

# Flood and gully erosion problems at the Pasir open pit coal mine, Indonesia: a case study of the hydrology using GIS

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**Abstract** This paper considers the flood and gully erosion problems at the Pasir open pit coal mine located in a humid region in Indonesia. Using the geographic information systems (GIS), quantitative information on the hydrological characteristics of the surface drainage system were obtained from a digital elevation model (DEM). Based on the results of the drainage analysis, raster-based spatial analysis was carried out to distinguish the bench slopes with concentrated surface drainage flows and to calculate the ratio between the amount of incoming water and the size of the temporary storage ponds. Finally, the bench slopes most vulnerable to gully erosion were identified and an optimal design for pump allocation suggested to reduce the risk of flooding during heavy rainfall. Since these recommendations were implemented, there has been no down-time due to flooding.

**Keywords** Open-pit mine · GIS · Drainage analysis · Digital Elevation Model · Indonesia

**Résumé** L'article considère les problèmes d'inondation et d'érosion par ravinement dans la mine à ciel ouvert de charbon de Pasir, située dans une région humide

de l'Indonésie. Utilisant un Système d'Information Géographique (SIG), des informations quantitatives sur les caractéristiques hydrologiques du système de drainage superficiel ont été obtenues, prenant appui sur un Modèle Numérique de Terrain (MNT). A partir des résultats de l'analyse du système de drainage, une analyse spatiale suivant un format raster a été réalisée afin d'identifier les pentes de gradins présentant de forts écoulements concentrés et de calculer, pour les zones de stockage temporaire, les rapports entre les quantités d'eau entrant et la taille de ces zones. Finalement, les pentes de gradins les plus sensibles à l'érosion par ravinement ont été identifiées et un schéma de mise en place de pompes a été proposé afin de réduire le risque d'inondation durant les périodes de pluies intenses. Depuis que ces recommandations ont été mises en oeuvre, il n'y a pas eu de temps d'arrêt d'activité dus à des problèmes d'inondation.

**Mots clés** Mine à ciel ouvert · Système d'Information Géographique (SIG) · Analyse de drainage · Modèle Numérique de Terrain · Indonésie

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## Introduction

The need for a sophisticated strategy for water management in open pit mines has increased in recent years, because laws passed and regulations implemented in most countries insist that open pit mine planning includes a detailed discussion dealing with water resource management for mine reclamation (Hustrulid and Kuchta 1995). The strategy for water management in open pit mines is usually dependent on the size of the operation, the geological conditions, the characteristics of the ore deposits

being mined and especially the climate. For example, in arid regions, a primary consideration is the storage of rainwater for future operational use (e.g., dust control, production preparation). In contrast, in humid regions, where annual rainfall is in excess of 1,000 mm, the primary concern for water management is surface drainage control to prevent flooding in the pit or other adverse affects on mining operations (Meek 1990). This study focuses on the flood and gully erosion problems in an open pit coal mine located in a humid region, Indonesia.

In open pit mines, two kinds of water flow can concentrate in the lowest parts of the pit. One is the surface water which rapidly flows over the ground during rainfall and the other is the groundwater which slowly infiltrates vertically as well as moving towards the free face during and after rainfall (Fig. 1). Surface drainage flows down to the bottom of the pit through benches, bench slopes and rampways and then accumulates in artificially constructed temporary storage ponds before being pumped to settling chambers outside the pit. During the wet season, the storage capacity may be insufficient for the fast inflow from surface water, leading to flooding in the lower working area of the mine. In addition, groundwater flows will also contribute to the rise in water level in the temporary storage pond, although this is more consistent due to the time taken for the water to pass through the bedrock geology.

