Coal mining subsidence data extraction and verification in a high groundwater area based on Landsat-8 imagery and subsidence prediction

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Abstract

Coal is the main energy resource in China, with its extraction and utilization playing an important role in national economic development. However, coal mining may be causative with respect to critical land subsidence and damage to land. The eastern plain coal mining region of China represents an example of overlapping crop cultivation and coal extraction, and is considered a coal mining area characterized by a high water table. Accordingly, declining ground elevation and seasonal water logging of land due to mining subsidence have become major concerns within the region. Based upon the existing procedure for land reclamation planning, both land damage boundaries and land damage magnitude were determined for the region via subsidence prediction and vertical displacement, respectively. In the current study, a coal mine in Shandong province was employed as a case study area with the following work phases implemented: 1) subsidence prediction was implemented, with land damage magnitude demarcated via the proposed standard; 2) mining induced water area and wetland was extracted via use of remote sensing; 3) comparative analyses of the aforementioned methodologies were undertaken, with a revised methodology proposed for effective provision of improved land damage demarcation. Results indicate that land subsidence at Dongtan coal mines during May 2013 was 1616.70 hm^2, of which categorically mild, moderate, and severe lands were 22.54 hm^2, 257.67 hm^2, and 436.49 hm^2, respectively.

Keywords: Landsat-8, high groundwater, mining subsidence, land damage information, subsidence prediction, damage assessment

1 Introduction

Coal mining induced mining subsidence is a pressing current issue in China as 92% of coal resources are currently extracted from subsurface mining operations [1]. Land characterized by mining induced subsidence in China reached one million hectares by late 2013 and is expected to increase at a rate of 70,000 hectares per year [2]. Regions in eastern China, including Henan province, Shandong province, Jiangsu province and Anhui province, are typified by high water tables and extensive coal mining operations, thus resulting in widespread surface water-logging. The aforementioned provinces produced a total of 230 million tons during the first half of 2014, representing 15.35% of national extraction. It is estimated that half of the land which has undergone subsidence may be entirely inundated due to high groundwater tables in parts of eastern China [3]; subsequent decreases in grain production may result from farmland having undergone subsidence.

Land damage assessment and classification is crucial for effective land reclamation and compensation, with compensatory standards based primarily on vertical displacement or water-logging extent [4,5]. The spatial extent of water-logging may vary due to topographic undulations, however, the use of vertical displacement as a single indicator for demarcation of land damage magnitude is not an appropriately accurate reflection of actual conditions.

With the recent development of remote sensing (RS) techniques, much attention has been given to subsidence boundary extraction based upon multi-source remote sensing data [6]. High resolution imagery is now customarily employed, with RS and geographic information system (GIS) technology also utilized within land subsidence monitoring [7-9]. The data used in these studies are typically high resolution imagery (e.g. Quickbird, D-InSAR or SAR) [10] and characterized by complex workflows. The Landsat-8 satellite was launched in February 2013, thus providing a new data source. Coal mining subsidence data extraction and verification in high groundwater areas based on Landsat-8 imagery and subsidence prediction may thus represent an effective and accurate reference for land compensation and reclamation efforts. Accordingly, the current study objectified the development of methodologies for coal mining subsidence data extraction based on Landsat-8 imagery and land subsidence prediction.

2 Study Area

The current study investigated the DT (Dongtan) coal mine which was developed and is managed by the Yanz-

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hou Coal Group. The DT coal mine is located in the southwest of the Shandong province, China (Longitude; 116°50′49″ - 116°56′56″ Latitude; 35°24′11″ - 35°31′25″ (Figure 1). The natural elevation is 42-54 m above mean sea level, in concurrence with a relatively flat pre-mining geomorphology, with a higher elevation to the northwest. The region is characterized by a continental marine transitional climate, with abundant sunshine and four distinct seasons. Annual precipitation occurs within the range 259 - 1263 mm (Annual Mean 715 mm), with the majority occurring during August and September. The area encompasses five districts, spanning three counties within Jining City.

