Spatial Variability of Soil Moisture in Mining Subsidence Area of Northwest China

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Research

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Spatial variability of soil moisture in mining subsidence area of northwest China

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Highlights

- **a.** The authors took Nalin River No.2 mine as the research object, and discussed the impact of coal mining subsidence on soil water in the aeration zone from the perspective of spatial variability rather than that of absolute soil water changes.
- **b.** This study applied the combined method of classical statistics and multi-dimensional geo-statistics to analyze the changes of soil moisture of time and space from 0-10m in the mining face of Nalin River No.2 Mine in Northwest China from the perspective of spatial variability.
- **c.** The spatial variability of soil moisture in the 1-year subsidence area and the 2-year subsidence area increased, and the variability showed a trend of increasing continuously with the increase of depth.
- **d.** During the principal component analysis, it was found that the change of soil texture caused by coal mining subsidence, the change of microstructure of soil pores caused by geotechnical deformation, as well as the preferential flow caused by changes in groundwater level were the main reasons for the increasing spatial variability of soil moisture.

Abstract

The current research only investigate the impact of coal mining on deep soil moisture from the perspective of the absolute value of soil moisture. This study applied the combined method of classical statistics and multi-dimensional geo-statistics to analyze the changes of soil moisture of time and space from 0-10m in the mining face of Nalin River No.2 Mine in Northwest China from the perspective of spatial variability. The results of the study showed that in time distribution, on the whole, the soil moisture in the partial areas of the 1-year and the 2-year subsidence area was lower than that in the control area, and the variability increased, but as the subsidence entered a stable period, the degree of variability decreased; vertically observed, in space distribution, the 0-10m soil moisture in the control area had obvious distribution rules with low spatial variability. However, the spatial variability of soil moisture in the 1-year subsidence area and the 2-year subsidence area increased, and the variability showed a trend of increasing continuously with the increase of depth. During the principal component analysis, it was found that the change of soil texture caused by coal mining subsidence, the change of microstructure of soil pores caused by geotechnical deformation, as well as the preferential flow caused by changes in groundwater level were the main reasons for the increasing spatial variability of soil moisture. This study revealed the principals of spatial variability of soil moisture in coal mining subsidence areas in Northwest China, which can provide a scientific basis for the restoration of mining areas.

Keywords: classical statistics and multi-dimensional geo-statistics; mining subsidence area; preferential flow; spatial distribution of soil moisture; spatial variability

1. Introduction

In China's energy structure, coal will still play an irreplaceable role for quite a long time. According to the statistics, by 2030, China's coal consumption will account for about 55% of primary energy consumption. In the short term, China's energy strategy of "coal-based, diversified development" will not be changed (Wang, 2015). The Shen Dong Coalfield is rich in resource reserves that account for about 1/4-1/3 of China's total coal reserves (Wang, 2017). Therefore, the Shen Dong Coalfield serves as the ballast stone of the coal industry and a stepping stone for China's energy safety and security. The region of Shen Dong is located in the transition zone between the Loess Plateau and the Mu Us Desert, with poor natural conditions and a fragile ecological environment (Fan, Xiang, & Peng, 2016; Peng & Bi, 2020); it is also located in the Yellow River Basin, with the low ecological threshold and poor anti disturbance ability. At present, due to coal mining, the underground water level of the Yellow River Basin is declining and the ecological environment is further deteriorating. In 2019, general secretary Xi Jinping inspected the ecological environment and economic development of the Yellow River Basin and delivered important speeches (Xi, 2019), which brought more and more attention to the Shen Dong coalfield located in the Yellow River basin. Therefore, the coal exploitation and ecological environment protection in Shen Dong coalfield have always been the focus of research.

In the semi-arid northwestern area with wind and sand, soil moisture is a key factor in restricting the growth of vegetation, and limiting the restoration of the ecological environment in subsided areas caused by coal mining (Bi et al., 2014; Dougill, Heathwaite, & David, 1998). High-intensity mining causes the movement and deformation of rock formations to form subsidence areas and produce cracks, which affects hydrogeology, soil, and vegetation from the bottom to top (Bi et al., 2014; Wang, 2017). The first result is the change in soil moisture caused by the formation of subsidence areas and cracks (Zhao, 2006). The transports and changes of soil nutrients are closely related to the changes of soil moisture, so changes of soil moisture in subsidence areas will inevitably lead to the transports and changes of nutrients such as nitrogen, phosphorus, potassium and organic matters (Li, Zhou, & Li, 2001; Wang, Zhang, Song, & Zhang, 2002; Zhao, Jia, & Wang, 1991). The changes of soil moisture also varies the distribution and circulation of the original water and material in the ecosystem, thus affecting the ecological environment. Therefore, it is of great significance to study the change law and influence mechanism of soil water under the condition of coal mining subsidence for vegetation restoration and ecological reconstruction in coal mining subsidence areas. However, currently there is no unified understanding of the changes in soil water caused by coal mining.

On the one hand, some scholars believe that ground fractures caused by coal mining are important factors in affecting the changes of soil moisture in subsidence areas (Guo, Ma, & Su, 2019; Liu, Wu, & Yu, 2016; Wang, Kang, & Hu, 2011; Wei, He, & Hu, 2006). In addition, the depth, density, width as well as distance from the fractures all influence the changes in soil moisture (Ma & Yang, 2019; Wu, Feng, & Hu, 2020; Wu, Tian, & Tang, 2019; Zhang, Bi, & Chen, 2015; Zou, Bi, & Zhu, 2014). Zhang, Bi, and Chen (2015) tracked and monitored the fractures in a fixed position in Bu Lian ta mine in Shen fu-Dongsheng Coalfield, and then found that the soil water content in the fractured and non-fractured areas within the subsidence area was less than that in the virgin area. Moreover, the soil water content around the ground fractures decreased significantly, with a significant downward trend in the depth of 0 -90 cm, ranging from 9.27% to 15.47%; Wu, Tian, and Tang, (2019) took the Fuxin subsidence area as the example to extend their research, finding that with the increase of the distance from the crack, the soil moisture content increased, but the influence was not obvious after 2m; Ma and Yang (2019) took the soil in the development area of ground fractures mined by Ephedra in northern Shanxi as the research object, finding that the moisture content of the soil near stepped ground fissures, except the surface, is higher than that in the non-cracked area at all depths. The above scholars believe that the ground fissures caused by coal mining are important factors in affecting the changes of soil moisture in the subsidence area, but a consensus has not been formed about the degree and scope of the influence.

