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Susceptibility mapping for sinkhole occurrence by GIS and SSI methods: A case study in Afsin-Elbistan coal basin

CBS ve SSI yöntemleri ile obruk oluşum hassasiyetinin haritalanması: Afşin-Elbistan linyit havzası örneği

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Abstract

The major structural defects that cause the displacement in rock are discontinuities (fracture-joint-fault) and karstic cavities. Depending on the position and geometry of the karstic cavities, sinkholes occur both within the bedrock and in the cover layers. Occurance of sinkholes primarily depends on existence of carbonate rocks containing sub-surface karstic cavities and loose and weak cover layers. Following the landslides occured in 2011, it was planned to reduce the hydraulic head of the karstic aquifer which lies at the bottom of the coal-bearing layers in order to restart the mining activity in Afşin-Elbistan Coal Basin. For this purpose, dewatering wells were drilled in January 2015. Two weeks after the drilling, the first sinkhole occured at the southwestern edge of the basin and during the following six months four other sinkholes occured close to the first one. The geological, hydrological, hydrogeological and geo-mechanical models of the basin has been composed in order to understand the mechanism of sinkhole occurence in the Afşin-Elbistan Coal Basin. Thematic maps showing the spatial distribution of parameters which determine the formation of sinkholes were obtained by using a Geographic Information System (GIS) based analysis method. Analytical Hierarchy Process (AHP) approach, which is one of the multi-criteria decision-making analyzes, has been adopted in determining the impact and weight coefficients of each effective parameter which plays a role in occurance of the sinkholes. The Sinkhole Susceptibility Index (SSI) was calculated by using all parameters which were classified and weighted. The SSI refers to the susceptibility of sinkhole occurance. The higher value of the SSI means that the risk of potential occurrence of a sinkhole is high. Calculated SSI in the study area ranges from 9 to 110 and the higher values were obtained for the area corresponding to the margin of the basin where the sinkholes occurred.

Keywords: Karst, Coal site, Sinkhole susceptibility Index, Dewatering, Groundwater.

Öz

Kaya ortamlarda çökme türü yerdeğiştirmelere neden olan önemli yapısal kusurlar, süreksizlikler (kırık-çatlak-fay) ve karstik boşluklardır. Karstik boşlukların konum ve geometrilerine bağlı olarak hem temel kayada hem de örtü tabakasında obruklar oluşabilmektedir. Obruk oluşumu, birinci derecede, karstik yapı içeren karbonatlı kayaçların varlığı ve bunları örten gevşek ve zayıf malzemenin olup olmamasına bağlıdır. Afşin-Elbistan maden sahasında 2011 yılında yaşanan heyelanlardan sonra madencilik faaliyetinin yeniden başlatılması için kömürlü çökellerin tabanında bulunan karstik basınçlı akiferin hidrolik yükünün düşürülmesi planlanmıştır. Bu amaca yönelik susuzlaştırma kuyuları Ocak-2015 ayından itibaren işletmeye alınmaya başlanmıştır. Havza kenarında ilki, bu tarihten iki hafta sonra olmak üzere 6 ayda toplam 5 adet obruk oluşmuştur. Maden Sahasında obruk oluşum mekanizmasının anlaşılmasına ve potansiyel obruk alanlarının belirlenmesine yönelik olarak yoğun bir araştırma ve inceleme programı yürütülmüştür. Bu kapsamda havzanın jeomorfolojik, jeolojik, hidrolojik, hidrojeolojik ve jeomekanik modelleri oluşturulmuş ve hazırlanan veri tabanına eklenmiştir. Coğrafi Bilgi Sistemi (CBS) tabanlı bir analiz yönteminden yararlanılarak obruk oluşumunu belirleyen parametrelerin alansal dağılımını gösteren tematik haritalar hazırlanmıştır. Obruk oluşumunda parametrelerin etki derecesi ve ağırlık katsayılarının belirlenmesinde çok ölçütlü karar verme analizlerinden biri olan Analitik Hiyerarşi Süreci (AHS) yaklaşımı benimsenmiştir. Sınıflandırma ve ağırlıklandırma işlemi yapılan tüm parametreler kullanılarak Obruk Hassasiyet İndeksi (SSI) hesaplanmıştır. SSI değeri ortamın obruk oluşumuna karşı hassasiyetini ifade eder. Yüksek SSI değeri ortamın obruk oluşumuna karşı hassasiyetin yüksek olduğunu göstermektedir. İnceleme alanında en yüksek SSI değerlerinin havza kenarına karşılık geldiği belirlenmiş ve oluşan obrukların da aynı bölgede yer aldığı görülmüştür.