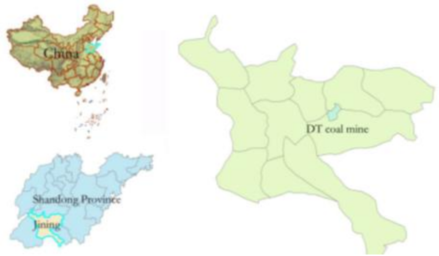

FIGURE 1 Study area: DT coal mine, Shandong province, China, with county boundaries

DT coal mine has an overall spatial extent of 59.96 km^2, and is thus one of the largest underground coal mines in eastern China, with a designed annual level of production equating to 7.5 million tons (Figure 2). By late 2010, the volume of proven coal reserves was 123.85 million tons. Due to the mines location within a highly productive agricultural district within the eastern Chinese plains, the area is characterized as a primary region for both coal and grain production. Mining activities have an inherent potential for damage to adjacent agricultural areas; accordingly, a local conflict of interest between people and land-use may arise, with land protection considered a priority. Thus, in order to effectively implement reclamation and/or compensatory measures, accurate subsidence monitoring and land damage demarcation is imperative.

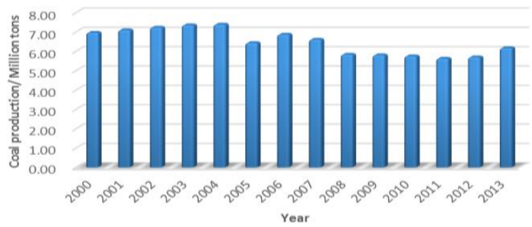

FIGURE 2 Coal production at DT coal mine from 2000 to 2013

3 Land damage magnitude

3.1 LAND DAMAGE MAGNITUDE DEMARCATION

Both surface and subsurface coal mining are characterized by potentially adverse impacts with respect to adjacent land. Subsurface mining may cause significant land subsidence, in addition to coal waste dumping at the surface. Accordingly, numerous environmental challenges arise, including soil erosion, dust and noise production, water pollution and impacts on local biodiversity. Subsided land arising from adjacent subsurface mining operations may undergo tensile and compressive forces, with subsequent horizontal and vertical displacement.

Within eastern China, due to its high mean groundwater table and relatively flat topography, the potentially adverse influence on adjacent agriculture caused by subsidence ponding is considered the most pressing issue. Thus, vertical displacement represents a key indicator for the reflection of local land damage. According to the Land Damage Assessment Rule as set out by Jining city administrative authority, subsided land may be divided into three distinct categories (Table 1), thus enabling classification of the magnitude of land damage.

TABLE 1 Land damage assessment standards in eastern China

Damage degree	Vertical displacement	Description
1 (Mild)	≤2m	Soil erosion, soil and water loss due to the changing inclination of the land
2 (Moderate)	2m~4m	Seasonal land water logging
3 (Severe)	≥4m	Water logging

3.2 DT COAL MINE LAND DAMAGE MAGNITUDE

The probability integration method of mining subsidence is the most frequently used subsidence prediction method in China; according to the probability integration method, the entire mining area is sub-divided into infinite mining units, with adverse influences caused by mine exploittation equal to the sum total of all mining units. The subsidence basins produced by mining units are represented by a normal (Gaussian) distribution and are consistent with the probability density distribution based upon stochastic medium theory. Accordingly, the subsidence profile equation represented by mine exploitation may be expressed as the integral formula of the probability density function. The subsidence basin may be expressed as follows:

$$w_e(x) = \frac{1}{r} e^{-\pi \frac{x^2}{r^2}}, \tag{1}$$

where r is the major influencing radius (primarily related to mining depth and major influencing angle). As shown in Equation (1), the functional form of the subsidence basin is analogous to the normal probability density function [11]. Based on the probability integration method, mining subsidence contours were obtained with respect to coal mining initiated from May 2013, with land damage magnitude demarcation concurrently undertaken (Figure 3).