On the other hand, some scholars believe that coal mining subsidence has no or unobvious effect on soil moisture. For example, Wang, Gao, and Wei (2006) studied the soil bulk density, porosity, saturated hydraulic conductivity, and nutrients in the subsided and non-subsided areas of the Bu Lian ta Coal Mine. The study discovered that the soil bulk density and porosity of the top and middle of the collapsed dune did not have significant changes while the soil bulk density at the bottom of the dunes and the lowlands between the dunes was significantly reduced with the significantly increased porosity. Additionally, the saturated hydraulic conductivity within 0-60cm did not change significantly when the total nitrogen, total phosphorus and total potassium content within 0-100cm did not change significantly. However, the research results of "ecological restoration technology experiment and demonstration research in Shen Dong mining subsidence area" completed by Inner Mongolia Agricultural University and China University of Mining and Technology in 2007 show that basically, coal mining subsidence does not affect soil nutrients and moisture (Li, He, & Gao, 2012). The scholars who hold the above views believe that the soil water supply comes from atmospheric precipitation, but not from groundwater. Mining disturbance affects groundwater, but has a limited impact on soil water.

To sum up, the authors believe that the main reason for the differences in previous studies is that the influence of coal mining on soil moisture was only studied from the absolute value of soil moisture, while ignoring the characteristics of the soil itself as a heterogeneous continuum. Even in the area with the same soil texture, various soil physical parameters are obviously different in kinds of spatial positions at the same time, which is the spatial variability of soil properties. As one of the important parameters of soil physical properties, soil moisture has high spatial heterogeneity. From a macro point of view, surface cracking and collapse affect the conditions of soil water infiltration and evaporation, thus resulting in the change of soil water; from a micro point of view, the factors affecting the change of soil water also include the change of soil texture, bulk density and pore structure (Zhao, Zhang, & Song, 2010). At present, scholars in China and other countries have carried out some works on the spatial variability of soil moisture in the surface layer (0-1m), but few reports on the spatial variability of soil moisture in the unsaturated zone of coal mining subsidence areas.

Therefore, the authors took Nalin River No.2 mine, whose reserves are at 6 years, in Yu Shen fu coal mine area in the east of Mu Us Desert as the research object, constructed classic statistics and multi-dimensional geo-statistics methods. Moreover, the study analyzed the variability of soil moisture in the unsaturated zone in the subsidence area from the perspectives of time and space, and discussed the impact of coal mining subsidence on soil water in the aeration zone from the perspective of spatial variability rather than that of absolute soil water changes, so as to provide the scientific basis for ecological restoration in mining areas.

2. Materials and methods

2.1 Overview of the Study Area

In the east of Mu Us Desert (108 ° 51 ′ 30 ″E - 109 ° 00 ′ 00 ″ E, 37 ° 58 ′ 00 ″N - 38 ° 05 ′ 30 ″ N), Nalin River No.2 mine is located in the ecologically fragile northwest region. The geographical location is shown in Figure 1. The region has an arid and semi-arid continental climate, dry and rainless, windy and sandy. The average annual precipitation is 350mm and the average annual evaporation is 2500mm here. At the same time, the region is located in the semi-desert area of plateau desert landform, with sparse and scattered vegetation and crescent or wavy dunes on the surface. The soil types are mainly fixed and semi-fixed aeolian sandy soil, and the vegetation types are mainly xerophytic and semi-xerophytic sandy. There are two seasonal rivers in the area, the depth of the phreatic water is 19.15-25.65m. Furthermore, the average buried depth of the main coal seam is about 602m, and the average thickness is about 4.65m. The mining method is longwall combined mining.

2.2 Collection and Determination of Soil Samples

According to the time of the mining completion, the study area was divided into control area (CK), 1-year subsidence area (S1) and 2-year subsidence area (S2) with partition sampling. According to the underground coal mining process, the checkerboard distribution method was adopted. The grid design was 75m * 100m, and each sampling point was in the center of the grid. The focus was on the subsidence basin areas and edge fracture development areas such as the edge and center line of the working face. A total of 60 soil sample collection points were set up in three areas, among them 12 were set in the control area, and 24 were respectively arranged in one-year subsidence area and two-year settlement area, as shown in Figure 2. Using soil drill, 0-10m soil samples were collected at each sampling point, with an interval of 1m. Three composite samples were randomly collected from each layer of soil depth, so totally 1,800 soil samples were collected from 60 sampling points. After natural drying, the samples were sieved with 2 mm mesh for the measure of soil moisture (SM). SM was measured by gravimetry, in which each fresh soil sample was dried at 105 ° C for 8 hours so that SM was generated by the difference between the fresh weight and dry weight of soil (Zou, Bi, & Zhu, 2014).

2.3 Data Analysis

2.3.1 Classical Statistical Methods

SPSS20.0 data analysis tool was used to conduct normal distribution K-S test on all data (p=0.05), and the mean, median value, standard deviation (SD), coefficient of variation (CV), maximum value and minimum value were calculated. Mean and median values reflect the centralized trend of samples, while the positional relationship between mean and median values reflects the relationship between data distribution and outliers. The SD and CV reflect the variability characteristics of data so as to measure the degree of data dispersion (Ma, 2013). It is generally recognized that CV > 40% is high variation, 10% < CV < 40% is moderate variation, and CV ≤ 10% is low variation (Mo, Zhou, & Yang, 2015).

2.3.2 Geostatistical Methods

Geo-statistics can be adopted to study the spatial distribution of soil heavy metals, soil nutrients and soil moisture (Chartres, 1986; Jing, Wang, & Zhu, 2018; Ma, 2013; Marcin & Marcin, 2014), where semi-variance function can be used to determine the spatial autocorrelation of variables, and Kriging interpolation method can also be used to simulate and estimate the regional content around the sampling point.

