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Assessing Spontaneous Combustion Risk in South African Coal Mines Using a GIS Tool

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ABSTRACT: The mapping of areas that are prone to spontaneous combustion can be achieved by using a Geographic Information System (GIS) as a database. This database can be considered as a collection of spatially referenced data that acts as a model of reality. The main spontaneous combustion risk factors are: coal factors, geological factors, environmental factors, and mining factors. The calculation of the coal factor will be explained in detail. For each factor that contributes to the spontaneous combustion problem a raster map is created. These maps are then assigned ratings according to pre-determined ranges of values and each are assigned a weighting. A risk map is obtained by combining t>e weighted maps.

I INTRODUCTION

The Witbank Coalfield in Mphumalanga Province of South Africa extends over a distance of approximately 180 km from the Brakpan/Springs area in the west to Belfast in the east and about 40 km in a north-south direction. It İs known that the Witbank Coalfield (Figure 1) has a recurring spontaneous combustion problem.

There are over 50 collieries operating throughout the coalfield. In order to study the spontaneous combustion problem various data had to be collected by visiting the collieries and through a literature survey.

A searchable database for existing literature has been created for easy access to the information. It reviews current practice in detecting, monitoring, preventing and controlling spontaneous combustion at all stages of coal production. Problem areas include underground, surface and abandoned mines, spoil piles, dumps, storage, transport and pillars. The number of papers and reports collected so far exceeds 400.

Tests have been performed on coal samples from various collieries to determine the Wits-Ehac Index, which measures self-heating liability by using differential thermal analysis (DTA). The test apparatus used was developed at the School of Mining Engineering, University of the Witwatersrand (Gouws et al., 1987). DTA has historically been considered a good predictor of self-heating liability.

Following a large experimental study, a new index was developed by Gouws (1987). This Wits-Ehac index makes use of tie crossing-point temperature and the slope of the differential temperature time curve, as follows:

$$Wits-Ehac\ Index = 0.5 * \frac{\text{slope of stage II}}{\text{crossing-point}} * 1000$$

A coal with a high Wits-Ehac index is more prone to spontaneous combustion than a coal with a lower index value (Gouws, 1987).

Because of the known incidents of spontaneous combustion, there was a need to locate problem areas within the Witbank Coalfield. It was found through the literature survey that a elationship exists between the coal properties and spontaneous combustion risk.

This relationship could either be studied by statistical methods or visualization of the coal properties on the map. The visualization technique developed to map the high-risk areas using a GIS tool is the subject of this paper.

2 RELEVANT FACTORS

Chakravorthy and Kolada (1988) grouped the critical factors contributing to spontaneous combustion into intrinsic (coal properties and geological features), and extrinsic, i.e. those than can be controlled (mining practices). These are listed in Table 1.

