



Coal pit lakes in abandoned mining areas in León (NW Spain): characteristics and geoecological significance

J. M. Redondo-Vega¹ · A. Melón-Nava¹ · S. A. Peña-Pérez² · J. Santos-González¹ · A. Gómez-Villar¹ · R. B. González-Gutiérrez¹

Received: 13 July 2021 / Accepted: 6 October 2021 / Published online: 21 November 2021
© The Author(s) 2021

Abstract

Mining activity introduces severe changes in landscapes and, subsequently, in land uses. One of the most singular changes is the existence of pit lakes, which occur in active and, more frequently, abandoned mines. Pit lakes are produced by water table interception when open-pit mines deepen. Their characteristics are highly variable, depending on the type of mine, the environment or the climate. In León province there is a long tradition of coal mining that dates back to the nineteenth century, and hundreds of open pits from the 1970s to 2018 have been opened, producing permanent landscape changes. This work analyses the main parameters, including morphological measurements, depth and pH values obtained from aerial photos and field work, of 76 coal pit lakes more than 30 m in length. The vast majority of these pit lakes were unknown until now and were not included in inventories or maps. The data obtained provide baseline knowledge that will allow, in the future, potential uses (storage of water for various uses, recreational use, wildlife habitat, and geological heritage sites) for these pit lakes and establish their importance as a new geoecological environment.

Keywords Coal pit lakes · Morphometry · Open pit mining · León province

Introduction

One of the human activities that most transforms our environment is mining (Tandy 1975; Trigg and Dubourg 1993; Townsend et al. 2009; Palmer et al. 2010; Oyarzun et al. 2011; Mossa and James 2013; Tsolaki-Fiaka et al. 2018; Kopec et al. 2020), especially if the mineral exploitation method is open-pit mining (Hüttl and Gerwin 2005; Sekhar and Mohan 2014). This method is at the origin of changes in the relief (Redondo Vega 1988; Townsend et al. 2009) and of the land uses of the areas affected by this activity

(Duncan et al. 2009; Tarolli and Sofia 2016; Jiaying et al. 2017; Redondo-Vega et al. 2017; Redondo Vega 1994, 2000; Qian et al. 2017; Werner et al. 2019). While these changes only occupy 0.4% of the Earth's surface (Hooke et al. 2012), the intensity and speed with which they occur make them a particularly aggressive, persistent (Chen et al. 2015) and almost always irreversible phenomenon (Larondelle and Haase 2012; Mossa and James 2013; Tarolli and Sofia 2016; Tarolli et al. 2018; Redondo Vega et al. 2017; Song et al. 2020), since the massive use of machinery and blasting manages to break apart entire mountains (Reece 2006; Bernhardt and Palmer 2011), transforming their landscape and changing their function and use.

In recent decades, the affected surfaces have increased exponentially (Townsend et al. 2009; Palmer et al. 2010; Bernhardt and Palmer 2011; Reece 2006; Wickham et al. 2013; Qian et al. 2017), and many of the studies analyse the subsequent land use changes (Latifovic et al. 2005; Bloodworth et al. 2009; Wu et al. 2008; Wang et al. 2011; Prakash and Gupta 1998; Sekhar and Mohan 2014; Yang 2008; Duncan et al. 2009; Bian and Lu 2013; Redondo-Vega et al. 2017; Jiaying et al. 2017; Xu et al. 2017; Dwiyanto et al. 2021) or present methodological (Chen et al. 2015) and

This article is part of a Topical Collection in Environmental Earth Sciences on Earth Surface Processes and Environment in a Changing World: Sustainability, Climate Change and Society, guest edited by Alberto Gomes, Horácio García, Alejandro Gomez, Helder I. Chaminé.

✉ J. M. Redondo-Vega
jmredv@unileon.es

¹ Department of Geography and Geology, Universidad de León, 24071 León, Spain

² Cartography Service, Universidad de León, 24071 León, Spain

management proposals for these spaces after mine closure (Nixdorf et al. 2005; Schultze et al. 2010; Larondelle and Haase 2012; Soni et al. 2014; Castendyk et al. 2016; Blanchet and Lund 2017; Marescotti et al. 2018; Kivinen 2017; Kivinen et al. 2018; Gulpinar Sebkan and Acar 2021).

Pit lakes (Castro and Moore 2000; Gammons et al. 2009), also called strip mine lakes (Hildmann and Wünsche 1996) and post-mining lakes (Hangen-Brodersen et al. 2005; Baeten et al. 2018), are one of the most unique elements that open-pit mining generates since they always involve a radical modification of the landscape with respect to the pre-operational situation (Redondo Vega et al. 2018). They are found at the bottom of abandoned open-air operations due to the inflow of waters of different origins, such as groundwater (Siegel 1997; Soni et al. 2014), direct precipitation and surface runoff from the watershed to the lake, or both origins in conjunction (Zhao et al. 2009). Their location characterizes these basins as endorheic unless they have an outflow channel (Redondo Vega 1988; Redondo-Vega et al. 2017) to release excess water.

Pit lakes can have a large surface area and could be hundreds of metres in depth, as in the lignite mines of Germany (Hildmann and Wünsche 1996; Antwi et al. 2014) or Spain (Aréchaga et al. 2011; Mijares Coto 2013) generated by forced flooding from a nearby river system (mine rehabilitation by flooding, Fitzgerald and Watkins 1997). They can also be small mining pit lakes with shallow water (Redondo-Vega et al. 2017, 2018), with depths between 0.70 and 15 m. These pit lakes are abandoned without any type of subsequent management after the mining ends and are the object of our study.

Despite the existence of thousands of pit lakes (Blanchet and Lund 2017; Baeten et al. 2018), there are few studies on this subject and those that exist focus on their ecological conditions and geochemical parameters (Castro and Moore 2000; Geller et al. 2013; McCullough and Lund 2006; Zhao et al. 2009; Bohrer et al. 2010; Schultze et al. 2010; Molléma and Antonellini 2016; Castendyk et al. 2016; Marszelewski et al. 2017; Sánchez-España et al. 2008, 2014; Palit et al. 2016a). Therefore, the main objective of this study is to inventory and study their basic physical parameters, since today they are an unknown phenomenon—at least in the province of León—and it is not even known how many there are, where they are and what they are like. Only by knowing about them can they be integrated into the management of these degraded and abandoned mining spaces (Hüttl and Gerwin 2005; Kumar et al. 2009; McCullough et al. 2020; Castendyk et al. 2016; Kivinen et al. 2018).

In León, there are 2000-year-old mining lakes generated by Roman gold mining and considered cultural heritage (Redondo-Vega et al. 2018), such as those within the UNESCO World Heritage Site of Las Médulas. The coal pit lakes currently do not have such consideration. It is

necessary to recognize them as being part of the cultural heritage (Marescotti et al. 2018) since the adoption of more sustainable energy sources has made these mines disappear, constituting the pit lakes as a cultural and landscape legacy of that activity.

The study covers a large area of the province of León, but focuses on the place occupied by pit lakes within the coalfields (Fig. 1). These zones extend from W to E inserted in the Palaeozoic structures and form with them the ancient massif generated after the Variscan Orogeny. They are materials of Westphalian or Stephanian age and almost always rest in angular unconformities with the rest of the Palaeozoic or Precambrian rocks. In addition, they are highly tectonized, which influences the discontinuity of the coal layers whose thickness, with few exceptions, is thin.

The thinness of the layers and the complexity of the mountainous territories where the deposits appear made initiating the work difficult, despite the quality of the coal and the abundant existing reserves. The Fabero, Toreno, Villablino and Valderrueda zones in which the pit lakes have been identified occupy an extensive territory in the northern part of the León province (Fig. 1).

Materials and methods

Monitoring land use and land cover and the state of the landscape using multitemporal remotely sensed data is fundamental for determining environmental impacts and ecological degradation caused by the exploitation of coal deposits and changes in land use (Werner et al. 2019; Yu et al. 2018; Xu et al. 2017; Liu et al. 2017; Ma et al. 2019; Dwiyanto et al. 2021). Through the photointerpretation of panchromatic aerial photos (American Series A 1945–1946, American Series B 1956–1957, Interministerial 1973–1986 and National 1980–1986) and recent orthoimage (The National Plan for Aerial Orthophotography 2017), open-pit coal mining areas and existing pit lakes were identified.

The comparative analysis of images from several years (using the ortophoto comparator tool provided by The National Aerial Orthophoto Program in Spain, https://www.ign.es/web/comparador_pnoa/index.html) allowed to exclude temporary pit lakes from permanent ones (Redondo-Vega et al. 2018), establishing a threshold of 30 m from the major axis to include them in the study. Small pit lakes were excluded due to their temporary nature, since they only contained water in exceptionally wet years, and pit lakes that disappeared due to different geomorphological, biological, hydrological and anthropic processes of mining restoration were also excluded (Mijares Coto 2013).

