REQUIREMENTS FOR THE INTEGRATION OF REMOTE SENSING AND FIELD DATA IN A GIS FOR THE MANAGEMENT OF FIRE FIGHTING IN COALFIELDS

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ABSTRACT

Coal seam fires and stockpile fires, unfortunately, are accompanying phenomena of coal mining. Prevention and fighting measures need exact information on several characteristics and parameters (e.g. location, amount of coal burnt) of these fires. This article summarises the lessons learnt about data needs and possibilities of using remote sensing during a decade-long research activity in coal fire monitoring. Using remote sensing data in the monitoring and management of fire fighting needs the consideration of their spatial, temporal and spectral resolutions as well as the requirements of the user. An analysis of the spatial variability of the different coal fire related phenomenon was carried out to define the optimal solutions for monitoring coal fires. This knowledge forms the basis of building a coal fire fighting and management information system for a coalfield in China, which helps the daily work of fire fighters.

1. INTRODUCTION

Monitoring of environmental effects of mining activities needs a wide range of input data. Data acquisition and processing is relatively simple when surface phenomena are examined directly, but become more complex when the surface phenomena are only indicators of the underground processes.

Fire is one of the greatest hazards in coal mining. Uncontrolled burning of coal may occur in the coal seams as well as during storage in stockpiles in and around the mines. Fires may occur in waste dumps of (partly) carbonaceous materials too. All forms will be referred to in the following as coal fires.

The feasibility of remote sensing for coal fire detection has been investigated by several authors before (Slavecki, 1964, Zhang, 1998). In this paper the theoretical and practical possibilities and limitations of the integration of remote sensing data in an operational monitoring system have been addressed.

2. DATA REQUIREMENTS IN COAL FIRE MONITORING

Monitoring is a systematic series of observations for detecting and predicting the changes in a phenomenon. Sometimes to detect the phenomenon indirect indicators have to be considered. Every observation has to be representative, i.e. the data has to be sufficient to describe the phenomenon with the required accuracy in the moment of the measurement. In this sense, the most important parameters of a remote sensing data set are the spatial, spectral and radiometric resolutions. The series of the observations has to be representative too, i.e. the data has to describe the changes of the phenomenon without leaving out important events. This can be achieved by properly selected temporal resolution.

2.1. Characteristics of Coal Fires

Spatial extent. Fires are controlled by three fundamental factors: fuel, heat and oxygen. Coal oxidation takes place even on relatively low temperature. If the heat loss is smaller than the heat generation by oxidation then heat accumulates and the process leads to spontaneous combustion. Because of its importance in the coal industry, this process has been studied and described by several authors, e.g., Bainbridge *et al*. (1994), Mohan (1996), Rao (1996).

In underground circumstances if coal exists the decisive factor is oxygen. Favourable conditions can be found for coal fires at outcrops, in regions with cracked overburden and in underground mines.

Only those coal fires are discussed here, which are close enough to the ground surface and produce enough heat to generate a surface temperature anomaly. Based on heat conduction modelling it can be stated that fires deeper than a few tens of metres are practically not detectable from the surface. In presence of cracks in the overburden the depth of detectable fires may reach or slightly exceed hundred metres. A general experience of fire fighters in the Rujigou Coalfield, Northwest China, is that in slightly dipping (1–7°) coal seams in that mountainous region the lateral extent of the fires do not exceed 200 meters from the outcrop in dip direction, but can stretch to several kilometres along the outcrop (BRSC, 1994; Cui, 1999).

Stockpiles and waste dumps are porous, so the carbonaceous material gets in contact with oxygen through the pores. Spontaneous combustion may occur, but sometimes burning material, i.e. the coal removed from active coal seam fires, is also directly placed on waste dumps. As a result, long-term smouldering and burning take place on the surface or very close to the surface of the dumps.

Changes in time. The length of the self-heating period depends on the properties of the coal, the available oxygen and the physical properties of the surrounding rocks. The process accelerates exponentially with increased temperature. In general it may last from a few days to a few months, from the occurrence of favourable conditions till the combustion of the coal. After combustion takes place the lateral spread of the coal fires is often in the range of a few metres per annum. The life time of an uncontrolled coal fire may reach hundreds of years (Zhang, 1998), depending on the availability of the above mentioned three important factors of burning.

