Progressive Sinkhole Occurrence Induced By Dewatering Activities in a Large Lignite Mine (SE Turkey)

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Abstract

Following two successive massive landslides in 2011with a total of 10 casualties at the Çöllolar open pit lignite mine located in southeast Turkey, an extensive dewatering program was initiated as a preventive measure against further slope stability problems. Based upon a series of studies on hydrogeological conceptualization and characterization, two major hydrostratigraphic units have been identified as target zones for dewatering. Failure in lowering groundwater in the Neogene sequence is has thus been attributed to the excessive inflow from karst aquifer. Therefore, a second dewatering program targeting the karst aquifer was scheduled and initiated in February 2015. Four sinkholes were developed progressively as a consequence of sudden collapse in a period of about 120 days after karst dewatering has started. Occurrence of sinkholes is restricted to an area of about 0.7 km^2 between the pit and the limestone outcrop. Progressive occurrence and development of sinkholes posed a serious risk for not only mining operations but also the settlements close to the sinkhole area. This study was conducted to explain the mechanism of sinkhole occurrence in the area and thereupon to suggest a solution to this hazardous risk. All information were put in a conceptual model that explains the most plausible mechanism of sinkhole occurrence which required a detailed comparative study of morphological, hydrographical, geological and hydrogeological characteristics of the sinkhole field and its near vicinity.

Key words: dewatering, open pit, karst, sinkhole, Afsin

Introduction

Mining operations have hydrologic and hydrogeological impacts on the environment by altering the surface landscape, surface water and groundwater systems. Hydrogeological conditions may require intensive dewatering of the groundwater system to secure safe and feasible mining operations. Subsidence is one of the most common consequences of such intensive dewatering activities. A gradual development of subsidence is easier to predict, control and remediate. However, sudden subsidence or collapse producing large and deep sinkholes are less predictable and difficult to control. This type of occurrences may be hazardous and dangerous. Therefore, understanding the mechanism of sinkhole occurrences is an important issue of mining hydrogeology (Blodgett and Kuipres 2002; LaMoreaux et al. 2008; Commonwealth of Australia 2015).

In 2011, two successive massive landslides in 2011 killed a total of 10 persons at the Çöllolar open pit lignite mine located in southeast Turkey (fig. 1). Analyses of the landslides have suggested that occurrence of excessive pore water pressure in the overburden was the major factor responsible for these occurrences. Consequently, an extensive dewatering program was initiated as a preventive measure against further slope stability problems. Four sinkholes were developed by sudden collapse successively in the vicinity of the open pit (fig. 1) in a period of 4 months following an extensive dewatering. Progressive occurrence and development of sinkholes posed a serious risk for not only mining operations but also the settlements close to the sinkhole area. Authorities have expressed their concern about the role of dewatering. Dewatering might have a double but contradicting effects: enhances slope stability in the pit but triggers sudden collapses in the vicinity. This paper aims at suggesting a model to explain the mechanism of sinkhole occurrence in the area and thereupon to suggest a solution to this hazardous risk.

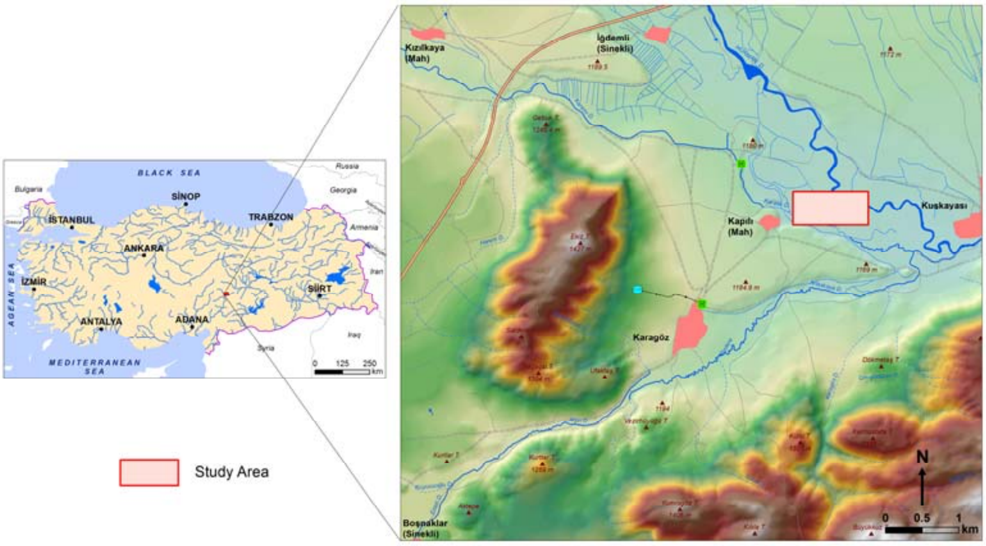


Figure 1 Location Map of the Study Area.

