and research gaps, challenges, and opportunities are discussed. A total of 10,274 articles were found, 39 of which were selected for qualitative and quantitative analysis. Among the methods, laboratory and field measurements using plots, and, to a greater extent, estimates are used worldwide to measure runoff in surface mining areas. Based on the reviewed articles, the surface runoff in the last decade ranged from 2.25 to 488 mm annually for rainfall between 386 and 2189 mm. Monthly values ranged from 0.5 to 83.3% of precipitation. Mine reclamation must primarily consider the vegetative cover, the soil structure, and the microrelief as factors that reduce surface runoff, which is the main trend when this is evaluated over time. The biggest challenges in monitoring surface runoff in mining areas are the long times required and the difficulty of collecting data in the field; in addition, when estimated by precipitation data, the values may have low precision.

Keywords Surface water · Impact · Precipitation · Vegetation · Soil

Introduction

Among the environmental impacts caused for surface mining activity are changes in vegetative cover (Espigares et al. 2011), physical, chemical, and biological degradation of soils (Vilas Boas et al. 2018; Wang and Wang 2020), and changes in the landscape (Zégre et al. 2014) and water resources (Gabarrón et al. 2019; Huang et al. 2015; Luan et al. 2020; Merino-Martín et al. 2012). One of the concerns regarding the impacts of surface mining on water resources is its effects on surface runoff (Ping et al. 2017). There are two types of surface runoff: water that moves freely over the land surface and water that flows in a defined watercourse (Valente and Gomes 2005).

Sustainable mining should be focused on reducing its environmental impacts, in addition to socioeconomic ones (Gorman and Dzombak 2018). Knowledge about the influence of mining on the quantity and quality of water

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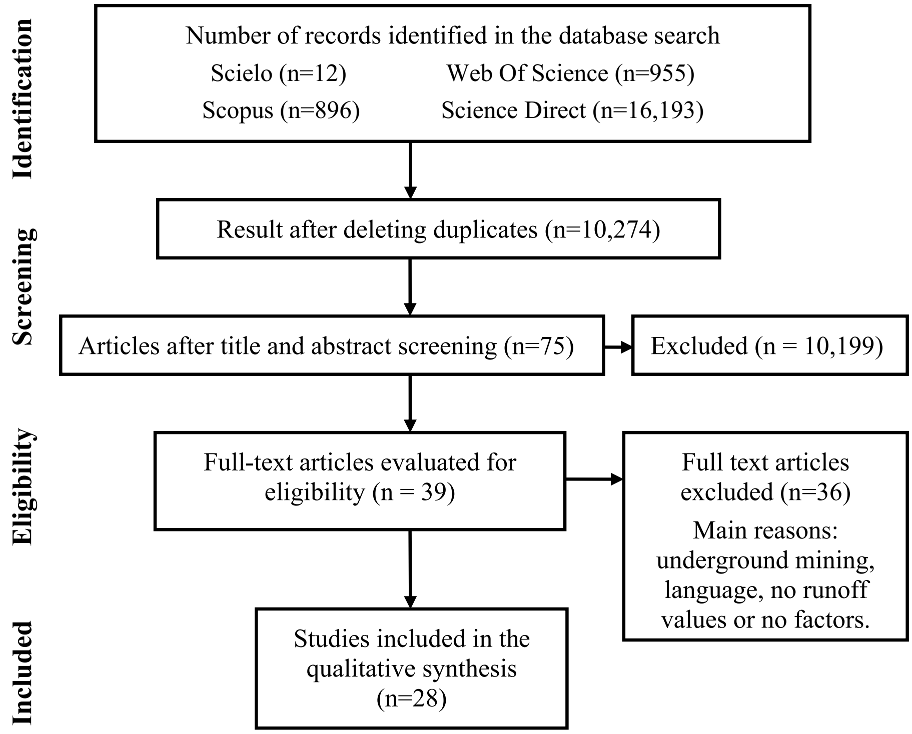

Fig. 1 Collection and selection flowchart of the systematic literature review, *n* number of articles

resources will greatly improve the planning, management, and sustainable development of natural resources (Awotwi et al. 2019). Therefore, it is important to understand the dynamics of surface runoff in open pit mining areas to identify gaps, challenges, and opportunities for further research and alternatives to managing impacts.

This review sought to answer the following questions: What methods are used to measure surface runoff in open pit mining areas? What factors affect surface runoff in these areas? What quantities of surface runoff are being obtained after surface mining? Our objectives were to: i) provide an overview of the effects of surface mining on surface runoff; ii) describe the most advanced methods for monitoring and predicting surface runoff; iii) discuss the main environmental factors that influence this runoff; and iv) show trends in surface runoff from open pit mining areas of those analyzed statistically in time series.

Materials and Methods

Systematic Literature Search

The design of this systematic review was performed according to the PRISMA checklist (Moher et al. 2009). The keywords: "runoff in mining areas", "trends in runoff in mining," and "surface runoff in surface mine" were searched in the online indexes of Science Direct, Scopus, Web of Science and Scielo databases in March 2021. Scientific articles in English from 2009 to 2020 were considered. Mendeley software version 1.19.4 was used for document collection and better management.

After the initial search through the databases (Identification phase; Fig. 1), the articles were sorted, first excluding duplicate articles (a filter was applied using Mendeley software resources). In screening, the studies were selected by relevance based on the title, excluding articles unrelated to the topic under study. Relevant titles were selected based on the abstracts and the full text was then analyzed.

In the eligibility phase with complete reading of the articles, a series of criteria were followed to standardize the reports included. The content criteria, focus on the subject, methods, data and main results of the study were considered. Only studies that specifically discussed the quantification of surface runoff in surface mining areas and the assessment of trends in this surface runoff throughout the rehabilitation process were included. Articles that present surface runoff values or analysis of influencing factors were also included. Studies with runoff data at the hydrographic basin scale, in the case of estimation studies, were also considered to expand the number of studies, provided that they presented at least one surface runoff result in millimeters (Fig. 1).

Database Construction

After selecting the articles according to the established criteria an evaluation of the thematic areas of these studies was carried out, separating those carried out in the field from based on estimation or laboratory studies. A database was built by extracting details from each article (author and year of publication), location, period of study, methods, and results (supplemental Table S-1). A synthesis of key findings was then undertaken to develop a framework of results that would show surface runoff in shallow (surface) mined areas worldwide over the past decade. This database framework was analyzed and opportunities for future studies were identified.

Data Analysis

A map with the distribution of studies worldwide was prepared in ArcGis 10.7 (Fig. 2). Articles with surface runoff values in millimeters or percentages were used for descriptive statistical analysis and graphs were constructed to demonstrate the range of surface runoff in mining areas during the last decade.

Results and Discussion

Literature on Surface Runoff in Surface Mining Areas

The systematic review resulted in 39 peer-reviewed articles (Fig. 1), of which 46% were published in the last two years (Fig. 2). Data from these articles are available in a spreadsheet (Table S-1). Sixteen annual and 15 monthly surface runoff values from open pit mining areas in different regions of the planet were obtained in mm, along with 17 monthly values in percentages, and 9 trend results (Fig. 2). In these articles, 26 values of annual precipitation, 6 monthly, one daily maximum, and 12 simulated rainfall intensities were reported.

China had the most published papers on surface runoff (8 articles), followed by the United States and Spain, both with five articles (Fig. 2). This is line with the predominance of surface mines in these countries, mainly associated with coal in China and the United States (Daemen 2004; Maus et al. 2020). China has the largest mapped area of surface mines in the world (11.5% and almost 5,000 mines); the United States (11.2%, with just over 2000 mines) came in third place (Maus et al. 2020).

Studies about surface runoff in surface mining published in scientific periodicals are rare, based on, for example, the absence of studies in Russia, and Chile, and only one study in Australia with, the three being among the five countries with the largest mapped area of surface mines in the world (Maus et al. 2020). In Brazil, with just one article, this research gap may be associated with the lack of requirements for long-term monitoring legislation for the rehabilitation and the environmental licensing process (Jeber and Profeta 2018), though some scientific studies were published showing surface runoff recently after surface mining of bauxite (Spletozer et al. 2021a, b).