2.2. Indicators of Coal Fires

Since coal fires are mostly underground phenomena, indicators have to be used for detecting them by observations about the ground surface using remote sensing. As a result of the heat produced by a fire, changes occur in the vicinity of it: the heat causes metamorphosis in the rocks (burnt rocks), the temperature increases in the medium and in favourable conditions on the ground surface (thermal anomalies). The higher soil and surface temperature effects the vegetation.

Burnt rocks. The pyrometamorphosis of rocks depend on the temperature, the length of time the rocks are exposed to that temperature and on the properties of the rock itself. The heat causes changes in the mineral composition, texture and structure of the rocks, but from the remote sensing point of view the burnt rocks can be best classified according to their colour or in a more general term, spectral reflectance.

Based on field experience it can be stated that the burnt rocks have generally different colours from the non-burnt rocks. From the spectrometric measurements on sandstones and shales by Katen (1999) it can be concluded that it is not possible to find generally representative characteristics of the spectrum of burnt rocks. Differences between the spectra of burnt and non-burnt rocks occur in the visible and in the near infrared wavelengths.

Burnt rocks also indicate paleo-coal fires, so the existence of burnt rocks do not refer directly to existing coal fires, but they indicate fires ever existed in the region.

Depending on the size of the area affected by a coal fire, the optimal spatial resolution for burnt rocks varies between one and a few tens of metres. These figures are obtained by considering the possible size of burnt areas and taking a diameter of 5 – 10 pixels for the safe recognition of the burnt areas. Even over active coal fires, scarce vegetation may occur on burnt rocks, since the temperature is not homogeneously high on the surface (see the following subsection).

Thermal anomalies. Heat is transferred in the overburden of burning coal seams by conduction (in the rock) and convection (in cracks). Positive thermal anomalies occur on the ground surface in areas affected by the coal fires. In places where the heat conduction plays role the spatial variance of the surface temperature is smaller than in areas where convection in cracks is the dominant process. Field experience showed, that the temperature in cracks may reach hundreds of degrees centigrade, whilst a few decimetres away from the cracks it is only in the order of tens of degrees.

To investigate the spatial variability of the surface temperature, the autocorrelation and the semivariogram for the thermal anomalies were calculated on the basis of airborne images (approx. 4 m pixel size) of two coal fires (Figures 1, 2 and 3).

The graphs of Figures 2 and 3 support the field experience: the correlation between pixel values decrease very quickly even at

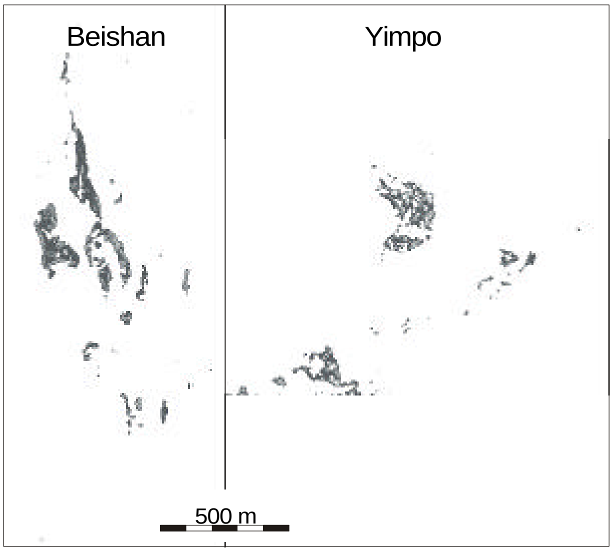

Figure 1 Airborne scanner image of thermal anomalies in coal fire areas (Rujigou Coalfield, Northwest China). The background was masked out from the images. The statistical analysis was carried out only on the thermal anomalies.

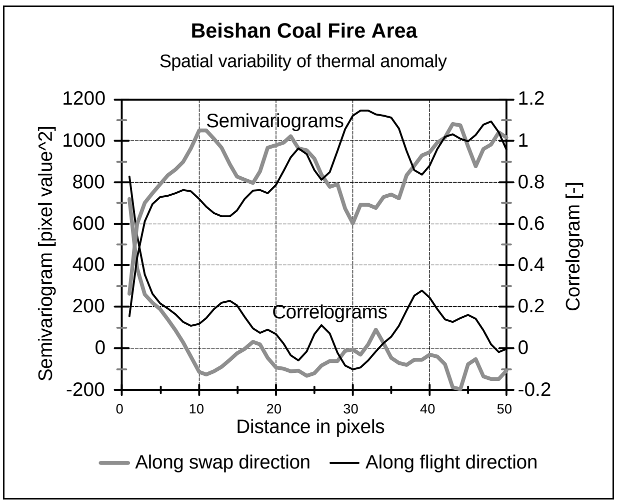

Figure 2 Spatial variability of the spatial anomalies in the Beishan Coal Fire Area (Figure 1a), Rujigou Coalfield, Northwest China