The technical approach applied in this study included a detailed desktop study on geological setting and analysis of hydrogeological data, followed by field work to characterize the sinkholes. Hydrographic, morphologic characteristics and hydrological conditions were analyzed to define the type of the sinkholes in accordance with the classification suggested by Waltham et al (2008). Once the type of the sinkholes were defined, the mechanism of development was hypothesized based upon the pre-mining hydrogeological conditions and the role and impact of dewatering on the occurrence.

Location and Basic Characteristics of Sinkholes

The four sinkholes occurred successively at the foothill of one of the metamorphic rock hills, 350 to 600 m to south-southeast of the Çöllolar pit (fig.2). The sinkhole area is covered by slope-wash material, colluvium and alluvium of Hurman stream which runs close to the periphery of the pit. The occurrence history and basic characteristics of the sinkholes are briefed below. The first sinkhole was developed at the end of February 2015 about 350 m distant from the southeast perimeter dewatering wells. The perpendicular distance to Hurman stream is measured as 152 m. This sinkhole is the smaller one with a diameter of 2.5 m and 1.5 m apparent depth.

Figure 2 Location of the Sinkholes in Relation to the Open Pit.

The second sinkhole was developed in April 2015, at the same area but closer (about 255 m).to the open pit. Development of this sinkhole was progressive. Diameter of this sinkhole continued to enlarge after its first development from 14 m to 16.5 m. Its depth was measured as 14 m. The third sinkhole occurred in May 2015 at a location between the first and second sinkholes. It progressively deepened from 4.5 m to 6 m in 15 days whereas its diameter remained the same at 7.5 m. The fourth and the last sinkhole was developed very close to the periphery of the open pit. This is the deepest sinkhole with a diameter of 9 m and depth of 18.60 m. All of the sinkholes are cylindrical in shape with steep walls (fig. 3).

Classification of sinkholes in karstic areas by Waltham et al (2005) suggests that sinkholes may also develop in overburden of karst systems through different mechanisms. Based on the morphological and geological characteristics of the studied sinkholes it can be postulated that they may be defined as suffosion or dropout type. The degree of cohesion of the overburden material determines which type will develop: suffosion in non-cohesive, dropout in cohesive overburden. Alteration of hydrological/hydrogeological is another basic factor underlying the mechanism that may produce these types of sinkhole.

First sinkhole

Third sinkhole

Fourth sinkhole

Figure 3 *Views From the Sinkholes Developed in the Study Area*

Geological Setting

A detailed study of regional geology by Bedi et al (2008) together with core log descriptions from a large number of boreholes at the site were utilized to describe geological setting at regional and local scale. The Çöllolar mine site is located within a large tectonic depression known as ion of the Afşin-Elbistan lignite basin. The depression is surrounded by high rock masses made of meta-carbonates and meta-clastics of Paleozoic-Mesozoic age. The depression is filled with Tertiary units. Miocene unconformably overlies the bedrock and is represented by alternation of mainly lacustrine siltstone, mudstone, sandstone, marl and limestone. Plio-Quaternary sequence is characterized by lacustrine units starting with clay and silt containing thick lignite horizons and a thick gyttja. The uppermost alluvial cover is composed of unconsolidated coarse and fine sediments. Figure 4 depicts the general geological setting in the region including the study area.

