SPATIO-TEMPORAL DISTRIBUTION OF LAND SUBSIDENCE AND WATER DROP CAUSED BY UNDERGROUND EXPLOITATION OF MINERAL RESOURCES

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ABSTRACT

Underground exploitation of mineral resources is often carried out in a watered rock mass. Dewatering of rock layers disturbs its geomechanical equilibrium, consequently resulting in deformations occurrence on the terrain surface. Furthermore, modeling of rock strata dewatering and related land subsidence is still a complex issue, mostly due to unambiguous qualitative and quantitative characteristics of rock mass.

Presented research aimed at determination of dynamics of hydrogeological changes and land subsidence induced by water withdrawal in fractured rock strata. They were carried out in the area of “Bogdanka” hard coal mine in Poland, at a depth of 1000 m, in a multi-layered aquifer system. Spatio-temporal distribution of depression cone and land subsidence in the period 1982-2018 was analyzed. Furthermore, based on the results of observations of water table in aquifers, land subsidence and geomechanical characteristics of rock mass, trend lines of logarithmic functions were estimated. Afterward, based on logarithmic functions, prediction of water table fluctuation and land subsidence was carried out in the entire area of hard coal mining in the period 2018-2025. Subsequently, a novel time factor was introduced. It determines the delay of deformation occurrence on the terrain surface induced by rock strata dewatering as a function of time and distance from drainage center. Finally, computation results were successfully compared with field data.

On the whole, the presented research provide better insight into mechanics of lands subsidence development and water flow in the fractured rock mass due to rock strata dewatering accompanying underground exploitation of mineral resources.

Keywords: time factor, depression cone, water pumping, land subsidence, mining

INTRODUCTION

Land subsidence is one of the most severe and threatening geomechanical consequence of groundwater pumping. That phenomenon is observed worldwide and results mainly from fluid withdrawal from underground reservoirs (Fig. 1). Excessive groundwater pumping in large urban areas causes substantial damage to infrastructure. What is more, in coastal cities it also implies an increase in flood risk [3, 5, 8].

In recent years, land subsidence related to water withdrawal accompanying mining is becoming increasingly important issue. This is mostly due to large range of influence of ground deformation, which often exceeds boundary of mining area. Another reason is relatively weak recognition of consolidation process of deep, fractured rocks, that occurs at a depth of 100 m or more.

Similarly to direct extraction of fluid resources, ground water withdrawal related to mining workings may lead to discontinuous deformation occurrence on the terrain surface, thus damaging buildings and threatening local inhabitants in mining areas [10-11, 14-15].