Using the ArcMap 10.6 application of ArcGIS software, the pit lakes were delimited, and the following parameters were calculated: A, surface, area delimited by the contour

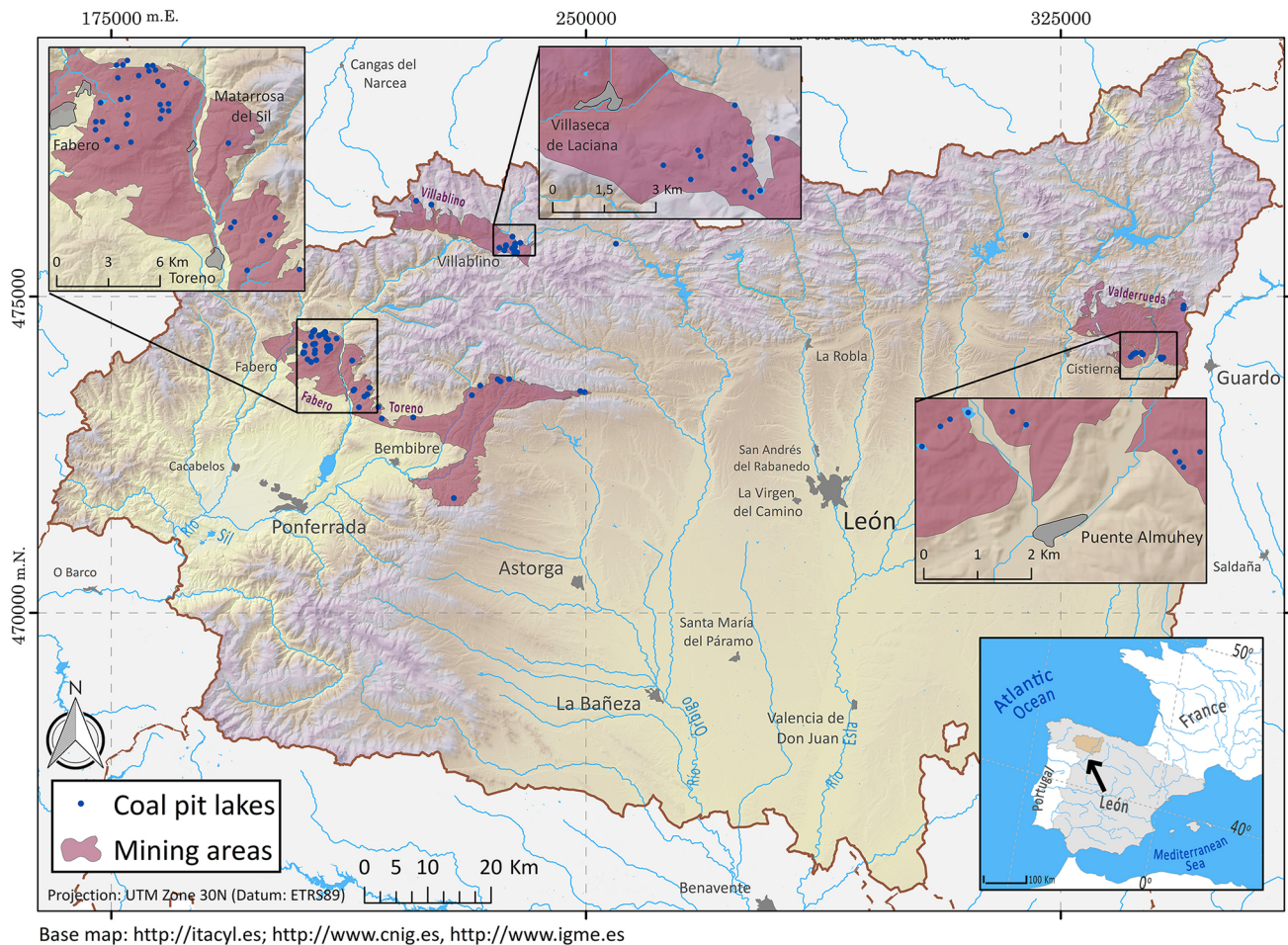


Fig. 1 Location of the main coalfields and pit lakes

of the lake; P , perimeter or length of the coastline that was almost constant throughout the year; L , maximum length, line connecting the two points farthest from the shore of a lake (Hakanson 1981); W , maximum width defined as the maximum distance corresponding to a straight line perpendicular to the line of maximum length (Del Castillo Jurado 2003). These are morphometric dimensions commonly used in limnology studies (Hakanson 1981; Del Castillo Jurado 2003; Vega et al. 2005; Mijares Coto 2013; Fuentes-Pérez et al. 2015). The basic morphometric data were represented on an interactive map.

The field work consisted of recognizing and verifying the pit lakes identified through photointerpretation and measuring those basic parameters that we could not obtain in the office, such as the maximum depth Z and the mean depth \bar{Z} ($\bar{Z} = V/A$, Del Castillo Jurado 2003) using a depth gauge (*DeeperPro+ Smart Sonar*) with a range of 100 m and 80 m depth. A water sample was also collected from the surface of the pit lake to obtain the pH value. The *Benchtop pH metre Basic 20* (*CRISON*, Spain) was used; pH is one of the

key parameters for determining the geoecological conditions of these environments. Finally, zenithal images were taken using a drone (*Phanton 4 Pro+*) to acquire the morphometrics of those pit lakes that had undergone recent changes (Fig. 2) and that do not appear in the most recent orthophoto available of 2017. This is the case for mines that have been active until very recently and whose pit lakes are the last that have been formed: Otero de Naraguantes (Fabero), La Mora (Villablino) and Tremor de Arriba (Toreno).

With the data obtained, the volume (V) of water was estimated from the mean depth and surface ($V = A \times \bar{Z}$, Del Castillo Jurado 2003). Then, the coastline development index (D_L) was calculated, which relates the lake perimeter (P) or length of the coastline, with the perimeter of the circumference whose circle is of equal area (A) as the lake. It is defined as $D_L = P / (2\sqrt{\pi A})$ (Del Castillo Jurado 2003; Contreras and Paira 2015) and indicates the shape of the pit lake contour: circular ($1 < D_L \leq 1.25$); subcircular, $1.25 < D_L < 1.5$; subrectangular elongated, $1.5 < D_L < 3$;



Fig. 2 Example of using a drone to make current orthophotograms. On the left, a recent (2020) drone-derived image of a mining pit lake in the Fabero area. On the right, the same pit lake in the available orthophoto (2017) from the Spanish National Geographic Institute (IGN)

dendritic, $D_L > 3$, (Kalf 2002; Del Castillo Jurado 2003; Contreras and Paira 2015).

The morphometric data were stored in a database for treatment and statistical analysis. To synthesize the morphometric parameters of the dimensions of the pit lakes and the pH of the water, descriptive statistics were calculated. These calculations were carried out based on three factors: the location of the pit lakes in four mining basins, the shape of the pit lakes and the age of the mining pit lakes. Likewise, graphs of the frequency distribution of the length, width, volume, surface, mean depth and pH of the water were made based on the location basin, age and plan view of the pit lakes.

Finally, principal component analysis (PCA), executed in R, was applied to the set of 76 mining pit lakes to reduce the number of variables (10), both qualitative and quantitative, to a smaller number of factors or dimensions to determine the relationships between variables. This made it possible to distinguish the pit lakes belonging to a certain age group or of a certain shape to those of other groups.

Results

In total, 76 mining pit lakes of more than 30 m from the major axis have been located in four mining zones of the León province: Fabero (28), Toreno (18), Villablino (17) and Valderrueda (13). All the basic morphometric parameters and location of each of the pit lakes can be consulted on the interactive map at the following link: https://rawcdn.github.com/amelon00/Coal_Pit_Lakes_Leon/54fdf2dbf04c9fff6c20e4ef8d1f89ffd2682ef7/CoalPitLakesMap_v08072021.html

Despite the diversity suggested by the morphometric data, these can be grouped into three categories according to their topographic location of the cuts that originated them (Fig. 3): hillside (52), valley bottom (16) and hilltop (8). In

all the basins, pit lakes on hillsides predominate (Fig. 4), while those located in valley bottoms are found mainly in the Valderrueda basin.

Regarding the shape of the pit lakes according to the D_L index, the circular (39) and subcircular (30) shapes predominate, followed by the elongated subrectangular (7) shape, with none reaching the dendritic category. If we look at the distribution of frequencies (Fig. 4) in all basins, circular basins predominate except in Toreno, where subcircular basins are predominant.

Regarding the age of the pit lakes (Fig. 4), there are 19 prior to 1987, 28 between 1987 and 1997, which is the period in which 37% of the total are created, 12 between 1997 and 2007, and 17 after 2007. The results show an unequal distribution according to the zone considered: In Villablino, they do not exist before 1987, while in Valderrueda, there are none after 1997.

The endorheic nature of the pit lake depends on its connectivity with the drainage network of the zone in which it is located. In general, they have low connectivity because there is a high percentage of pit lakes (88% in Toreno and 78% in Fabero) with no outflow that are confined in their basins.

Regarding the morphometric parameters according to the cumulative frequency distribution for length and width, small-sized pit lakes with a major axis less than 100 m in length predominate in all mining zones, except in Villablino, where most are between 100 and 200 m (Fig. 5), and some less than 50 m wide.

Overall, small- to medium-sized pit lakes predominate since most of their surfaces are less than 5000 m² (in Valderrueda and Toreno, almost 80% of the total; in Fabero, more than 60%), while in Villablino they are slightly more than 50% and shallow (depths < 5 m). Consequently, the volume of most is less than 25,000 m³ (Fig. 5).