Semi-variance function, also known as variogram, is used to quantify the randomness and spatial structure of variables, below is the calculation formula:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(X_i) - Z(X_i + h)]^2 \qquad (1)$$

In this formula, γ (h) is the variogram; h is the spatial distance between two variables; N (h) is the number of sample point pairs; Z (x_i) is the observation value of the spatial position point x_i; Z (x_i + h) is the observation value of the point h away from x_i [i = 1,2, N(h)]. The commonly used semi-variogram models include spherical model, Gaussian model and index model:

$$\gamma(h) = C_0 + C\left[1 - e^{-\frac{h^2}{\alpha^2}}\right] \qquad (2)$$

$$\gamma(h) = \begin{cases} C_0 + C\left[\frac{2}{3}\left(\frac{h}{\alpha}\right) - \frac{1}{2}\left(\frac{h}{\alpha}\right)^2\right] \\ C_0 + C \end{cases} \qquad (3)$$

$$\gamma(h) = C_0 + C\left[1 - e^{-\frac{h}{\alpha}}\right] \qquad (4)$$

In these formulas, α is the range; C_0 is the nugget constant, which represents the variance caused by random error; C is the space structure value caused by systematic factors; C_0 + C is the abutment value, representing the total variance of variables; C / (C_0 + C) is the spatial structure ratio. If $C_0/(C_0+C) < 25\%$, it can be shown that the data has strong spatial correlation; when $25\% < C_0/(C_0+C) < 75\%$, it can be shown that the data has medium spatial correlation; when $C_0/(C_0+C) > 75\%$, that the data has weak spatial correlation can be shown (Bogunovic, Pereira, & Brevik, 2017).

The standard for selecting the semi-variance function model is that the closer the mean absolute error(MAE) and the root mean square error (RMSE)of the cross-check result is to 0, the closer the regression fitting coefficient of determination R^2 is to 1, the higher the accuracy of the model's simulation is.

Kriging interpolation method is based on the spatial autocorrelation, using the original data of the regionalized variables and the structure of the variogram, with the adoption of linear, unbiased, and optimal interpolation methods for the unknown sampling points of the regionalized variables. The formula is as the following:

$$Z(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i) \tag{5}$$

In this formula, Z (x_0) is the value of the point to be estimated; n is the number of sampling points; Z (x_i) is the value of the i sampling point; λ_i is a group of weight coefficients; $\sum\lambda_i = 1$; the selection of λ_i ensures that the estimation of Z (x_0) is unbiased and the estimation variance is minimum.

2.3.3 Principal Component Analysis Method

Principal component analysis (PCA) is a multivariate statistical analysis method that uses linear transformation to select a few important variables. After Kaiser Meyer Olkin (KMO) and sphericity test by Bartlett, the correlation analysis of vertical soil moisture in the study area was further adopted, and eventually the influencing factors of vertical distribution of soil moisture were determined (Zhang, Yang, & Bai, 2017).

KMO test statistics are mainly used in factor analysis of multivariate statistics to check the correlation and partial correlation between variables with a value between 0-1. The closer the statistical magnitude of KMO is to 1, the stronger the correlation between variables is and the weaker the partial correlation, the better the effect of factor analysis. Bartlett's sphere test is mainly used to test the distribution of data and the independence of various variables. In SPSS, if the test result shows Sig.<0.05, the data will show a spherical distribution. Common factor variance means that every variable can be represented by a common factor. The larger the extracted value is, the better the variable can be expressed by the common factor.

3. Results

3.1 Statistical Characteristics of Soil Moisture

It can be found from Figure 3 that: (a) no matter the mean or the median, the soil moisture of CK is higher than that of S1 and S2 on the whole. Moreover, the mean of soil moisture at each depth is basically close to the median value, indicating that the centralized distribution of data is not dominated by outliers; (b) the variation trend of SM in the vertical direction in different regions is basically the same. SM shows a downward trend above 2m, and reaches the lowest value in the range of 1-2m soil layer (4.49%, 3.07%, 3.02%, respectively). SM, however, increases from top to bottom with the increase of soil depth below 2m, and reaches the maximum value in the range of 9-10m soil layer (10.19%, 8.49%, 8.63%, respectively).

At the same time, descriptive statistics of 0-10m soil moisture in CK, S1 and S2 regions were carried out (Table1). According to table 2, P > 0.05 of 0-10m soil moisture in the three regions, and there was no significant difference in SM among different depth of soil layers, indicating that the value of soil moisture in each depth passed the K-S normal distribution test. Overall comparison of the three regions showed that the CVs from large to small were S1, S2 and CK, with an average CV of 43.60%, 29.31% and 25.68% respectively, ranging from 24.7% to 65.53%, 20.32% to 39.04% and 13.37% to 36.78%, indicating that the spatial variability of soil moisture in 1-year subsidence area was the highest. The above data show that there is no significant difference between the subsidence area and the control area, but there are still varying degrees of variability between different areas.

Compared with the CV of the same soil depth in different regions, the spatial variability of CK increased at the depth of 0-3m and 4-10m. The variability of S1 gradually increased in the range of 0-5m and 7-9m, with the highest variability in 3-4m and 8-9m. S2 showed an increasing trend as a whole, but the variability was in the middle of CK and S1, indicating that coal mining and other factors had a certain impact on the soil moisture in the two-year subsidence area. But as the subsidence stabilizes, the area itself may complete certain self-repairs (Li, He, & Gao, 2012) so the degree of variation is relatively reduced. The above data show that the variation trend of subsidence area and control area is discrepant in different soil depths due to mining activities.

To sum up, the variation trend of soil moisture in the vertical direction in each area is basically similar. However, due to the different effects of coal mining activities and other factors on the soil at different depths, there are some differences in the variation degree. For example, the variation degrees of soil moisture in 0-1m and 5-10m in the control area were significantly lower than that in the subsidence area, while there was no consistent rule in the 2-5m soil moisture variation, indicating that the surface subsidence increased the variation degree of soil moisture; with the subsidence entering the stable stage, the variation degree was relatively decreased, but in 0-1m soil surface layer and 5-10m soil deep layer the variation degree was still greater than that in the control area.

3.2 Change of Soil Moisture Spatial Structure

Table2 shows the best-fitting models of CK, S1 and S2 in 0-10m soil layers. C_0 is the variation caused by experimental errors and the microdomain structure smaller than the actual sampling scale, reflecting the size of random variation C (Cambardella et al., 1994). It can be found from table 3 that the vertical comparison of C_0 value in the subsidence area shows that the random variation of deep soil was larger than that of surface soil, which may be caused by the difficulty of deep soil sampling.

According to C_0+C, all soil layers in the control area were lower than those in the subsidence area, which indicates that the variation of soil moisture in the control area was small within the range of variation. However, considering the variation trend of C_0 in the three areas, it is found that the C value (structural variance, representing the variation of non-random causes in the subsidence area) at 0-1m and 5-10m was relatively larger than that in the CK, which indicated that the structural factors including climate, coal mining subsidence, and soil texture have a greater impact on the subsidence area.