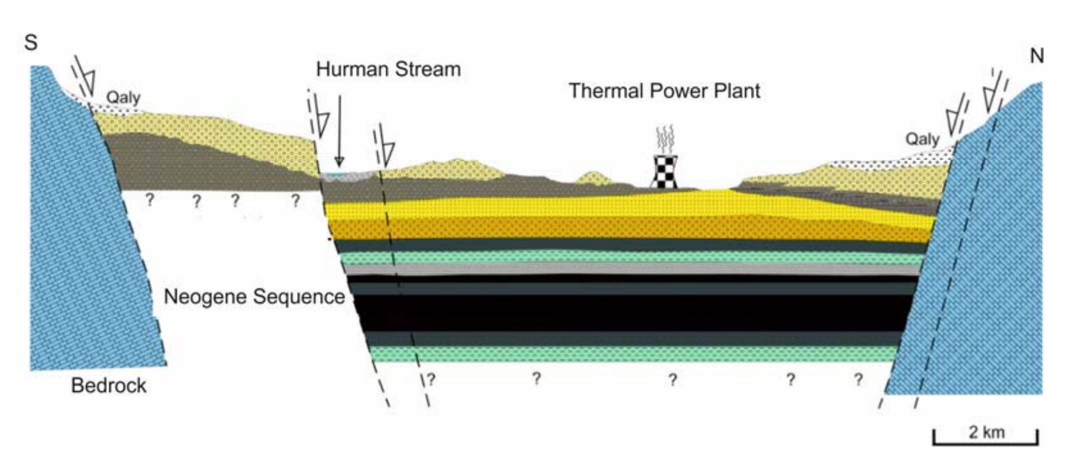
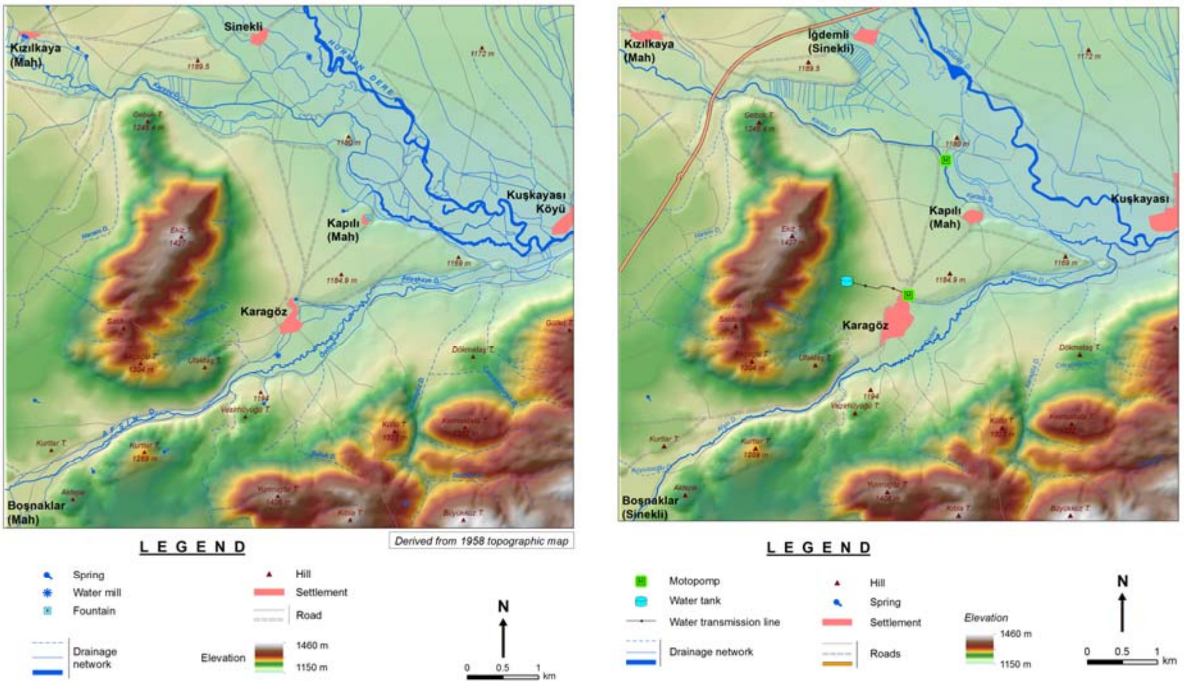


Figure 4 *Geological cross-section of the Afşin-Elbistan Lignite Basin (after Bedi et al 2009).*

Comparison of Pre and Post Mining Hydrographic Layout

Pre-mining hydrographic layout in the area of sinkhole development was derived from topographic map dated 1958 while the present conditions were reproduced from more recent topographic map and the GoogleEarth™ image. The hydrographic layout shows that the region was rich with respect to surface waters such as springs, streams and wetlands before the mining operation (fig.5a). Water mills suggests that the flow rate of springs and streams was high. Apparently, the mining operations have impacted the surface water occurrences in the area. Wetlands and springs have disappeared and streams have either dried up or their flow has been significantly reduced (fig. 5b). Alteration of the hydrographic setting in the vicinity of the pit was regarded as a consequence of dewatering and as indication of interaction of surface water-groundwater.



a

b

Figure 5 *Hydrographic Setting of the Area. a) Pre-mining b) Post-Mining conditions*

The sinkhole area is also characterized with some closed crypto-depressions where the surface runoff is disappeared (fig. 6). These crypto-depressions are evaluated as indications of localized seepage in the alluvium. This information was used in developing a representative hydrogeological conceptual model of the site.

