Surface erosion and sediment control at open-cast mines in southern Africa

ANDY WARD, ADRIAN SMITH & JACK CALDWELL
Steffen Robertson and Kirsten Inc.,
20 Anderson Street, PO Box 8856, Johannesburg
2000, South Africa

ABSTRACT Coal production will increase rapidly in the next 20 years due to the development of large-scale open-cast mines. This method of mining disturbs large areas of land which need to be restored following mining. Sediment yield from these areas can be several hundred times greater than from undisturbed areas. This paper presents an outline of surface erosion problems associated with coal mining operations. Potential sediment control techniques are discussed and a case study for a proposed southern African coal mine is presented.

L'érosion du terrain et le contrôle de sédiments en chantiers à ciel ouvert dans l'Afrique du sud

RESUME A cause du développement de très grands chantiers à ciel ouvert la production de charbon augmentera rapidement dans les 20 ans suivants. Cette méthode d'exploitation des mines bouleverse de grandes étendues de terrain et il faut les remettre en état après l'exploitation. La production de sédiments dans ces étendues peut être environ cent fois supérieure à celle observée les zones qui n'ont pas été remuées. Ce rapport présente les grandes lignes des problèmes de l'érosion du terrain dans l'exploitation du charbon. On discute des techniques du contrôle potentiel de sédiment et on présente une étude pour un projet de mine de charbon en Afrique de sud.

INTRODUCTION

Coal currently provides over 80% of southern Africa's energy and in South Africa coal production increased from 57 to 138 million tonnes between 1970 and 1980 (Kempe, 1983). This rapid expansion can be attributed to recent advances in coal mining techniques and the development of large-scale open-cast mines. Associated with this rapid expansion will be modifications in the hydrological regimes of the mined basins, a greater potential for water pollution and increased demands on southern Africa's limited water resources.

Surface mining activities disturb large tracts of land and produce greatly increased downstream sediment loads. Sediment production from surface mined areas can be 100 to 2000 times that from a forested area and more than 10 times that from grazing lands (Curtis, 1971; Environmental Protection Agency, 1976). In addition to being a major
source of water pollution, these high sediment loads can result in: reduction in the agricultural potential of an area, storage capacity losses in downstream reservoirs, increased flooding due to reduced river channel capacities, geomorphic changes in stream structure and increased turbidity and associated changes in all riverine life forms.

This paper presents an outline of open-cast coal mining surface erosion problems, methods for determining sediment yields, measures for reducing or controlling sediment discharges and a discussion on the advantages and disadvantages of the different techniques. A case study is presented for a proposed southern African coal mine.

OPEN-CAST COAL MINING SURFACE EROSION PROBLEMS

Soil erosion and sediment transport depend on the following factors:
(a) climatic conditions,
(b) soil and spoil erositivity,
(c) overland slope and slope length,
(d) ground cover,
(e) soil conservation control practices,
(f) catchment drainage characteristics.

Open-cast mining activities tend to change radically several of these factors and severe sediment production could occur in the following locations:
(a) topsoil stockpiles,
(b) spoil piles,
(c) waste dumps,
(d) bare topsoil areas,
(e) steep outslopes,
(f) ramps,
(g) haul roads.

Scalping, blasting, material handling, heavy vehicular travel over replaced spoils, and topsoiling activities generally produce compacted areas of soil and spoil materials with a high colloidal content. The runoff potential from these areas is increased due to a reduction in infiltration and, if fine silts and colloidal particles are transported into major water courses, the impact of the increased sediment production might occur hundreds of kilometres downstream of the mine location. Colloidal particles require a very long detention time in an impoundment before they will settle out of suspension and frequently deposition does not occur until the sediment laden flows discharge into large water supply dams.

SEDIMENT YIELD DETERMINATION

Most methods for determining soil erosion and sediment transport have been developed based on studies with agricultural lands. Although relatively little work has been done with surface mined lands, they will in general have similar sedimentation characteristics to agricultural areas.