Among the 39 articles found, 27 were on coal mining (Merino-Martín et al. 2012; Hoomehr et al. 2013; Guo et al. 2017, 2020; Nigam et al. 2017; Ma et al. 2020; Wu et al. 2020a), three did not specify the type of mining because they were simulations at the watershed level (Awotwi et al. 2019; Liang et al. 2019; Isniarno et al. 2020), and two were on gold mining (Awotwi et al. 2017; Labonté-Raymond et al. 2020). The other mining operations addressed were wolframite (Gomez-Gonzalez et al. 2016), rare earths (Liu et al. 2020), quarry (Zhang et al. 2016), lignite (Biemelt et al. 2011), phosphate (Wang et al. 2016), iron (Lv et al. 2020), and bauxite (Rubio et al. 2013). Most of the published articles on surface mining contained runoff data in or near the northern subtropical zone (Fig. 2). Therefore, the need for research in most countries is evident, even in deposits that are still unexplored.

Factors that Influence Surface Runoff

Changes in surface runoff in relation to natural ecosystems are attributed to the influences of climatic factors and human activities (Awotwi et al. 2017). Precipitation is the main climatic factor that influences surface runoff (Li et al. 2017). Changes in surface runoff due to mining are mainly associated with modifications in the topography (Zegre et al. 2014), soil structure (Wang and Wang 2020), and vegetative cover (Espigares et al. 2013) (Fig. 3).

The volume and intensity of precipitation are the main factors in generating surface runoff (Labonté-Raymond et al. 2020; Li et al. 2017; Wu et al. 2020b). The runoff volume is directly influenced by the precipitation volume and can be linearly correlated with an adjustment of 0.9995 (Liu et al. 2020). In similar soil and slope conditions, runoff increases gradually with the amount of rain. For example, in a 40° slope, the runoff coefficient can increase from 0.516 to 0.758, with precipitation ranging from 56.27 to 129.57 mm, which corresponds to a 46.9% change in the runoff coefficient (Li et al. 2017). This increase is related to the effect of precipitation intensity on the sealing of the soil surface, which impairs water infiltration into the soil (Wang and Wang 2020). A high amount of precipitation tends to quickly saturate the soil, consequently reducing infiltration, and generates high values of surface runoff (Nigam et al.

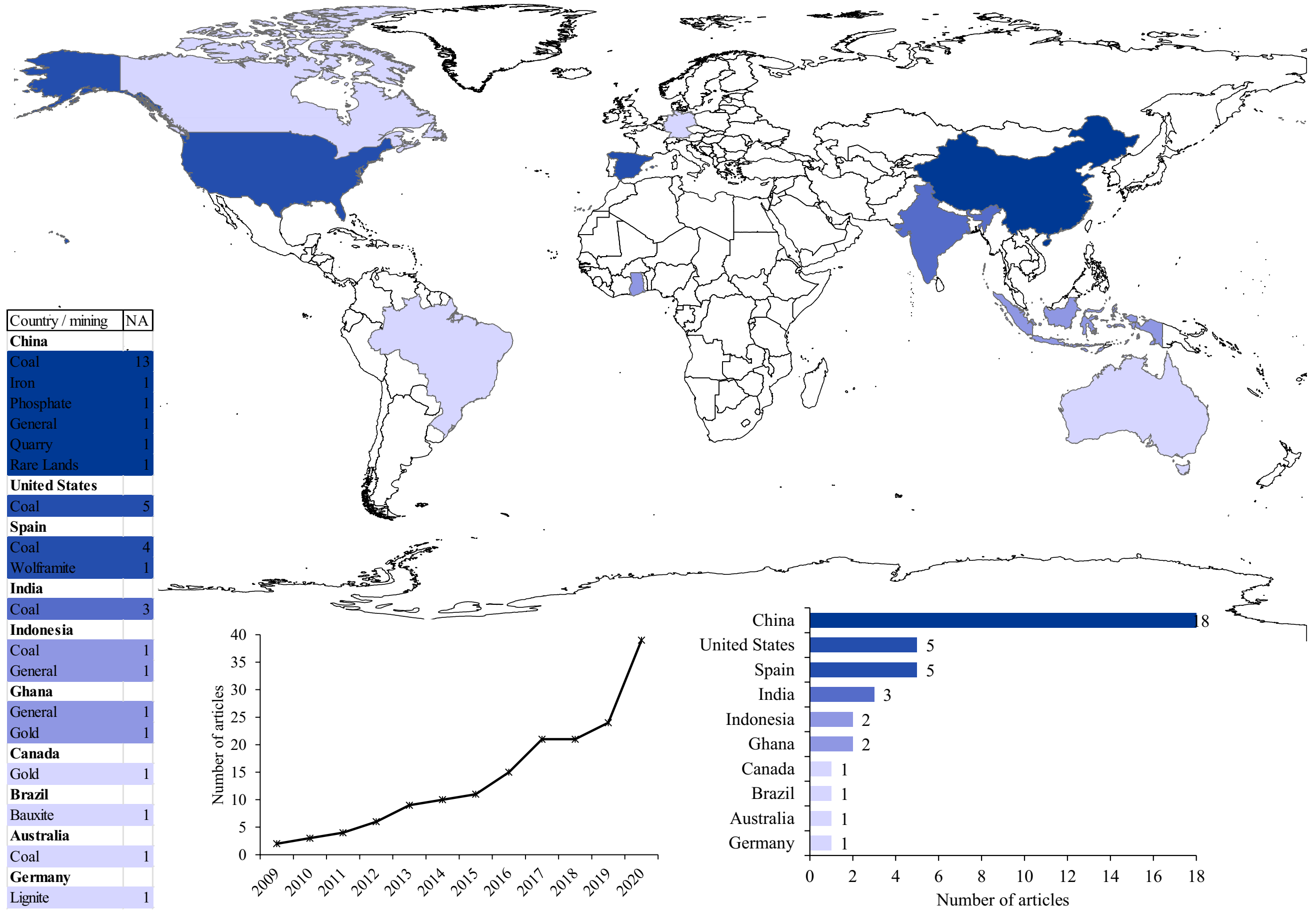

Fig. 2 Selected studies in the literature review distributed in their respective countries and number cumulative of studies published per year (2009–2020), and types of mining with studies by country. The articles were highlighted in different intensities of blue according to the number of articles registered. *NA* number of articles

2017). Based on the stepwise regression method, precipitation was the main factor that influences runoff, followed by coal mining activity, water conservation measures, and temperature (Wu et al. 2020a).

Analysis of the relationship between runoff and rain event characteristics indicated that the maximum and average intensity of preceding precipitation events and the nature of the storm were significantly correlated with runoff (Moreno-de-las-Heras et al. 2020). Previous rain events can cause changes in the hydrological and hydrophobic properties of the substrate in mined areas, depending on the availability of moisture over time (Biemelt et al. 2011; Lv et al. 2020). Wet substrates reduce infiltration, which generates more surface runoff (Biemelt et al. 2011). The runoff rate increases by up to 5.4 times as the number of rain events increase (Lv et al. 2020). The volume of surface runoff may also increase after a dry period due to water repellency by the substrate surface (Biemelt et al. 2011).

Vegetation is another factor that affects surface runoff in mined areas (Moreno-de las Heras et al. 2009; Espigares et al. 2013). Low runoff volumes are observed at mines with high amounts of vegetation, which improves soil properties, accelerates ecological succession, and prevents the loss of water and soil resources (Espigares et al. 2013). Vegetation has an exponential effect on reducing surface runoff, increasing both the time for runoff to begin and the infiltration rate (Moreno-de las Heras et al. 2009). The hydrological response of reclaimed mines with less than 30% vegetative cover is very different from those with coverage above 50%, this value being the practical threshold for restoring soil cover to control surface runoff. This coverage limit can be considered a useful criterion in the evaluation and management of restoration practices in recovered environments (Moreno-de las Heras et al. 2009).