The pH of the water in the pit lakes is predominantly between 6.5 and 7.5, almost always far from the normal or

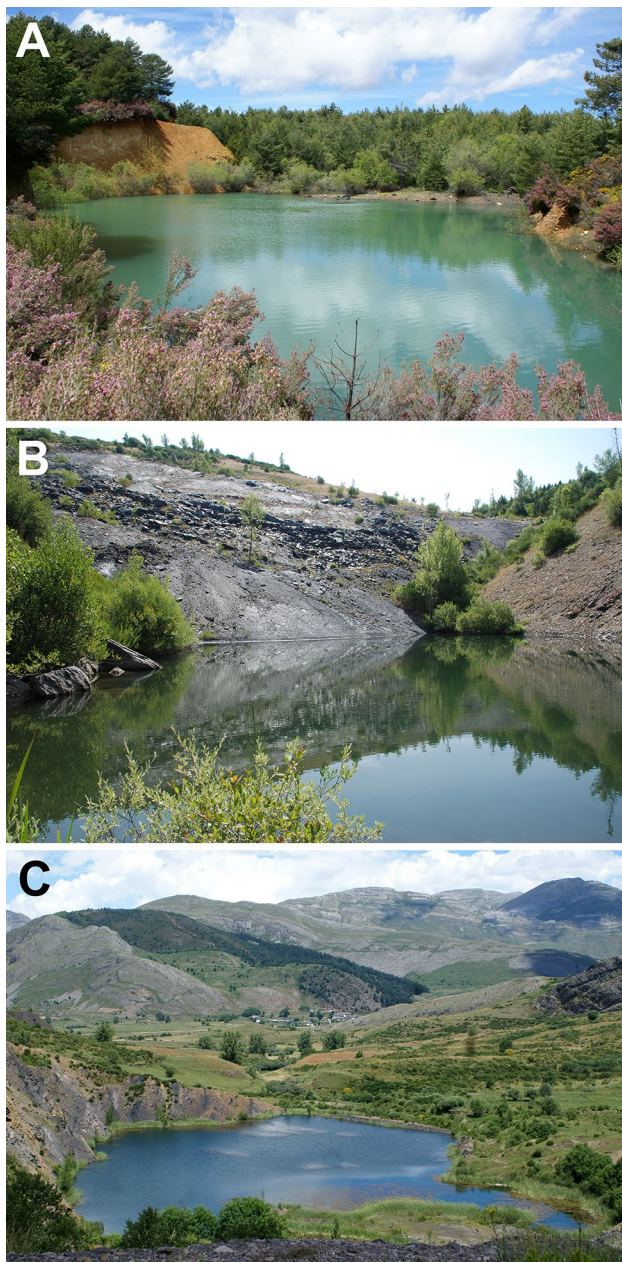


Fig. 3 Examples of coal mining cuts and associated pit lakes. **A** Hilltop (Fabero); **B** hillside (Valderrueda); **C** valley bottom (Cabrillanes)

neutral value of approximately 7 (Ayala Carcedo and Vadillo Fernández 1989). However, pH values even further from neutral value were also obtained. The lowest values recorded (water with the highest acidity) are 3.59 (Fabero-05), 3.97 (Fabero-06) and 4.43 (Fabero-14). The most alkaline waters are 8.86 (Villablino-13), 8.42 (Villablino-01) and 8.45 (Valderrueda-04). On the other hand, the frequency distribution of alkalinity and acidity indicates differences according to the mining zone considered (Fig. 5). Thus, some zones are clearly above pH 7 with alkaline values (Valderrueda,

Villablino and Toreno), while in Fabero most values (over 60%) are below 7, that is, acidic waters.

PCA was applied using the ten variables for each pit lake, differentiated into two categories (by shape and by age): eight variables referring to morphological and morphometric parameters (surface, perimeter, maximum length, maximum width, maximum and mean depth, volume, coastline development) and two environmental variables (open-pit lake orientation and water pH).

The correlations between numerical variables used in the PCA are shown in Fig. 6. The correlations are moderate and high, and positive, between the morphometric parameters indicating the morphology of the pit lakes, except when these are related to the coastline development index, which is an indicator of the irregularity of the pit lake contour. The variables of water pH and orientation also show low or no correlations with the rest, which indicates that these three variables do not depend on the morphometry of the pit lakes.

PCA allowed the extraction of two main components that explained 65.78% of the variance (Fig. 7). The first principal component explains 51.2% of the variance and is related to strictly morphometric variables (mean and maximum depth, width, perimeter, length and area). The second component has a lower weight on the variables, explaining ~ 14.6% of the variance. In the same way as in the correlation analysis, different relationships between groups of variables are observed: on the one hand, there are two groups of variables with relationships between them, such as the variables of depth and volume, and on the other, the variables related to the dimensions of the pit lakes (surface, length, width and perimeter). The variables of coastline development, pH and orientation are less related, both with each other and with the rest of the variables.

Figure 8 is a map of individuals (pit lakes) factor map, showing some of the pit lakes with higher contribution to the plane. Dashed lines indicate the mean values for each dimension. Individuals are distinguished according to shapes (8A) and ages (8B) (the position of the individuals does not change in both graphs). In Fig. 8, the pit lakes with circular shapes are to the right of the first factorial plane (dimension 1). In the upper plane (Fig. 8A), the deepest pit lakes stand out: Valderrueda-06 and 03, formed before 1987, of large dimensions, with alkaline pH, and those of Villablino-02 and Fabero-09, with similar morphometric values but more recently formed (1987–1997), all located in the valley bottom. In the lower plane (Fig. 8B) are the largest pit lakes, Fabero-07 and Fabero-11, and more recently, after 2007 (also Fabero-04 and 05), with soft acid waters (Ayala Carcedo and Vadillo Fernández 1989) located on the hillside. All of them share, in addition, large width, perimeter and length values. The Fabero 11 pit is striking, the most extensive of all those analysed, which is subcircular in shape but shows characteristics that are more typical of circular

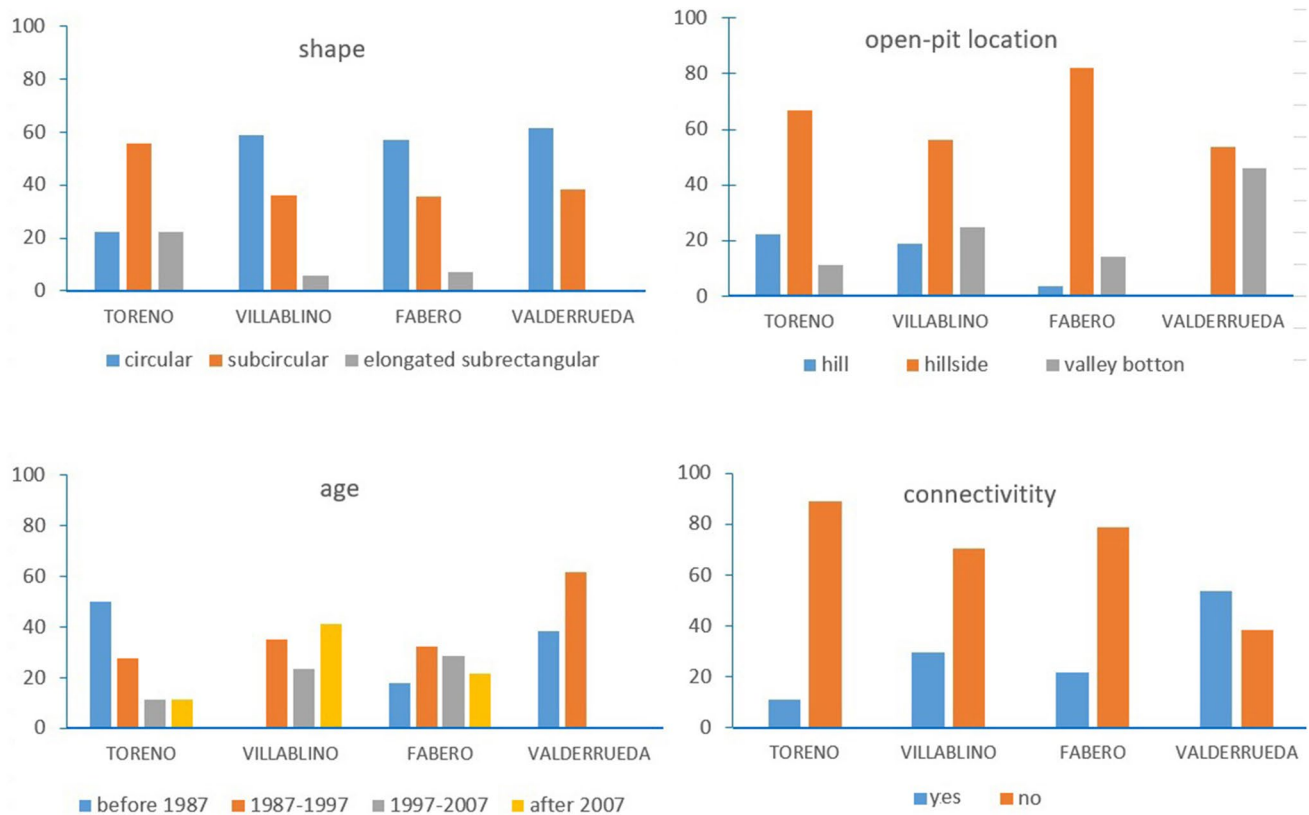


Fig. 4 Distribution of the qualitative characteristics (shape, type of cut, age and connectivity) of the pit lakes in the four coal mining zones where the open-pit mines are located

pit lakes. It was created after 2007, and its waters show an alkaline pH.