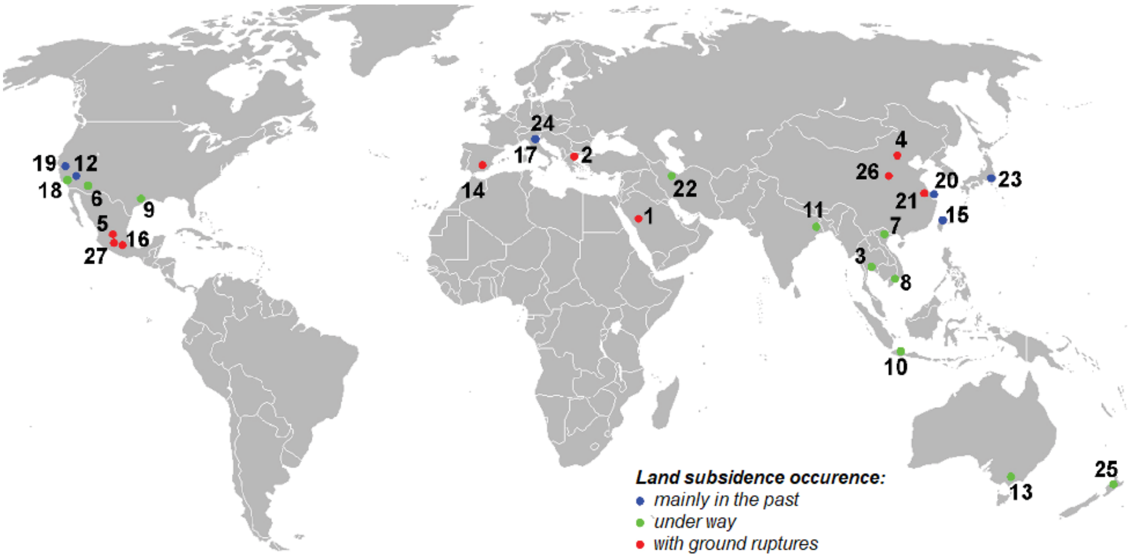

Fig. 1. Major worldwide areas of anthropogenic land subsidence due to groundwater withdrawal, after [4]

Prediction of spatio-temporal distribution of land subsidence due to water pumping in mining areas is complex and problematic issue. In the past, the methods used for prediction of this type of phenomena consisted mainly of theoretical models and analytical or numerical methods that required good recognition of qualitative and quantitative characteristics of rock mass [1-2, 6-8]. Currently, only a few studies have been carried out developing reliable methodology in order to predict that kind of land subsidence [11, 13, 15]. For this reason, a need for developing a new method for prediction of dehydration subsidence is still a significant research problem.
Aim of presented investigation was to develop a novel method for prediction of spatio-temporal distribution of depression cone and the corresponding land subsidence due to water withdrawal accompanying underground exploitation of mineral resources. The research works were carried out in the area of one of the underground hard coal mines in Poland. Based on empirical data, logarithmic functions have been determined. These functions describe relationship between the distance from drainage centre and the time of water extraction from the rock mass and the values of depression cone and land subsidence on the terrain surface, respectively. Presented solution enabled us to predict values and estimate dynamics of land subsidence and depression cone, which will be accompanying mining workings in the period 2018-2025.

STUDY AREA

The research works presented in this paper were conducted in ‘Bogdanka” underground hard coal mine in the eastern part of Poland (Fig. 2a).
The hard coal deposit in the research area is located at a depth of ca. 820 m to 1005 m.

Rock strata grouped in the Quaternary, Cretaceous, Albian and Jurassic formations dominate in the analyzed area. They constitute a caprock for Carboniferous coal beds. Its thickness ranges from ca. 670 m to 745 m (Fig. 2b).