The spatial structure ratio $C_0/(C_0+C)$ represents the proportion of system variation in the total variation. According to the standard by Cambardella (Cambardella et al., 1994), CK exhibited a strong spatial autocorrelation between 0-3m and 5-10m ($C_0/(C_0+C)<25\%$), with moderate spatial autocorrelation in 3-5m ($25\% < C_0/(C_0+C) < 75\%$); S1 had strong spatial correlation only in 1-4m while moderate or weak spatial correlation in other depths; S2 had a strong spatial correlation only at 1-5m while moderate or weak spatial correlation in other depths; especially at a depth of 5-10m, the $C_0/(C_0+C)$ of 1-year and 2-year subsidence areas were larger than 50%, and the degree of spatial variation was high. In conclusion, the soil moisture in the one-year subsidence area and 2-year subsidence area shows strong or moderate spatial variability on the surface of soil (0-1m) and deep soil (5-10m), which is consistent with the variation trend in the classical statistical results. Meanwhile, it is shown that the contribution of random factors to the spatial distribution of soil surface and deep layer is relatively small, and the spatial variation is mainly caused by structural factors.

Based on the above results, it is found that the overall variation degree of subsidence area is higher than that of the control area, and the variation caused by structural factors such as climate, mining subsidence and soil texture has a greater impact on the subsidence area, especially the spatial variability of surface and deep soil.

Use cross-check to verify the accuracy of the interpolation results in the three regions, and calculate the MAE, RMSE, and R^2 between the predicted value and the true value (Figure 4 and Table 3). The interpolation accuracy of the control area is generally higher than that of the subsidence area, and the interpolation accuracy of the subsidence area is the lowest in 1 years. It can be concluded that as the spatial variability of soil moisture increases, the accuracy of Kriging interpolation decreases.

3.3 Spatial Distribution of Soil Moisture

From the above analysis, it can be seen in Figure 5 that soil moisture has great spatial variability in 0-1m and 5-10m. Therefore, Kriging interpolation method was used to draw the spatial distribution map of soil moisture in CK, S1 and S2 layers (0-1m, 5-6m and 9-10m).

Comparing the interpolation results of CK, S1 and S2 in 0-1m, 5-6m and 9-10m, it was found that there were no significant spatial variability in 0-1m, and there were one low value area and two high value areas of SM. The low value area was located in the one-year subsidence area, while the high value area was located in the control area and the two-year subsidence area. This is mainly because the control area was not affected by the ground fissures caused by coal mining, while the two-year subsidence area was gradually stable so that the soil moisture was restored. At 5-6m, the high value area was mainly located in the control area and 1-year subsidence area, but the soil moisture distribution in the subsidence area had poor spatial continuity so as to indicate that the subsidence caused by coal mining had a certain impact on the soil moisture distribution. In 9-10m, the distribution of high value and low value areas of soil moisture were similar to that of 0-1m soil layer. The high value area was mainly located in the northwest of the control area and the 2-year subsidence area. However, the low value area and the high value area in the 2-year subsidence area had poor spatial continuity, which referred to high spatial variability. On the whole, the distribution of soil moisture is that the high value area was located in the control area, followed by the 2-year subsidence area and the 1-year subsidence area, which proves that the surface subsidence has a greater impact on the soil moisture; the areas with obvious spatial variability of soil moisture were mainly in the subsidence area, especially in the deep soil, whose reason is the control area has not been mined. The surface subsidence and ground fissures caused by the disturbance of coal mining changed the soil structure and the water transport channel, so the soil moisture decreased and the spatial variability increased.

The results of soil water interpolation of CK, S1 and S2 in 0-1m, 5-6m and 9-10m were compared vertically, and then it was found that the soil moisture in the three regions decreased initially and then increased, which was consistent with the changing trend of water in the results of classic statistical analysis. At the same time, it can be seen that in CK area, there was weak spatial variability in each depth, and the vertical distribution of soil water had obvious regularity, showing a decreasing trend from northwest to Southeast; in S1 and S2 areas, the soil moisture in each depth layer was less than that in CK area, and there was no obvious regularity in the vertical distribution, and the variation degree of soil moisture in each depth layer was also obvious. The reason is that the coal mining collapse caused the soil layer in the subsidence area to be vertically inverted and reorganized, so that it caused changes in soil texture, bulk density, porosity, and other physical properties of the soil, resulting in a significant decrease in the subsidence area in soil moisture compared to that in the control area. Moreover, it was also shown a strong variability existed in the spatial distribution.

By comparing the soil water distribution in three regions vertically and horizontally, it is found that the results of Kriging interpolation are basically consistent with the results of classical statistics and model fitting. The water content in the control area is higher than that in the subsidence area, while the variation degree of subsidence area is higher than that of the control area. The main reason may be that the surface subsidence and ground fracture caused by mining disturbance changed the soil structure and soil physical properties, Then, it affected the water migration channel, which led to the decrease of soil water and the increase of spatial variability.

4. Discussion

4.1 Analysis of Influence Factors

It can be seen from 2.1 and 2.2 that the spatial variability of soil moisture in 1-year subsidence area was relatively high. Therefore, the principal component analysis of 0-10m soil moisture in 1-year subsidence area was used to study the main influencing factors. The results are shown in table 4 and table 5. In this study, three principal component factors Y1, Y2 and Y3 were obtained, and their corresponding variance contribution rates were 41.879%, 19.387% and 14.838% respectively. The total cumulative variance rate was 76.104%.

From the matrix after rotation, the main influencing factors of the vertical distribution of soil moisture in 1-year subsidence area can be found that the vertical distribution of 0-1m soil moisture is mainly affected by factor Y3. The factor load is -0.797, which may be surface factors such as vertical cracks and subsidence (Niu & Yu, 2005), evaporation (Cambardella et al., 1994) and vegetation cover caused by coal mining subsidence. The vertical distribution of soil moisture at 5-10m was mainly affected by the factor Y1, possibly due to underground factors such as changes in the microstructure of soil pores caused by rock and soil deformation, to changes in groundwater level caused by disturbances in coal mining (Zhao, Shao, & Jia, 2014), and their factor loads are respectively 0.694, 0.817, 0.611, 0.804, 0.820. The factors

Y1 and Y3 had little effect on the vertical distribution of soil water in the range of 1-5m, and were mainly affected by factor Y2, which might be the water holding capacity and infiltration capacity of the soil itself, and their factor loads were 0.920, 0.905, 0.919 and 0.755, respectively. Considering the above factors, it can be found that no matter ground fractures, subsidence, deformation of rock and soil layer, or groundwater change, it is ultimately because the coal mining activities change the soil porosity and texture. Those activities form the priority channel of water migration, which affects the distribution of water and its circulation migration channel.

