The 6th International Conference on Mining Science & Technology

Environment cumulative effects of coal exploitation and its assessment

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Abstract

Environment cumulative effects characteristics, sources, approaches and types aroused by coal exploitation are discussed. Based on studies in Lu’an, Pingdingshan, Yanzhou mining areas and so on, such quantitative assessment methods for coal exploitation environment cumulative effects are summarized as Geographic Information System, Earth Observation and Remote Sensing and Telemetry Information Acquisition, chart, mathematics models, computer simulation and laboratory testing and the integrated methods. Spatio-temporal evolution of land subsidence in Yanzhou coal mining area, time series mining landscape classification in Pingdingshan mining area, and some causal relationships analysis between resources, environment and economic system in Lu’an mining area were put forward. Based on field theory, this paper proposed the technology route, ideas and some quantitative assessment results for analyzing the ecology and environment cumulative effects impacts. Theories and practices both demonstrate that the coal exploitation activities have strong characteristics of time persistency, space scalability, long development cycle, more forms of mining area environment system perturbation, wide impacts source and complex mechanisms. For the requirements of sustainable development, the traditional environment impact assessment of coal exploitation shows many defects, it is essential, urgent and feasible to carry out analysis on the cumulative effects.

Keywords: coal exploitation, environment cumulative effects, sustainable development, assessment method

1. Introduction

Coal exploitation activities have strong characteristics of time persistency, space scalability, long development cycle, more forms of mining area environment system perturbation, wide impact sources and complex mechanisms. For the requirements of sustainable development, the traditional environment impact assessment of coal exploitation shows many defects, such as inadequate consider of spatio-temporal effects of environment impact, impacts on the environment from the integrated and cumulative effects of different projects. Therefore, it is urgent to carry out researches of environment cumulative effects analysis in resources and environment assessment and planning and design for the coal exploitation.

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2. Coal exploitation environment cumulative effect and its characteristics

Environment cumulative effects \(^{[1-3]}\), which derives from the manual of implementing “National Environmental Policy Act” promulgated by the United States in 1973. At present, the concept, proposed by the United States Commission on Environmental Quality (USCEQ) in 1997, is generally accepted, namely is “cumulative effects is the persistent effects on the environment resulted from a series of actions in the past, present and future which can be reasonably forecasted”.

The environment cumulative effects have the characteristics of time, space and human activities, that is to say the phenomenon of time cumulative effect or jam will be happened when the interval between two perturbations on the environment is less than the time needed by the environment system recovered from each perturbation. The phenomenon of spatial cumulative effects will be happened when the spatial distance between two perturbations is less than the distance needed by eliminating each perturbation. Modes and results of accumulative effects can be affected by the mode and characteristics of human activities when time repeats and spatial aggregation or expanded features exist in the human activities. The cumulative effects is a manner in which people considers environment issues from another new perspective, which reveals a significant phenomenon which will result in fatal environment consequences when the regional environment is at the critical level of sustainable development, the development activities whose environmental impacts of their own are small, cumulated with other environment impacts of development activities.

The environment cumulative effects have three obvious characteristics in the coal exploitation. For example, there exits persistence in the time scale for the land subsidence leaded by coal exploitation, waste water and waste solid, etc, and every perturbations is less than the time needed by the environment system recovered from each perturbation, at the same, the time accumulation is happened. There are many production mines, coal mine preparation plants, power plants and other production units or residential district, etc. these facilities and human activities impact on the environment altogether, which will result in the spatial cumulative.

3. Impact sources, means and types of environment cumulative effect of coal exploitation

3.1. Sources of impact

The impact sources of environment cumulative effects include all human activities, such as production (mining, processing, using, etc.) and living activities in the mining area, which also can be divided into single and multi-development project (activity) categories.

3.2. Means of the cumulation

The main means of cumulation are as following: firstly, the mining goaf becomes bigger and bigger with continuous coal exploitation, and many overlapped subsidence areas of mining goaf form a large area of land subsidence. Secondly, coal mining drainage from many mines can damage a large area of groundwater environment. Thirdly, the surface water is damaged or polluted for the production and living waste water. Lastly, the environment is polluted by the piled gangue and gas-discharge, etc. In short, the coal exploitation activities provide a “source” mechanism for the environment cumulative effect on the scale of spatio-temporal. Activities and environment changes in the mining area can cause cumulation and expand from a point or polygon area to a larger space.