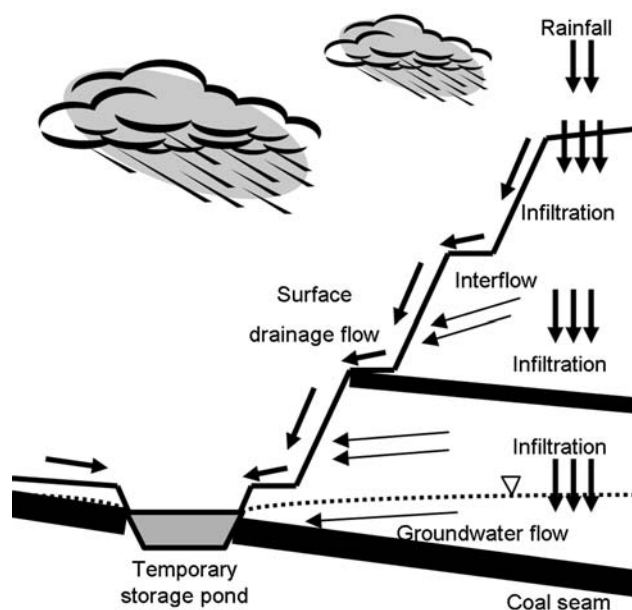
The steep gradient of the batters in open pit mines can significantly accelerate the velocity of surface drainage flow; valleys/trills can be created on the bench slopes due to these concentrated fast flows. Rapid gully erosion

processes at the rear of the benches allows infiltration into existing discontinuities, creating enhanced pore pressures, widening of the discontinuities and eventually slope failures which endanger the safety of the mining operations. Therefore, control of the concentrated surface drainage flows and protection of the bench slopes vulnerable to gully erosion is critical in open pit mines.

This study presents an effective and convenient methodology to consider the flood and gully erosion problems in open pit mines using Geographic Information Systems (GIS). Traditionally, such software packages as Minescape (<http://www.mincom.com>), VULCAN MineModeller (<http://www.vulcan3d.com/openpit.html>), etc. have been widely used in the mining industry. Although the software packages provide many convenient tools which are specific to mining applications, they have no function to analyze the surface drainage patterns and to support the rapid decision-making necessary for water management in open pit mines where the landform changes are much faster than those in nature. As a consequence, mining engineers depend on manual methods for drainage analysis, which can be tedious, time-consuming, error-prone and highly subjective.

As most GIS software packages include tools for hydrological modeling of surface drainage systems and spatial analysis (Garbrecht and Martz 2000; Burrough et al. 2005; Maidment et al. 2005), this system could provide a convenient methodology for drainage analysis. GIS is already used in the mining industry, eg to assess the mineral potential (Jusmady 1999); to assess the environmental impact of open pit quarries (Berry and Pistocchi 2003); to support the prioritizing of personnel issues (Knezic and Mladineo 2006) and to support stream remediation of acid mine drainage (Ayad 2006). Although a few studies have attempted to use GIS for drainage analysis in underground mining areas (Ayad 2006; Knezic and Mladineo 2006), little attention has been paid to the flood and gully erosion problems related to surface drainage flows in large-scale open pit mines.

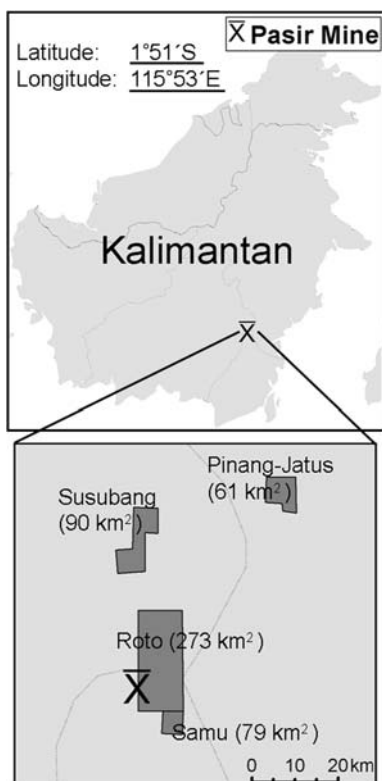
This paper presents a case study considering the wet season flooding of temporary storage ponds in the Pasir open pit coal mine, Indonesia, and the gully erosion problems which result in instability in the bench slopes. The surface drainage flows, closely related to the seasonal and rapid rise of water level in the temporary storage ponds, are mainly analyzed using GIS. Whilst it is appreciated that groundwater flows can also be important for the long term planning and design of temporary storage ponds in open pit mines, their effects are beyond the scope of this study.