4.2 Effect of Coal Mining on Soil Moisture

The schematic diagram of the effect of coal mining on soil moisture is shown in figure 6. The underground coal mining makes the underground goaf and surface collapse. The tensile action in the process of collapse develops a large number of surface fissures (fissures) resulting in changes of the original texture and structure of the soil and the presence of preferential flow. Therefore, the hydraulic conductivity of the soil as well as the evaporation area and intensity of soil water are increased. At the same time, the field water holding capacity, the water holding capacity of the whole aerated zone, and the soil moisture content is reduced. As a common form of soil water transport and a sign of soil water movement from homogeneous to heterogeneous, preferential flow is the rapid and non-equilibrium seepage flow of water in the soil. Preferential flow can reduce the effectiveness of water and nutrients, threaten groundwater, and cause natural disasters such as avalanche, landslide and mudslides (Lei, 2010; Lu, Lu, & Li, 2015). As a common phenomenon in soil, fissures have complex effects on the generation and process of preferential flow. When the cracks are small, the rainfall first needs to supplement the moisture loss of the upper soil, and then infiltrates downward; when the cracks are large, the rainfall infiltration mode also changes from "piston" infiltration in the non-collapse area to the "shortcut" one. The surface water infiltrates directly along the large cracks, and directly connects with the groundwater and mine water, changing the original soil moisture circulation path, which is the generation of preferential flow. At the same time, the fissures increase the surface area of water infiltration, which leads to an increase in the transport speed of water and solutes (Li, 2007), resulting in changes in soil moisture. Therefore, the soil fissures caused by coal mining will lead to the production of preferential flow. The study on the characteristics of soil priority flow in Shen Dong subsidence area shows that the soil preferential flow in coal mining subsidence area mainly includes the soil macropore flow. The soil water infiltration process in the studied area has the characteristics of non-equilibrium. The steady rate of infiltration and outflow of the soil layer with preferential flow is greater than that of the soil layer with uniform flow. Therefore, it can be found that the subsidence caused by coal mining collapse as well as the soil priority flow caused by cracks are reasons for the change of soil surface water.

In addition, soil moisture is also affected by its own water holding capacity, infiltration capacity and other factors, which are closely related to its bulk density, porosity, texture and other soil properties. The disturbing effect of coal mining on the soil is not only reflected in the surface or a certain level, but from top to bottom, it will be directly or indirectly disturbed by coal mining. In this regard, due to the indirect influence of surface subsidence or ground fissures, the soil properties of the middle soil have changed to a certain extent, such as the increase of porosity and the decrease of bulk density (Clothier, Green, & Deurer, 2008; Jarvis, 2007; Zhu, 2017). Those changes will inevitably affect the water holding capacity and infiltration capacity of the soil, thus affecting the movement of soil water. The preferential flow mentioned above initially refers to the phenomenon of water flowing through macropores and bypassing the soil matrix to move down rapidly. Therefore, the change of soil moisture in the middle is caused by the macropores resulted from the disturbance of coal mining, that is preferential flow, which changes the channel of soil water movement. In Suning's research, it is pointed out that as the depth of the soil increases, the spatial differentiation and variation of the preferential flow of the soil in the coal mining subsidence area continues to increase, and the spatial morphology of the flow in the area where preferential flow occurs becomes more complex (Clothier, Green, & Deurer, 2008).

At the same time, after the underground coal seam is mined out or the ore body aquifer is discharged, the stress equilibrium of the rock mass around the goaf changes. The changes will inevitably cause the deformation, breakage and movement of the rock layer, and then change the microstructure of soil pores (i.e., produce cracks), so as to affect the movement of soil water. In addition, due to coal mining, the groundwater level in the underground part of mining and the surrounding area drops, resulting in a large amount of water loss of the surface soil and soil volume shrinkage. Finally the fissure preferential flow is formed (Li, Zhang, & Wang, 2015) and affects the movement and distribution of soil water. The depth of this fissure is generally above the phreatic water level, or in the entire soil aerated zone. Its scale and distribution are often closely related to the scale of underground engineering, mining technology and mining speed, the physical and mechanical properties of the land and hydraulic power, as well as to the soil moisture content of the soil in the tensile deformation stage (Cheng, 2016). To sum up, the changes of soil pore microstructure and groundwater level caused by the deformation of rock and soil caused by coal mining will lead to the formation of preferential flow of soil fissure and change the soil water transport channel. Moreover, the mining scale and intensity are different in various areas, and the spatial variation of soil water will be different.

Considering the above conclusions, it can be inferred (Figure 5): the collapse and cracks caused by underground coal mining have changed the surface soil texture to a certain extent and caused preferential flow, which in turn affected the evaporation, infiltration and migration of soil moisture. However, due to the limited influence range of collapse and cracks, although the average value of soil water content in the subsidence area has decreased, there is no consistent change law in the overall spatial distribution, and an increase in spatial variability is shown. In addition, the changes in soil hydraulic properties caused by the indirect influence of coal mining disturbances, the changes in the microstructure of soil pores caused by the deformation of rock and soil caused by coal mining as well as the fluctuations of groundwater level also have significant effects on the moisture in the deep unsaturated zone of the soil, so that the disturbance spatial variability is enhanced.

5. Conclusions

In this study, the classical statistics and multi-dimensional geo-statistics method were used to analyze the spatial and temporal distribution of 0-10m soil moisture in the 1-year subsidence area, 2-year subsidence area and control area of Nalin River No.2 mine. Through the above research, it is found that:

(a) The vertical variation of soil moisture in both mining subsidence area and control area firstly decreases and then increases with the increase of soil depth, while the horizontal variation of soil moisture in the control area is higher than that in the mining subsidence area.

(b) Classical statistical analysis showed that the variation degree of soil moisture in different layers of 0-10m in the control area was not significant on the whole; the variation degree of soil moisture in each layer of 1-year subsidence area and 2-year subsidence area was quite different, but with the subsidence entering the stable period, the variation degree decreased and still higher than that in the control area. Geostatistical analysis showed that the spatial variability of soil moisture in the control area was weak at all depth layers, while the spatial variability of soil moisture in the subsidence area was significantly enhanced at 5-6 and 9-10m.