The type of vegetation covering the soil also affects surface runoff generation patterns at reclaimed mines. Vegetation patches can be grouped, according to runoff rates and soil moisture, into microenvironments with hydrological roles of sinks and sources of surface runoff. Bare patches between plants with poor soil and low infiltration capacity

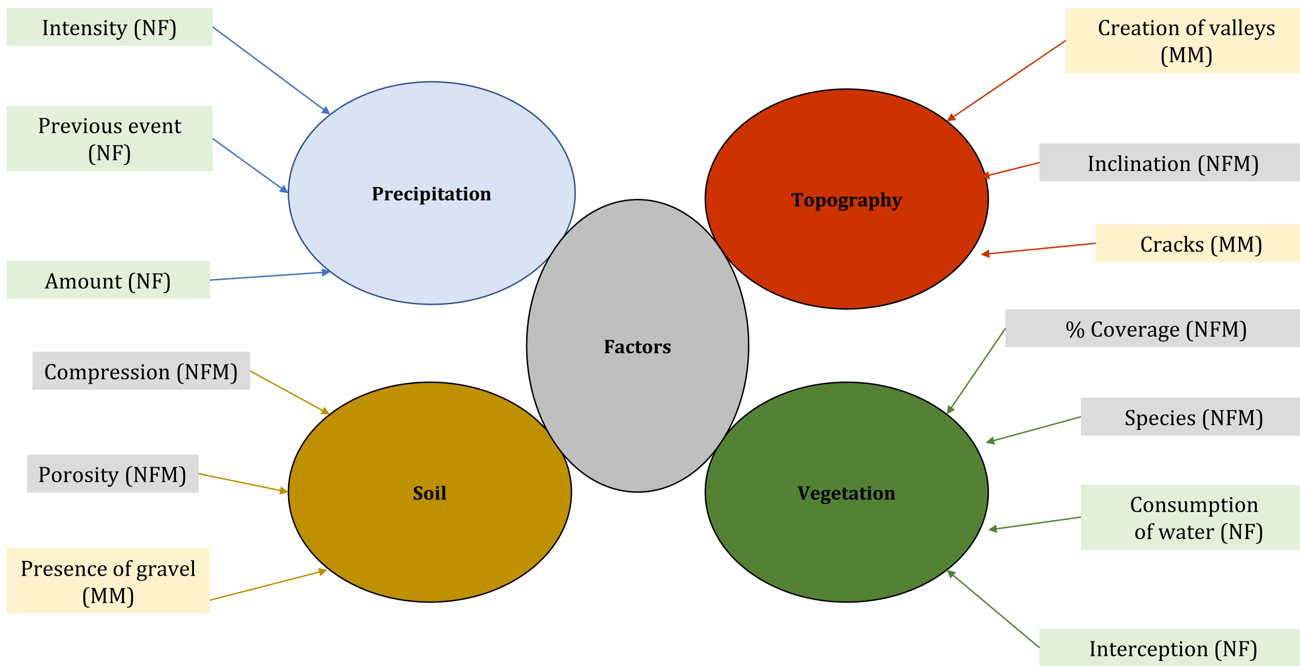

Fig. 3 Factors influencing in surface runoff of open pit mining areas. The specification corresponds to what are natural factors (NF), man-made factors (MM) and natural and man-made factors (NFM)

are runoff generating areas (sources). In contrast, areas with clusters of plants function as a drainage sink, because the organic matter content is higher, which favors the aggregation and activity of soil fauna, increasing macroporosity and infiltration (Merino-Martín et al. 2012).

The surface runoff is controlled by vegetation cover and plant morphology. Introducing key species, such as *Genista scorpius* with dense foliage, during hillside revegetation can accelerate the recovery of soil severely disturbed by mining (Merino-Martín et al. 2012). Mine revegetation is an effective way to reduce surface runoff. Roots create fissures and holes in the soil, increasing porosity and infiltration and reducing soil density. Grass roots are distributed mainly in the surface layer, with tree roots in the deeper soil layers and shrub roots at intermediate depths. The mixture of these three habits generates a rich distribution of roots and the greatest water storage capacity in the soil. The good water absorption capacity that is associated with rain interception and surface roughness reduce the direct impact of rain on the soil, reducing the volume and speed of runoff (Zhang et al. 2015).

Another factor that linearly influences surface runoff is the slope of the terrain. Increasing the slope from 40° to 50° in coal waste can change the runoff coefficient from 0.504 to 0.516 (Li et al. 2017). Among the factors influenced by human action, the topography associated with land use and slope parameters were the factors that most defined the runoff coefficient in a coal mine in Indonesia (Suyono et al. 2020). Despite this influence of slope on increasing runoff, the presence of gravel on slopes intercepts runoff and can reduce the effects of slope by 33% with an increase in slope from 35° to 40° (Guo et al. 2020). However, with the same slope, the presence of high amounts of gravel of aggregates in piles of mining waste can waterproof the surface and increase surface runoff by up to 3.05 times compared to undisturbed land (Guo et al. 2020).

Surface mining disturbs the topsoil and topography by forming fissures and depressions (Ma et al. 2020; Shinde et al. 2017). These temporarily store surface runoff, reducing it (Shinde et al. 2017; Zegre et al. 2014). On the other hand, the use of heavy machinery during open pit mining can cause soil compaction. Severe soil compaction has a negative effect, reducing porosity and water transport in the soil and leading to increased surface runoff (Wang and Wang 2020).

The construction of water conservation structures is another factor that changes runoff (Liu et al. 2020). Open pits trap rainfall and runoff and consequently affects groundwater. Differential water flow responses to surface mining are primarily due to different mining and reclamation practices, different scales of disturbance, different disturbance histories, and land cover mosaics (Song et al. 2020). The presence of ditches on the surface of a watershed can retain water, as shown in Indonesia (Isniarno et al.

2020). The effects can be on a local scale in the recharge of underground reservoirs, generating a regional and global effect on water reservoirs.

In this context, among the factors that influence surface runoff, it is important to mention the most important ones in the recovery of surface-mined ecosystems are the design of the topography, the management of soil properties, and revegetation (Espigares et al. 2013). Precipitation is the first factor in conditioning surface runoff in surface mining areas, followed by vegetation conditions that condition the arrival of water to the ground. When precipitation reaches the soil surface, the physical and chemical characteristics of the soil and the presence of gravel conditions infiltration. After reaching the infiltration capacity of the soil, runoff begins at a speed determined by the slope and micro- and macro-topography.

Methods Used to Measure Surface Runoff

In the last decade, surface runoff in surface mining areas was monitored through analysis of the mined substrate in the laboratory (three articles), field studies with the installation of in situ collecting plots (eight articles), and estimates (28 articles).

Laboratory

Laboratory-scale surface runoff studies were mainly focused on analyzing the effects of soil compaction (Wang and Wang 2020), bioengineering techniques, such as the installation of ecological bags and bamboo fences (Zhang et al. 2016), and substrate types and mixtures (Lv et al. 2020) under different rain intensities. In three laboratory studies conducted in China, disturbed topsoil from open pit coal (Wang and Wang 2020) and iron mines (Lv et al. 2020), and from a quarry (Zhang et al. 2016) were collected and taken to the laboratory to carry out experiments (Table 1).

In the laboratory, substrates collected from mines were placed and evaluated in acrylic columns (Fig. 4a) (Wang and Wang 2020), containers (Fig. 4b) (Zhang et al. 2016), or experimental troughs (Fig. 4c) (Lv et al. 2020), the last two being at variable inclinations of 30° and 40°, respectively. These were adapted with an outlet or orifice for measuring the flow volume, time for flow to start, and water content at different depths, with the flow being collected and measured with measuring cylinders (Zhang et al. 2016; Lv et al. 2020; Wang and Wang 2020).

Laboratory studies use simulated rain to measure the surface runoff of substrates with intensities from 23.12 to 120 mm h^{-1} (Zhang et al. 2016; Lv et al. 2020; Wang and Wang 2020). The different rainfall intensities, along with other compared parameters, such as density, types, and mixtures of substrates and waste (Lv et al. 2020; Wang and Wang 2020) and the application of conservation techniques, such as ecological bags and bamboo fences (Zhang et al. 2016), were statistically tested for analysis of variance (ANOVA) and least significant difference (Lv et al. 2020). The results of these statistical comparisons are presented below in the "Quantification in the Laboratory" section.

Field

Among the eight field experiments, three were conducted under simulated rain with intensities of 28 mm h^{-1} (Gomez-Gonzalez et al. 2016), 63 mm h^{-1} (Moreno-de las Heras et al. 2009), and between 1 and 3 mm min^{-1} (Guo et al. 2020). The five others were monitored under natural rain, measured using rain gauges or pluviographs (Espigares et al. 2013; Merino-Martín et al. 2012; Moreno-de-las-Heras et al. 2020; Rubio et al. 2013; Zhang et al. 2015) (Fig. 5).