Anahtar kelimeler: Karst, Kömür sahası, Obruk hassasiyet indeksi, Susuzlaştırma, Yeraltısuyu.

1 Introduction

In unconsolidated geological environments, the drawdown of the groundwater level results in two different types of displacement: settlement and collapse. Effective stress increases due to the drawdown of groundwater level. As the effective stress increases, consolidation settlement takes place especially in cohesive grounds. Another factor causing the ground to settle down is the decrease in level of piezometric surface in the confined aquifers.

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If the (fine grained) material is transported (internal erosion) during the drop of water-level in aquifers, displacement occurs as a collapse. The major structural defects that cause collapse type displacements in rock environments are discontinuities (fracture-joint-fault) and karstic cavities. Depending on the location and geometry of the karstic cavities, sinkholes can form both in the bedrock and overburden on top. The occurrence of this type of sinkholes depends primarily on the existence of carbonate rocks with sub-surface karstic cavity and loose and weak cover layers [1].

Cases that control the formation of sinkholes associated with karstic cavities are:

i. Decrease of piezometric pressure in karstic cavity due to groundwater drainage,
ii. Transportation of fine grained material from the covering units to the karstic cavity,
iii. Increase in effective stress due to the drop of groundwater level in unconfined aquifer on top,
iv. Vertical stress exceeding the strength of the bedrock bridge above the karstic cavity.

Many sinkholes in central Anatolia were documented by previous researchers [2]-[6]. [6] investigated sinkhole susceptibility and the effect of sinkhole formation-related factors (FR) in vicinity of Karapınar, using the FR and the GIS. [6] concluded that most of sinkholes were related with the lowering of local and regional ground water levels in karst prone area.

It has been widely accepted that sinkholes can be classified in two major categories: sinkholes formed in the karstic rock (limestone, gypsum or salt), and sinkholes formed in soils overlying the karstic rocks [7]. Cover type of sinkholes (i.e., sinkholes formed in soils) are a more widespread geo-hazard. The occurence of cover type sinkholes is generally caused by the erosion, transport and failure of the soils that overlie cavernous rock. Because of its low strength compared to rock, which, if left over a cave can still be strong enough to stand for a long period, a soil arch over a void is inherently unstable and its collapse can occur rapidly. Their underlying mechanisms are extremely intricate and have traditionally received more attention from the geotechnical communities [8]-[11].

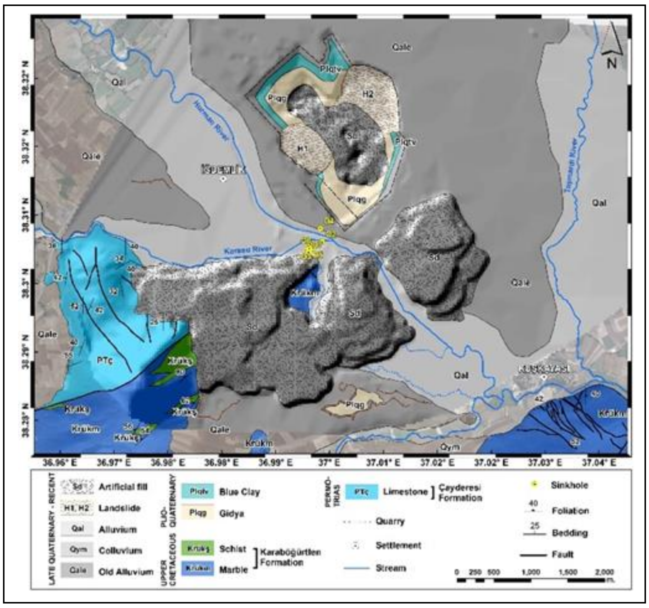
After experiencing landslides in Afsin-Elbistan Coal basin in 2011, in order to restart the mining activity, reducing the hydraulic head of the karstic aquifer, which is below the coal-bearing layers, was planned and wells for dewatering were drilled for this purpose. Following the dewatering studies, sinkholes occurred in the southwestern edge of the basin.