**Fig. 1** Conceptual view of runoff phenomena in open pit coal mines during rainfall

## Study area

The Pasir open pit coal mine is located on the east side of Kalimantan, Indonesia (lat 1°51'S; long 115°53'E); see



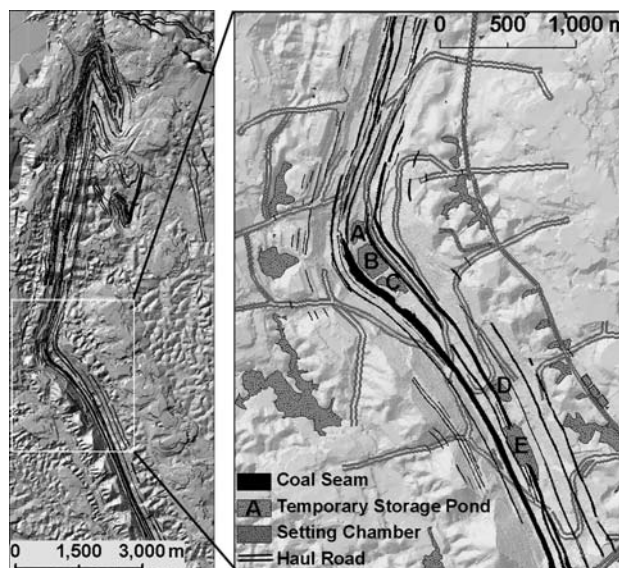
**Fig. 2** Location map of the Pasir open-pit coal mine, Indonesia

Fig. 2. This figure also shows the four coal blocks in the Pasir mine: Roto, Samu, Susubang, Pinang-Jatus. The Roto block has approximately a billion tons of recoverable reserves of bituminous coal and has been developed using large-scale open pit mining techniques since 1993. Annual production of coal at the Roto block is currently 22 million tons. The other coal blocks have not been developed.

The bedrock geology of the Pasir open pit coal mine is dominated by sedimentary sequences of mudstone, sandstone and coal of Eocene age (Chung et al. 2000). The coal deposits are almost vertically bedded and strike almost N–S (Fig. 3) with 80°–90° dips as a result of faulting during compression. In the Roto block, the thickness of the coal seams varies from 2 to 60 m. The volume of mine waste moved each year is 114 million BCM (billion cubic meters). The discards are end tipped and compacted at the nearby waste dumps.

A 11.89 km<sup>2</sup> area (2,900 × 4,100 m) in the south part of the Roto block was selected for the study (Figs. 3, 4). The relief varied between 182 m above sea level (asl) and 46 below sea level (bsl). The final pit plan indicates the lowest elevation will extend to 230 bsl. At the time of the study the mine cut extended from 220 to 150 m asl, consisting of 20 m high benches with average gradients of 40°.

The long-term average temperature is 32°C. The annual rainfall varies from 1,700 mm in dry years to 3,400 mm in



**Fig. 3** Thematic map showing coal seams in the Roto block (left) and topographical characteristic of the study area (right)



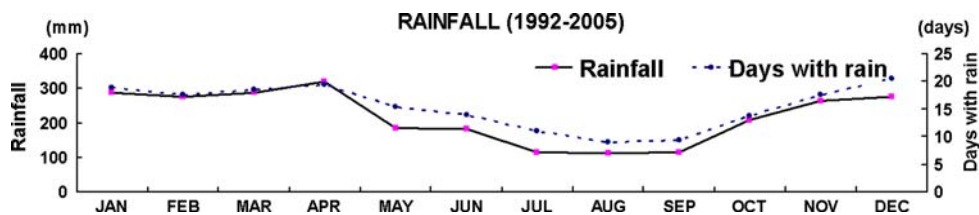
**Fig. 4** View of the study area

wet years (average 2,600 mm). As seen in Fig. 5, the average monthly rainfall varies considerably with the seasons, from just over 100 mm in July to September to 300 mm in November to April. The average monthly effective rainfall in wet seasons is 230 mm. A large proportion of the precipitation needs temporary storage in the wet season as the mudstone bedrock has low permeability and hence there is little infiltration (Chung et al. 2000).