Surface runoff can be monitored on plots of various sizes and shapes. The records were from circular plots of 0.24 m^2 (Fig. 5A, E) (Gomez-Gonzalez et al. 2016; Moreno-de las Heras et al. 2009), rectangular plots varying from 3 m^2 (Fig. 5D) (Guo et al. 2020) to 270 m^2 (Zhang et al. 2015), type Gerlach plots of 1–16 m^2 or those with a natural limit of 498 to 1474 m^2 (Fig. 5C) (Espigares et al. 2013; Moreno-de-las-Heras et al. 2020). The inclination where the plots were installed varied from 3 to 40°, with a single study comparing the effect of slope on surface runoff (Zhang et al. 2015). Similar slope conditions are necessary in studies with parametric statistical comparisons of data, as this factor influences the surface runoff speed. Therefore, studies comparing different slopes in the same type of mining and those with homogeneous slopes and different mined substrates are still necessary.

Surface runoff collection plots can be constructed from various materials. In most of the studies, they were delimited with steel sheets (Espigares et al. 2013; Guo et al. 2020), galvanized iron (Gomez-Gonzalez et al. 2016), rubber mats (Hoomehr et al. 2013) or cement walls (Fig. 5B) (Zhang et al. 2015). The purpose of the delimitation was to prevent water from leaving the plot and ensuring that the area remained constant. In all of the plots, the delimitation material were inserted ≈ 35 cm into the soil, while 15 cm remained above the soil surface. The type of material can influence the stability of the plots, the waterproofing of the plot boundary, in addition to generating different costs to the project.

The runoff generated in the plots was directed by pipes or by the cement construction itself to gallons, containers, drums, wells, or storage tanks and measured by the water level in the container or in measuring cylinders after runoff events (Espigares et al. 2013; Merino-Martín et al. 2012; Moreno-de-las-Heras et al. 2020; Zhang et al. 2015). In all of the experiments, precipitation was also monitored using

Table 1 Classification of methods used to collect and analyze surface runoff in open pit mining areas in the last decade (2009–2020)

Experiment	Method	Data
Laboratory	Acrylic column with soil Container with soil Ground gutters	It has precipitation and slope control; Compared by parametric statistics;
Field	Plots of 0.24–270 m^2 constructed from various materials	Collected under natural or simulated rain; Evaluated by parametric statistics when environmental factors are controlled or non-parametric;
Estimates	Most used was the CN and developed for specific mining conditions as YRWBM and GDHCMA	Evaluated, for example, using the coefficient of determination (R2);
Trends	Trend analyzes can be evaluated using the Mann–Kendall test or the Double Cumulative Curve;	

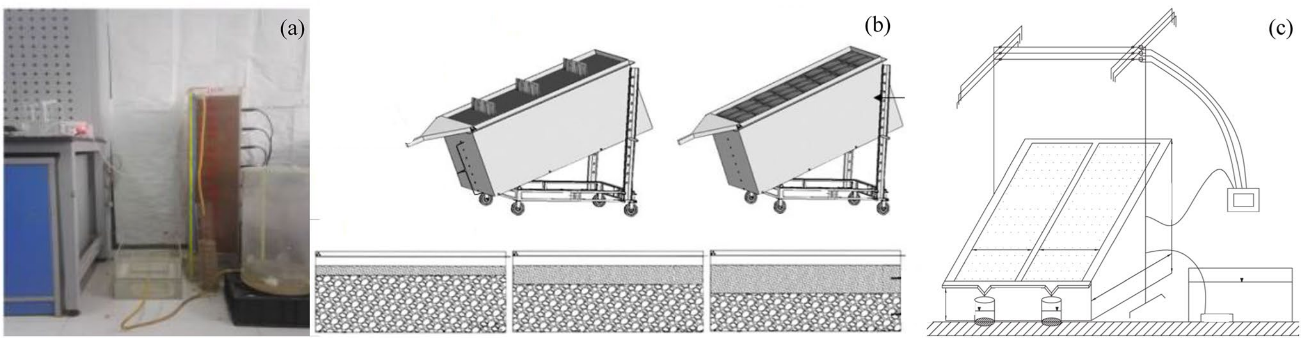

Fig. 4 Instruments used to study the surface flow of mining substrates in the laboratory: acrylic column to evaluate compaction and intensity (**a**) (Wang and Wang 2020); container with soil and waste associated with ecological bags and bamboo fences (**b**) (Zhang et al. 2016); e, the rain simulator and the ground gutters (**c**) (Lv et al. 2020)

rain gauges (Merino-Martín et al. 2012) or pluviographs (Zhang et al. 2015).

Field experiments under simulated rainfall were conducted to monitor the effect of soil on waste piles, sediments (Gomez-Gonzalez et al. 2016), or gravel waste and compared to undisturbed land (Guo et al. 2020) as well as the influence of perennial grass, and leguminous herb coverage on surface runoff (Moreno-de las Heras et al. 2009). Those with natural rainfall mainly evaluated the effect of vegetative cover, such as the percentage of cover (ranging from < 5% to > 70%) and the effect of species on surface runoff (Merino-Martín et al. 2012; Espigares et al. 2013; Moreno-de-las-Heras et al. 2020). The influence of the type of vegetation, such as grasses, leguminous herbs, shrubs, forests, and forests with shrubs was also evaluated (Zhang et al. 2015).

The number of plots used was higher in the simulated rainfall experiments, ranging from about 25 (Moreno-de las Heras et al. 2009) to 60 plots (Guo et al. 2020). Field monitoring that includes collections for at least one year had four to eight plots per environment (Moreno-de las Heras et al. 2009; Espigares et al. 2013). These repetitions were statistically compared by ANOVA, with subsequent Tukey test, t-test and chi-square, or non-parametric tests such as Kruskal–Wallis and Mann–Whitney post-hoc. Furthermore, the flow was evaluated in association with other factors that influence it using principal component analysis (PCA), correlation of Spearman, or linear regression (Moreno-de las Heras et al. 2009; Merino-Martín et al. 2012).

No plot experiments were reported in Brazil between 2009 and 2020, but the construction of a set of micro-dams using transverse dikes and settling boxes for water retention was used to control surface water and increase water infiltration in a bauxite mine in the Amazon (Fig. 5F). For this, the rainfall and height of water accumulated in the tanks were measured daily (Rubio et al. 2013).

Field experiments under simulated rain are faster and can have environmental factors controlled; therefore, parametric statistics are recommended for comparison. Field experiments under natural rain or with heterogeneous slope take longer and data analysis can be more descriptive and can use non-parametric statistics (Table 1).

Estimates

Most of the studies reviewed (28 articles = 71.8%) estimated or evaluated surface runoff trends in surface mining areas,

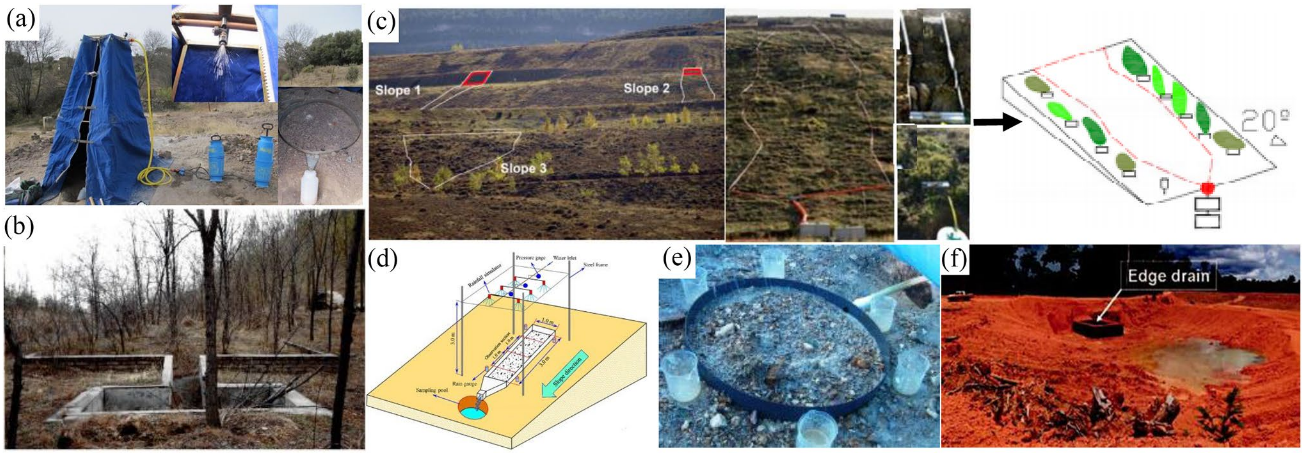

Fig. 5 Surface runoff collection systems in the field in surface mining areas: **A** view of the rain simulation under the experimental plot (Gomez-Gonzalez et al. 2016); **B** portion of runoff collecting masonry (Zhang et al. 2015); **C** nested plots with natural boundaries and Gerlach plots (Merino-Martín et al. 2012); **D** sketch of the experimental plot of simulated rain in the field (Guo et al. 2020); E) Permanent plot during execution of a rainfall simulation experiment (Moreno-de las Heras et al. 2009); and, **F** micro-dam built in a drainage channel (Rubio et al. 2013)

with 11 models and four approaches for trend analysis being found.