Soil erosion involves detachment, transport and subsequent deposition. The most commonly used method for predicting erosion is the
Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978):

\[ A = R \cdot K \cdot L \cdot S \cdot C \cdot P \]  \hspace{1cm} (1)

where \( A \) is the soil loss per unit area, \( R \) is a rainfall factor usually expressed as the product of rainfall energy times the maximum 30 minute intensity for a given rainstorm, \( K \) is soil erodibility, \( L \cdot S \) is a dimensionless length slope factor, \( C \) is a dimensionless soil cover factor and \( P \) is a dimensionless conservation practice factor. A good account of the determination of these factors for surface mined lands is presented by Barfield et al. (1981).

The method should be used with caution for although it has been calibrated for some southern African conditions (McPhee et al., 1983; Smithen and Schultze, 1982) it should be remembered that it was developed for American agricultural watersheds and is based on American data.

Equation (1) should only be used to determine gross erosion from an area. To determine the sediment yield at a downstream point the gross erosion needs to be multiplied by a sediment delivery ratio term (sediment yield/gross erosion). Numerous methodologies have been developed to predict sediment delivery ratios. Unfortunately very little work has been done in developing delivery ratios for southern Africa.

A method known as the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) overcomes the problem of determining a delivery ratio and has seen widespread application. The method is defined by the following equation:

\[ Y = 11.8 \cdot (Q \cdot q)^{0.56} \cdot K \cdot L \cdot S \cdot C \cdot P \]  \hspace{1cm} (2)

where \( Y \) is a single storm sediment yield in tonnes, \( Q \) is the storm runoff volume in cubic metres, \( q \) is the peak storm discharge in cubic metres per second and \( K, L \cdot S, C \) and \( P \) are the standard USLE terms used in equation (1). This method is discussed further in the outline of the case study.

SEDIMENT CONTROL TECHNIQUES

The major causes of erosion problems at a surface mining operation are the extent of the disturbed areas, poor drainage plans and the lack of a sediment control strategy which is integrated with the mining operations. In developing a sediment control plan the following basic approach should be adopted:

(a) minimize the area which is disturbed at any one time;
(b) develop a drainage control system for the mine lease area;
(c) integrate drainage, erosion and sediment control into each stage of the mining operation;
(d) develop a mining and rehabilitation plan prior to initiating mining activities;
(e) construct drainage and erosion controls in advance of mining activities;
(f) divert storm runoff away from areas with high erosion potential;
TABLE 1 Control measures for mining operations (source: Barfield et al., 1981)

<table>
<thead>
<tr>
<th>Drainage, Erosion, and Sediment Control measures</th>
<th>Access and Haul Road</th>
<th>Exploratory Drilling</th>
<th>Timber Stand Removal</th>
<th>Clearing and Grubbing</th>
<th>Trenching</th>
<th>Soils Segregation</th>
<th>Drill Bench Construction</th>
<th>Overburden Removal</th>
<th>Overburden Placement</th>
<th>Trenching</th>
<th>Reclaimed Area Stabilization</th>
<th>Sediment Basin Removal</th>
<th>Small Scale Control</th>
<th>Road Closure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Stabilization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selective Grading and Shaping</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical Preparation</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mulches</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mulch Tack and Anchoring</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matting and Netting</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical Addition</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grass Cover</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Runoff, Interception and Conveyance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diversion Ditch or Channel</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Downdrain</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open-Top Culvert</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level Spreader</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ditch Relief Culvert</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terracing</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road Dip</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Bars</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pit Pumping</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sedimentation</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediment Trap</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Check Dam</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetative Filter</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brush Barrier</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filter Fabric</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swirl Concentrator</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(g) incorporate measures to reduce the flow velocity of storm runoff;
(h) limit the handling of spoil and topsoil materials;
(i) rehabilitate areas as soon as possible;
(j) maintain drainage and erosion control measures.

A summary of drainage and erosion control measures which are commonly employed at different phases of a surface mining operation are presented in Table 1. A discussion on the effectiveness and advantages and disadvantages of these measures is presented in the
EROSION AND DRAINAGE CONTROL TECHNIQUE SELECTION

A fundamental philosophy in erosion abatement is to minimize the problem at the source. Preventive measures are far more effective than control and treatment measures. In Table 1 all the measures, except those listed under sedimentation, are preventive techniques. Selection of a particular technique should be site specific and in many instances several techniques will need to be used in conjunction with each other. A discussion on the effectiveness of the different techniques follows.