To the left of the graph, with negative values are the subcircular pit lakes, formed between 1987 and 1997, and the elongated subrectangular pit lakes, mainly developed between 1998 and 2007. They have high coastline development values and low width, mean depth, perimeter, length, maximum depth, area and volume, respectively. The Fabero-20 and Fabero-27 pit lakes, which are circular, are morphometrically similar to the subcircular pit lakes. The Fabero-27 pit lake is smaller and shallow; its waters have an acidic pH compared to Fabero-20, which is more recent with an alkaline pH.

Discussion

The location of the pit lakes in the relief is related to the exploited deposit and the specific method used in open-pit mining (Redondo Vega 1987), that is, the type of mine that originated them. Their location reveals their accessibility for a possible use, but also the influence they can exert on their immediate environment. The predominance of pit lakes

on hillsides is due to the mining operation being controlled by the location of the deposits. As deposits are frequently located in mountainous areas, sometimes with steep slopes, this usually are also the locations of pit lakes. Whenever it was possible to mine deposits in valley bottoms or hilltops, it was preferred because the lower slope of these sites favour mining works when compared to the locations on hillsides.

The predominance of circular shapes (between 40 and 60%) and subcircular shapes (more than 30% of the total) would indicate an adaptation of the pit lakes to the abandoned bottoms of the open-pit mines regardless of their dimensions (Fig. 4). Only in Toreno do the subrectangular pit lakes have a significant frequency of 20% (the predominant in this case are the subcircular type) which is consistent with the numerous small pit lakes that have been adapted to small hillside (Redondo Vega 1988) or contour mines. This type of open-pit mining was a way to extract coal early on in the process (more than 50% of the Toreno pits are prior to 1987, Fig. 4) and in many mining zones applied mainly, because the coal deposits with thin steep layers and with unfavourable topography due to their inclination (Ayala Carcedo and Vadillo Fernández 1989) made it especially suitable. Therefore, many of the older pit lakes, generally small, now have a subrectangular shape, or are at

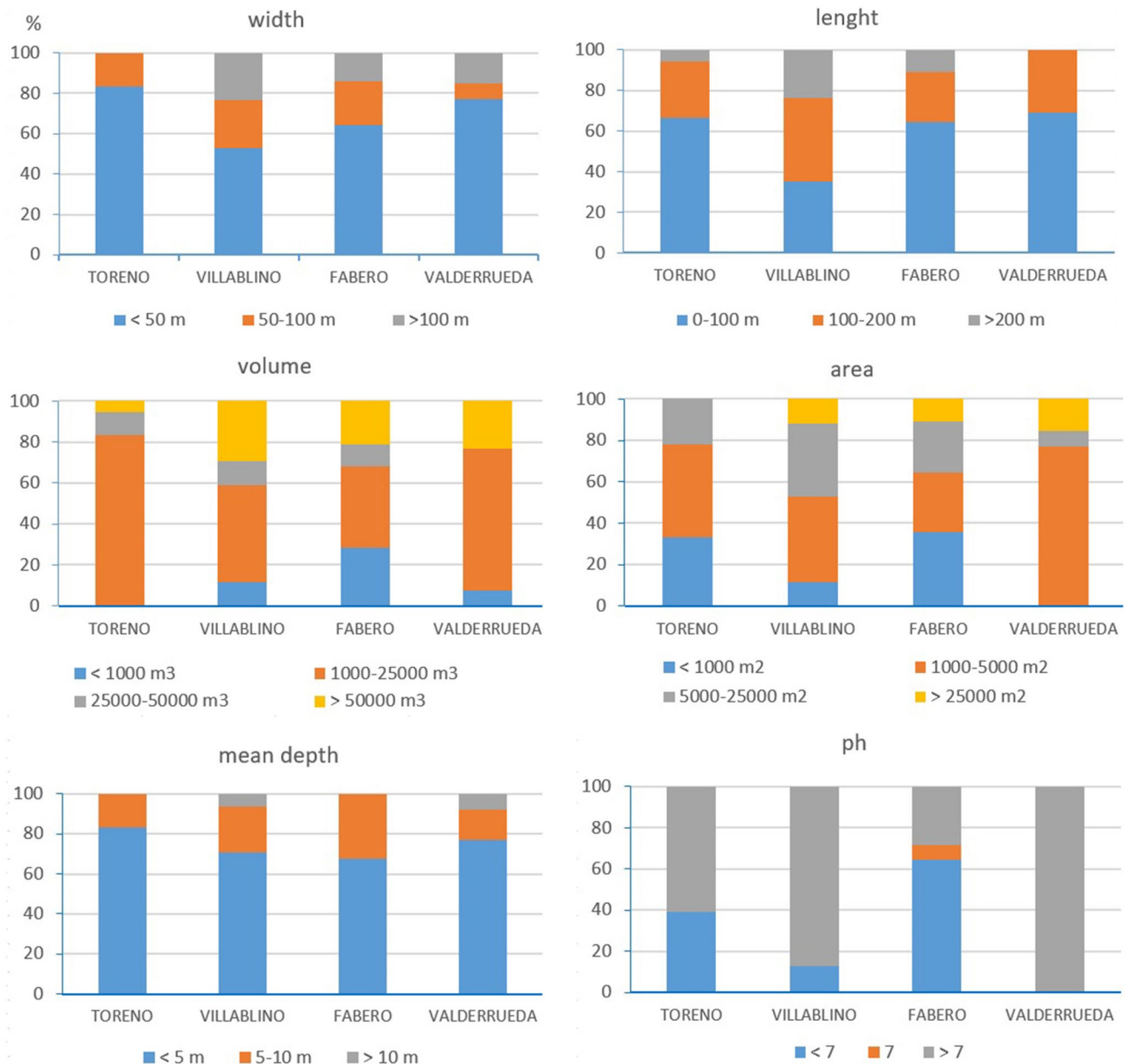


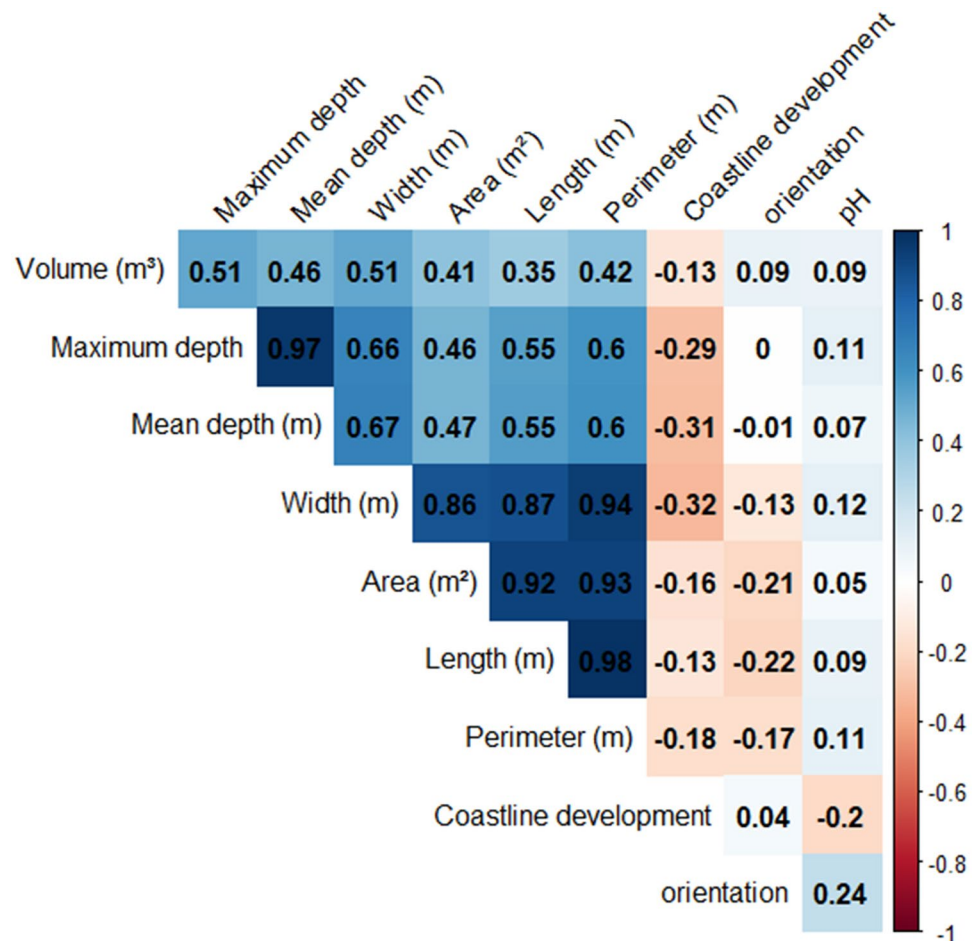
Fig. 5 Cumulative frequency histogram of the morphometric and pH parameters of the pit lakes according to their distribution by mining zone

least subrounded, which is more consistent with hillside and contour mining.

The low values of the D_L index, with the predominance of circular and subcircular shapes are due to the lack of foresight in the mining work regarding the appearance of the final cut of the mine pits that were abandoned. This differentiates them from many pits of natural origin that almost always show more irregular coastlines or from others of mining origin, such as those of the gravel pits, which are already designed with dendritic shapes to favour the recovery of the post-mining space.