**Pumping at the temporary storage ponds**

There are five temporary storage ponds in the lowest parts of the pit (A–E in Fig. 3). Most surface drainage flows down the inner pit during rainfall and accumulates in these five temporary storage ponds. In three of the temporary storage ponds there are pumping facilities to raise the water to the settling chambers outside the main mine area (Fig. 6). The daily running time of pumping facilities varies from 5 h to 24 h according to the amount of rainfall. However, despite

**Fig. 5** Monthly mean rainfall data averaged 1992–2005

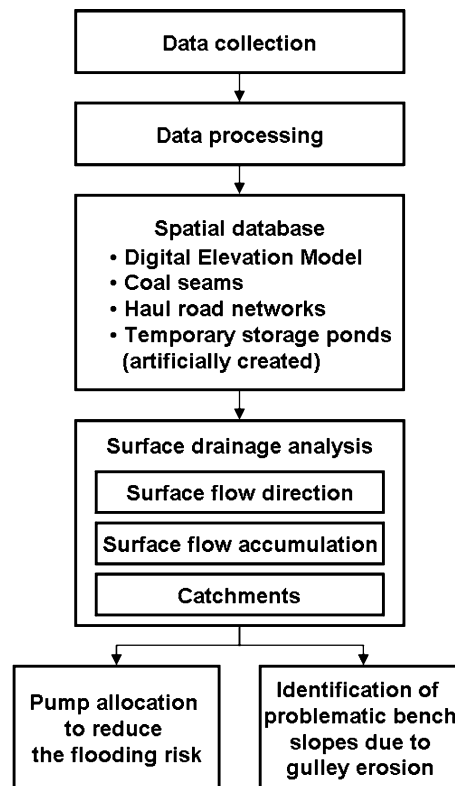


**Fig. 6** Current allocation of pumping facilities on temporary storage ponds in the study area

consistent pumping at these three temporary storage ponds, flooding of ponds has occasionally occurred in the wet season. In 2005, there were 432 unproductive hours whilst the site was drying after severe flooding. In view of this, it was considered important to re-assess the current allocation of pumping facilities in the study area (i.e., at temporary storage ponds A, B and E) taking into account the patterns of surface drainage flows during rainfall.

## Materials and methods

The procedures of this study are shown diagrammatically in Fig. 7. Data was collected from thematic maps to construct a spatial database. The thematic maps, representing coal



**Fig. 7** Flow chart of study procedures

seams, temporary storage ponds and haul road networks (including rampways) were available as CAD data formats in the mining site and were converted to the Shapefile format used in ArcGIS 9.1 (GIS software developed by ESRI).

For generating a reliable Digital Elevation Model (DEM) in the spatial database, a digital topographic map with 2 m contours was used. A triangulated irregular network (TIN) surface was created from the topographic map and converted to a DEM with a 20 m grid spacing using ArcGIS 9.1. The accuracy of the generated DEM was confirmed through ground inspection in the study area.

To determine the hydrological characteristics of the surface drainage system (i.e., surface flow direction, surface flow accumulation, catchment areas of temporary storage ponds) drainage analysis was performed using the generated DEM and the Hydrology tools in ArcGIS 9.1. It should be noted that many cave-in terrains (depressions) are present in the study area as a consequence of the open pit mining operations, most of which could be resolved in