Fig.1 shows the basic ways of resulting in environment cumulative effects in the mining area \(^{[4]}\). As shown in Fig.1, way 1 means that a single action can lead to overall overlay through a continuous simple increase or reduction in the environment, for example, the groundwater level will continue to decline for continuous coal mining drainage. Way 2 refers to that the interaction of single action will induce a variety of effects or biological amplification effect, for instance, the coal exploitation may lead to land subsidence, soil erosion, changes in surface water system, vegetation damage and other effects. Way 3 is about the environment cumulative effect from two or more actions impacts on environment changes, which is in cumulative manner rather than synergistic manner, and the sources of inducing changes are independent on each other, while the nature is similar each other. For example, sewage discharges from different units (such as mines, coal mine preparation plants, coking plants and the related units, living areas and other sewage outfalls) result in water system pollution. Way 4 points out the environment...
cumulative effect from two or more actions impacts on environment changes in the synergistic manner, as a result of the cooperative effect, the total environment effect is greater than the sum of single actions. The characteristic can be proved in the environment impact caused by “three wastes” emission from coal exploitation and mining subsidence. And the effect is amplified, for example, gas, dust, gangue and other emissions resulted in air pollution, at the same time the soil was polluted by the deposition of pollutants which fall down and come into the soil. Mining subsidence leads to soil pollution, desertification and soil erosion, while the soil desertification, erosion increase dust in the atmosphere and increased air pollution, etc. we should know that those ways are not completely independent. Many ways may happened simultaneously and cause interrelation and interaction, the effect in which the time is delayed or exceeds the threshold in a process will stimulate or promote another process in the complex mining area environment system.

![Fig. 1. Basic ways of causing cumulative effect](image1)

Table 1. Types of cumulative effects

<table>
<thead>
<tr>
<th>Type</th>
<th>Main features</th>
<th>Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-huddled</td>
<td>Frequent and repeated perturbations on environment</td>
<td>Repetitive mining</td>
</tr>
<tr>
<td>Space-huddled</td>
<td>High density perturbation effect on environment</td>
<td>Large area and scale mining</td>
</tr>
<tr>
<td>Compound effect</td>
<td>Effect of Many impact sources synergistic actions</td>
<td>Smoke generated from SOX and NOX compound</td>
</tr>
<tr>
<td>Boundary extension effect</td>
<td>Effect apart from source</td>
<td>Atmosphere pollution and acid rain</td>
</tr>
<tr>
<td>Time delay</td>
<td>Long detain between happen and result</td>
<td>Mining subsidence and deformation</td>
</tr>
<tr>
<td>Fragmentation effect</td>
<td>Changes in landscape structure mode</td>
<td>Forest fragmentation</td>
</tr>
<tr>
<td>Indirect effect</td>
<td>Sub-effect by the initial activities</td>
<td>Agricultural production reduction for land subsidence</td>
</tr>
<tr>
<td>Trigger point and threshold</td>
<td>Changes of system functions and structures</td>
<td>Soil pollution, no agriculture harvest</td>
</tr>
<tr>
<td>Nibble effect</td>
<td>Increase or decrease effects</td>
<td>Gradually reduction of farmland</td>
</tr>
</tbody>
</table>

Table 2. Types and features of ground water environment cumulative effects in mining area

<table>
<thead>
<tr>
<th>Cumulative effect types</th>
<th>Main features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-huddled</td>
<td>The time interval is shorter than the time required for self-purification, when the waster water are discharged into the rivers from mine, ground production and living units, etc</td>
</tr>
<tr>
<td>Space-huddled</td>
<td>The pollution sources present the intensive trends and overpass the capacity of water system in the river networks space</td>
</tr>
<tr>
<td>Boundary extension effect</td>
<td>Pollutants in the river upper move with the water system, which results in polluting the downstream region far from the sources of polluting</td>
</tr>
<tr>
<td>Indirect effect</td>
<td>As a result of pollution of surface water systems, resulting in affecting residents drinking water, industrial and agricultural water supply, aquatic life</td>
</tr>
<tr>
<td>Trigger point and threshold</td>
<td>Mining area surface water pollution degree is beyond the state water quality standards</td>
</tr>
</tbody>
</table>
3.3. Cumulative effect type