In this study; geomorphological, geological, hydrological, hydrogeological and geomechanical models the Afşin Elbistan Coal Basin (Figure 1) were generated and all models were added to a GIS database in order to analyze and understand the mechanism of sinkhole formation due to dewatering and also in order to map the potential locations of future sinkholes. [12], [13] and [14] remarked the determining parameters of sinkhole occurance mechanisms as; the presence of the karstic system, the thickness of the cover layers, the thickness of clay layers at the bottom and upper part of the stratigraphic section, the distance to the surface drainage channels, vertical hydraulic conductivity and loss of hydraulic head. In this study, an index, which describes the susceptibility of sinkhole formation, was calculated for areas where similar boundary conditions apply; and a map, which shows potential areas of sinkhole occurance in the study area, is produced.

Figure 1. Location of study area.

2 Geology and hydrogeology of the study area

The geological structure of the Afsin-Elbistan basin is studied in detail in order to understand the causes of sinkhole occurance in the basin. In addition to field observations, a large number of exploration and research pits were used to investigate both the cover deposits and basement rocks at the basin edge. The formation of the basin is related only to erosional and depositional processes with no tectonic events included. The absence of any morphologic lineaments or faults at the margins of the basin support non-tectonic origin of the basin formation. Paleozoic and Mesozoik rocks, which are mostly marble, limestone and calcshist, lie at the basement and also around the margins of the basin. Basement rocks are overlain unconformably by coal-bearing terrestrial and lacustrine Tertiary deposits. Both basement and Tertiary rocks are overlain unconformably by river deposits of late Quaternary-Recent (Figure 2a-b).



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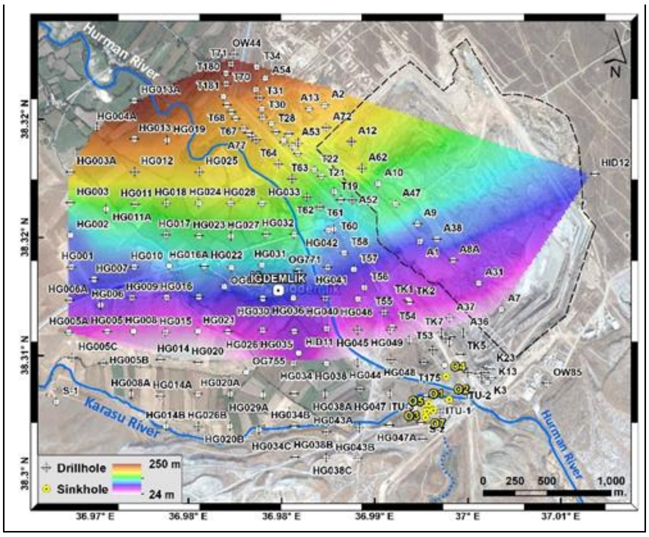


(b)

Figure 2. (a): Geological map of the study area. (b): Isopach map of Plio-Quaternary deposits [12].

The stratigraphic positions and lithological properties of geological formations in Afşin-Elbistan Coal Basin were studied and they were classified according to physical and hydrogeological properties. Both the aquifer properties and hydraulic parameters of hydrogeological systems were defined by use of pumping tests in exploration wells (Table 1).

Table 1 shows, that the green clay (base clay) as an impermeable boundary condition above karstic limestone does not continue toward to the edge of basin. Therefore, there is an interaction between the upper hydrogeological system and the karstic aquifer at the sinkhole area. The basement rock classified as a confined aquifer. The Coal-bearing deposits are semi-confined aquifer and alluvium deposits unconfined aquifer.

Table 1. Litologic and hydraulic properties of hydrogeologic systems [12].