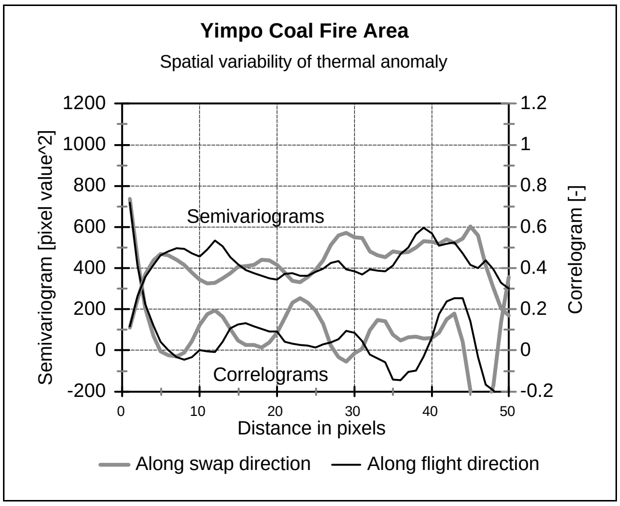

Figure 3 Spatial variability of the spatial anomalies in the Yimpo Coal Fire Area (Figure 1b), Rujigou Coalfield, Northwest China

short separation distances (1–4 pixels, i.e. 4–16 metres). In other words, the values of the pixels located very close to each other show an almost random pattern. It can be concluded that the surface temperature over a coal fire in the investigated regions varies considerably on shorter distances than the pixel size, i.e. in less then 4 metres. Although similar data were not reported in the literature, on the basis of geological similarities it can be assumed that this value is representative to a large number of other regions too.

Vegetation. Vegetation reacts on anomalously high temperatures by wilting or even by combustion. It can be used for indicating coal fires only in areas where the climatic conditions are favourable for reasonable ground cover. The authors worked in regions of China where vegetation could not be used as an indicator for coal fires.

2.3. Indicators of fire hazard.

Prevention is much cheaper than fire fighting. Therefore, it is important for the mining community to know in which parts of the mining area the coal fires are most likely to develop.

As was discussed above, for underground coal fires the most important question is whether the coal gets in contact with oxygen. Therefore, the indicators for coal fire hazard are the presence of factors which make this possible.

Coal seam thickness and depth. The characteristics of the coal seams and their overburden cannot be directly analysed from remote sensing data, but the coal seam data has to be fused with remote sensing data in the hazard analysis. Thus, these parameters have to be analysed with the same methods as the other indicators.

Geological processes may strongly affect the spatial continuity of the coal seams. Tectonic movements create discontinuities or folds in the seams, so a geological analysis has to be carried out before the spatial statistical analysis to check assumption of spatial continuity.

In the Rujigou Coalfield the geological analysis showed that no major faults dissect the coal seams so a meaningful variogram analysis can be carried out.
As Figure 4. shows, the spatial variability of the coal seam thickness is different from the variability of the thermal anomalies (Figures 2 and 3.). Coal seam thickness changes on much longer distances than the surface temperature (note that the scales of the horizontal axes on the figures are comparable, since the pixel size is 4 m in Figures 2 and 3.).

Spatial characteristics of the coal seam depth are dependent on the relief and the characteristics of the coal seam itself. Thus the parameter with greater variability is the determining factor in selecting the spatial resolution. Using the same method as described above, it was found that in the Rujigou Coalfield the optimal spatial resolution for the coal seam depth is 50 m.