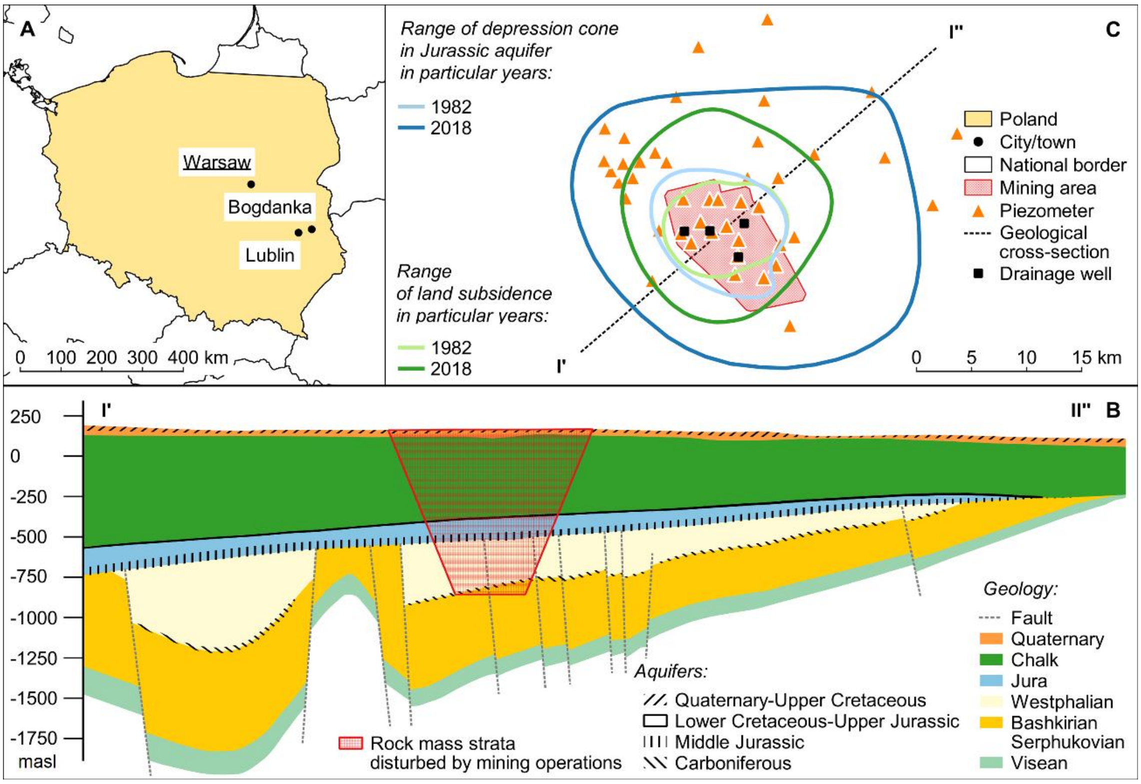

Fig. 2. Location of study area (a), schematic cross-section through geological and hydrogeological formations in the research area (b), water extraction from mining-induced area, spatial distribution of piezometers, range of depression cone in Jurassic aquifer and land subsidence in particular years (c), based on: [9]

Four water-bearing horizons can be distinguished in the research area. The Jurassic aquifer is the dominating one. It lies directly above coal deposit and is constantly drainaged due to progressing mining workings. Jurassic aquifer is built by rocks of good water transmissivity properties, up to about 100 m thick. Waters from this aquifer are perched. They are separated from the roof with a series of impervious carbonate layers, which thickness reaches up to ca. 400 m (Fig. 2b).

In the analyzed area water has been extracted since 1976. Initially, only rock strata in the direct vicinity of the drilled mine shafts were drained (Fig. 2c). With time, as the opening-out works advanced and production developed, the drainage area extended to the mining-induced area. Estimated volume of water pumped out of the rock mass in the years 1976-2018 exceed 240 mln m^3.

The maximum values of depression cone in Jurassic aquifer in 2018 reached ca. 500 m and the radius of influence of dewatered rock strata was about 15 km. Furthermore, time delay between the land subsidence and the depression cone occurrence were observed. In 2018, total area affected by land subsidence induced by rock mass dewatering due to mining workings reached ca. 141 km^2, with a maximum values of vertical ground movement up to 571 mm (Fig. 2c).

METHODOLOGY

The presented research methodology consisted of 5 stages (Fig. 3).
In the first stage of research, the values of depression cone in Jurassic aquifer and the corresponding values of land subsidence in the given time periods were determined. These works were based on the analysis of hydrostatic pressure observation results, which were carried out in 44 piezometers, as well as the results of geodetic levelling in 1982, 1984, 1986, 2010 and 2018 (Fig. 2c).