***Figure 6** Hydrographic Setting of the Area. a) Pre-mining b) Post-Mining conditions*

Hydrogeological Setting Under Natural Conditions

Based on detailed analyses of geology, borehole data, hydrochemistry and stable isotope data the pre-mining hydrogeological setting was conceptualized as illustrated in Figure 7. The paleogeographic development has suggested that karstification of pre-Neogene carbonate rocks was interrupted and karstic features were choked by the lacustrine sediments in Neogene. The karstic bedrock forms an extensive aquifer in the region. However, the groundwater flow through the aquifer is slow and the phreatic part contains almost stagnant groundwater due to the much less permeable Neogene sediments. The springs that issue at the foothill of the carbonate rock are of overflow or depression type. The foothill is consisted of coarser and therefore higher permeability slope-wash and fan material. Toward the plain, finer material dominates the alluvial deposits, thus reducing its permeability. The rich surface water occurrence before mining operations is thus explained by the groundwater overflow due to the shallow water table.

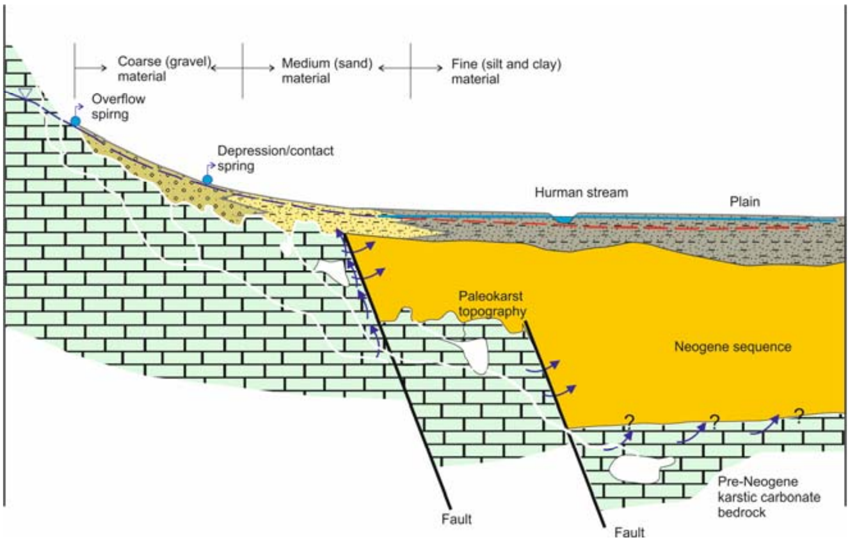


***Figure 7** Schematic Cross-sections Illustrating Natural Hydrogeological Conditions (not to scale)*

Pit Dewatering and Its Hydrogeological Impacts

Two major hydrostratigraphic units have been identified as target zones for dewatering as a result of a series of studies on hydrogeological conceptualization and characterization. The upper zone is composed of a sequence of clastic material with various grain sizes and organic material content of Neogene age. Gyttja having a thickness up to 70 m within the Neogene sequence is given a special importance in dewatering due to the fact that this material was defined to be sensitive to mass wasting. The lignite seam is seated on extensive clayey layer at the bottom of this sequence. Beneath the Neogene sequence there extends a thick limestone of Mesozoic age. It is well karstified and forms a high yield aquifer with confined groundwater to be depressurized and dewatered. Dewatering the Neogene sequence (upper unit) has increased to a total of abstraction rate of 2.5×10^4 m^3/day in 2012 immediately after the landslides. Dewatering of this unit was found to be ineffective in lowering the groundwater to the targeted level which is the bottom of the pit. This was mainly due to the low transmissivity of the gyttja. According to the hydrogeological conceptual model described for the site, the karstic limestone aquifer is in contact with the Neogene sequence at the southern edge of the basin where karst groundwater feeds the gyttja and other layers of Neogene sequence.