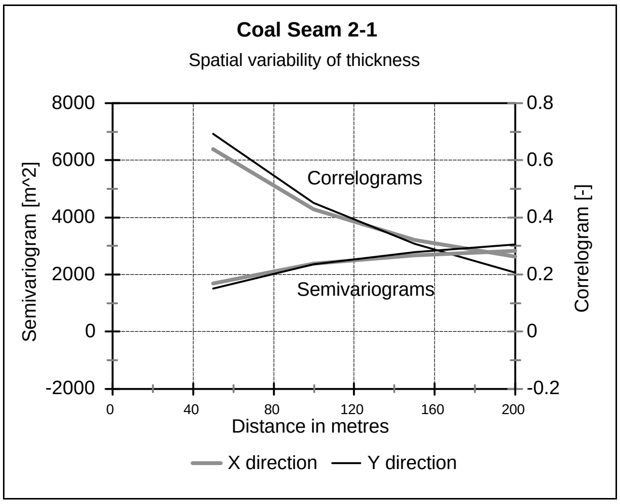

Figure 4. Spatial variability of the coal seam thickness in the Rujigou Coalfield, Northwest China.

Cracks and mining activity. Cracks in the overburden are related to land subsidences. They occur when mining or a fire removes the coal seam and the overburden collapses. Chen (1997) showed that the most important factor in the generation of cracks is mining, although the fires themselves may lead to the occurrence of cracks in the overburden too.

The width of cracks which play a role in the ventilation of coal fires may vary from centimetres to decimetres (in some cases to metres), whilst their length may reach hundreds of metres. A spatial resolution of a few centimetres is required for the accurate mapping of cracks.

A wealth of literature can be found on the use of remote sensing for monitoring activities and effects related to mining, especially to open cast mining (Glaesser et al. 1999; Prkash and Gupta, 1998; Rathore and Wright, 1993). It is obvious that large open cast operations are detectable even on images with a resolution as coarse as 80m but accurate mapping needs surveying precision, i.e. a resolution of a few centimetres.

Stockpiles, waste dumps. Overheating of coal dust on the surface by solar irradiation is one of the most hazardous factors leading to spontaneous combustion (Rosema, 1999). Thus stockpiles and waste dumps represent direct fire hazards. Their size varies from a few metres to several hundreds of metres, so a spatial resolution of a few metres is needed for recognising and mapping them.

2.4. Information Requirements of the Fire Fighters

Based on the above-discussed characteristics of coal fires and their indicators, it is easy to define the parameters of a theoretically optimal monitoring system (Table 1). In practice, the realisation of such a system is not feasible, mostly due to financial limitations. Therefore, to optimise the system design it is necessary to review and to rank the requirements of the users, i.e. the coal mining managers and the fire fighters.

Requirements for fire fighting. Fire fighting is based on the elimination of any of the three major components (fuel, oxygen or heat) of a fire. The success of the fire fighting depends highly on the information about these components.

Information on the size and location of the fire centre addresses the first component, the fuel. If the setting and the size of the coal reserves is mapped properly and the and the location of the fire is known then the fire fighters can decide whether it is economically feasible to remove the burning coal or cut the fire with trenches from the rest of the coal seam. The required locational accuracy is in the range of a few metres. The same accuracy is needed to calculate the volume of the overburden and the burning coal.

Cracks and underground mines form the ventilation system of a coal fire. Temperature in the cracks linked to a fire gives an indication of their roles: relatively low temperatures indicate the oxygen intake, whilst high temperatures show the cracks which remove the exhaust gases from the fire. Therefore, fire fighters need to know both the locations of the cracks and the temperatures in the cracks. In fact this is where the fire fighters need the highest accuracy: smouldering of coal seams can go on in the presence of very little oxygen. If the ventilation system is not known accurately and not sealed properly then leakage occurs and the fire cannot be set out.

Lowering the temperature of a fire is always linked to other fire fighting methods, usually to the sealing of the fire from oxygen. In fact fire fighters use the temperature as an indicator of the burning process. Information is needed about the temperature of the surrounding area of a fire to deduce information about the fire itself.

Requirements for prevention, early warning and monitoring of the results of fire fighting. It is important to know where spontaneous combustion is most likely to occur. In these areas indicators of coal fires have to be monitored. In coal mines, temperature and gas monitoring is daily practice, but in abandoned mines and not-mined areas usually monitoring is not carried out. These are the areas where remote sensing can help.

An important aspect is the frequency of monitoring. On the one hand, depending on the quality of the coal and the availability of oxygen, the self-heating process may last between a few days to several months. On the other hand the cooling down of a controlled fire typically takes several months or years. In areas, where coal fires may directly endanger human lives (in active underground mines), practically continuous monitoring is needed for early warning. In other areas the monitoring frequency has to be a few weeks or a month.