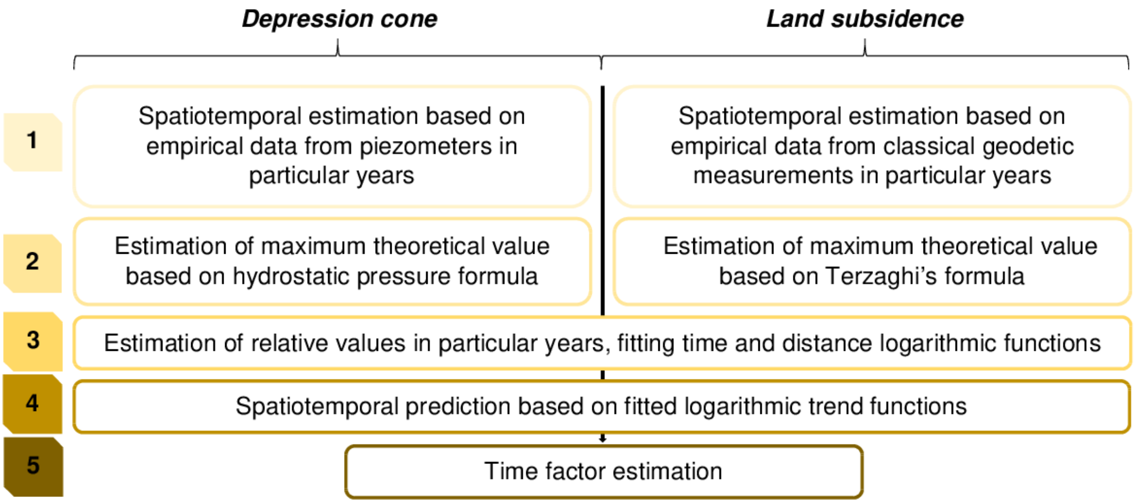

Fig. 3. Scheme of an algorithm for prediction of land subsidence due to water withdrawal

In the second stage of the study, the maximum theoretical values of depression cone and land subsidence, which may occur in the given observation points, were calculated.
The maximum theoretical values of depression cone were determined based on the initial hydrostatic pressure in Jurassic aquifer, which was observed in the piezometer network prior to the start of water pumping. They were calculated with the use of basic equation of fluid physic (Eq. 1):

$$L_{max} = \frac{P_h - P_o}{\rho g} \tag{1}$$

where: L_{max} is maximum, theoretical value of depression cone defined as height of liquid column; P_h is initial liquid pressure; P_o is pressure of overlaying rock strata exerted on the bottom of Jurassic aquifer; ρ is density of liquid; g is acceleration of gravity

The maximum theoretical values of land subsidence were computed on the basis of the consolidation equation of rock strata proposed by Terzaghi (Eq. 2) [12]:

$$S_{max} = -\frac{\Delta e H}{1 + e} \tag{2}$$

where: S_{max} is maximum, theoretical value of land subsidence defined as value of aquifer compaction; H is thickness of aquifer; e is voids ratio

Datums of the surface, roof and bottom of particular geological layers, as well as physico-mechanical properties of rock strata were established on the basis of laboratory analyses of geological cores [9].
In the third stage of the study, the normalized values of depression cone and land subsidence in given observation points and time periods were calculated based on Eq. 3 and 4:

$$L_{i_{nor}}=\frac{L_{i_{obs}}}{L_{max}}100\% \quad \text{and} \quad S_{i_{nor}}=\frac{S_{i_{obs}}}{S_{max}}100\% \tag{3, 4}$$

where: $L_{i_{nor}}$ i $S_{i_{nor}}$ are normalized values of depression cone and land subsidence, respectively; $L_{i_{obs}}$ i $S_{i_{obs}}$ are observed values of depression cone and land subsidence, respectively

The obtained results were compared as a function of the distance from drainage centre and the time of observation. Subsequently, logarithmic trend functions were fitted into received data sets. Therefore, spatio-temporal generalization of analyzed phenomena were determined. The correlation coefficient R^2 of estimated functions at least equalled to 0.73.
In the penultimate stage of research work, prediction of the values of depression cone in Jurassic aquifer and accompanying land subsidence in the period 2018-2025 was carried out. Values of these phenomena were calculated based on logarithmic trend lines. They were re-fitted into generalized time-dependent development of decreasing water head table and land subsidence. The analysis was carried out in the arguments of the distance from drainage centre, which ranged from 0 m to 30000 m. The correlation coefficient of re-estimated functions at least equalled to 0.81.
Finally, in the last stage of the study, the time factor T was determined based on Eq. 5. It defines spatio-temporal, normalized ratio of the values of land subsidence to depression cone in the aquifer that compresses due to water withdrawal from the rock mass. Therefore, the proposed time factor is a generalised measure of the time delay of land subsidence occurrence on the terrain surface in relation to the lowering hydrostatic pressure due to water pumping induced by mining workings.

$$T_i=\frac{S_{i_{nor}}}{L_{i_{nor}}} \tag{5}$$

where: T_i – time factor; $L_{i_{nor}}$ i $S_{i_{nor}}$ are normalized values of depression cone and land subsidence, respectively

RESULT

Estimated values of depression cone and land subsidence in 2025

In 2025, predicted values of depression cone in Jurassic aquifer will reach maximum 524 m in the drainage centre. However, substantial values of rock strata dewatering are prognosed in the vicinity of mining shafts, solely. That is, at least 30% of the values of L_{max} are predicted at a distance of ca. 5 km from drainage centre, at that time.