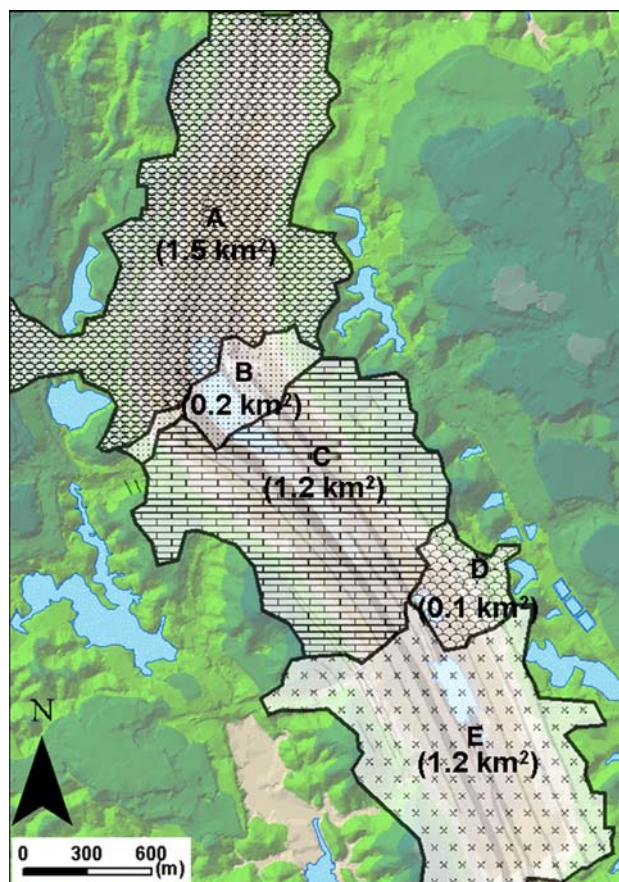
the generated DEM. In the real world, small depressions can be completely filled with water during heavy rainfall and overflow. However, in the algorithms implemented by ArcGIS 9.1 for drainage analysis, the depressions cannot be filled with rainwater but can only be considered as sinks of surface drainage flows. The elevation of the depression grids in a DEM should be increased to the level of the surrounding grids to ensure that continuous surface flow patterns appear in the results of the drainage analysis (Jenson and Domingue 1988; Wang and Liu 2006). As a consequence, the technique for filling depressions developed by Jenson and Domingue (1988) was first applied to the generated DEM. Most depression grids in the DEM were modified by the filling depressions technique. However some depression grids which represent the temporary storage ponds and the settling chambers were preserved by using the threshold value (i.e., the maximum depth of a depression filled, Wang and Liu 2006). The depression grids preserved in the DEM have the role of a sink if allocated facilities start to lower the water level.

The direction and accumulation of surface drainage flows in each grid in the modified DEM were then analyzed using the D8 method (Mark 1984; Jenson and Domingue 1988), which specifies the steepest gradient for each grid in eight possible directions to determine the surface flow accumulation. Finally, the individual catchments were delineated based on surface flow direction.

**Reduction of flooding risk**

Figure 8 shows the catchment areas for the five temporary storage ponds in the study area. Temporary storage ponds A, C and E have relatively large catchments (>1.2 km<sup>2</sup>) compared with those for B and D which were <0.2 km<sup>2</sup>. The current allocation of pumping facilities (Fig. 6) was evaluated using two variables (i.e., catchment area at each pond and pond area) to calculate the CP-value (i.e., the Catchment area divided by the Pond area) at each temporary storage pond (Table 1). As the amount of incoming surface drainage at each temporary storage pond is related to its catchment area and the possibility of flooding increases when the pond area is small, the temporary storage pond with the higher CP-value was given a higher priority for pump allocation (Table 1).

Comparing the current allocation of pumping facilities (Fig. 6) with the calculated priority orders (Table 1), it is clear that pumping facilities would be better placed at temporary storage ponds C and D rather than B. In order to determine the amount of pumping facility which should be moved to C and D, the Normalized CP values (NCP) were calculated and multiplied by the total pumping capacity available (i.e., 7,300 m<sup>3</sup>/day). Table 2 shows the optimal



**Fig. 8** Catchments of five temporary storage ponds extracted from DEM by drainage analysis

**Table 1** Calculation of the priority order for pumping facility allocation

Pond	Catchment area (m <sup>2</sup> )	Pond area (m <sup>2</sup> )	CP <sup>a</sup>	Priority order
A	1540,853	12,582	122.46	1
B	216,503	34,725	6.23	5
C	1244,304	14,740	84.42	2
D	186,758	10,377	18.00	4
E	1207,955	39,877	30.29	3
Total	4396,373	112,301	261.41	

<sup>a</sup> CP: catchment area divided by the pond area

allocation of pumping facilities at each temporary storage pond, based on the available two units of 2,300 m<sup>3</sup>/day and three units of 900 m<sup>3</sup>/day.