The cumulative effects of coal development can be divided into 9 classes, as shown in Table 1. The classification rules are cumulative process (such as time-huddled, space-huddled, synergistic and indirect effect, etc.), structure changes (such as fragmentation accumulation, nibble effect), the system nature changes (such as trigger point and threshold effect) [5], various types are often not independent. From mining area atmosphere environment, ground environment, water environment, etc, we can refine and obtain the spatio-temporal characteristics, types and features of cumulative effects leaded by coal exploitation. Table 2 shows the analysis results of types and features of surface water environment cumulative effects in the mining area.

4. Coal exploitation environment cumulative effects assessment

Environment cumulative effects assessment is to systematically analyze and assess the cumulative effects of ecology and environment resulted from coal exploitation, including cumulative sources, cumulative process, cumulative effect investigation, analysis, identification, description and explanation, the cumulative effect caused by the past, existing and planned development activities, the evaluation and prediction of impacts on society economy development, suggestions of development scale, speed and mode which is in accord with the sustainable development requires. Single factor assessment and comprehensive assessment are involved in the cumulative effect assessment, compared with general environment assessment, the traditional coal mining environment impacts assessment (EIA) usually aims at the individual development project assessment, while the cumulative impacts assessment (CIA) includes a wide range of mining environmental problems. EIA only considers the impact of individual project, while CIA not only includes impacts from a number of projects or behaviors, the direct and indirect effects of each item should be taken into account. EIA covers the period of time in which the project lasts a period of time (medium-term), while past, present and future are considered, CIA is dynamic evaluation. EIA only considers the space including a specific space projects, for example, the mine area should be taken into account when the new mine will be built. While the CIA should fully consider the space. EIA usually considers only a single system, while the CIA has to consider the mining complex systems (ecology and socio-economic system). Such impacts as synergism, accumulation, etc are overlooked in EIA, on the contrary, those effects must be considered carefully. The general EIA only takes release measures for the mining area environment effect, but the CIA has to predict the future and promote the sustainable development in mining area.
At present, there is a lack of studies on the mine environment assessment of the cumulative effects in a strict sense both at home and abroad. However, there are a lot of studies on the spatio-temporal evolutions of mining subsidence, water, land, gas resulted from the coal exploitation, which reflects the cumulative effects concept more or less, especially some of the abundant studies on mining subsidence deformation laws and prediction methods are modified directly or indirectly to analyze and assess the mining subsidence deformation cumulative effects. We had done a preliminary exploration of quantitative assessment of the cumulative effects of mining subsidence, water, land, gas resulted from the coal exploitation, etc. the methods were as follows:

4.1. Geographic information system method

Spatio-temporal data management laws analysis are the feature and basic work of the environment cumulative effects. on the one hand, Geographic Information System (GIS) can manage various evaluation data, such as space-positioning data, graphics data, remote sensing image data, attribute data, etc. on the other hand, on the basis of GIS, Spatio-temporal cumulative laws are showed, calculated and analyzed. Combined with such methods as geostatistics analysis, geo-info-spectrum analysis, system dynamics analysis, network analysis, bio-geographic analysis, cross-matrix analysis, ecological simulation models analysis, multi-index evaluation, fuzzy system analysis and other quantitative analysis methods, etc, GIS can determine and analyze the causal relationship of the cumulative effects better, distinguish the cumulative types. GIS is the indispensable platform for the mining environment cumulative effects studies, moreover, GIS makes it possible to study the cumulative effects in a mine, mining area and more large area.