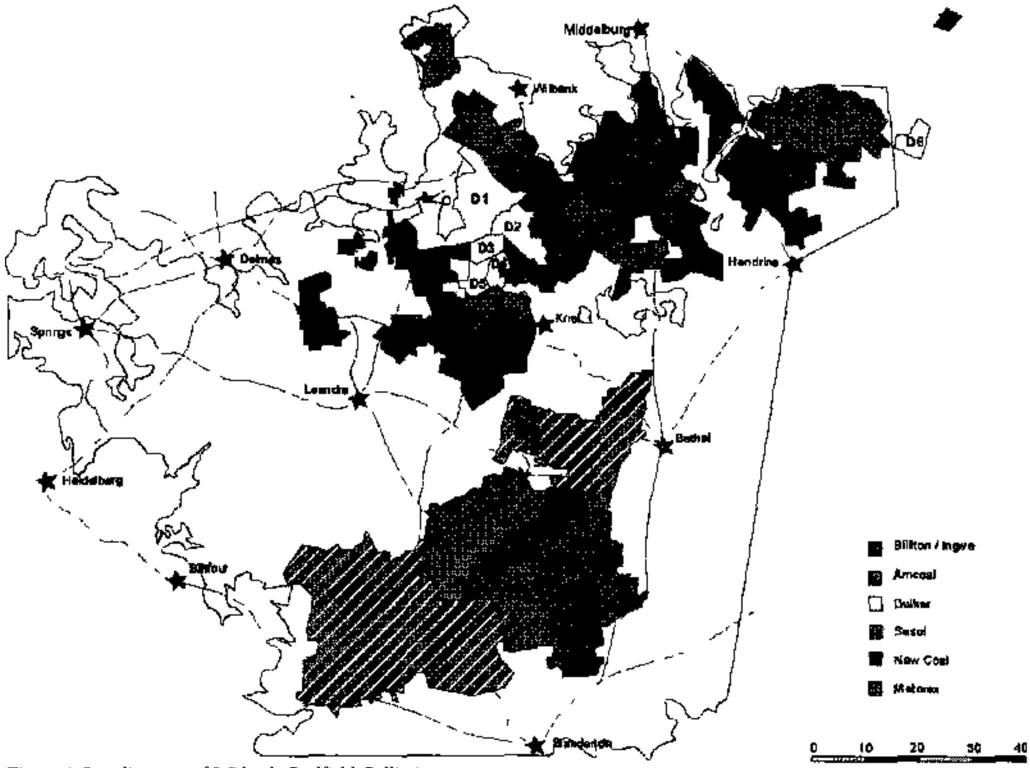

Figure 1. Locality map of Witbank Coalfield Collieries.

Table I Critical factors contributing to spontaneous combustion

Coal Properties	Geological Features	Mining Practices
High volatiles	Thick seams	Coal left at roof and floor
High Moisture	Pynte bands and carbonaceous shale	Poor maintenance of roadways
High Pyrites	Presence of faults	Air leakage through air crossings, doors, pillars
Presence of exinite, vitrini te. inertinite	Weak and disturbed strata	Caving to surface under shallow overburden
High friability	High strata temperature	Close proximity to multi-seam working
		Poor ventilation management

3 DATABASE BUILDING

Management of spontaneous combustion depends largely on how information is handled in order to define and monitor problem areas. By studying the Witbank Coalfield a methodology has been developed to locate and define problem areas.

Data handling should be approached in a systematic manner by using databases and computer programs that are capable of handling various kinds of input.

There are a few expert systems and/or fire risk indices developed by various organizations in different countries. Many of these expert systems were developed for unique circumstances such as opencast mining or mine dumps only. These expert systems were not found suitable for the coalfield concerned.

The Witbank coalfield is currently worked by many collieries with varying mining methods and environmental factors. This means that the whole coalfield cannot be assessed by a single formula containing all the risk factors. Nevertheless, a coal risk factor map can be produced irrespective of the mining methods employed at the individual mines.

A different approach was used to assess the potential risk of spontaneous combustion for the Witbank coalfield. Various maps (contour maps, polygon maps, segment maps, point maps, raster maps and topographical maps) are generated as tools for the database. A GIS software package (ILWIS) capable of integrating land and water information was chosen for generating these maps.

In this knowledge database the Wits-Ehac liability index İs included together with coal properties.

3.1 *Wits-Ehac Liability Index and the Test Apparatus*

Differential Thermal Analysis (DTA) and crossing point temperature tests have been carried out to find the Wits- Ehac index value of the coal samples from the Witbank area collieries.

The apparatus consists of an oil bath, coal and inert material cell assembly, oil circulator, heater, flow meters for airflow monitoring, air supply, compressor and a microcomputer. The temperatures are recorded every 15 seconds by the microcomputer during an average of a 3-4 hour testing time. The coal is heated from 30 °C to 200 °C. The kick-point and the crossing point temperatures are determined. The kick-point can be defined as the temperature at which the coal starts burning. Crossing point temperature is the temperature at which the coal temperature is higher than the inert material (Calcined Alumina) used.

Three sets of differentials (the difference between the temperature of inert material and that of coal) are obtained. These are used to form DTA curves. There are three slopes on these curves. *Slope I* starts at minimum differential to crossing-point temperate where the differential is zero. *Slope II* starts from crossing point temperature to the kick-point. *Slope III* is where the coal starts burning after the kick-point temperature. Stage II slope is one of the best indicators of spontaneous combustion. The steeper the Stage II slope the more liable the coal is to spontaneously combust.

The calculated Wits-Ehac values may range from as low as 2 to as high as 7. Through experience it was found that coals with values up to 3 are considered low risk, 3-5 are considered medium risk and 5 and upwards are considered high risk coal.

In order to determine the Wits-Ehac index for Witbank collieries several laboratory tests have been performed on samples taken from various collieries.

3.2 *Coal Properties*

Previous researchers have established a link between the coal rank, coal petrography, moisture, presence of pyrites and spontaneous combustibility.

In particular, there is said to be an inverse correlation between the rank of the coal and spontaneous combustion propensity. It is reported that lignite and sub bituminous coals are more liable than anthracite. Bituminous coals with high volatile matter result in relatively higher self-heating rates than those with low volatiles. The Witbank coalfield is bituminous throughout and therefore rank is not included in the calculations.