**Problematic bench slopes due to gully erosion**

Figure 9 shows the surface flow accumulation in the study area during rainfall. As seen in Fig. 9, this gradually increases from the upper pit to the five temporary storage ponds; the surface flow paths frequently being concentrated

**Table 2** Optimal allocation of the pumping facilities in the study area

Pond	NCP	NCP × T <sup>a</sup> (m <sup>3</sup> /day)	Pump allocation (units)		Newly allocated pumping capacity (m <sup>3</sup> /day)	Change of allocated pumping capacity (m <sup>3</sup> /day)
			P1 <sup>b</sup>	P2 <sup>c</sup>		
A	0.47	3,420	1	1	3,200	+2,300
B	0.02	174	0	0	0	−3,200
C	0.32	2,357	1	0	2,300	+2,300
D	0.07	503	0	1	900	+900
E	0.12	846	0	1	900	−2,300
Total	1.00	7,300	2	3	7,300	0

<sup>a</sup> T: total amount of capacity of available pumping facilities in the study area = 7,300 m<sup>3</sup>/day

<sup>b</sup> Pumping capacity of P1: 2,300 m<sup>3</sup>/day

<sup>c</sup> Pumping capacity of P2: 900 m<sup>3</sup>/day

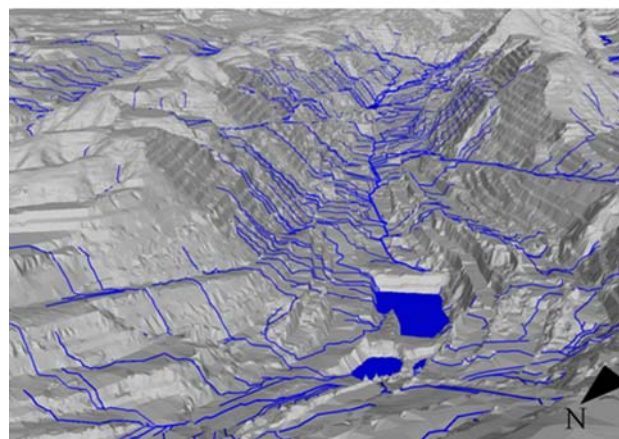
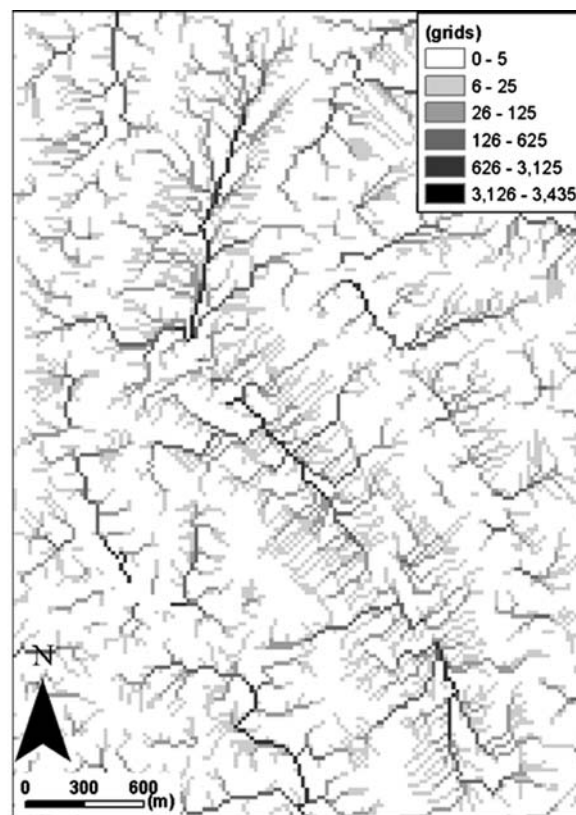
along rampways/benches. The excessively steep gradients contribute to the gully erosion problem by concentrating surface drainage flows and accelerating flow velocity.

To identify the bench slopes prone to gully erosion, those with the more concentrated drainage flows were analyzed by the Boolean operations in GIS. The ranges of surface flow accumulation were reclassified and newly rated values assigned, as shown in Table 3. Figure 10a shows the rated value map derived from the surface flow accumulation in the study area. The grids with the highest rated value (>1,000) are distributed mostly at the bottom of the pits in a N–S direction. The gradient of terrain surface was calculated from the DEM by searching the maximum change in elevation over the distance between each grid and its eight neighbours. As the gradient of bench slopes in the study area is generally  $\geq 30^\circ$ , the grids with slope gradients  $\geq 30^\circ$  were extracted as illustrated in Fig. 10b. Finally, the logical intersections of the two rated value maps (Fig. 10a, b) were obtained (Fig. 10c). As seen in Fig. 11, field survey showed that the highly rated locations in Fig. 10c are unstable.