(c) Through analysis, it is found that the change of soil texture and preferential flow caused by coal mining subsidence may be the main reason for the increase of variation degree of soil moisture in the surface layer (0-1m); the change of soil hydraulic property caused by the indirect influence of coal mining disturbance, the change of soil pore microstructure caused by the deformation of rock and soil caused by coal mining and the fluctuation of groundwater level may be the main reasons for the increase of variation degree of soil moisture in the deep layer (5-10m).

(d) In coal mining, it is suggested to reduce the disturbance of soil water by timely landfill treatment of surface collapse and cracks, and to reduce the impact of mining on the groundwater level by using water conservation mining technology, and then to reduce the impact on surface vegetation.

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Conflict of interest The authors declare no competing interests.

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Tables

Table 1. Descriptive statistical results of SM

Deep Soil	CK			S1			S2		
(m)	SD	CV	P	SD	CV	P	SD	CV	P
0-1	0.73	13.37	0.2	1.12	24.7	0.2	1.14	23.6	0.09
1-2	0.95	21.21	0.2	1.5	48.71	0.2	0.68	22.47	0.2
2-3	2.09	31.99	0.2	1.86	49.2	0.2	0.84	20.32	0.2
3-4	0.87	18.17	0.13	2.57	59.05	0.12	1.05	26.93	0.06
4-5	1.4	36.78	0.2	2.37	47.75	0.2	1.03	25.02	0.13
5-6	2.05	34.83	0.2	2.05	37.6	0.2	1.62	36.39	0.2
6-7	1.63	33.1	0.11	1.36	29.55	0.14	2.46	32.5	0.05

7-8	2.13	24.43	0.2	2.45	36.15	0.2	2.9	35.14	0.2
8-9	1.9	17.65	0.17	5.06	65.53	0.2	2.26	31.68	0.06
9-10	2.57	25.22	0.2	3.21	37.8	0.2	3.6	39.04	0.16

674 **Table 2.** Best-fitted semi-variogram models and structure parameters of SM

Region	Deep Soil(m)	Model	C_0	C_0+C	Range (m)	C/(C_0+C)
CK	0-1	Gaussian	0.005	0.160	253.468	3.13
	1-2	Gaussian	0.005	0.327	238.971	1.53
	2-3	Gaussian	0.004	4.411	263.565	0.09
	3-4	Gaussian	0.061	0.138	450.000	44.20
	4-5	Index	0.552	1.114	213.438	49.55
	5-6	Index	0.450	0.261	450.000	0.00
	6-7	Gaussian	0.121	0.423	298.380	0.00
	7-8	Gaussian	0.231	0.297	450.000	10.44
	8-9	Gaussian	0.340	0.808	288.841	0.00
	9-10	Spherical	0.421	0.857	300.000	0.00
S1	0-1	Gaussian	0.344	0.682	266.497	50.44
	1-2	Gaussian	0.107	1.582	208.319	6.76
	2-3	Gaussian	0.003	2.882	200.261	0.10
	3-4	Index	0.436	4.029	294.072	10.82
	4-5	Gaussian	1.340	4.978	475.805	26.92
	5-6	Gaussian	1.683	2.389	252.140	70.45
	6-7	Index	0.895	0.895	797.141	100.00
	7-8	Gaussian	2.315	3.100	421.271	74.68
	8-9	Gaussian	8.232	15.336	797.141	53.68
	9-10	Index	4.079	4.08	797.14	100.00
S2	0-1	Gaussian	0.273	0.896	452.761	30.47
	1-2	Gaussian	0.049	0.337	252.140	14.54
	2-3	Gaussian	0.000	0.694	299.757	0.00
	3-4	Index	0.000	0.500	195.877	0.00
	4-5	Gaussian	0.005	0.515	173.878	0.97
	5-6	Index	1.000	1.208	152.896	82.78
	6-7	Gaussian	2.247	3.882	679.738	57.88
	7-8	Gaussian	3.104	3.503	722.239	88.61
	8-9	Gaussian	1.210	1.722	183.909	70.27
	9-10	Gaussian	3.874	4.506	252.14	85.97

675 **Table 3** The validation of SM

Region	MAE	RMSE	R^2

CK	0.7092	1.1483	0.7597
S1	0.8707	1.3736	0.5910
S2	0.7212	1.2246	0.7072

Table 4 The principal component analysis of SM

Component	Initial Eigenvalue			Extract the Load Sum of Squares			Sum of the Square of the Rotating Load		
	total	variance percentage	accumulate %	total	variance percentage	accumulate %	total	variance percentage	accumulate %
0-1m(x1)	4.188	41.879	41.879	4.188	41.879	41.879	3.112	31.116	31.116
1-2m(x2)	1.939	19.387	61.266	1.939	19.387	61.266	2.960	29.595	60.711
2-3m(x3)	1.484	14.838	76.104	1.484	14.838	76.104	1.539	15.392	76.104
3-4m(x4)	0.960	9.605	85.709						
4-5m(x5)	0.583	5.830	91.539						
5-6m(x6)	0.376	3.756	95.295						
6-7m(x7)	0.267	2.674	97.969						
7-8m(x8)	0.164	1.641	99.610						
8-9m(x9)	0.037	0.365	99.975						
9-10m(x10)	0.003	0.025	100.000						

Table 5 The rotated matrix principal component analysis of SM

Deep Soil(m)	Factor Load After Rotation		
	Y1	Y2	Y3
0-1m(x1)	0.354	0.205	-0.797
1-2m(x2)	0.278	0.920	-0.200
2-3m(x3)	0.340	0.905	-0.072
3-4m(x4)	-0.052	0.919	0.063
4-5m(x5)	0.246	0.755	0.000
5-6m(x6)	0.694	0.197	0.142
6-7m(x7)	0.817	-0.079	0.112
7-8m(x8)	0.611	0.421	0.411
8-9m(x9)	0.804	-0.026	-0.161
9-10m(x10)	0.820	0.276	-0.238

Figure Captions

Figure 1. Schematic diagram of geographic location for study region.

Figure 2. Layout of sample points in different areas (a.S1 and S2; b. CK).

Figure 3. Box chart of 0-10m water content in different areas.

Figure 4. Crosscheck charts: a.CK; b.S1; c.S2

Figure 5. Spatial variability of SM.