Surface stabilization

The main purpose of using a surface stabilization technique is to reduce erosion until a vegetative cover is established. Mulches and chemical stabilizers only provide short term benefits and can be expensive. Matting and netting is only recommended for application in steep sloping areas where there is a severe localized problem. Landscaping and mechanical preparation of a disturbed area is very important in the establishment of a good vegetative cover. A basic problem at surface mines is that these type of operations are frequently conducted with heavy mining equipment. To prevent over compaction problems it is very important that agricultural equipment be used for rehabilitation activities.

Runoff, interception and conveyance

Development of a drainage control system is probably the most important aspect of erosion control and rehabilitation at a surface mine. It is also the most commonly overlooked aspect.

The effectiveness of drainage control measures will be site specific. In general, however, the magnitude of virtually all erosion problems can be significantly reduced through effective drainage control. The purpose of a drainage control system should be to reduce the volume and velocity of flows crossing disturbed areas and to prevent the mixing of clean and dirty flows.

A basic philosophy which should be adopted is the establishment of a clean and dirty water drainage systems. Clean systems will primarily divert water from undisturbed or rehabilitated areas away from disturbed areas. Dirty systems will collect water from disturbed areas and convey them to treatment facilities. Included in these systems would be pumped flows from the open pit and effluent discharges from washing plants.

Sedimentation controls

Removal of sediment from a flow is generally achieved through gravity settling. With the exception of swirl concentrations (cyclones), each of the techniques presented in Table 1 are based on this principal. Cyclones are used to split a sediment laden flow into two parts; a relatively clean part which might contain 80% of the
fluid, and a sediment laden part which might contain over 80% of the original sediment load. Cyclones are generally used in conjunction with sediment ponds and their purpose is to reduce the size of these ponds and to improve the efficiency of the system.

The effectiveness of any of the sediment control measures will depend on the settling characteristics of the sediment load and the residence (detention) time of the flow in the control measure.

The performance of the following control structures depends on the retardation of the flow velocity:
(a) check dams (small permeable control structures);  
(b) vegetative filters (areas of grass and reeds which are designed to retard flow and deposit sediments);  
(c) barriers/fences (hay bales and pole or brush barriers);  
(d) filter fabric fences (semipermeable fences made of artificial fabric materials).

They provide a very short residence time and limited benefits. Another disadvantage of these type of measures are that overland flows are conveyed towards a single point and downstream of the control erosion can be more severe than if the measures were not used.

To remove colloidal particles from suspension requires large sediment ponds or the use of chemical flocculants. With the use of chemical flocculants virtually 100% removal can be achieved. The major problem with sediment ponds (or any sediment control measure) is the cleaning out and rehabilitation of these facilities. To remain effective, most sediment control measures need to be cleaned out several times during their active life. Dry handling of sediments is very costly and ineffective. A good portion of the trapped material is washed downstream during these operations. Slurry pumping can be effective but requires a nearby disposal facility.

A basic problem in current practice is that the design of the clean out systems is not incorporated into the design of the sediment basin.

Procedures for quantifying the effectiveness of sediment control facilities are still in a state of development. The most commonly used approach for designing sediment pond facilities at American surface mines is the DEPOSITS computer model (Ward et al., 1979). Recently a computer model called SEDIMOT-II has been developed for modelling the hydrology and sedimentology of a disturbed watershed (Wilson et al., 1981). This model is described in an accompanying paper.

A SOUTHERN AFRICAN CASE HISTORY

An illustration of the application of the methodology and techniques contained in this paper is now presented based on a typical case history. To protect the confidential nature of this study, it is not possible to identify the exact location of the mine.

As part of a study for a proposed surface coal mine, an evaluation was made of the sediment pollution potential, drainage control requirements and sediment abatement measures. The mine is in an environmentally sensitive area. Rivers and streams in the area are fed by a baseflow from the groundwater and are breeding grounds for
Sediment production potential

An evaluation was made of the erositivity characteristics of topsoil materials at the mine. Soil samples were obtained from trial pits and borehole cores and, based on standard laboratory procedures, grading curves and permeabilities values were established for materials in the top 2 m. The erodibility factor, K, was then determined by using Fig. 1. The results of this investigation are summarized in Table 2. Estimates of potential gross erosion were determined for different topographic conditions and are presented in the diagram below.