In all of the models, input data was required to generate the equation, and estimate or validate the surface runoff data. The main inputs for estimation were the surface runoff data measured in collecting plots in the field (Hoomehr et al. 2013; Taylor et al. 2009), observed infiltration and soil moisture (Ma et al. 2020), or associated with precipitation and temperature of meteorological (Labonté-Raymond et al. 2020), hydrological, and pluviometric stations (Liu et al. 2020). In addition, satellite images, such as Landsat, were used to define land use and cover (Zégre et al. 2014), topographic data such as digital elevation model (Awotwi et al. 2019; Liang et al. 2019; Ma et al. 2020), inclination (Manna and Maiti 2016), depressions (holes) (Shinde et al. 2017), soil types and properties (Ma et al. 2020; Shinde et al. 2017), vegetative cover (Awotwi et al. 2019; Manna and Maiti 2016; Nigam et al. 2017; Shinde et al. 2017), and leaf area index (Luan et al. 2020). In trend analysis, daily, monthly, or annual surface runoff and precipitation data were used to detect changes generated by surface mining over time (Awotwi et al. 2017; Luan et al. 2020; Zégre et al. 2013, 2014).

Surface runoff modeling was done at two scales: local, by the installation of collecting plots (Hoomehr et al. 2013) with the data extrapolated to the river basin (Taylor et al. 2009), or directly at the watershed level (Awotwi et al. 2019; Guo et al. 2017, 2019a; Liang et al. 2019; Wang et al. 2016; Zhang et al. 2020; Zégre et al. 2013, 2014), with estimates being found for a maximum of 53 micro-watersheds with mined areas (Manna and Maiti 2016).

The flow estimation models were mostly deterministic in the prediction stage, as the output is predictable from the input data. Among the various models used to predict surface runoff in mining areas, those based on curve numbers (CN) were the most frequently used around the world (Hoomehr et al. 2013; Manna and Maiti 2016; Nigam et al. 2017; Taylor et al. 2009; Warner et al. 2010). The runoff CN was developed by the U.S. Department of Agriculture (USDA 1972), with the CN being a land cover index for a given type of soil that indicates the amount of rain that infiltrates the soil and the amount that becomes surface runoff for a specific rain event (USDA 1972). This index ranges from 0 to 100, with 100 indicating the highest possible runoff potential of an area (Warner et al. 2010).

The CN can be used to estimate surface runoff volume from runoff data measured on field plots over a period of one year associated with precipitation data and rainfall return period (Hoomehr et al. 2013). Runoff volumes measured on mine plots under 12 rainfall events greater than 25.4 mm can be extrapolated to calculate CN at the catchment level (Taylor et al. 2009). The CN can also be determined for watersheds disturbed by coal mining by considering 42 events from combinations of precipitation and runoff (or flow) (Warner et al. 2010). In addition, surface runoff for coal mine in the open pit areas was estimated by the NC method using 21 years of daily rainfall data and considering pasture as the land use and land cover (Nigam et al. 2017).

Another model, runoff curve number (RCN), adapts the CNs by correlation with land cover and soil type to estimate surface runoff per watershed in a geographic information system (GIS). This model was used to evaluate changes in surface runoff due to excavations in mining areas. In this model, GIS was used to map channels and mines and to calculate the contribution area and flow length to obtain the volume of rainwater that were retained in each excavated mine (Manna and Maiti 2016).

Variations of the CN model have also been used to simulate surface runoff in mined areas, for example, the soil and water assessment tool (SWAT) model that uses CN (USDA 1972) or the Green–Ampt model (Green and Ampt 1911). SWAT was invented by the USDA in the early 1990s and simulates the process of rainfall-runoff, sediment production, and pollutant or nutrient transport at different watershed scales (Arnold et al. 1998). Surface runoff in SWAT is calculated using a CN equation modified for use in GIS and also considers precipitation, land use, and soil conditions and can be used to assess with satisfactory precision the impacts of mining activities on hydrological processes (Awotwi et al. 2019; Liang et al. 2019; Shinde et al. 2017).

The SWAT was used to model the hydrological response of open pit mines in a watershed using topographic data, where mine depressions are defined as holes, soil properties, climate, land cover and vegetative information (Awotwi et al. 2019; Liang et al. 2019; Shinde et al. 2017). The hydrological effect of the mines was obtained by simulating the SWAT model calibrated and validated with historical data of five (Shinde et al. 2017), ten (Liang et al. 2019), or 40 years (Awotwi et al. 2019). Mined and non-mined and land use conversion scenarios, considering their respective responses to changes in soil characteristics, land use, and slope, were simulated to obtain hydrological responses and to calculate surface runoff (Awotwi et al. 2019; Liang et al. 2019; Shinde et al. 2017). Furthermore, multiple regression analyzes were performed to evaluate the relationship between changes in land use and surface runoff estimated for the SWAT model (Awotwi et al. 2019).

The storm water management model (SWMM) was also used to estimate event-based and long-term surface runoff in areas of new (8–15 years) and old (more than 30 years) coal waste (Li et al. 2017). The Yellow River Water Balance Model (YRWBM) was developed to simulate surface runoff in the Kuye River basin (China) and was used to estimate surface runoff with data on monthly runoff, daily precipitation, and average daily temperature from 1955 to 2010 in this same basin (Guo et al. 2017).

Another modeling system used in mining areas was MIKE SHE, which was developed in Europe, where runoff was estimated from finite difference methods and using meteorological, terrain, and land use data. Additionally, observed runoff was used for model calibration and validation. The simulated flow with real and simulated values before and after mining can be compared to verify the influences of mining on the flow, as was done for the Gujiao River in China (Ping et al. 2017). This system was updated (Mike Hydro River software—MIKE 11) and used in mining areas in Canada to evaluate changes in runoff using the Nedbod Afrstromnings rainfall-runoff model and 133 days of data from Van Essen pressure sensors in four river basins and rain-gauge-measured precipitation (Labonté-Raymond et al. 2020).

The effects of coal mining on runoff can also be estimated using the SIMHYD-PML hydrological model, which, in addition to climate variables and land use, considers the vegetation dynamics included the leaf area index (Luan et al. 2020; Song et al. 2020). Another alternative for modeling daily surface runoff at the watershed level used in West Virginia (USA) is the hydrography transfer function (Jakeman and Hornberger 1993) included as a routine part of the transfer function hydrography separation (Transep) model (Weiler et al. 2003). This function uses data on average daily runoff and precipitation and allows the construction of models that must be calibrated in each hydroclimatic condition and land use of the basin (Zégre et al. 2013).

Geographic information systems can be used to monitor hydrological processes based on spatial data. In this case, runoff is calculated using the rational method developed in the United States, which considers data on precipitation intensity, area, and runoff coefficient to estimate runoff. From the estimate, it is possible to design the construction of ditches to store the runoff water that flows in mining areas, considering the slope and type of soil (Isniarno et al. 2020). A grid-model-based distributed hydrological model for a coal mined-out area (GDHCMA) was also developed in GIS to estimate the distribution of rainfall and runoff in coal mined areas in Shanxi province, China. The digital model of elevation, soil moisture, laboratory estimated infiltration, land use, soil class, temperature, precipitation, and flow were used in GDHCMA, where within each square grid, the model follows a simple water balance (Ma et al. 2020). After detecting change in time series, monthly water-balance model (MWBM) of the Thornthwaite (McCabe and Markstrom 2007) and observed data were used to verify the contributions of coal mining to the decrease in flow (Guo et al. 2019a).