There are four lithotypes in banded coal, which are: vitrain, clarain, durain, and fusain. Recent work generally concluded that vitrain, clarain and durain, İn that order, are more susceptible to oxidation than fusain. Therefore, it was decided that vitrinite, exinite and mertinite (they exist in the "composition of vitrain, clarain, and durain) should be used as contributing factors in the risk calculations.

Another important factor in determining the self-heating liability is the change İn moisture content with time. The significance of this factor İs itself dependent on the environmental conditions in the coal seam. If the temperature difference is very high after rain then there is a good chance that it will increase risk. However, in normal conditions in-situ moisture would decrease the risk of spontaneous combustion. Based on this fact, in-situ coal seam moisture is used as a factor, where the less the moisture content the higher is the risk. In order to consider the effect of weather conditions the climate variations can be mapped and added to the risk calculation.

In addition to the factors mentioned above, the factors listed in Table 2 should also be used in generating risk maps and in the calculations.

To date the research has not used all of the factors mentioned here but most of the coal factors and depth of coal seams have been used.

Table 2. Contributing nsk factors for each category

Coal Factors	Geological Factor	Environmental Factors	Mining factors
Coal reactivity, Calorific value. Density, Ash content, Volatile matter, Inherent moisture, Pynte content. Total sulfur, Vitrnite, Exinite, Inertinite, Friability, Porosity	Presence of dykes and sills, Presence of faults. Depth of the seams. Floor rolls, Parting, Overlying strata, Seams in proximity,	Mean annual temperature and rain fail distribution Water table variations, Subsidence, Shallow abandoned workings. Sinkholes, Source of hot spots, springs, adjoining fires	Method of working (opencast or underground, retreat or advancing, etc), Coal left at roof and floors Rock bumps, Scope of accumulation of fines. Rate of face advance, Nature of extraction (one lift, multiple lifts)

4 GENERATING MAPS

There are two important components of geography dependent data; its geographic position and its attributes or properties. In other words, spatial data (where is it?) and attribute data (what is it?) are distinguished. In the Geographical Information Systems spatial and attribute data are linked to get real information.

Attribute data in this case will be factors that affect spontaneous combustion.

The process undertaken has followed a particular sequence. Firstly, maps of the Witbank Coalfield collieries were digitized by using 15 sheets (1:50000). The topography of the Witbank Coalfield is shown in Figure 2. Another map is digitized showing the boundaries of major collieries and overlaid onto the topography map.

The digitized maps are of three types: point maps (showing collieries or sample points), polygon maps (boundaries of the collieries) and segment maps (topography and main reference points such as major towns, railways, main roads, etc.). These maps can be overlaid on each other, or mathematical and statistical calculations can be performed. In order to simplify comparisons between them, each map was created with the same resolution.

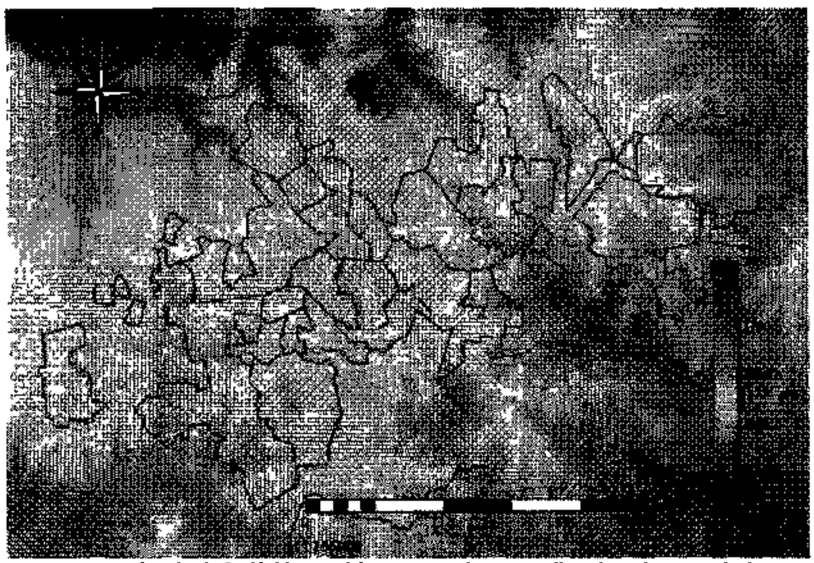

Figure 2 DEM of Witbank Coalfield created from topography map; colliery boundaries overlaid on it.