Figure 6. Spatial variation of soil moisture in mining subsidence area

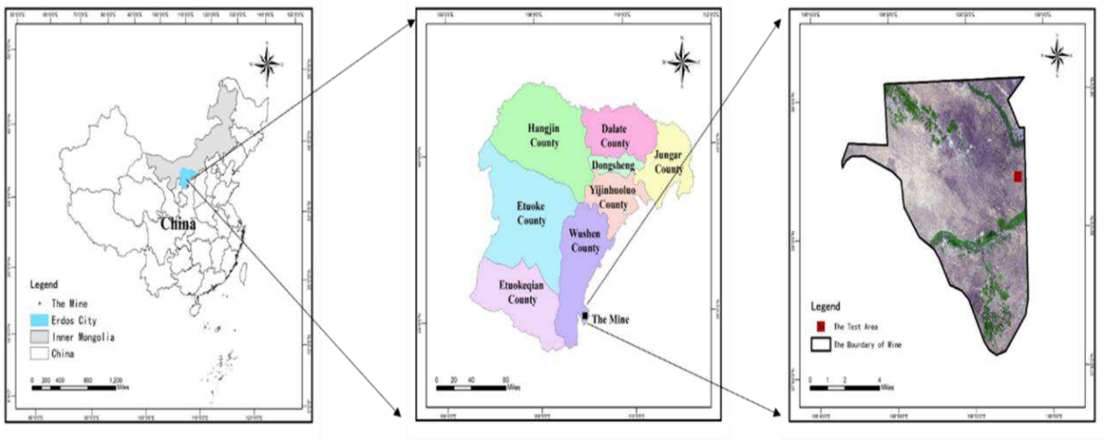

Figure 1

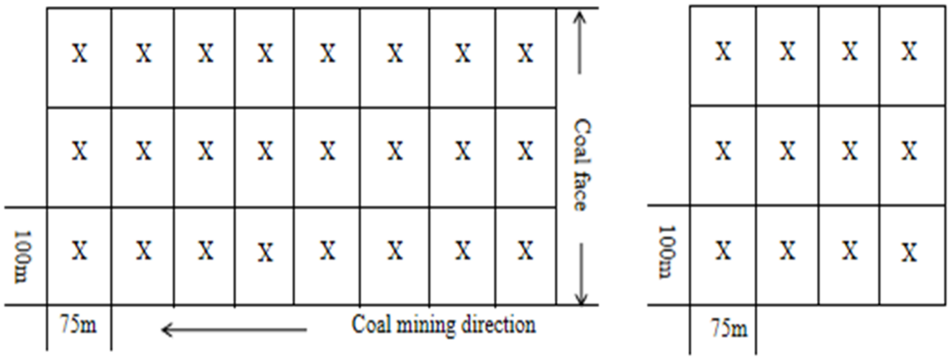

Figure 2

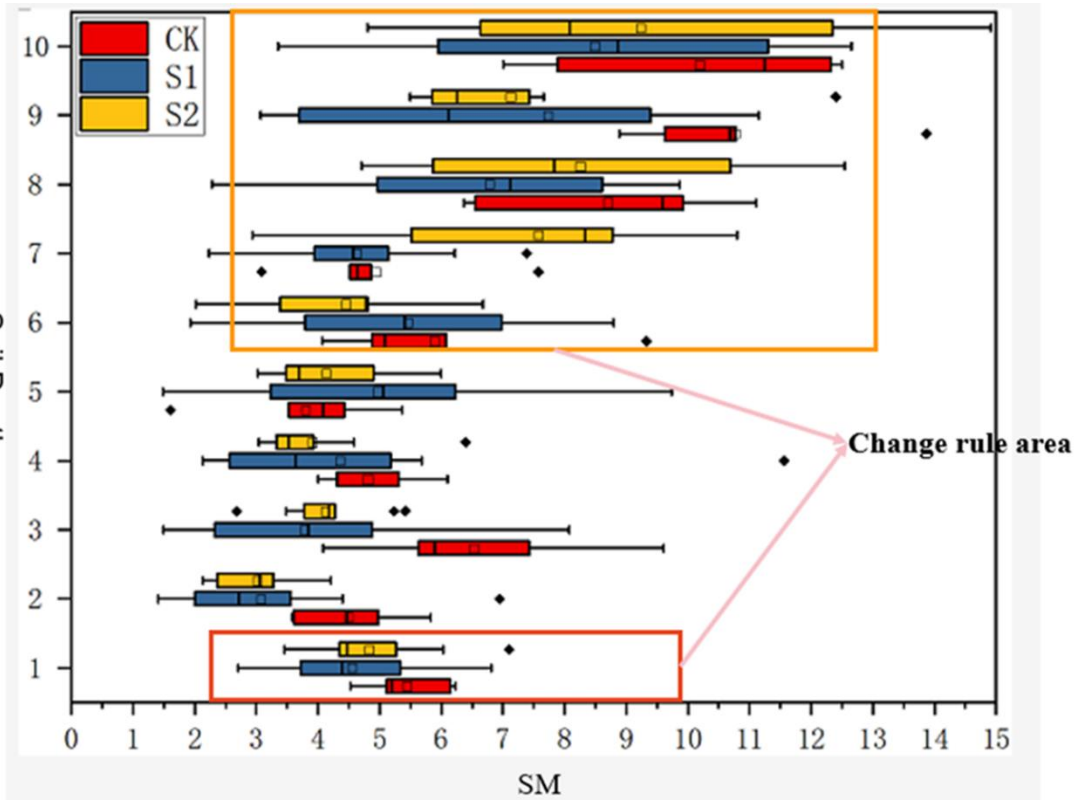

Figure 3

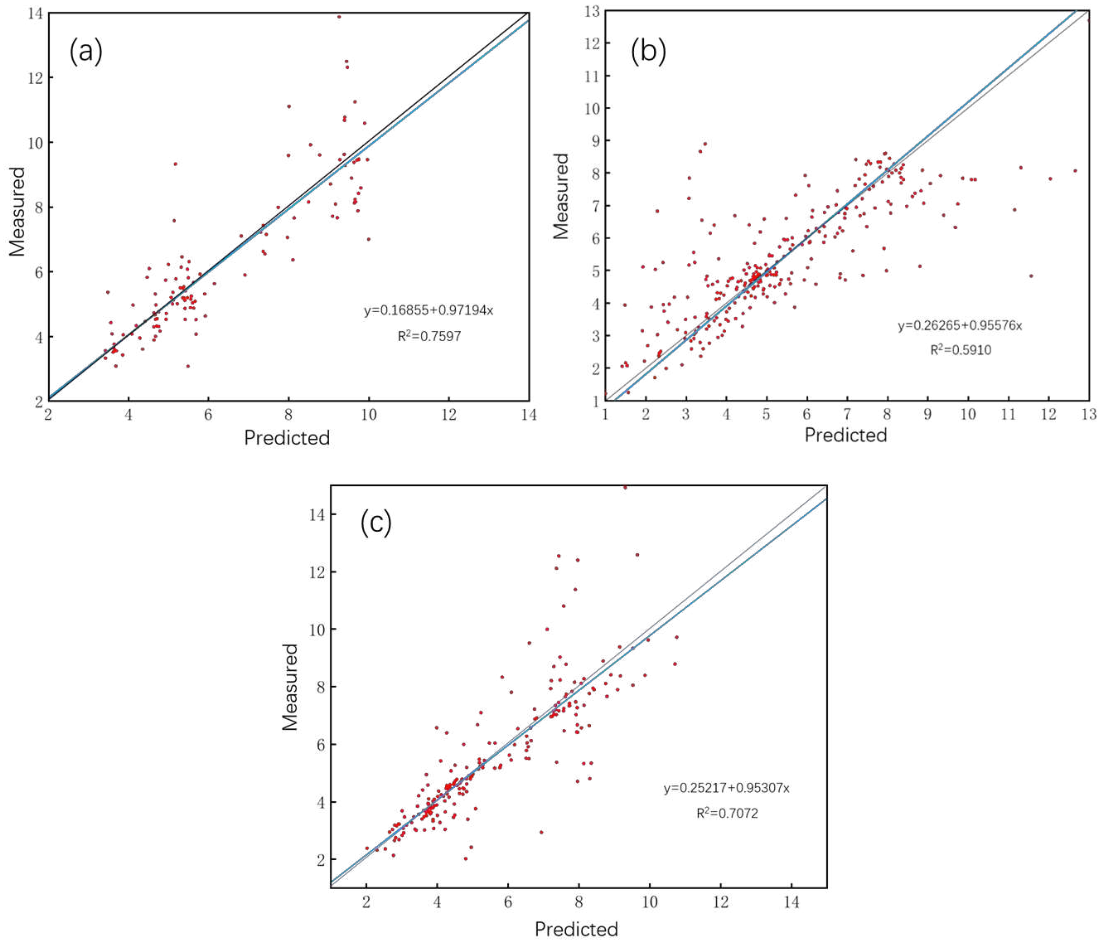

Figure 4

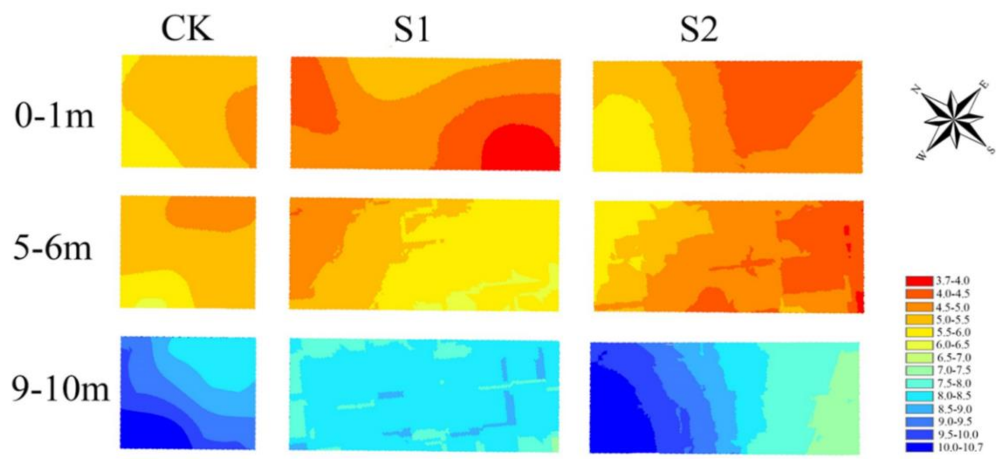

Figure 5

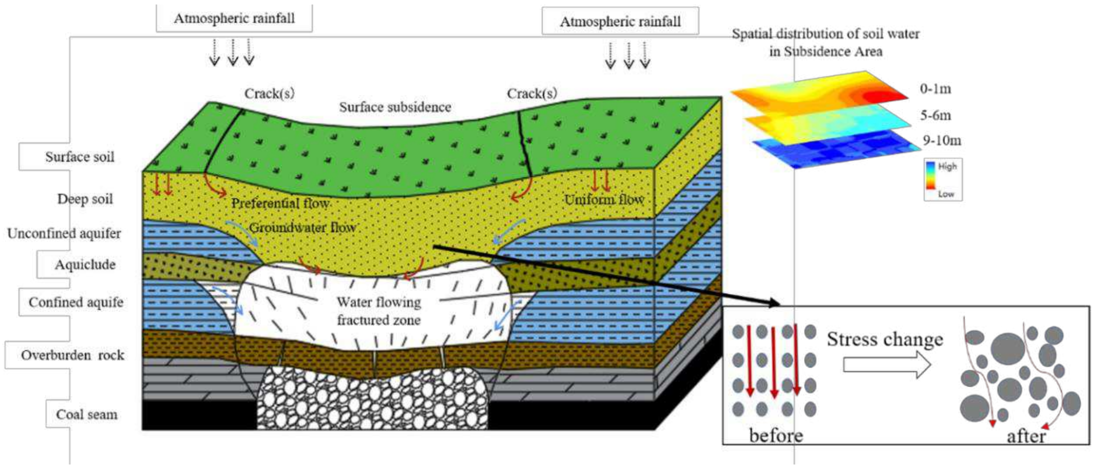
Atmospheric rainfall
Atmospheric rainfall
Spatial distribution of soil water
in Subsidence Area
0-1m
5-6m
9-10m
High
Low
Crack(s)
Surface subsidence
Crack(s)
Surface soil
Deep soil
Preferential flow
Uniform flow
Unconfined aquifer
Groundwater flow
Aquiclude
Confined aquife
Water flowing
fractured zone
Overburden rock
Coal seam
Stress change
before
after

Figure 6