Systematic stepwise regression analysis was used to investigate the factors that influence runoff in the Kuye River basin to provide information for the ecological restoration of ecosystems in coal mining areas. Data of 55 years of runoff were used and linked to data on precipitation, temperature, water consumption, a Soil and Water Conservation Measures area, and coal mining, using Statistical Package for the Social Sciences (IBM SPSS) software to perform all of the analyses (Wu et al. 2020a).

The value of the runoff coefficient can be estimated in different ways and used to assist in the design of surface water retention channels. Different estimation approaches can be compared and evaluated to assist in sizing retention ditches from precipitation data, as was done at the coal mine in Tanah Bumbu Regency, South Kalimantan (Suyono et al. 2020).

The efficiency and performance of models can be indicated by the coefficient of determination (R^2; Liang et al. 2019), Nash–Sutcliffe coefficient of efficiency (NSEGuo et al. 2019a; Liang et al. 2019; Ma et al. 2020; Zégre et al. 2013), percentage bias (PBIAS; Liang et al. 2019) and relative error (RE; Ma et al. 2020). The most used and recommended model in different mining locations and conditions was the CN. Other models, such as YRWBM and GDHCMA, were developed for specific mining conditions. The best model for each condition also depended on the availability and ease of collecting input data (Table 1).

Trends

Trend analysis can also be used to detect changes in hydrological long-term time series in mining areas, mainly at the river basin scale. The Mann–Kendall trend test was the most common of these among the studies (Awotwi et al. 2017; Guo et al. 2019a, b; Luan et al. 2020; Zégre et al. 2013). This is a non-parametric test derived from the correlation between the ranking order of observed values and their order in time (Hamed and Rao 1998).

Trend analysis can be applied before estimating runoff, for example, using the five-year moving average and the Mann–Kendall test (Hamed and Rao 1998) to verify runoff trends with cumulative anomaly analysis and the Pettitt test to detect years of abrupt change in runoff (Luan et al. 2020). The trend can also be evaluated after modeling, as was done in four mined basins in West Virginia (USA), where estimated daily runoff data were aggregated like mean annual runoff for trend analysis using the non-parametric Mann–Kendall test (Zégre et al. 2013).

In the Big Coal River watershed in North Carolina (USA), this test was applied to verify trends on the annual and monthly scale of mean, minimum, and maximum runoff based on river runoff and daily precipitation data from 1969 and 2010. Furthermore, land use changes in the basin were measured from 1973 to 2010 using Landsat images and considering the active mining, recovered, and licensed forest classes to relate them to surface runoff trends (Zegre et al. 2014).

In the Taojiang River watershed, where shallow land mining occurs, daily runoff volumes recorded at the Julongtan Hydrological Station, as well as 58 years of daily precipitation data collected at 27 rain gauge stations were subjected to Mann–Kendall trend testing to diagnose increasing or decreasing trends (Liu et al. 2020). The impacts of phosphate mining on the hydrology of surface waters in the Huangbai River basin in China were also analyzed using the Mann–Kendall test. Surface runoff was compared before (from 1978 to 2002) and during (from 2003 to 2014) mining and the trend of rainfall and runoff time series were identified during the wet and dry seasons (Wang et al. 2016). Considering more historical data (1955 to 2013) in the same basin, annual surface runoff was analyzed using the modified Mann–Kendall trend test, adapting to autocorrelated data (Hamed and Rao 1998). Cumulative anomaly curves and Pettitt test were performed after trend analysis to detect years of change (Guo et al. 2019a). The same authors (Guo et al. 2019b) evaluated surface runoff between 1954 and 2015 in the same river basin through temporal analysis using the Mann–Kendall trend test and change detection using the cumulative anomaly curve. A simple regression model between rainfall and runoff was used to quantify the influence of mining on runoff (Guo et al. 2019b).

In addition to the Mann–Kendall test, time series analysis can be evaluated by the double accumulation curve of precipitation and runoff to reveal the influence of mining on surface runoff. This method is based on the gradual accumulation of two variables at the same time and when the flow is affected by mining, the curve will deviate (Guo et al. 2017). The Mann–Kendall test can be associated with a double accumulation curve, as was done with41 years of data (1970 to 2010) in the Pra River, Ghana (Awotwi et al. 2017). The authors used Mann–Kendall to analyze monthly, annual, and seasonal trends in surface runoff and the Pettitt test and the dual cumulative curve of runoff were applied to evaluate changes due to gold mining (Awotwi et al. 2017).

In Australia, daily flow and precipitation data from more than a century (1913 to 2015) were separated into phases (pre-mining, underground mining, and open pit mining) and evaluated by the double mass curve (DMC) method (Song et al. 2020). The DMC method can be applied to daily runoff and monthly precipitation data to estimate the period of change in surface runoff, as was done for the Kuye River in China. This definition allows you to separate the base years (without mining) from the impact years (post-mining) for comparison purposes (Luan et al. 2020). Long-term studies can help assess the consequences of past mining and provide a perspective on the best ways to control the adverse environmental effects to maintain and protect the environment.

Another option for evaluating trends in surface runoff affected by coal mining on drought risk at the basin scale is the entropy method. This method estimates the points of interference in the hydrological series and is complemented by the runoff anomaly percentage method defines the threshold value in the division of the drought process influenced by mining (Zhang et al. 2020).

Trend analysis can be evaluated using the Mann–Kendall test on annual, monthly, or daily data, or the double cumulative curve (DCC), which is more suitable for daily data. The evaluation periods vary from five years to more than a century. Knowing the periods of change in a temporal trend analysis helps in decision-making in mitigating environmental impacts and in rehabilitation activities in mined areas (Table 1).

Volume of surface Runoff

Surface runoff in open cast mining areas in the last decade ranged from 2.75 to 488 mm annually and 1.02 to 48.75 mm monthly, measured in height of water depth in different areas of mined soil (Fig. 6). These values were recorded for annual precipitation ranging from 386 mm, in the semi-arid region of China (Guo et al. 2019b; Luan et al. 2020) to 2,189 mm in the Brazilian Amazon (Rubio et al. 2013).

The highest average annual surface runoff (488 mm) was estimated in the Big Coal River watershed in the United States, where in the monitoring period (1994–2010), the area occupied by mines increased from 2.7 to 9.1% of the basin (Zégre et al. 2013). In the same area, the 37-year historical series of surface runoff (1973–2010) showed average monthly surface runoff values of 23.6 mm, with a tendency to decrease by 12.7 mm over the study period as the mined area increased from 3.9% to 9.2% due to the creation of valleys that retained rainwater and enhanced infiltration (Zégre et al. 2014).

The second largest annual runoff (413.3 mm) was measured at a coal mine in India. The annual runoff estimated from 21 years of precipitation, using the CN method corresponded to 31.7% of the average annual precipitation (1303.4 mm). The high surface runoff was explained by the high saturation of the soil during the monsoon period, which tends to reach a constant rate of infiltration and generate high runoff (Nigam et al. 2017).

An increase in surface runoff from 3.4 to 33.44% was observed in the Pra River Basin in the forest of Ghana. This was attributed to the increase in mining areas at the expense of forests and arable land between 1986 and a projected 2025 scenario. The authors mentioned that mining in the basin made the soil surface less permeable (Awotwi et al. 2019).

Under natural annual rainfall of 550 mm, three 20° slopes were evaluated for the influence of vegetation cover on surface runoff in a coal mining field in Spain. The slope with 67% coverage of grasses and subshrubs generated 11.17% (67.43 mm), with 93% grasses coverage caused 2.04% (11.23 mm), and the one with 81% shrub coverage generated the least runoff of 0.5% (2.75mm). The low runoff of this last slope was explained by the active role of the *Genista scorpius* shrub in creating islands of improved vegetal and hydrological productivity that function as runoff sinks in the recovery phase (Espigares et al. 2013).

In the same region, at a coal mine in Urtilhas, Spain, the plants also influenced surface runoff on three slopes of a revegetated coal mine. The 703 mm (2007–2008) of precipitation generated 36.7 mm of surface runoff. The fragmented slope with *Genista*, *Brachypodium*, and *Lolium* had the lowest surface runoff rates (Merino-Martín et al. 2012). Also on these slopes, a network of grooves connected the runoff areas at the top of the experimental slope with the bottom of the slope and the outlet. The surface runoff varied from 6 to 72% according to the vegetation and slope type. The undrained portion was redistributed or infiltrated into the slope due to the presence of vegetation (Moreno-de-las-Heras et al. 2020). This result confirms that the type of cover on the slope influences the generation of runoff from reclaimed mines and indicates that this type of cover functions as a surface runoff sink.