With increasing distance from mining shafts, the values of depression cone will decrease exponentially. The maximum, estimated range of rock strata dewatering will reach about 30 km (Fig. 4a).

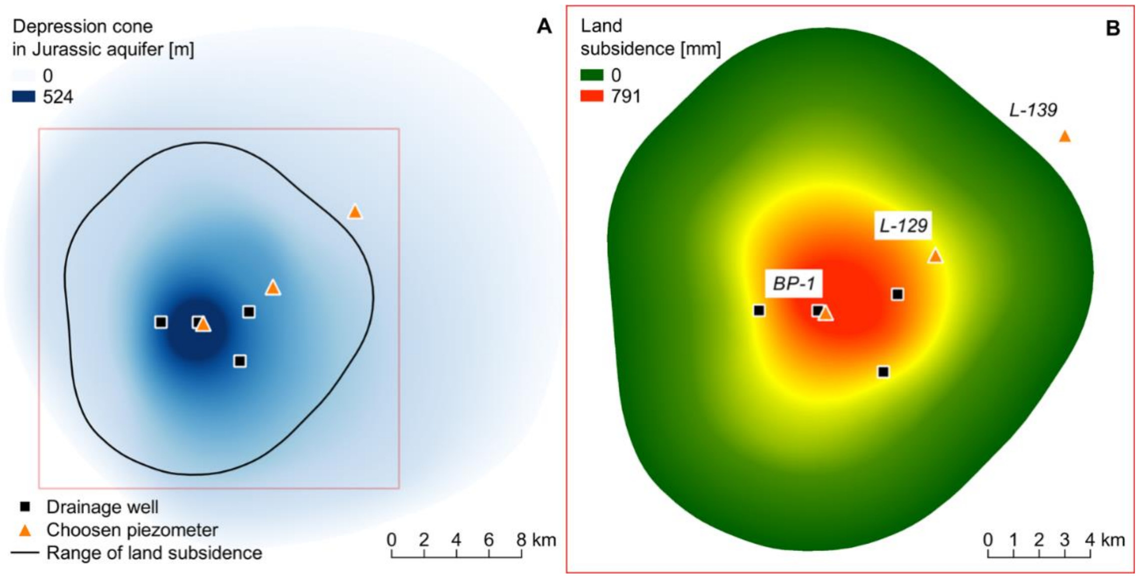

Fig. 4. Spatial distribution of depression cone in Jurassic aquifer (a) and land subsidence (b) in 2025 estimated with the use of logarithmic trend functions

The predicted values of land subsidence in the research area will amount to about 790 mm in 2025. Significantly, they will occur in the region of the maximum, predicted values of depression cone. Moreover, spatial distribution of land subsidence will correspond to lowering water head table in Jurassic aquifer. At that time, land subsidence will reach about 21 km from drainage centre. Nonetheless, 25% of its maximum, theoretical values (S_{max}) will occur at the distance of up to ca. 3.5 km from mining shafts, exlusively (Fig. 4b).

Dynamics of development of depression cone and land subsidence, time factor

For showing the dynamics with the depression cone and land subsidence development in time, 3 piezometeres were selected. They were located in the vicinity of drainage center (BP-1), at the distance of ca. 10 km from mining shafts (L-129) and in the peripherial area of research works (L-139) (Fig. 4b).

It can be observed at point BP-1 the biggest dynamics of the increase in the values of depression cone and land subsidence. In the years 1982-2018 at least half of its maximum, theoretical values occurred at that point. A similar dynamics of depression cone and land subsidence development is characterized by point L-129. However, the values of particular parameters in this area reach about twice lower than at point BP-1. This indicates realtively low dewatering of rock strata and its small deformation in relation to drainage center. In the last of the analyzed points, L-139, the initial phase of depression cone development and noticeable time delay in land subsidence occurrence is observed (Fig. 5).