We had done many researches of land subsidence spatio-temporal cumulative effects in Yanzhou coal mining area. First of all, some related maps and data were collected and the land subsidence thematic maps were digitized with the digitization, then land subsidence database was established based on ArcInfo GIS software. On the basis of the database and spatial analysis functions of ArcInfo, spatio-temporal evolution of land subsidence maps were obtained by overlaying and calculating the land subsidence thematic layers of 1994, 1996 and 2000 (as shown in Fig.2), accordingly, land productivity changes cumulative effects and characteristics induced by coal mining subsidence had been analyzed in Yanzhou coal mine area [6].

4.2. Earth observation and remote sensing and telemetry information acquisition methods

With Earth Observation and Remote Sensing information and Telemetry technologies (such as multi-spectral / hyperspectral remote sensing, laser radar, InSAR, GPS, three-dimensional laser scanning, infrared imaging, digital photogrammetry, remote sensing UAV telemetry, etc.), we can effectively reveal and discover environment damages and spatio-temporal changes caused by coal exploitation, and reveal evolution processes of ecology and environment and surface disaster from background, status, pattern, process, anomalies, etc. which provides important sources of information for researching in environment cumulative effects caused by coal exploitation. Fig.3 shows the time series results of Pingdingshan mining landscape classification (water, woodland, farmland, industrial land, road traffic land, etc.) which are generated from remote sensing images (water, woodland, farmland, industrial sites, road traffic sites, etc.) from 1994 to 2006, the landscape pattern indices are calculated from the results, finally, with some corresponding underground mining data, the cumulative effects model is built for the surface landscape impacts resulted from the coal exploitation in Pingdingshan mining area.

4.3. Chart method
It is a simple and basic method of analyzing the cumulative effects. For example, we can use charts to denote spatio-temporal distribution of one or integrative environment element testing value. Tree charts are used to describe and analyze relationships between reasons, processes and results for mining affecting the environment element. As is shown in Fig.4, by using of system dynamics (SD) method, we obtain the relationship chart of mining resources, environment and economic systems affected by coal exploitation, the chart feedback loops can reflect the interaction and interrelation of environment factors, the cumulative characteristics will be identified by selecting the status variables during building the chart[7].

4.4. Mathematics models method

Spatio-temporal changing processes, laws and cumulative effect of these environment elements impacted by mining can be expressed in mathematics models. At present, there are many related models including mining subsidence prediction model, water pollution prediction model, air pollution model, soil pollution and erosion model, soil and water loss model, vegetation cover model, etc. for example, in mining subsidence predicting methods, the function of section (type curve method, the negative exponential function method), the influence function method (probability-integral method, integral grid method), the impacts of time delay, spatial distribution, repeat mining, stack deformation are all considered carefully.

Take time factor for example, it had been proved that the subsidence values of the ground points could be affected by the time factor described by the negative exponential function, namely could be represented by formula \( w(x, y, t) = w_0(x, y)(1 - e^{-ct}) \), here, \( w_0(x, y) \) the static subsidence value of the ground point, \( c \) is a parameter about overburden character and is time factor impact coefficient, if the speed of coal face advancing is \( v \), when \( L_0 \) is the mining size when the Full Subsidence occurs, then \( c \) can be calculated by formula \( c = \frac{-v\ln(0.02)}{L_0} \), formula \( \delta w_t = -w_0(x, y)e^{-ct} \) denotes the effects of time cumulative effect of land subsidence. It is complex that the coal exploitation impacts on such environment elements as the surface, water, gas, soil and others, in order to achieve the desired results, many models are involved in the mathematics modelling, such as the statistical model, analysis model, fuzzy mathematics model, artificial intelligence model, nonlinear mathematics model and so on, which should be chose reasonably according to specific requirements.

Fig. 4. Relationships chart of resources, environment and economic systems in mining area

4.5. Computer simulation and laboratory test methods
The method is to use computer simulation and laboratory simulation test to show the cumulative effects laws, characteristics, size and scope which are resulted from coal exploitation activities for the mining area environment. It is uncertain, dynamic and non-linear that the coal exploitation impacts on the environment, which proves computer simulation and laboratory simulation test methods are necessary and feasible. For example, we had developed the mining subsidence prediction and visualization software with the characteristics of multi-dimension, dynamics in Lu’an mining area, with this software, we can predict and simulate the mining subsidence and damage according to different mining methods, plans, mining face layout modes, advancing speeds and precautions for subsidence, etc, and the cumulative effects caused by coal mining can be quantitatively analyzed. Based on system dynamics method, we had simulated the effects resulted from coal exploitation activities for the mining area environment according to different conditions, which proved that the roles of different mining modes played in the coordinated development between resources environment and social economic [8].