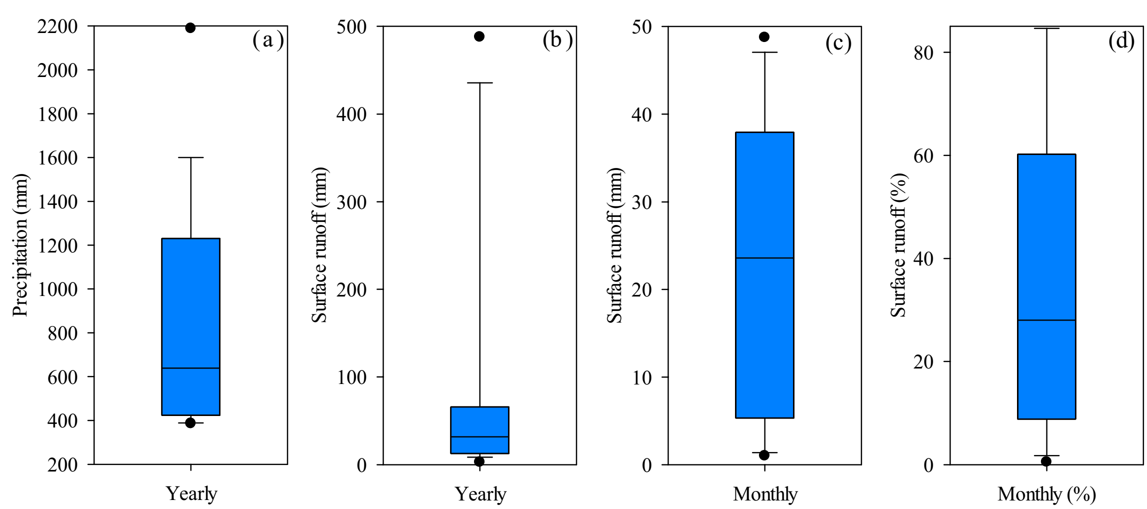

Fig. 6 Annual precipitation, annual and monthly surface runoff in the last decade in surface mining areas

Another technique for reducing surface runoff was the construction of a micro-dam system at a bauxite mine in the Brazilian Amazon (Rubio et al. 2013). The set of micro-dams stored surface water runoff on the mined surface during and after recovery. Furthermore, the micro-dams favored increased infiltration and evaporation of surface water and substantially reduced the discharge of solids into downgradient streams (Rubio et al. 2013).

In the simulated rainfall experiments, the 28 mm h^{-1} at the wolframite mine in Spain generated 1.63 mm (6%) of surface runoff in the waste pile, 5.33 mm (19%) in the vicinity of the mine bed river, and 4.81 mm (17%) in the sediment from an artificial sedimentation tank (Gomez-Gonzalez et al. 2016). On the slopes of the Shenfu-Dongsheng coal mine, precipitation intensity between 1.3 and 3.0 mm min^{-1} generated the maximum runoff (2 mm h^{-1}) in the waste pile with the most gravel. Comparing this value with undisturbed land (control), an increase of 71.39% was observed. A ratio of 1.89 times between the maximum and minimum value was recorded and explained by the gravel content, with the presence of high-density gravel aggregates increasing the surface runoff rate (Guo et al. 2020).

At reclaimed mines in central-eastern Spain, increased herbaceous vegetation cover exponentially reduced the runoff coefficient and increased infiltration rates. Low surface runoff coefficients and high rates of infiltration and soil profile humidification were obtained on the most vegetated slope (59.4%), being 30%, 37 mm h^{-1}, and 24 cm h^{-1}, respectively. The opposite was observed on the least vegetated slope (1.1%), with runoff of 70%, infiltration of 10 mm h^{-1}, and humidification of 8 cm h^{-1} (Moreno-de las Heras et al. 2009).

In coal mines in China, vegetation also greatly influenced surface runoff on flat (3–5°) and steep (36–40°) slopes. The 331 mm of rainfall generated 301.6 mm of runoff in the flat area and 138.1 mm in the slopes, contradicting the expectation that greater runoff accompanies steep slopes. This was explained by the high runoff from the bare plot, which generated 126.7 mm of runoff in the flat area and three times that volume on the bare sloped portion (Zhang et al. 2015).

Runoff estimates using the CN method for steep (20°), low compaction slopes in the eastern Tennessee coal mining region showed a wide range of runoff events between 0.6 and 125.3 mm (averaging 23.47 mm) (Hoomehr et al. 2013). For the Little Millseat watershed, also in the United States, CN values ranged from 54 (2.5 mm) to 93 (26.0 mm), with an average CN of 83 (13.65 mm), with portions of the areas being revegetated mined land. The average value exceeded literature values (55 to 70) for good forest conditions and was explained by low evapotranspiration rates as well as decreased infiltration capacity (Taylor et al. 2009).

The CN at the Starfire mine in the United States was between 62 and 94 with an average of 85 (Warner et al. 2010). These values corresponded to river flows ranging from 12 to 691 m^3 for precipitation events between 5 and 58.9 mm. The results indicated that the intervals between rain events allowed the infiltration rate to recover, which resulted in less runoff (Warner et al. 2010).

The CN was correlated with land use at 53 basins affected by coal mining in India that had an estimated annual runoff of 42.78 mm. This was less than expected for the basins and was explained by better infiltration in the valleys and the existence of depressions and excavations, which stored precipitation, enhancing infiltration (Manna and Maiti 2016).

In the Olidih river basin, India, the simulated average annual surface runoff (2005–2010) for a non-mined scenario (232 mm) was 51.33% higher than that for the mined scenario (153.3 mm). This was also explained by the presence of holes and disturbances in the soil surface at mined sites, where water is stored, resulting in increased infiltration and reduced surface runoff (Shinde et al. 2017). In the Taojiang River basin, China, a reduction in forest area at the expense of mining areas increased surface runoff by 0.08% (38.09 mm) from 2005 to 2010 and 0.16% (38.12 mm) from 2010 to 2015 (Liang et al. 2019).

High runoff coefficient values (0.504–0.838) were estimated for an abandoned coal mine in China, meaning that more than 50.4% of the rainwater is converted into runoff. This high value was explained by the low vegetative cover and the loose and unstable surface soil (Li et al. 2017). Also in China, the SIMHYD-PML hydrological model estimated an annual surface runoff of 48.86 mm for an observed value of 26.97 mm and 386 mm of rainfall in mined areas in the Kuye River basin (Luan et al. 2020). In the coal mined area of the Wujiayao watershed, a grid-based distributed hydrological model showed an increasing trend of surface runoff since 1990. The observed annual runoff ranged from 14.3 mm to 27.0 mm while the estimated runoff was between $\approx$ 5.5 and 16.3 mm (Ma et al. 2020). In the Gujiao River, surface runoff decreased by 1.4 mm and this was explained by the presence of fissures in the soil that trapped water in the mined areas (Ping et al. 2017).

The runoff coefficient of a river basin in Indonesia was 0.854, requiring a ditch with a capacity of 23.997 $m^3.s^{-1}$ to retain these waters. Planning the design of water retention ditches in GIS is essential for decision-making in hydrological control and monitoring (Isniarno et al. 2020). In Canadian river basins with gold mines, the surface runoff coefficient was between 0.28 and 0.71, with the lower value being explained by runoff flowing to other basins before reaching the measurement channel. These data were recorded for 544 mm of rain in 133 days and an increase in water levels in basins was recorded after rainfall above 20 mm (Labonté-Raymond et al. 2020).

In the Tanah Bumbu Regency basin, South Kalimantan, different methods of estimating the surface runoff coefficient resulted in values between 0.15 and 0.9, with topography, land use, and slope parameters being the most influential factors in this variation. This value directly influenced the size of the open channel of the surface runoff retention ditch (Suyono et al. 2020). The main factors influencing the flow of the Kuye River (China) were defined using stepwise regression analysis. Without mining, temperature and precipitation influenced runoff. Large-scale coal mining activities initiated in 1998 have decreased Kuye runoff, as have water conservation measures (Wu et al. 2020a).