Most of the analysis is based on raster maps. In a raster model, spatial data are organized in grid cells or pixels (a term derived from "picture element"). Pixels are the basic units for which information is explicitly recorded. A resolution of 200mx200m per pixel was chosen, since this allows the smallest items within the coalfield, such as panel length to be seen.

A map was created for each contributing factor. The pixel values of each map can be combined according to a formula, e.g. MapA + MapB = MapC. The IL WIS GIS software can calculate each pixel with the same coordinates according to the defined formula and records the results in another map.

One may ask why the use of maps instead of spreadsheets in order to calculate risk or define problem areas. To be able to add, for example, the risk factor of the Wits-Ehac Index and subsidence, point form cannot be used, as the data types are different. Risk of subsidence can only be expressed in an area map. Therefore all the point maps with coal properties information have to be converted into two-dimensional maps.

A point map of collieries (sample points) is digitized and linked to an attribute table in which " there are separate columns for each coal property such as percent of volatiles, percent of ash, pyrites, vitrinite, etc. For each attribute column a point map is created with a value domain. These point maps are rasterized in order to be able to make mathematical calculations.

The rasterized point maps can be analyzed by using spatial autocorrelation of pomt data. The statistical analysis referred to as spatial autocorrelation examines the correlation of a random process with itself in space. A point interpolation performs an interpolation on randomly distributed point values and returns regularly distributed point values. Filling in the spaces between the points depends on the chosen resolution and the type of interpolation method. For coal factors a resolution of 200 m is chosen. For the total Witbank Coalfield the size of the map is 564 x 599 pixels, each pixel being 200 x 200 m^2. Various interpolation methods can be used: Voronoi tesselation, moving average, moving surface and trend surface. However, the best interpolation method for most geological features is moving average (1LWIS2.1 Applications Guide, 1997) and so it was used to obtain the coal factor maps. Inverse distance is selected as the weighting function. The resultant map is a raster map with equally distributed values in space, e.g. the ash percentage distributed throughout the coalfield has been mapped using the moving average method and can be seen in Figure 3.

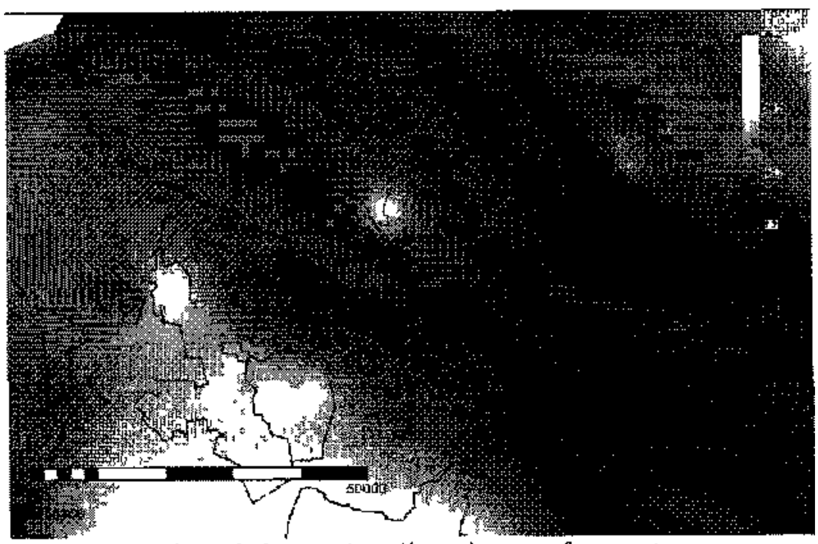

Figure 3. A rasterized map of *ash content* obtained by moving average from a point map.

5 MAPPING PROBLEM AREAS

Each of the maps created using the moving average method has also been assigned weighting values depending on the range of data. In order to assign weighs the value range within a map has to be divided into regions of high to low risk.

The map in Figure 4 shows the depth of seam factor, which is obtained by inserting the ranges of values from high to low risk. According to local mining experience, where the depth of seam is less than 40 m risk is high while between 40 and 300 m below surface spontaneous combustion risk İs considered low. Therefore a weighing of 2 is assigned for depths less than 40 m and 0 for deeper seams.

Other maps of different coal factors are created similarly. The risk ratings for each contributing factor have been determined by examining the literature and are also based on practice. Singh and Demirbilek (1984) classified the risks and determined factor ratings; the rates from their paper and from other literature were the main basis of detenriining the weightings used in this research.