The hydrogeological impact of dewatering of the Neogene sequence on the regional hydrodynamics has not been significant due to the low transmissivity of the sequence. The radius of influence remained limited and did not expand (fig. 8). Failure in lowering groundwater in the Neogene sequence has thus been attributed to the excessive inflow from karst aquifer. Therefore, a second dewatering program targeting the karst aquifer was scheduled and initiated in February 2015. As a first phase of dewatering of karst aquifer 5 boreholes have been drilled close to the southern edge of the pit where the karstic limestone crops out at only a few hundreds of meters from the pit wall. The boreholes have been screened only at the limestone and pumped with an average rate of 40 L/s (a total of 200 L/s). The sudden increase of pumping rate from karst aquifer had a significant impact on the hydrodynamics which altered the hydraulic interactions in the area. The first sinkhole was developed only after about three weeks following the massive dewatering of karst aquifer (fig.9). The impact of this dewatering on the hydrogeological behaviour is depicted in Figure 10.

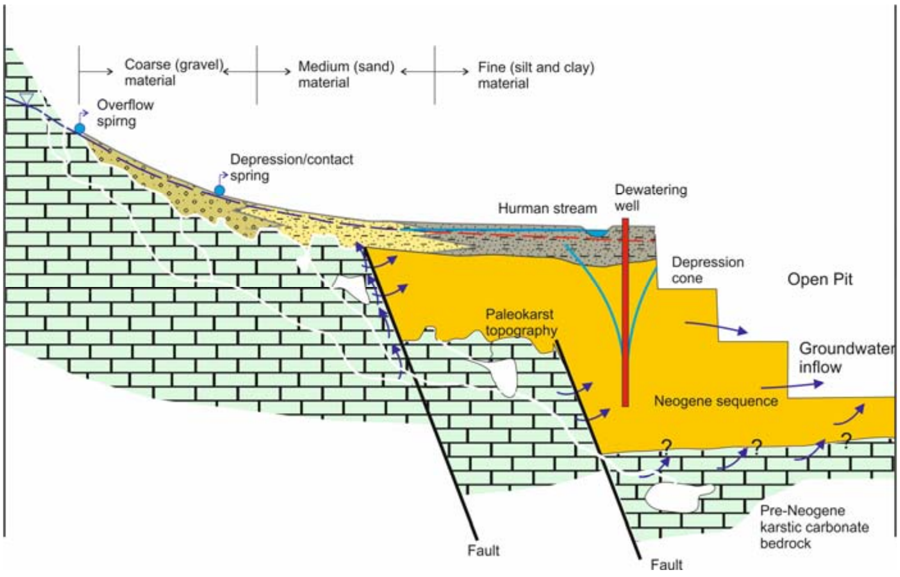


Figure 8 *Schematic Cross-sections Illustrating Hydrogeological Conditions Under Dewatering the Neogene Sequence (not to scale)*

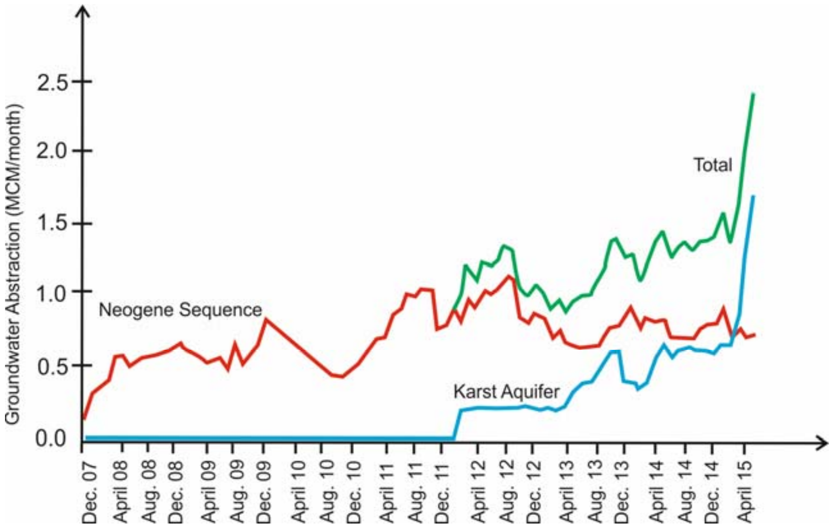


***Figure 9** Groundwater Abstraction For Dewatering Karst Aquifer and Neogene Sequence (in millioncubicmeter per month)*