One of the greatest difficulties encountered in the work has been the correct temporal sequencing of the mining work generating the pit lake, because it is always a very uneven process in time and space. The time elapsed between the beginning of the extractive activity and the appearance of the pit lake is highly variable and depends on the extraction pace of the deposit and the depth reached. Therefore, in some cases it has been difficult to know precisely the age of the pit lake since mining is a rapid process and the photos available are sometimes 10 years apart. In any case, the use of the orthophoto comparator (https://www.ign.es/web/comparador_pnoa/index.html) allowed in almost all cases to obtain

Fig. 6 Correlation matrix of the variables used in the PCA



a temporal sequence of the exploitation. It shows the pre-operational situation, the moment in which the mine was active, and when activity ceased implying the appearance of the pit lake (and, therefore, its age).

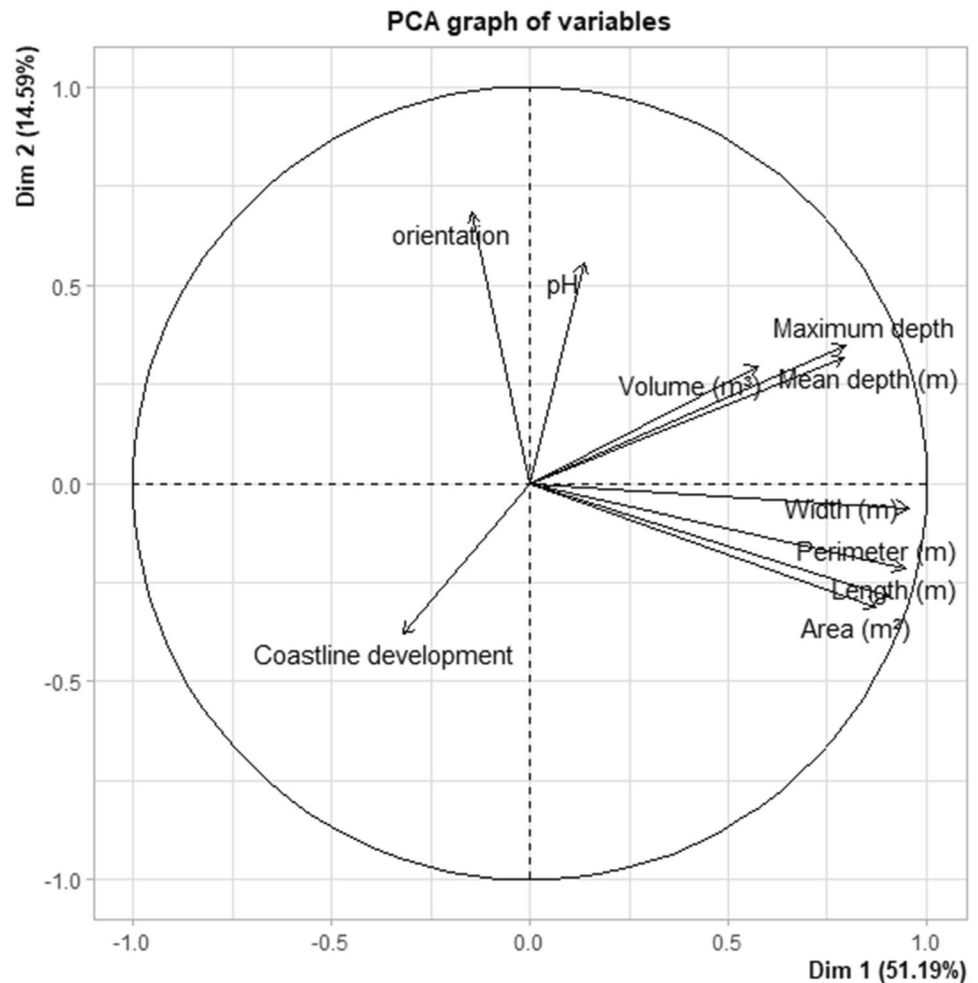
Four time periods (Fig. 4) were established for the mining pit lakes according to the available photographic sources. Thus, the oldest prior to 1987 represent the beginning of the process; in Toreno, more than half correspond to that time, while in Villablino, we have not detected any; in Valderueda, pits only exist in the first two periods and are nonexistent in the most recent periods—in fact, of the four mining zones, this zone is the first one to stop. The two intermediate periods of 1987–1997 and 1997–2007 had a large number of pits concentrated in Fabero and Villablino. There is also a significant number of pit lakes formed since 2007 in the same areas, with Fabero showing continuous data with a very uniform distribution of pit lakes over the last 40 years (Fig. 4), consistent with sustained open-pit mining of the deposit.

While old pit lakes show very little biodiversity, generally, the elapsed time is an important factor in transforming the initial characteristics of the pit lake and its environment and its conversion into something ‘more natural’ (Fig. 9) as

seen in other parts of the world. Thus, recent studies referring to old coal pit lakes in India show that after 30 years, many pit lakes naturally became wetland ecosystems that host abundant aquatic life, excellent water quality and stabilized shores (Palit et al. 2016b, 2019). In any case, the qualitative and quantitative data obtained show a great diversity in the characteristics of the pit lakes, which is related to the singularity of the deposits and the mining carried out, so that for the future use of these spaces almost in each case, it should be assigned the most appropriate post-exploitation use (Kivinen 2017; Gulpinar Sebkan and Acar 2021). If they are repurposed as multi-use water reservoirs (Kumar et al. 2009), a detailed study is necessary to accurately determine their quality.

The connectivity data (the existence or absence of an outlet channel through which the pit lake connects with the drainage network) show a very low connectivity in general (Fig. 4), with around 90% of pits in Toreno and almost 80% in Villablino and Fabero having no outflow. This endorheic character of coal pit lakes would be even greater if only those channels that are currently functional were considered. In many cases, while the channel does exist, it is filled with sediment and colonized by vegetation after abandonment

Fig. 7 Variables factor map (PCA). Grey labelled variables are quantitative supplementary variables (age, shape, connectivity and location)



and therefore does not actually fulfil the function for which it was designed.

The change in water pH to a greater acidity or alkalinity is one of the most important issues addressed when rehabilitating the land once mining has ceased (Ayala Carcedo and Vadillo Fernández 1989). In the pit lakes, pH is a key parameter to determine if their water reflects a chemically inert environment, which could favour recreational uses, wildlife habitat (wetlands), water storage for different uses, and even aquatic farms (Palit et al. 2019). In contrast, the presence of certain minerals and compounds (Eary 1999; Zhao et al. 2009; Kumar et al. 2009) confers to the waters a marked acidity or alkalinity that would make these uses impossible, and thus restricted to research, teaching (McCullough and Lund 2006; Gammons et al. 2009), or geomining heritage. The pH data would be one piece of information more to integrate in the appropriate land-use planning of the mining spaces in which the pit lakes are inserted; this will require a prior assignment of uses geared either towards anthropic uses (cultural values),

nature (natural values), or mixed uses (Gulpinar Sebkan and Acar 2021).

The data referring to the maximum values of acidity or alkalinity of water coincide with those expressed above in the frequency distribution that showed the most acidic waters being in the Fabero Zone and the most alkaline in Villablino and Valderrueda (Fig. 5).

In many pit lakes studied in other countries, pH changes over time, usually correcting towards more neutral values. We do not have old data on the water pH of the León pit lakes, and those mentioned above (except that of Fabero-05, which is one of the most recent pit lakes because until 2017, the open-pit mine was active) are very old pit lakes, some more than 40 years old. They do not have an outflow channel, which makes them closed basins with little possibility of water renewal and therefore of appreciable changes in the acidity or alkalinity conditions of the water retained there.

Fig. 8 Representation of individuals (pit lakes) in the first factorial plane differentiated by their **A** pit shape and **B** age (individual factor map (PCA): **A** pit shape and **B** age