Additional information on the dynamics of aformentioned phenomena is provided by the time factor T (Fig. 6). Its values can range between <0; 1>.

However, for reliable interpretation of the values of time factor, the analysis of the monotonicity of the estimated function is required. This function determines generalised relationship between the value of time factor and the distance from drainage center in a given period. Moreover, it has a dichotomous character, which consist of two phases. In the first phase, the growing values of estimated function correspond to the divergence of the depression cone in relation to land subsidence. That is, divergence indicates a greater dynamic of development of depression cone comparing to land subsidence occurence on the terrain surface. On the contrary, second phase of estimated function corresponds to convergence of the values of land subsidence in relation to depression cone. In short, the divergent nature of the function of time factor determines initial and intermediate stage of aquifer compaction as a result of progressive water dewatering due to mining workings. In contrast, the convergence phase occurs mostly in the final stage of rock strata deformation caused by water pumping.

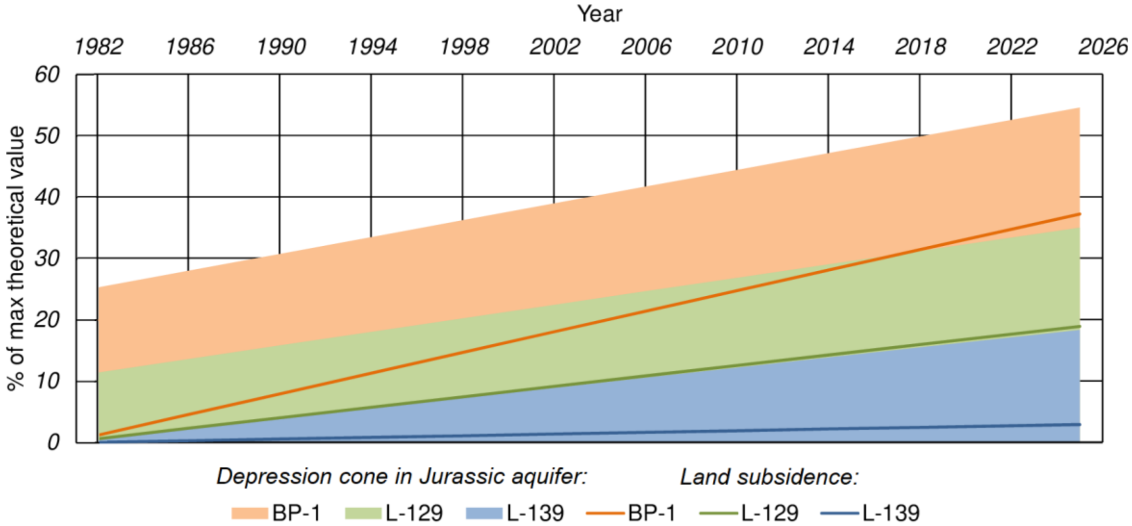

Fig. 5. Dynamics of depression cone in Jurassic aquifer and land subsidence development in time in choosen piezometers

Based on the analysis of the obtained values of time factor, it can be assumed divergence phase of depression cone and land subsidence development in all observation points in the years 1982-1986. The greatest dynamics of this phase occurred in the vicinity of mining shafts, reaching up to ca. 5, 7 and 8 km from drainage center, in 1982, 1984 and 1986, respectively. Furthermore, range of divergence decreases exponentially with the function of distance from drainage center. On the contrary, since 2010 in the area within a radius of about 5-6 km from mining shafts, convergence phase occurs. In the years 2010-2015, an intermediate or initial phase of rock strata deformation development induced by progressive drainage of Jurassic aquifer was observed (Fig. 6).

Prediction accuracy

The modeling accuracy estimation was carried out with the reverse engineering method. The predicted values of depression cone and land subsidence in 2025 were compared with empirical data.