The weighted maps are then created from the raster maps of coal properties. They are then simply added to obtain the risk map (Figure 5). The resultant map can be *"sliced"* to highlight areas with high risk

As an example of comparing research results with practice, it can be seen in Figure 5 that part of a colliery shown by the arrow is in the high-risk area and İt is known that this colliery is currently experiencing serious spontaneous combustion problems. However for this risk map only the coal factors and the depth of the seam have been used. Other factors such as mining, geology and environmental conditions have not been included. In this colliery opencast mining of old pillars left from previous underground operations is practiced. This is a mining factor that contributes heavily to the spontaneous combustion problem.

It is accepted mat the weightings used are still not perfect. This is merely a technique developed for application of GIS for environmental risk assessment.

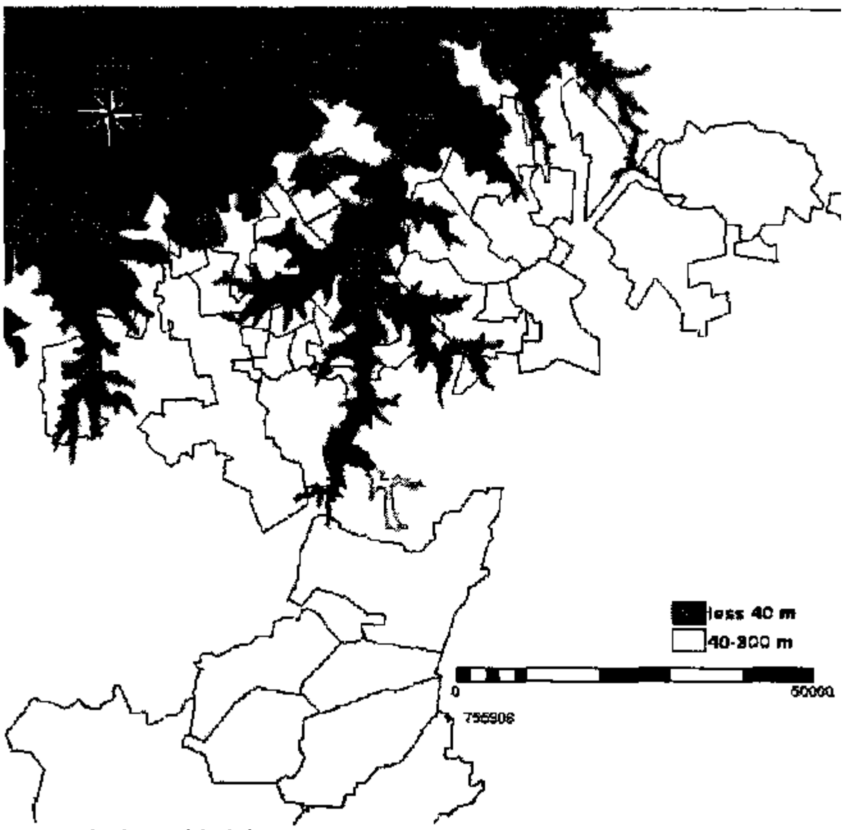

Figure 4 Sliced map of depth factor.

A comparison of actual incidents and this theoretical information - depending on future incidents of spontaneous combustion - can be used to perfect this technique.

The way to determine the range should be based on local experience, supplemented by an iterative process of comparing results with observed conditions on the mines. The maps are applied the slicing operation after defining the range and determining the rating limits (Figure 4).

6 CONCLUSIONS

The above techniques for risk calculation and mapping of the nsk areas is a simple approach as far as the mapping of spontaneous combustion propensity is concerned. In the literature nsk factor calculation is usually in the form of formulas and tables. This research has shown it is possible to bnng together all kinds of information by using GIS techniques. It is also suggested that the monitoring of existing coal fires can be undertaken by using the same software.

Coal fire monitoring by aerospace remote sensing and GIS techniques is an advanced approach, which has been implemented in the Rujigou coalfield, Normwest China. There they have developed a PC-based information system with the aim of monitoring spontaneous combustion and managing infonnation such as remote sensing and geological surveys (Wang et al, 1999).

One advantage of computerized risk analysis is that the database that is needed to analyze the coalfields can be updated as information becomes available. Updating risk maps is fairly quick and easy. The software allows update of the risk maps as new data is entered without having to recreate all the maps.

In the future we can find out the effect, changing environment and mining conditions has on the overall risk map. This can be done by comparing the old risk maps to the new by keeping the database alive.

Figure S Combined nsk map (lighter colors showing high nsk areas)

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