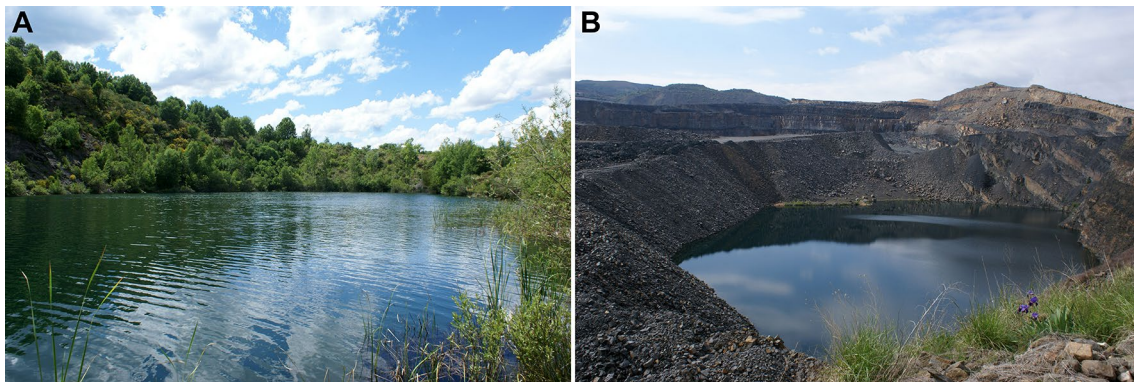
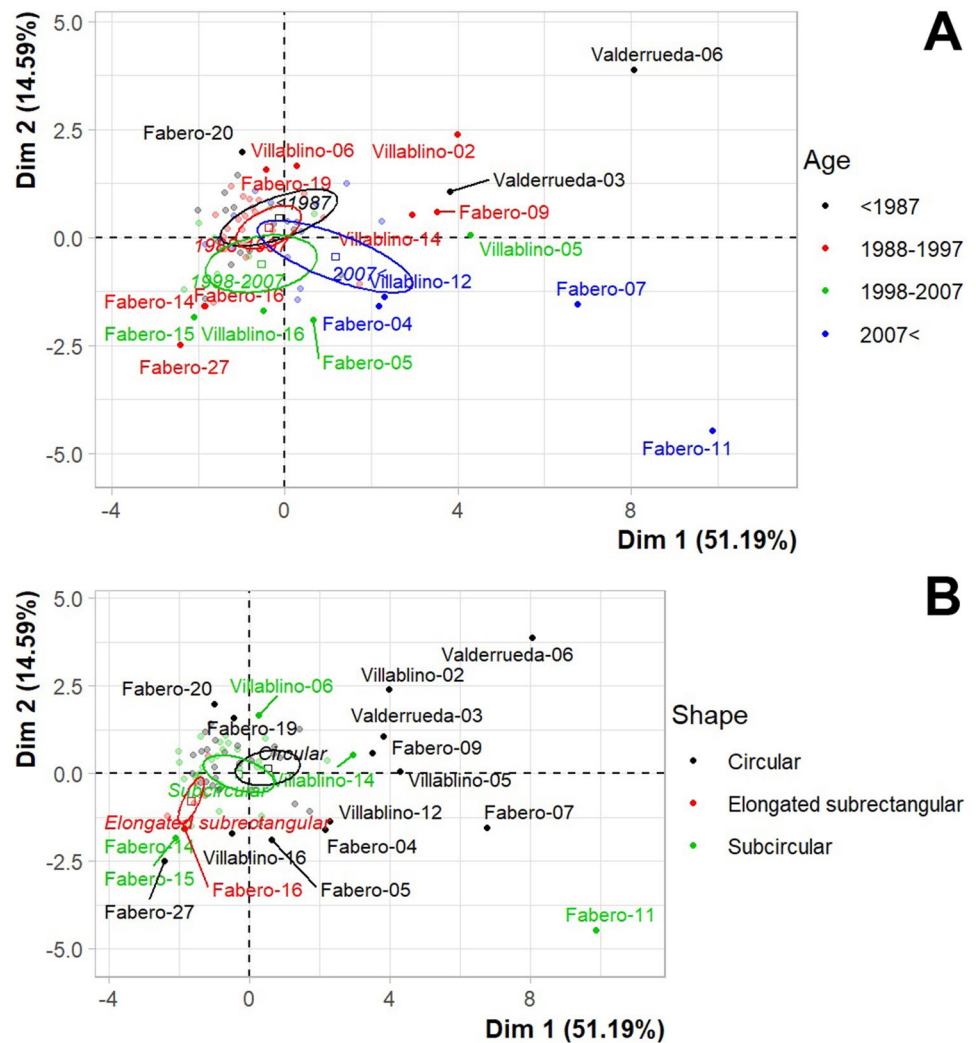


Fig. 9 Example of a very old pit lake (Villablino-14) with abundant natural vegetation to the left. To the right is a very recent pit lake (Fabero-07, 2018) with no vegetation, very unstable rocky escarpments and abundant tailings

Conclusions

- The pit lakes, except for isolated cases, are small, shallow

and, therefore, with modest volumes of water. However, the presence of permanent water in environments that almost always present summer aridity would make them attractive for the development of ecological enclaves of

interest. This would favour their use as natural, recreational environments or as water reservoirs (unless the physicochemical characteristics of the water advise against it).

- There is a preponderance of rounded and subcircular shapes with a low coastline development index ($D_L < 1.5$), that is, their perimeter in relation to their surface is small and would indicate they remain strictly within the bottom of the open pit. The uniformity of the perimeters differentiate them from many pit lakes of natural origin and others of mining origin, such as the gravel pits that are designed with dendritic forms to facilitate their environmental recovery.
- Coal pit lakes have low connectivity because only a small number of them are exorheic, with a functional output channel, and barely show low water marks. Most occupy endorheic basins with low water marks according to the time of year. They always assume an irreversible alteration of the natural runoff and the original landscape. On the other hand, this closed system can control the runoff waters when these do not have sufficient quality and are thus confined without producing unwanted discharges.
- There is a predominance of pit lakes on hillsides which reflect the underlying coal deposits and the open-pit mining method used at the time. This location on hillsides, sometimes very steep, implies a low accessibility that, together with the remoteness of population centres, would favour its use as a natural enclave over its use for recreational purposes, for example.
- From a geoecological point of view, the time elapsed since the creation of a pit lake is an important factor in how the initial characteristics of the pit lake transform and its conversion into something 'more natural'. Thus, the oldest areas show dense vegetation in their surroundings and shores that have practically erased any evidence of the mining landscape (tailings and stripped slopes, absence of vegetation, visible geological structure), and even the presence of ichthyofauna. However, there are also cases of old pit lakes that show very low biodiversity, usually in these cases with markedly acidic waters.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. This work was supported by the project LE080G19 (Paleo-environmental significance and relationship with the global change of the Cantabrian Mountains rock glaciers: relative age dating and analysis of the internal structure using electrical tomography), founded by the Junta de Castilla y León.

Declarations

Conflict of interest The authors confirmed no conflict of interest concerning this research.

Availability of data and material The basic morphometric parameters and location of coal pit lakes analysed in this work can be referred on the interactive map at the following link: https://rawcdn.github.com/amelon00/Coal_Pit_Lakes_Leon/54fdf2dbf04c9fff6c20e4ef8d1f89ffd2682ef7/CoalPitLakesMap_v08072021.html

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Antwi EK, Boakye-Danquah J, Asabere SB, Takeuchi K, Wiegleb G (2014) Land cover transformation in two post-mining landscapes subjected to different ages of reclamation since dumping of spoils. *Springerplus* 3:702. <https://doi.org/10.1186/2193-1801-3-702>
- Aréchaga F, Ferrero T, Gil A, Menéndez JA, Valle R (2011) Riqueza restaurada. Historia de la mina de As Pontes. Endesa Generación, Madrid. <http://ingeminas.es/producto/as-pontes-a-coruna-riqueza-restaurada-historia-de-la-mina/>
- Ayala Carcedo FJ, Vadillo Fernández L (1989) Manual de restauración de terrenos y evaluación de impactos ambientales en minería. Instituto Tecnológico Geominero de España
- Baeten J, Langston N, Lafreniere D (2018) A spatial evaluation of historic iron mining impacts on current impaired waters in Lake Superior's Mesabi Range. *Ambio* 47:231–244. <https://doi.org/10.1007/s13280-017-0948-0>
- Bernhardt ES, Palmer MA (2011) The environmental costs of mountaintop mining valley fill operations for aquatic ecosystems of the Central Appalachians. *The Year in Ecology and Conservation Biology. Ann N Y Acad Sci* 1223:39–57. <https://doi.org/10.1111/j.1749-6632.2011.05986.x>
- Bian ZF, Lu Q (2013) Ecological effect analysis of land use change in coal mining area based on ecosystem service valuing: a case study in Jiawang. *Environ Earth Sci* 68:1619–1630. <https://doi.org/10.1007/s12665-012-1855-0>
- Blanchette ML, Lund MA (2017) Pit lakes are a global legacy of mining: an integrated approach to achieving sustainable ecosystems and value for communities. *Curr Opin Environ Sustain* 23:28–34. <https://doi.org/10.1016/j.cosust.2016.11.012>
- Bloodworth AJ, Scott PW, McEvoy FM (2009) Digging the backyard: mining and quarrying in the UK and their impact on future land use. *Land Use Policy* 26(1):317–325. <https://doi.org/10.1016/j.landusepol.2009.08.022>
- Boehrer B, Kastner S, Ollesch G (2010) High accuracy measurements of water storage change in Mining Lake111, Germany. *Limnologica* 40:156–160. <https://doi.org/10.1016/j.limno.2009.12.002>