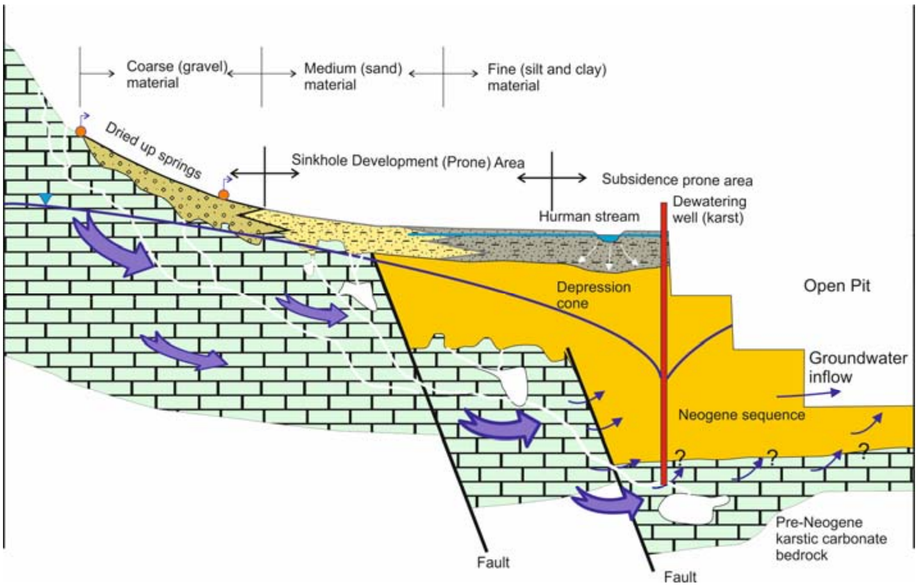


***Figure 10** Schematic Cross-sections Illustrating Hydrogeological Conditions Under Dewatering the Karst Aquifer (not to scale)*

Mechanism of Progressive Development of Sinkholes

The results of data analyses and observations in the field allowed us to suggest a plausible mechanism explaining the progressive development of the sinkholes. The area where sinkholes developed is located at the foothill of a carbonate rock outcrop. The overburden is made of unconsolidated alluvial and colluvial deposits. Toward the pit, the deposit becomes thicker, and composed of finer and more cohesive whereas close to the foothill it is thin, coarser and less cohesive. The sinkholes are developed within the overburden and all characteristics indicates that there has been no collapse in the bedrock. This has suggested that the sinkholes are of either suffusion type or dropout type, classified according to Waltham et al (2008). Those developed close to the foothill (the first and third sinkholes) are of suffusion type while those close to the pit (second and fourth sinkholes) are of dropout type.

Under natural hydrogeological conditions (before dewatering the karst aquifer), the groundwater in the karst aquifer is almost stagnant and the overburden is saturated. Groundwater in karst aquifer discharges through overflow springs and as base flow to the streams. After mining operations has started, the Neogene sequence only was dewatered. Dewatering the low permeability Neogene sequence had no significant effect on the hydrogeological setting in the area because of the limited extension of the drawdown cone (see fig. 8). However, following the destructive landslides, the karst aquifer was started to be dewatered. Dewatering of this high yield aquifer required massive and extensive pumping. Groundwater abstraction has had significant consequences on the hydrodynamics resulted in sinkhole development. Firstly, pumping has accelerated the groundwater movement and the groundwater was forced to move toward the pit with high velocity. Secondly, the high transmissivity caused a very rapid expansion of the drawdown cone, which reached the foothill in a timeframe less than a month. Drawdown in the non-cohesive material triggered suffusion of the finer particles in the coarser material. The first sinkhole has developed close to the foothill because the overburden is thin and as soon as the drawdown reached this area, suffusion has initiated. The drawdown was much greater close to the pit. However, the material is cohesive and thick. Therefore, there had been a time lag between the drawdown and the development of cavities in the contact zone between the carbonate bedrock and the overburden. After about four months, the cavities were large enough to cause dropout of the cohesive material, which resulted in formation of the second and fourth sinkholes.

Conclusions

A model explaining the plausible mechanism of the progressive sinkhole development in a large open pit was proposed based on geological, morphological, hydrographic and hydrogeological conditions. Massive dewatering of the karstic bedrock aquifer was found to trigger suffosion in thin, non-cohesive overburden at a distance of radius of influence of the pumping wells. Closer to the pit, the thick cohesive soil was affected from dewatering with a time lag and the sinkholes occurred in this section are of drop-out type. Based on the model, it was possible to delineate a sinkhole-prone area.

The study has shown that consequences of dewatering can be hazardous and may appear short after the dewatering program commences. Therefore, it is of great importance to predict also the consequences of the suggested dewatering program in mining areas. This can be achieved by integrating the results of groundwater flow models with geotechnical models of subsidence and collapse.

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