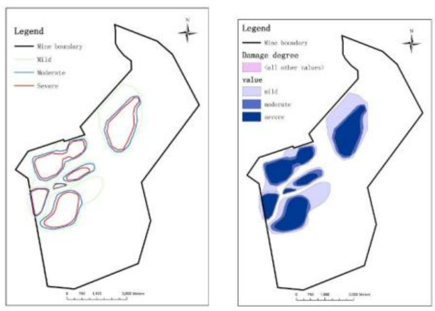

FIGURE 3 Demarcation of land damage based on predicted vertical displacement

4 Land classification using Landsat-8 data

Landsat data have enabled continuous global monitoring of anthropogenic and natural land cover disturbance since 1972. Recent deteriorations in performance and service intermittence with respect to the Landsat-7 and Landsat-5 sensors have raised concerns surrounding the condition of global observation programs. Nonetheless, Landsat imagery remains a valuable data source for landscape change detection. Landsat-8 data are processed and presented as 185 × 180 km Level-1 terrain-corrected (L1T) products, with a 950 MB compressed GeoTiff file size (over twice that of previous Landsat L1T products). All OLI and TIRS spectral bands are stored as geo-located 16-bit digital numbers within the same L1T file [12]. All 100 m TIRS bands are re-sampled via cubic convolution to 30 m resolution and co-registered with 30 m OLI spectral bands. An associated metadata file stores spectral band gain and offset numbers that may be employed for linear conversion of digital numbers to ‘at-sensor’ radiance and conversion of OLI digital numbers to ‘at-sensor’ reflectance (i.e. unitless). Accordingly, it is not necessary to perform non-linear transformation from radiance to reflectance [13].

4.1 MATERIALS

In the current study, contemporary Landsat-8 satellite imagery with OLI Land Imager data was selected for May 21, 2013 (Path/Row No122/35, 122/36). Employed imagery included nine bands, with an associated spatial resolution of 30 m and a 15 m panchromatic band; Landsat-8 imagery increased two-band data, thus resulting in increasingly subtle division, in comparison with ETM+ imagery.

Data were subjected to both radiometric and geometric correction (UTM-WGS84 projection), with pretreatment of raw data comprising radiometric calibration and atmospheric correction. Original images underwent integration of multi-bands and the panchromatic band, thus improving the resolution of multi-band imagery. The Gram-Schmidt pan sharpening method provided by ENVI 5.1 was employed expressed as follows:

$$HMS_i = LMS_i + w_t(HRP - LRP), w_t = \rho(LMS_i, LRP)\frac{\sigma(LMS_i)}{\sigma(LRP)}, \qquad (2)$$

where *LMS* represents multispectral imagery after re-sampling, *HMS* represents multispectral imagery after sharpening, *LRP* represents low-resolution panchromatic imagery, *HRP* represents high resolution panchromatic imagery, w represents spatial detail injection coefficient, ρ represents the correlation coefficient and σ represents standard deviation.

The DT coal mine boundary vector layer was used to obtain the subset image originally acquired from Landsat-8 via overlaying the vector layer with RS imagery.

4.2 CLASSIFICATION

In order to accurately classify land use, a false color composite with Band 5, 4, 3 was selected Figure 4:

FIGURE 4 DT coal mine land use false colour composite with Band 5, 4, 3

With Bayes maximum likelihood classification function utilized for image classification. Based on fieldwork and visual interpretation of the subset image, a supervised classification was performed using a classification workflow tool on the ENVI 5.1 platform. Five land-use classes were identified including farmland, construction land, land under water, wetlands and bare land. Classification accuracy was verified via a stratified random sampling method, with 60 samples randomly distributed into five land-use classifications. Reference data were collated via fieldwork and land-use mapping. Overall classification accuracy was 80.15%. Land cover classification using Landsat-8 imagery is presented in Figure 5.

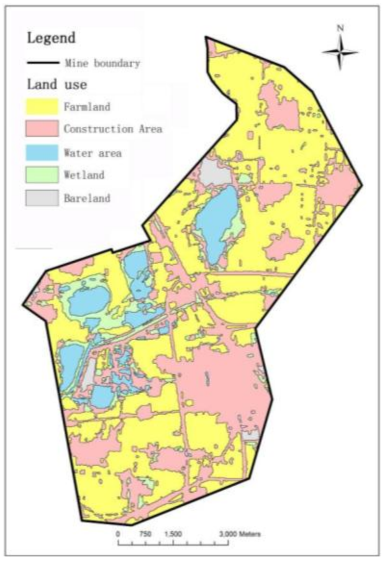

FIGURE 5 Land use classification of DT coal mine based on Landsat-8 imagery

5 Results and Conclusions

5.1 RESULTS

In accordance with the Chinese Law of Land Management, coal mining operations must undertake appropriate requisition and compensation for damaged agricultural land, based upon crop yield reduction due to mining-induced subsidence. According to the Land Reclamation Regulation (LRR), as issued and implemented by State Council, coal mines are required to provide an appropriate land reclamation plan, including identifycation of disturbed adjacent land and reclamation arrangements [14]. Lands requiring reclamation are divided into one of three functional categories (mild, moderate or severe); moderately and severely damaged lands correspond with seasonal and permanent area under water, reflected by wetlands and land under water in Landsat-8 imagery. Due to undulating topography, predicted maps developed as part of the current study cannot reflect true conditions (Figure 6).