- Castendyk DN, Eary LE, Balistrieri LS (2016) Modeling and management of pit lake water chemistry 1: theory. *Appl Geochem* 57:267–288. <https://doi.org/10.1016/j.apgeochem.2014.09.004>
- Del Castillo Jurado M (2003) Morfometría de lagos Aplicación a los lagos del Pirineo. Tesis doctoral, Departament d'Ecologia, Universitat de Barcelona. <https://www.tesisenred.net/handle/10803/1428>
- Castro JM, Moore JN (2000) Pit lakes: their characteristics and the potential for their remediation. *Environ Geol* 39(11):1254–1260. <https://doi.org/10.1007/s002549900100>
- Chen J, Li K, Cnag KJ, Sofia G, Taroli P (2015) Open-pit mining geomorphic feature characterization. *Int J Appl Earth Obs Geoinf* 42:72–86. <https://doi.org/10.1016/j.jag.2015.05.001>
- Contreras FI, Paira AR (2015) Comparación morfométrica entre lagunas de la planicie aluvial del río Paraná Medio y La Lomada Norte (Corrientes, Argentina). *Cuadernos Geogr Rev Colomb Geogr* 24(1):61–71. <https://doi.org/10.15446/rcdg.v24n1.47774>
- Duncan EE, Kuma JS, Pimpong S (2009) Open pit mining and land use changes: an example from Bogoso-Prestea area, SouthWest Ghana. *Electron J Inf Syst Dev Ctries* 36(3):1–10. <https://doi.org/10.1002/j.1681-4835.2009.tb00250.x>
- Dwiyanto MR, Damayanti A, Indra TL, Dimiyati M (2021) Land use changes due to mining activities in Penajam Paser Utara Regency, East Kalimantan Province. In: IOP Conference series: earth and environmental science, vol 1811, no 1. <https://doi.org/10.1088/1742-6596/1811/1/012088>
- Eary LE (1999) Geochemical and equilibrium trends in mine pit lakes. *Appl Geochem* 14:963–987. [https://doi.org/10.1016/S0883-2927\(99\)00049-9](https://doi.org/10.1016/S0883-2927(99)00049-9)
- Fitzgerald V R, Watkins M (1997) Literature review on mine rehabilitation by flooding. HRL Technology Pty Ltd. State Electricity Commission of Victoria. <http://hazelwoodinquiry.archive.vic.gov.au/wp-content/uploads/2015/12/Paragraph-205-EAY.0001.003.0081.pdf>
- Fuentes-Pérez JF, Navarro Hevia J, Ruiz Legazpi J, García-Vega A (2015) Inventario y caracterización morfológica de lagos y lagunas de alta montaña en las provincias de Palencia y León (España). *Pirineos*. <https://doi.org/10.3989/Pirineos.2015.170006>
- Gammons CH, Harris LN, Castro JM, Cott PA, Hanna BW (2009) Creating lakes from open pit mines: processes and considerations, with emphasis on northern environments. Canadian Technical Report for Fisheries and Aquatic Sciences, vol 2826. https://digit.alcommons.mtech.edu/geol_engr/2/
- Geller W, Schultze M, Kleinmann R, Walkersdorfer Ch (2013) Acidic Pit Lakes: the legacy of coal and metal surface mines. Springer, New York. <https://doi.org/10.1007/978-3-642-29384-9>
- Gulpinar Sebkan DU, Acar C (2021) Determining usages in post-mining sites according to landscape design approaches. *Land Degrad Dev* 32:2661–2676. <https://doi.org/10.1002/ldr.3933>
- Hakanson L (1981) A manual of lake morphometry. Springer, Berlin, Heidelberg. <https://doi.org/10.1007/978-3-642-81563-8>
- Hangen-Brodersen Ch, Strempe P, Grünewal U (2005) Characteristics of catchments disturbed by lignite mining—case study of Schlabendorf/Seese (Germany). *Ecol Eng* 24(1–2):37–48. <https://doi.org/10.1016/j.ecoleng.2004.12.005>
- Hildmann E, Wünsche M (1996) Lignite mining and its after-effects on the Central German landscape. *Water Air Soil Pollut* 91(1–2):79–87. <https://doi.org/10.1007/BF00280924>
- Hooke R, Martín-Duque JF, Pedraza J (2012) Land transformation by humans: a review. *GSA Today* 22(12):4–10. <https://doi.org/10.1130/GSAT151A.1>
- Hüttl RF, Gerwin W (2005) Landscape and ecosystem development after disturbance by mining. *Ecol Eng* 24(1–2):1–3. <https://doi.org/10.1016/j.ecoleng.2004.12.002>
- Jiaying X, Gang L, Jiaqi Y, Hua Z, Pengcheng Y, Wenmin H (2017) Effects of coal exploitation on land use and landscape pattern change in coal mining area. *Trans Chin Soc Agric Eng* 33(23):252–258. http://www.tcsae.org/nygcxb/ch/reader/view_abstract.aspx?file_no=20172333&flag=1
- Kalff J (2002) *Limnology. Inland Water Ecosystems*. Prentice Hall, New Jersey. <https://livresbioapp.files.wordpress.com/2016/03/limnology-kalff.pdf>
- Kivinen S (2017) Sustainable post-mining land use: are closed metal mines abandoned or re-used space? *Sustainability* 9(10):1705. <https://doi.org/10.3390/su9101705>
- Kivinen S, Vartiainen K, Kumpula T (2018) People and post-mining environments: PPGIS mapping of landscape values, knowledge needs, and future perspectives in Northern Finland. *Land* 7(4):151. <https://doi.org/10.3390/land7040151>
- Kopeć A, Trybała P, Głębicki D, Buzcynska A, Owczar K, Bugajska N, Kozinska P, Chojwa M, Gattner A (2020) Application of remote sensing, gis and machine learning with geographically weighted regression in assessing the impact of hard coal mining on the natural environment. *Sustainability* 12(22):1–26. <https://doi.org/10.3390/su12229338>
- Kumar RN, McCullough ChD, Lund MA (2009) Water resources in Australian mine pit lakes. *Min Technol* 118(3–4):205–211. <https://doi.org/10.1179/174328610X12682159815028>
- Larondelle N, Haase D (2012) Valuing post-mining landscapes using an ecosystem services approach—an example from Germany. *Ecol Ind* 18:567–574. <https://doi.org/10.1016/j.ecolind.2012.01.008>
- Latifovic R, Fytas K, Chen J, Paraszcak J (2005) Assessing land cover change resulting from large surface mining development. *Int J Appl Earth Obs Geoinf* 7:29–48. <https://doi.org/10.1016/j.jag.2004.11.003>
- Liu P, Li K, Han RM, Cheng QX, Ma C (2017) Landscape pattern taking Jiaozuo as an example. In: Land Reclamation in Ecological Fragile Areas—Proceedings of the 2nd International Symposium on Land Reclamation and Ecological Restoration, LRER. <https://doi.org/10.1201/9781315166582>
- Ma S, Xie F, Ding C, Zhang H (2019) Spatio-temporal change of landscape ecological quality and influencing factors based on four-quadrant model in overlapped area of cropland and coal production. *Nongye Gongcheng Xuebao Trans Chin Soc Agric Eng* 36(4):259–268. http://www.tcsae.org/nygcxb/ch/reader/view_abstract.aspx?file_no=20200431&st=alljournals
- Marescotti P, Brancucci G, Sasso G, Solimano M, Marin V, Muzio Ch, Salmona P (2018) Geoheritage values and environmental issues of Derelict Mines: examples from the Sulfide Mines of Gromolo and Petronio Valleys (Eastern Liguria, Italy). *Minerals* 8(6):229. <https://doi.org/10.3390/min8060229>
- Marszelewski W, Dembowska EA, Napiórkowski P, Solarczyk A (2017) Understanding abiotic and biotic conditions in post-mining pit lakes for efficient management: a case study (Poland). *Mine Water Environ* 36:418–428. <https://doi.org/10.1007/s10230-017-0434-8>
- McCullough C, Lund MA (2006) Opportunities for sustainable mining Pit Lakes in Australia. *Mine Water Environ* 25(4):220–226. <https://doi.org/10.1007/s10230-006-0136-0>
- McCullough CD, Schultze M, Vandenberg J (2020) Realizing beneficial end uses from abandoned Pit Lakes. *Minerals* 10:133. <https://doi.org/10.3390/min10020133>
- Mijares Coto MJ (2013) Procedimiento de actuación para la aplicación de la Directiva Marco del Agua a los lagos artificiales creados por la rehabilitación de las explotaciones mineras a cielo abierto. Tesis Doctoral, Departamento de Métodos Matemáticos y de Representación, Universidade da Coruña. <http://hdl.handle.net/2183/11702>. Accessed 6 Apr 2018