To use the nomograph, enter the left-hand scale with the silt plus very fine sand content and proceed to points representing the % sand, % organic matter, structure, and permeability in that sequence as illustrated by the dotted line on the nomograph. Interpolate between plotted curves.

FIG. 1 The soil erodibility nomograph of Wischmeier et al. (1971).
TABLE 2 Topsoil erositivity characteristics

<table>
<thead>
<tr>
<th>Location</th>
<th>Soil Description</th>
<th>Depth (m)</th>
<th>% finer 0.10 mm</th>
<th>% between 0.10-2.00 m</th>
<th>% coarser 2.00 mm</th>
<th>soil structure</th>
<th>Permeability</th>
<th>Erodibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Slightly moist light yellowish-brown mottled dark grey LOOSE (-VERY LOOSE) slightly silty SAND and fine rounded ferricrete GRAVEL with occasional medium sub-angular ferricrete gravel. Ferruginised aeolian sand.</td>
<td>0.2-0.7</td>
<td>12</td>
<td>28</td>
<td>60</td>
<td>3</td>
<td>2</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>Slightly moist light red mottled yellow black and red-brown MEDIUM DENSE clayey silty SAND and fine GRAVEL. Poorly to moderately developed ferricrete and ferruginised transported</td>
<td>1.0</td>
<td>39</td>
<td>44</td>
<td>17</td>
<td>3</td>
<td>4</td>
<td>0.35</td>
</tr>
<tr>
<td>3</td>
<td>Slightly moist to moist light yellowish-brown mottled light grey FIRM TO STIFF becoming FIRM with depth possibly slightly micro-shattered slightly sandy silty CLAY. Probably residual clayey siltstone reworked with alluvium above.</td>
<td>1.4</td>
<td>55</td>
<td>33</td>
<td>12</td>
<td>2</td>
<td>5</td>
<td>0.40</td>
</tr>
<tr>
<td>4</td>
<td>Moist dark to light red mottled light and dark reddish-orange LOOSE MEDIUM DENSE slightly clayey and silty fine SAND and sub-angular to sub-rounded FERRICRETE &amp; SILTSTONE GRAVEL. Transported</td>
<td>1.8-2.05</td>
<td>42</td>
<td>26</td>
<td>32</td>
<td>3</td>
<td>3</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 3.

Table 3 can now be used as a basis for developing a sediment control strategy. It can be seen that if highly erodible soil (K of 0.4) is placed on steep outslopes, soil erosion could be over 70 times greater than during pre-mining conditions. If, however, this same material is placed on flatter areas, and terraces or diversion ditches are provided every 25-50 m, erosion will be very similar to that from undisturbed areas. Table 3 also illustrates the importance of rapid rehabilitation. Erosion from a bare soil condition is 5 times that from a well established grassed area.

The information in Table 3 is of value in planning terrace spacings, diversion ditch requirements and revegetation scheduling. To size hydraulic controls such as diversion ditches and sediment ponds it is necessary to develop single event hydrographs and sedimentographs. In the case study, the WASHMO computer program (Ward & Stern, 1983) was used to develop storm hydrographs for different frequency events. General hydrological relationships were then developed for the mine lease area (see Fig.2). These relationships were then used to size hydraulic structures and to predict single event sediment yields. Using equation (1) it was established that single event sediment yields would be very high and that sediment ponds would be required. Single event sediment yields from a 100 ha disturbed area with a slope of 1:30, slope length of 100 m and K of 0.4, varied from 2500 to 8000 t for the 1:10 year and 1:100 year 24 h events respectively.

The particle size distribution of waste dump and topsoil materials
indicated a high silt content and it was established that sediment ponds with a detention time of 2-6 h would be required. Based on the single event hydrological analysis it was established that it would be impractical to design ponds for events larger than a 1:10 year 24 h flood and that the ponds would need to be cleaned out several times during their life.