Quantification in the Laboratory

Soils from a quarry in China were taken to the laboratory and tested for the effects of three depths of soil cover and the use of eco-friendly bags and bamboo fencing. With 30, 60, and 120 mm h^{-1} of precipitation and 30° of inclination, the eco-bags and bamboo fences decreased runoff and improved infiltration, with bamboo fences being better at intercepting runoff and reducing it by 17.98, 19.06, and 20.85% in the three precipitation intensities, respectively. The highest runoff was with greater rainfall intensity (120 mm h^{-1}) with a value of 74.95 and 74.94 mm h^{-1} for the ecological bags and bamboo fences, respectively. This was explained due to the imbalance between rainfall intensity and water infiltration into the soil (Zhang et al. 2016).

Wang and Wang (2020), investigating coal mined soils in a laboratory in China, found that given the same soil density, rainfall intensity increased surface runoff. With the same rainfall intensity and high soil density, infiltration was low and runoff was increased. This result indicated that greater intensity and severe soil compaction increased surface runoff and decreased runoff time. This result was because compaction reduces soil macroporosity, which is responsible for water transport in the soil, suggesting that engineering and revegetation measures were necessary to improve the quality of compacted soil at surface mines (Wang and Wang 2020).

Substrates from iron mines in China showed differences in surface runoff rates in the laboratory under simulated rainfall events of up to 120 mm h^{-1}, with tailings incorporated with soil showing a high runoff rate throughout the rain event. Mushroom waste had low rates in the first 15 min and increased with the amount of rain. The runoff rate with only soil was relatively less and differed from the other substrates (Lv et al. 2020).

Surface Runoff Trends

Nine studies evaluated surface runoff trends in open cast mining areas and were conducted at the river basin scale, referring to surface runoff of free water or flow. Eight of the nine studies detected a decreasing trend in runoff (Guo et al. 2017, 2019a, b; Luan et al. 2020; Zégre et al. 2014). In contrast, in gold mining areas in the Pra River Basin in Ghana, annual runoff showed an increasing trend, with a rate of 309 $m^3 s^{-1}$ per year. The increase in surface runoff was explained by the sealing of the surface created by clay from the new surface soil filling the pores and the washed gravel, preventing water infiltration into the soil (Awotwi et al. 2017).

In the Kuye River basin in China, the DCC of the surface runoff time series from 1999 to 2010 showed a decreasing trend, with a reduction of 29.69 mm. The increase in coal mining activities was responsible for 71.13% of the reduction in runoff in this period (Guo et al. 2017). In the same basin, a reduction in average annual runoff has been detected since 1960 (Guo et al. 2019a, b). The average annual impact of coal mining was – 2.15 mm (12.01%) between 1979 and 1996 to – 29.88 mm (54.24%) between 1997 and 2013 (Guo et al. 2019a). In a longer annual series, the average runoff rate of 69.13% in 1954–1979 fell to 59.36% between 1997 and 2015 (Guo et al. 2019b). One explanation for this is the increase in mining activities and the generation of fissures on the surface, which altered infiltration and reduced runoff in the river basins (Guo et al. 2019a, b).

Runoff trends in Kuye River basin, in China, were also evaluated under the influence of coal mining (Luan et al. 2020; Zhang et al. 2020). Overall, annual runoff showed a decreasing trend from 1956 to 2017. The simulated total runoff showed that coal mining reduced total runoff by 29.35% for the Wangdaohengta sub-watershed, by 55.41% for Shenmu, and by 49.44% for the entire Kuye River watershed (Luan et al. 2020).

The historical series of surface runoff in this basin was also evaluated regarding the influence of the reduced surface runoff on the occurrence of droughts and its relationship with mining. The authors (Zhang et al. 2020) found that annual runoff in the Kuye River basin began to decline in 1979, when the hydrological drought began, coincidentally with the beginning of large-scale mining. The maximum drought severity was 145.1 mm in periods with mining, indicating that this activity significantly increased the risk of drought in the region, threatening the sustainable development of local ecology (Zhang et al. 2020).

The influence of mining on the hydrology of the Huangbai River basin was assessed by comparing the results before (from 1978 to 2002) and during (from 2003 to 2014) the phosphate mining period. Annual runoff before mining ranged from 301 to 758 mm and from 335 to 691 mm during phosphate mining. The average surface runoff coefficients before mining was 0.447 and greater than during mining at 0.402. Furthermore, a significant decreasing trend was observed for the surface runoff series from 2008 to 2014. The reduction in surface runoff was explained by fractures in the rocks generated during the extraction of phosphate and due to the mines themselves, which intercept runoff and increase the water infiltration capacity and evaporation losses of the area (Wang et al. 2016).

The Big Coal River watershed was evaluated for runoff trends for 16-year (1994–2010) (Zégre et al. 2013) and 37-year periods (1973-2010) (Zegre et al. 2014) relative to changes in land cover. In the first series, no statistically significant trends were detected, although the total area of mining disturbance increased from 2.7% (1994) to 9.1% (2010) and changes in land cover occurred on time scales greater than the study period (Zégre et al. 2013). The 37-year series had a decreasing trend in runoff, decreasing 12.7 mm over the study period with an increase in mining areas from 3.9% to 9.2% of the basin. This decrease was explained by the creation of valleys in the mines that tend to control surface runoff (Zégre et al. 2014).

In the Taojiang River basin, which had been mined for rare earths, the average annual surface runoff showed a general declining trend between 1962 and 1972 due mainly to the construction of water conservation structures (Liu et al. 2020). Coal mining activities in the Goulburn River Basin, Australia also decreased surface runoff, from 10.51 mm year^{-1} to 2.84 mm year^{-1}, a 73% reduction in flow (Song et al. 2020). Most of the studies that evaluated runoff trends were carried out in China, making these scientific analyzes necessary in most parts of the planet.

Conclusion

We reviewed runoff studies on surface mined lands between 2009 and 2020, most of which were conducted in China and the United States, with the hydrological impacts of mining not recorded on a local scale in scientific articles for most of the planet. In general, studies indicate that surface runoff is quite variable in surface mines, ranging from minimum annual values (2.25 mm) to very high values (488 mm). Research with field plots and watershed estimates suggest that surface runoff is not stable years after mining and reclamation are completed, with the main trend being a reduction relative to non-mined environments.

Surface runoff was measured in field and laboratory tests and estimated with models to assess the effects of mining. In the field, runoff was monitored in plots of different areas and shapes, from circular plots of 0.24 m^2 to rectangular plots of 270 m^2. The estimates encompassed several models, with the CN used for estimation and the Mann–Kendall test for time series analysis being predominant. The comparison methods in the studies can be divided into three classes: simple statistical comparison, application of regression models, and application of hydrological models.

There are several factors that influence surface runoff. Studies have shown that vegetative cover, bioengineering techniques (bamboo fences and ecobags), the presence of cracks on the surface, and the creation of valleys are factors that tend to reduce surface runoff. In contrast, the amount and intensity of rainfall, soil compaction, the presence of gravel, and increases in slope were the main causes of increased surface runoff in surface mining areas.

In general, mined sites with established vegetation, uncompacted well-structured soils, and good infiltration should reduce the level of hydrological impacts caused by mining compared to unmined conditions. These are aspects that must be highlighted when seeking to mitigate the effects of surface mining on local surface waters.

Machine learning is already being applied to estimate surface runoff, but no studies were found in mining areas with this focus, making the use of this method a possibility to better manage areas undergoing rehabilitation. Also, few studies have directly recorded mine reclamation practices conducted to restore pre-mining surface runoff or mitigate the hydrological impacts of surface mining. Among the practices with gaps are the construction of relief forms and reconstruction of the surface to allow infiltration, restrict the movement of surface water, and reestablish vegetation in mined soils.

The studies were carried out in just a few locations on Earth, mainly in China, the United States, Spain, and India. Countries like Chile did not have articles registered and in Australia and Brazil, only one study was found. Greater spatial scope of research is needed to determine whether the available results are valid for other locations. Furthermore, the effect of mining on surface runoff has been investigated directly in few studies, because most of the studies only used precipitation-runoff modeling without considering the effects of vegetation change and field-observed data on surface runoff. The effects of increased or decreased runoff from open pit mines on water quality and the environment in areas affected by mining are also opportunities for new research.

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