- Mollema PN, Antonellini M (2016) Water and (bio) chemical cycling in gravel pit lakes: a review and overview. *Earth Sci Rev* 159:247–270. <https://doi.org/10.1016/j.earsci.2016.05.006>
- Mossa J, James LA (2013) Impacts of mining of geomorphic systems. In: Shroder J, James LA, Harden CP, Clague JJ (eds) *Treatise on geomorphology*, vol 13, *Geomorphology of human disturbances, climate change, and natural hazards*. Academic Press, San Diego, pp 74–95. <https://doi.org/10.1016/B978-0-12-374739-6.00344-4>
- Nixdorf B, Lessmann D, Deneke R (2005) Mining lakes in a disturbed landscape: application of the EC Water Framework Directive and future management strategies. *Ecol Eng* 24:67–73. <https://doi.org/10.1016/j.ecoleng.2004.12.008>
- Oyarzun R, Higuera P, Lillo J (2011) Minería ambiental. Una introducción a los impactos y a su remediación. Ediciones GEMM. <https://eprints.ucm.es/14046/>
- Palit D, Mukherjee A, Kar D, Roychowdhury Sh, Garai B, Kar P, Gupta S (2016a) Determinants of Pitlake Usage in Raniganj Coalfield Region, West Bengal: implications for sustainable use. *Int J Innov Res Eng Manag* 3(2):72–79. https://ijirem.org/view_abstract.php?title=Determinants-of-Pitlake-Usage-in-Raniganj-Coalfield-Region-West-Bengal-Implications-for-Sustainable-Use&year=2016&vol=3&primary=QVJULTEwMQ==
- Palit D, Kar D, Roychowdhury S, Mukherjee A, Garay B, Kar P (2016b) Species Composition of Plant Communities in Pitlakes of Raniganj Coal Field, West Bengal, India. *Int J Curr Res Biosci Plant Biol* 3(6):82–86. <https://doi.org/10.20546/ijcrbp.2016.306.010>
- Palit D, Kar P, Mukherjee A, Gupta S (2019) Pitlakes of Raniganj Coal Field, W.B, India. Inventory and Water Quality Status. Natural Science, Technical Report, GRIN
- Palmer MA, Bernhardt ES, Schlesinger WH, Eshleman KN, Foufoula-Georgiou E, Hendryx MS, Lemly AD, Likens GE, Loucks OL, Power ME, White PS, Wilcock PR (2010) Mountaintop mining consequences. *Science* 327(5962):148–149. <https://doi.org/10.1126/science.1180543>
- Prakash A, Gupta RP (1998) Land-use mapping and change detection in a coal mining area: a case study in the Jharia coalfield, India. *Int J Remote Sens* 19(3):391–410. <https://doi.org/10.1080/01431698216053>
- Qian D, Yan C, Xing Z, Xiu L (2017) Monitoring coal mine changes and their impact on landscape patterns in an alpine region: a case study of the Muli coal mine in the Qinghai-Tibet Plateau. *Environ Monit Assess* 189(11):559. <https://doi.org/10.1007/s10661-017-6284-9>
- Redondo Vega JM (2000) Minería y degradación del medio en la provincia de León. La incidencia de la legislación minero-ambiental. *Medio Ambiente En Castilla y León* 14:17–24. <https://docplayer.es/91904039-Medio-ambiente-junta-de-castilla-y-leon-consejeria-de-medio-ambiente-en-castilla-y-leon.html>
- Redondo Vega JM (1988) Las minas de carbón a cielo abierto en la provincia de León. Transformación del medio y explotación de recursos no renovables. Universidad de León, Secretariado de Publicaciones, León
- Redondo Vega JM (1994) Ejemplos de la convergencia espacial entre el abandono de los aprovechamientos agrarios y la explotación minera en la montaña de León. In: Cabero Diéguez V, Llorente Pinto JM, Plaza Gutiérrez JI y Pol Méndez C (eds) *El Medio Rural español. Cultura paisaje y naturaleza. Libro Homenaje a D. Ángel Cabo Alonso*. Universidad de Salamanca, Salamanca, pp 793–805
- Redondo-Vega JM, Gómez-Villar A, Santos-González J, González-Gutiérrez RB, Álvarez-Martínez J (2017) Changes in land use due to mining in the north-western mountains of Spain during the previous 50 years. *CATENA* 149:844–856. <https://doi.org/10.1016/j.catena.2016.03.017>
- Redondo-Vega JM, Gómez-Villar A, González-Gutiérrez RB, Santos-González J (2018) El origen de las lagunas de León. In: Blanco
- Chao R, Castillo Rodríguez F, Costa Casais M, Horacio García J, Valcárcel Díaz M (eds) *Xeomorfoloxía e paisaxes xeográficas. Catro décadas de investigación e ensino. Homenaxe a Augusto Pérez Alberti*, Universidade de Santiago de Compostela, pp 469–486
- Reece E. (2006) *Lost Mountain. A year in the vanishing wilderness radical strip mining and the devastation of appalachia*. Riverhead Books, New York
- Sánchez España J, López Pamo E, Santofimia Pastor E, Diez Ercilla M (2008) The acidic mine pit lakes of the Iberian Pyrite Belt: an approach to their physical limnology and hydrogeochemistry. *Appl Geochem* 23:1260–1287. <https://doi.org/10.1016/j.apgeochem.2007.12.036>
- Sánchez-España J, Diez Ercilla M, Pérez Cerdán F, Yusta I, Boyce AJ (2014) Hydrological investigation of a multi-stratified pit lake using radioactive and stable isotopes combined with hydrometric monitoring. *J Hydrol* 511:594–508. <https://doi.org/10.1016/j.jhydrol.2014.02.003>
- Schultze M, Pokrandt K-H, Hille W (2010) Pit lakes of the Central German lignite mining district: creation, morphometry and water quality aspects. *Limnologia* 40:148–155. <https://doi.org/10.1016/j.limno.2009.11.006>
- Sekhar PH, Mohan SK (2014) Assessment of impact of opencast mining on surrounding forest: a case study from Keonjhar district Odisha, India. *J Environ Res Dev* 9(1):249–254. <https://www.semanticscholar.org/paper/ASSESSMENT-OF-IMPACT-OF-OPENCAST-MINE-ON-FOREST-%3A-A-Sekhar-Mohan/c7dad83f9378f8dc56da971649a3f2ac4eb197f9c>
- Siegel J (1997) Ground water quantity. In: Marcus JJ (ed) *Mining environmental handbook, effects of mining on the environment and American Controls on Mining*. Imperial College Press, London, pp 164–168. <https://inis.iaea.org/search/searchsinglerecord.aspx?recordsFor=SingleRecord&RN=30010475>
- Song W, Song W, Gu H, Li F (2020) Progress in the remote sensing monitoring of the ecological environment in mining area. *Int J Environ Res Public Health* 17(6):1846. <https://doi.org/10.3390/ijerph17061846>
- Soni AK, Mishra B, Singh S (2014) Pit lakes as an end use of mining: a review. *J Min Environ* 5(2):99–111. <https://doi.org/10.22044/jme.2014.326>
- Tandy C (1975) *Landscape of industry*. Wiley, London
- Tarolli P, Sofia G (2016) Human topographic signatures and derived geomorphic processes across landscapes. *Geomorphology* 255:140–161. <https://doi.org/10.1016/j.geomorph.2015.12.007>
- Tarolli P, Sofia G, Cao W (2018) The geomorphology of the human age. *Environ Anthropol* 1:35–43. <https://doi.org/10.1016/B978-0-12-809665-9.10501-4>
- Townsend PhA, Helmers DP, Kingdon CC, McNeil BE, de Beurs KM, Eshleman KN (2009) Changes in the extent of surface mining and reclamation in the Central Appalachians detected using a 1976–2006 Landsat time series. *Remote Sens Environ* 113:62–72. <https://doi.org/10.1016/j.rse.2008.08.012>
- Trigg AB, Dubourg WR (1993) Valuing the environmental impacts of opencast coal mining in the UK: the case of the Trent Valley in North Staffordshire. *Energy Policy* 21(11):1110–1122. [https://doi.org/10.1016/0301-4215\(93\)90261-D](https://doi.org/10.1016/0301-4215(93)90261-D)
- Tsolaki-Fiaka S, Bathrellos GD, Skilodimou HD (2018) Multi-criteria decision analysis for an abandoned quarry in the Evros Region (NE Greece). *Land* 7(2):43. <https://doi.org/10.3390/land7020043>
- Vega JC, De Hoyos C, Aldasoro JJ, De Miguel J, Fraile H (2005) Nuevos datos morfométricos para el Lago de Sanabria. *Limnetica* 24(1–2):115–125. http://www.limnetica.com/Limnetica/Limnetica24/L24a115_morfometria_lago_Sanabria.pdf
- Wang XF, Wang YJ, Ma XL, Chen M (2011) Cumulative effects of landscape changes in coal mining area: a case study in Lu'an coal

- mining area, Shanxi Province. *Geogr Res* 30(5):879–892. <https://doi.org/10.11821/yj2011050012>
- Werner TT, Bebbington A, Gregory G (2019) Assessing impacts of mining: recent contributions from GIS and remote sensing. *Extr Ind Soc* 6(3):993–1010. <https://doi.org/10.1016/j.exis.2019.06.011>
- Wickham J, Bohall Wood P, Nicholson MC, Jenkins W, Druckenbrod D, Suter GW, Strager MP, Mazzarella Ch, Walter Galloway W, Amos J (2013) The overlooked terrestrial impacts of mountaintop mining. *Bioscience* 63(5):335–348. <https://doi.org/10.1525/bio.2013.63.5.7>
- Wu W, Yao J, Kang T (2008) Study on land use changes of the coal mining based on TM image. *J Coal Sci Eng* 14(2):287–290. <https://doi.org/10.1007/s12404-008-0062-9>
- Xu J, Li G, Yu J, Zhao H, Yin P, Hu W (2017) Effects of coal exploitation on land use and landscape pattern change in coal mining area. *Nongye Gongcheng Xuebao Trans Chin Soc Agric Eng* 33(23):252–248. <https://doi.org/10.11975/j.issn.1002-6819.2017.23.033>
- Yang JJ (2008) Detecting landscape changes pre and post surface coal mining in Indiana, USA. *Geogr Inf Sci* 14(1):36–43. <https://doi.org/10.1080/10824000809480637>
- Yu L, Xu Y, Xue Y, Li X, Cheng Y, Liu X, Porwal A, Holden EJ, Yang J, Gong P (2018) Monitoring surface mining belts using multiple remote sensing datasets: a global perspective. *Ore Geol Rev* 101:675–687. <https://doi.org/10.1016/j.oregeorev.2018.08.019>
- Zhao LL, McCullough CD, Lund MA (2009) Mine Voids Management Strategy (I): Pit Lake Resources of the Collie Basin. Cowan University Perth, Australia. https://www.water.wa.gov.au/__data/assets/pdf_file/0012/5601/96275.pdf

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.