DISCUSSION

The case study illustrates that, without careful management and the development of a sediment control scheme, erosion from a surface mine can be severe. In South Africa, the Chamber of Mines have developed a set of guidelines for the rehabilitation of surface coal mines (Chamber of Mines of South Africa, 1982). Under these guidelines an area which is rehabilitated to an arable state should satisfy the following standard: the % land slope times the erodibility factor \( K \) should be less than 2. From Table 2, the highest \( K \) factor is 0.4 and it can be seen that all areas with a slope of less than 5% will achieve the arable land standard. Less than 10% of the rehabilitated areas will not satisfy the arable land standard. These areas will, however, provide good grazing land but will need careful management as they are susceptible to severe erosion.

Consideration was primarily given to diversion ditches, terracing and sediment ponds. In southern Africa, surface coal mines are generally located in summer rainfall areas. Thunderstorms dominate and small local controls such as filter fabric fences and brush barriers will provide very limited benefits during those high intensity rainfall events.

It is beyond the scope of this paper to discuss sediment pond design criteria (refer to Ward et al., 1979) but it can be seen from

<table>
<thead>
<tr>
<th>Erodibility factor (K)</th>
<th>BARE SOIL</th>
<th>1:30</th>
<th>1:10</th>
<th>1:3</th>
<th>1:30</th>
<th>1:10</th>
<th>1:3</th>
<th>1:30</th>
<th>1:10</th>
<th>1:3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.50</td>
<td>0.40</td>
<td>0.85</td>
<td>6.00</td>
<td>0.16</td>
<td>0.60</td>
<td>4.00</td>
<td>0.50</td>
<td>0.40</td>
<td>0.85</td>
</tr>
<tr>
<td>0.2</td>
<td>1.00</td>
<td>0.80</td>
<td>1.70</td>
<td>12.00</td>
<td>0.32</td>
<td>1.20</td>
<td>8.00</td>
<td>1.00</td>
<td>0.80</td>
<td>1.70</td>
</tr>
<tr>
<td>0.3</td>
<td>1.50</td>
<td>1.20</td>
<td>2.55</td>
<td>18.00</td>
<td>0.48</td>
<td>1.80</td>
<td>12.00</td>
<td>1.50</td>
<td>1.20</td>
<td>2.55</td>
</tr>
<tr>
<td>0.4</td>
<td>2.00</td>
<td>1.60</td>
<td>3.40</td>
<td>24.00</td>
<td>0.64</td>
<td>2.40</td>
<td>16.00</td>
<td>2.00</td>
<td>1.60</td>
<td>3.40</td>
</tr>
<tr>
<td>GROUND COVER 20%*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>0.22</td>
<td>0.18</td>
<td>0.39</td>
<td>2.64</td>
<td>0.07</td>
<td>0.27</td>
<td>1.76</td>
<td>0.22</td>
<td>0.18</td>
<td>0.39</td>
</tr>
<tr>
<td>0.2</td>
<td>0.44</td>
<td>0.35</td>
<td>0.75</td>
<td>5.28</td>
<td>0.14</td>
<td>0.53</td>
<td>3.52</td>
<td>0.44</td>
<td>0.35</td>
<td>0.75</td>
</tr>
<tr>
<td>0.3</td>
<td>0.66</td>
<td>0.53</td>
<td>1.14</td>
<td>7.92</td>
<td>0.21</td>
<td>0.80</td>
<td>5.28</td>
<td>0.66</td>
<td>0.53</td>
<td>1.14</td>
</tr>
<tr>
<td>0.4</td>
<td>0.88</td>
<td>0.70</td>
<td>1.50</td>
<td>10.56</td>
<td>0.28</td>
<td>1.06</td>
<td>7.04</td>
<td>0.88</td>
<td>0.70</td>
<td>1.50</td>
</tr>
</tbody>
</table>

*Per cent of canopy in contact with the ground.
FIG. 2  (a) Peak discharge from open-case pit areas, (b) Runoff depth for different storm conditions.
the case study that large ponds will generally be required. Any sediment pond should have a minimum temporary storage volume which is 1.5 times the volume of flow entering the pond during a period equal to the detention time. For a 100 ha drainage area in the case study, a minimum temporary storage volume of 100 000 m$^3$ would be required for the 1:10 year flood.

REFERENCES


Environmental Protection Agency (1976) Effectiveness of Surface Mine Sedimentation Ponds. EPA Report 600/2-76-117.