4.6. Integrated method

Each of the above methods has its own advantages in time and space cumulative impacts, synergies effect, cumulative process, the cumulative effect causal relationship analysis, evaluation and so on, at the same time, there are many defects, thus, we should combine these methods in accordance with the practice.

Based on field theory [9-11], RS and GIS, etc, we had studied the ecology and environment cumulative effects lead by mining subsidence in Lu’an mining area, the technology route is shown in Fig.5.

As is shown in Fig.5, according to compare of the ecology potential differences of different ecounit during the same period, spatial distribution characters of mining cumulative effects were analyzed. Considering the time series generated from ecounit potential energies of different post-mining years in the same mine area, we determined laws of mining subsidence ecology and environment time evolution. In the study, we divided the mining area into stable ecounit, mining subsidence ecounit and background ecounit to estimate mining area niche, and then determined the ecological potential through comparing niches between begin and end of one period. Based on the time series changing trends of niche during the different periods, the mining subsidence cumulative effects of mining ecology and environment are revealed. In Fig.5, the mining subsidence ecounit is the ecounit when the surface movement...
and deformation do not stop. The stable ecounit is the ecounit when the surface movement and deformation had been stopped. While the background ecounit is the non-mining area which is similar with the study area in ecological economics and production and living ways. Without the non-mining factors (such as economic development, lifestyle changes, natural disasters and other factors), If ecology and environment index values of the stable ecounit are still different in mining subsidence ecounit values, we can obtain the hysteretic effects on surface ecology and environment from mining subsidence. A case study in Wuyang mine, we had obtained the spatial distribution characteristics, evolvement trends, and mining subsidence cumulative effects laws of land cover, vegetation cover, soil erosion and other indices, and found that mining subsidence delay of land cover was 13 years and mining subsidence delay of soil erosion was 17 years after mining \cite{12}.

5. Conclusions

Coal exploitation activities have strong characteristics of time persistency, space scalability, long development cycle, more forms of mining area environment system perturbation, wide impact source and complex mechanism. For the requirements of sustainable development, the traditional environment impact assessment of coal exploitation shows many defects, it is essential, urgent and feasible to carry out analysis on the cumulative effects.

It is needed to combine the existing mining environment impacts assessment with environment damage cumulative effects assessment to study the mining environment cumulative effects assessment. Based on deeply analyzing environment impact assessment cases, content requirements, indices system of existing mining area layouts and building projects, import environment cumulative effect theories, during each step of mining area environment impacts assessment (for example, determine the time and space scope of evaluation, analyze the environment character in the assessment region, analyze the impacts on environment, suggestion for releasing impacts on environment, assess the degree of surplus effects, the post monitoring of impacts on environment, etc), the key point is how to take into account of environment damage cumulative effects impacts problem and so on in order to achieve the assessment principles, analysis frameworks and assessment methods of environment cumulative effects caused by coal exploitation, build the assessment indices system and methods for assessing the impacts on environment. If the environment cumulative effects caused by coal exploitation had been obtained, in theory, we can determine the development size, mining region, etc on the basis of carefully considering the capacity of ecology and environment, control and optimize the mining and related activities from spatio-temporality, layout, size, etc, reduce the occurrence of cumulative effect, as a result, the damages to the mining area environment aroused by the coal exploitation were effectively reduced.

Acknowledgements

Financial support for this work, provided by the National Natural Science Foundation of China (Project No. 50774080) and the Science and A Foundation for the Author of National Excellent Doctoral Dissertation of PR China (Project NO 200348), he national Environment Protection for Public Welfare (Project NO 200809128).are gratefully acknowledged.

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