That is to say, based on estimated logarithmic trend lines, the values of depression cone and land subsidence in 44 observation points were computed. Moreover, the calculations were performed for the years 1982-2010 (Fig. 2c). The average mean square errors of predicted values of land subsidence and depression cone reached +-31 mm and +-29 m, respectively. In addition, the obtained maximum tolerance between observed and modelled value equaled to 84 mm and 66 m, respectively. Instead of average prediction accuracy, its results were assumed as acceptable.

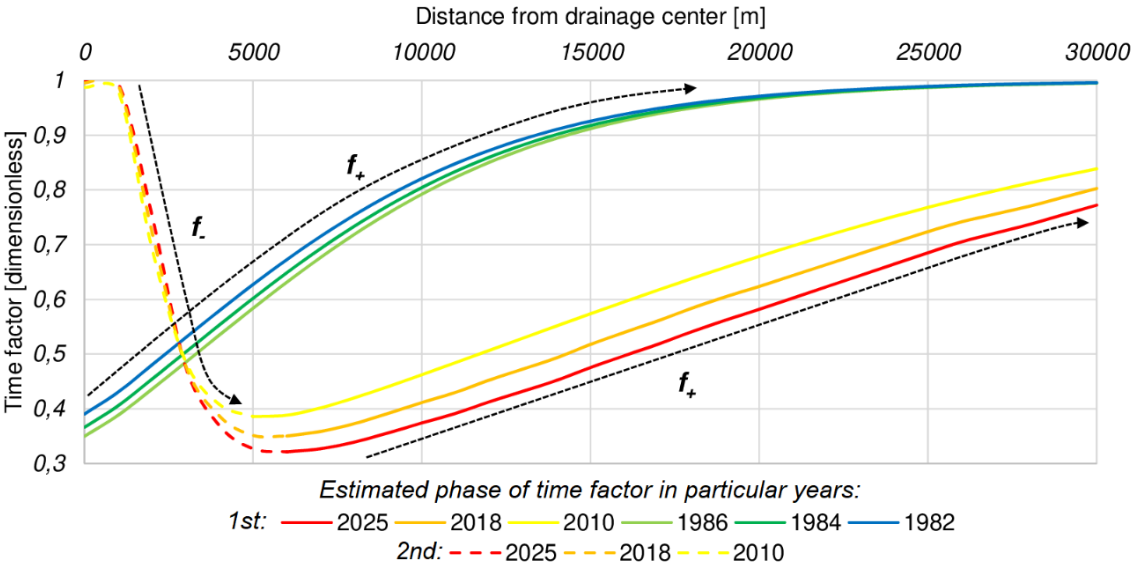

Fig. 6. Normalized values of time factor as a function of time and distance from drainaged centre

CONCLUSION

Prediction of rock strata dewatering and land subsidence induced by water pumping due to underground exploitation of mineral resources remains a challenge. Main problems associated with this issue result from the limited possibilities of recognition of complex qualitative and quantitative properties of rock strata, which lie at considerable depths. For this reason, the implementation of prediction models based on advanced numerical solutions to simulate depression cone and land subsidence development in time remains ineffective and often does not allow to obtain reliable modeling results.

The aim of presented research was to develop a novel methodology for prediction of depression cone and land subsidence in time. The developed solution enabled us to estimate the values of these phenomena in the area of underground hard coal exploitation with satisfactory accuracy. Furthermore, based on determined logarithmic trend functions, a novel time factor was introduced. Its values were used to assess the time delay between land subsidence occurrence and development of depression cone.

Nevertheless, the presented approach has also considerable limitations. Proposed methodology can be implemented in the areas, where the results of empirical observation of water head table in aquifers, as well as values of land surface deformation are available, solely. In addition, due to the use of logarithmic trend functions, the obtained computation results will be characterized by a substantial degree of generalization. The degree of results generalization will be the bigger, the higher the dispersion scale of the input empirical data sets used in regression process.

However, the obtained accuracy of prediction results proves the presented approach can be successfully applied in the initial assessment of the expected scale of studied phenomena in the areas of deep mining of mineral resources.

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