In order to prevent the collapse of bench slopes due to concentrated surface drainage flows, periodic monitoring of bench slopes vulnerable to gully erosion is recommended. The rated value map (Fig. 10c) can be effectively used to select the optimal locations for periodic monitoring. The number of monitoring locations in the study area can be adjusted according to managerial conditions by changing the ranges in Table 3 at the time of assigning the rated value to the surface flow accumulation.

## Discussion and conclusions

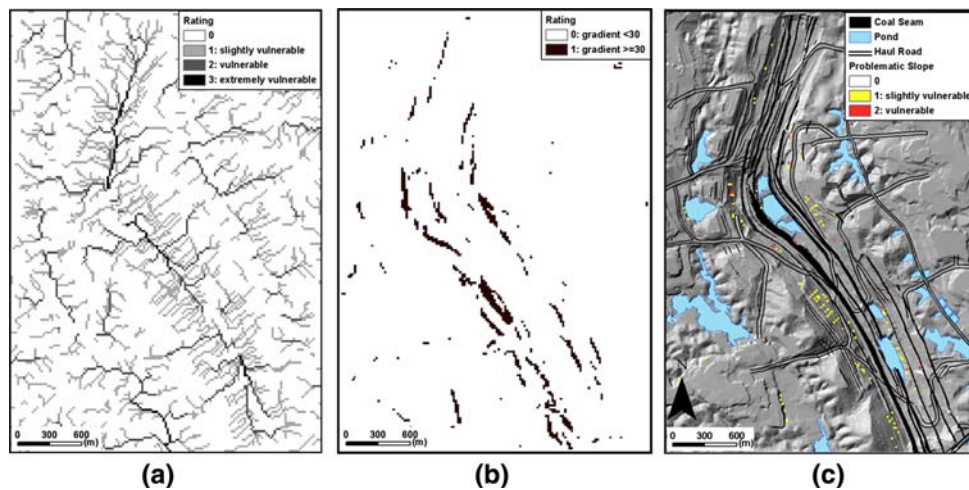
In this study, drainage analysis and raster-based spatial analysis were applied to the Pasir open pit coal mine in



**Fig. 9** Surface flow accumulation (*above*) and 3D view of concentrated surface drainage flows (accumulation value >10 grids) (*below*)

**Table 3** Factors of raster-based spatial analysis for identifying the problematic bench slopes

Factor	Range	No. of cells in domain	Percentage (%)	Rating
Flow accumulation (Unit: cells)	1,000–3,435	122	0.4	3
	100–1,000	1,069	3.6	2
	10–100	4,163	14.0	1
	0–10	24,371	82.0	0



**Fig. 10** Rated value maps. **a** Rating the vulnerability to erosion from the flow accumulation of surface drainage. **b** Rating the slope gradient to extract the steep bench slopes ( $\geq 30^\circ$ ). **c** Locations of bench slopes vulnerable to gully erosion during rainfall



**Fig. 11** Field survey in a vulnerable location derived from spatial analysis. The condition of the highly rated bench slope in Fig. 10c was highly unstable due to the valley created by concentrated surface drainage flows

Indonesia to support the decision-making process for solving the flood and gully erosion problems related to surface drainage flows. By using GIS, faster, less subjective and more reproducible information about the hydrological characteristics of the surface drainage system can be obtained.

To reduce the flooding risk at temporary storage ponds in the study area, a new allocation of pumping facilities was suggested, taking into account both the catchment and the pond areas. No down-time has occurred due to the flooding of temporary storage ponds in the study area since the re-allocation of the pumping facilities, even in wet seasons.

This GIS-based methodology, which considers the flood problem only, requires data which can be easily acquired through surface drainage analysis. Therefore, it is most

applicable to operating open pit mines, where the changing terrain means there is insufficient time for long-term monitoring or a detailed hydrological investigation based on field survey.

Bench slopes prone to gully erosion were also analyzed using GIS. As the raster-based spatial analysis was based on quantitatively rated values, it was possible not only to identify the problematic bench slopes but also to prioritise the problem. Mining engineers can find optimal solutions for periodic monitoring and surface protection at their own sites by re-assessing the rated values according to their specific managerial conditions and repeating the spatial analysis using the newly rated values.

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