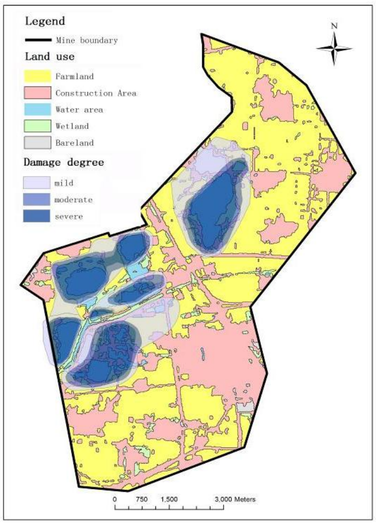

FIGURE 6 Overlapped Landsat-8 imagery and predicted vertical displacement

Results from the current study predict a total subsided area (up to May 2013) of 1616.7 hm^2 within the study area, with categorically mild, moderate and severe land damage predicted to be 622.99 hm^2, 251.44 hm^2 and 742.27 hm^2, respectively. Based upon Landsat-8 imagery extraction, the true conditions equate to 922.54 hm^2 (mild), 257.67 hm^2 (moderate) and 436.49 hm^2 (severe) (Table 2).

TABLE 2 Subsided area comparison between study predictions and Landsat-8 extraction

No	Degree	Predicted/hm^2	Extracted by Landsat-8/hm^2
1	Mild area	622.99	922.54
2	Wet land	251.44	257.67
3	Water area	742.27	436.49
Total		1616.70	1616.60

As shown (Table 2), there were significant differences noted between study predictions and Landsat-8 extractions; accordingly, a comprehensive methodology and associated workflow has been proposed in order to provide increasingly accurate land damage imagery:

1) Implementation of mining subsidence predictions based upon mine layout. Subsidence boundary obtained via 10mm vertical displacement.
2) Land use classification based upon contemporary Landsat-8 imagery, particularly with respect to wetlands and areas under water
3) Overlapping of maps obtained from Steps 1 and 2; determination of damaged land boundary from Step 1, with regions characterized by moderate and severe land damage represented as wetlands or areas under water from Landsat-8 imagery.

Via application of the proposed methodology outlined above, DT coal mine land damage demarcation was undertaken, as shown in Figure 7.

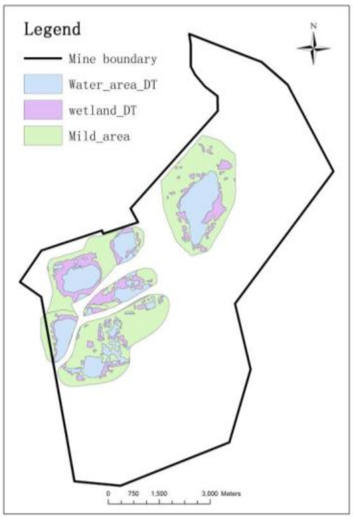

FIGURE 7 Land management map based on vertical displacement predications and Landsat-8 extraction

5.2 CONCLUSIONS

The current study presents a novel methodology for accurate determination and assessment of zones of damaged land for subsequent crop compensation, land requisition and land reclamation in the eastern plain coal mining area of China. The primary study findings and conclusions were as follows:

1) Subsidence prediction was implemented, and land damage magnitude was demarcated via the current proposed standard.
2) Mining induced areas under water and wetlands were extracted by using remote sensing technology.
3) A comparison between these two methodologies revealed that the comprehensive method could provide a more realistic reflection of conditions for subsided land demarcation. Taking DT coal mine as a case study area, the predicted subsided land total was 1616.70 hm^2, comprising 922.54 hm^2 mild, 257.67 hm^2 moderate and 436.49 hm^2 severe.

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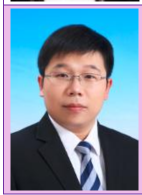

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