Due to the slow cooling down process, less frequent observations are needed for the monitoring of the results of the fire fighting. It is important that before a fire is declared to be extinguished not only the indicators are checked but direct measurements are made on the previously burning coal (bore hole observations). It is not sufficient to rely only on remote sensing data to declare a fire to be extinguished.

2.5. Aspects of Data Integration for Monitoring

The monitoring software and hardware stands in between the observed phenomena and the user. Some aspects have to be considered to process the data optimally in a monitoring system:

Table 1. Requirements for the best recognition and mapping of coal fire related phenomena. Note that the values presented here are site specific, although considered to be representative to a wide range of coal mining areas.

Phenomenon	Requirements for best recognition and mapping	
	Spatial resolution[1]	Radiometric resolution (band)
Burnt rocks	1 – 50 m	multi-channel in the optical and near infrared
Thermal anomalies	< 4 m	thermal
Vegetation	1 – 50 m	multi-channel in the optical and near infrared
Depth and thickness of coal seam	50 – 150 m	n.a.
Cracks, mining activity	0.01 – 0.5 m	optical
Stockpiles, waste dumps	1 – 10 m	optical

[1] Methods to calculate the optimal resolution based on the variogram or correlogram are described by Hendriks (1990) or Vekerdy (1996).

- A limited number of spatial resolutions can be used. All the input data have to be converted to comparable geometrical bases during the preprocessing steps.
- Comparable classes are to be used in representing the analysis results. This becomes extremely important when time series analysis is to be carried out on the data.

3. INTEGRATION OF REMOTE SENSING DATA AND DATA FROM OTHER SOURCES IN A GIS FOR COAL FIRE MONITORING

The results of the above described analysis methods were used in defining the data structure of the Coal Fire Monitoring and Management Information System, CoalMan (Vekerdy and Genderen, 1999).

Three basic spatial resolutions are used in the remote sensing data analysis. Both resolutions were selected to minimise the information loss during the preprocessing of the data:

- 30 m for satellite images. This resolution is conform with the resolution of the Landsat optical images, and the thermal band is resampled to this resolution too, although it is obvious, that this does not improve the information content.
- 4 m for airborne thermal data. This resolution is conform with the results of the Daedalus scanner data.
- Approx. 0.5 m for aerial photographs. In fact these data are not stored in the digital database, but used off-line as the basis of the topographic mapping and the mapping of cracks. Only the results are stored in the database as vector maps.

Some other, spatial resolutions are also used, which are conform with the available map and point data:

- 50 m for the representation of the coal seam data. As was shown above, gridding bore hole data with smaller pixel size does not result in more information. To avoid data redundancy the coal seam maps are stored with this resolution, and it is be further densified only if needed for comparison with other data.
- 5 m for the elevation model. This is conform with the available contour lines of the 1:5000 topographic maps.

The backbone of the monitoring system is formed by the thermal remote sensing images. Landsat TM images are used for general monitoring of the fires on an annual basis. An example is described by Prakash *et al.* (1999). This allows the assessment of the success of the fire fighting. Airborne scanner thermal data are used for the mapping of the hot spots. Due to financial limitations these data cannot be acquired by higher temporal frequency than 2–3 years. Overlaying these data with the crack maps compiled from aerial photographs (taken by every 5–10 years) the oxygen intake and the exhaust outlet areas can be defined.

Different modelling techniques are available for deducing the parameters of coal fires from surface temperature data (Rosema *et al.*, 1999; Cassells, 1997, Zhang *et al.*, 1999). All these techniques have serious limitations e.g. they either fail to match the complexity of reality or too much data is required or have not been operationally tested yet.

Models described by Rosema *et al.* (1999) are used to approximate the fire parameters in CoalMan. These models are substituted by a tool which allows the comparison of the geological sections with the location of the fires mapped from satellite images or airborne scanner data.

4. CONCLUSIONS

Analysis of the spatial and temporal characteristics of coal fire related variables formed the basis of developing the data structure and the analysis tools of the CoalMan monitoring system. This lead to the modifications of the original ideas in several cases to achieve the best possible results.

In spite of all the technical and scientific considerations described above, in practice, the development of a monitoring system is frequently a data driven process. System developers have to get the best possible results from the available data, bound by the limitations of the data sets. Analysis of the spatial and temporal characteristics of the observed phenomena and the measured variables provides information even in such circumstances on how to best fulfil the requirements of the users.

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