Formation	Lithology	Hydrogeologic System and Hydrolic Conductivity-K(m/s)
Alluvium (Quaternary)	Young Alluvium	Coarse Unconfined Aquifer $3.10x10^{-4}$
	Old Alluvium	Poorly cemented Unconfined
Coal-bearing deposits (Plio-Quaternary)	Upper (blue) clay	Cohesive/Aquitard $1.00x10^{-7}$
	Marl	Consolidated/Aquitard
	Gyttja Coal	Coarse/fissured/Cohesive Semi Confined $3x10^{-7}$ – $0.90x10^{-6}$
	Base (green) clay	Cohesive /Aquitard $1.73x10^{-7}$
Clastic deposits (Eocene)	Alternating sandstone-claystone with sand and gravel interbeds	Coarse poorly cemented, fractured Confined Aquifer
Basement rocks (Mesozoic-Paleozoic)	Limestone Marble Schist	Karstified and fractured Confined Aquifer $1.00x10^{-3}$

3 Conceptual model of cover sinkholes

The conceptual hydrogeological model based on the field survey and boring is depicted in Figure 3. The main geological, hydrological, hydrogeological boundary conditions are represented in this figure. The interaction between aquifers after groundwater drawdown induced by pumping the water from karst wells. Karstified base rock and shallow karstic cavities in it are also taken into account. When new dewatering K wells put into operation, the drawdown within the edge of basin is lowered and pore water pressure decreased sharply. As a result the turbulent flow has occurred and the groundwater flows turned to vertical direction around the sinkhole area. The water pumped from confined aquifer flowed throughout cavities being inside the base rock and its velocity has been considerably increased.

From the site survey on the southwestern slope and sinkhole walls behind the Çöllolar Open Pit, it is understood that the river alluvium and slope wash deposits have high permeability. The main branches of the drainage network on the surface, the exploration boreholes and the morphology indicate the young and unconsolidated alluvial deposits have considerable thickness in area where sinkholes occurred (Figure 3).

In order to control the conceptual model shown in Figure 1, a research pit (AÇ-1) was excavated to control the flow direction and level of the groundwater in area where the sinkholes were developed. The groundwater level measured in this pit was compared to Kurudere's water level between the pit and the dewatering well. It was noticed that the water level elevation in Kurudere (1157.23 m) is higher than that of AÇ-1 (1156 m). The same comparison was also repeated for the level at İTÜ-3 and the nearest point of Kurudere.

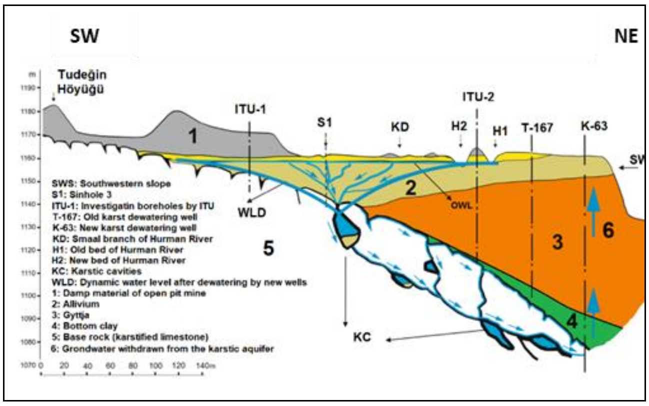


Figure 3. Schematic description of conceptual model, interaction between unconfined and confined aquifers at the edge of basin after dewatering operation [12].

4 Boundary conditions

4.1 Sinkhole susceptibility index (SSI)

The basement rocks are represented by a karstic system on the south-western boundary of the Afsin-Elbistan Coal Plant. A GIS based analysis method was used to determine and to map potential areas of sinkhole occurance in case of a reduce in hydraulic head of this karstic system. The field observations on the south and south-western parts of the Çöllolar Section-B revealed that the bedrock limestones involve karstic cavities of significant size. Because the exact location and the size of the karstic cavities were undefined, they were not included in the analysis of sinkhole susceptibility analyzes.

Analytical Hierarchy Process (AHP) approach, which is one of the multi-criteria decision-making analyzes, has been adopted in determining the impact and weight coefficients of each effective parameter which plays a role in occurance of the sinkholes [15]. Six parameters, which have a major affect on the formation of the sinkholes on the south-west of the open-pit mine, and their range of class (RC), rating values (RV) and weight coefficients (W) are listed on Table 2.

The Sinkhole Susceptibility Index (SSI) can be calculated by the formula below, by using all six parameters which were classified and weighted (Equation-1).

$$SSI = RV_1 \times W_1 + RV_2 \times W_2 + RV_3 \times W_3 + RV_4 \times W_4 + RV_5 \times W_5 + RV_6 \times W_6 \quad (1)$$

Table 2. The parameters that control the formation of sinkholes in Afşin-Elbistan coal basin and their class ranges, rating values and weight coefficients.

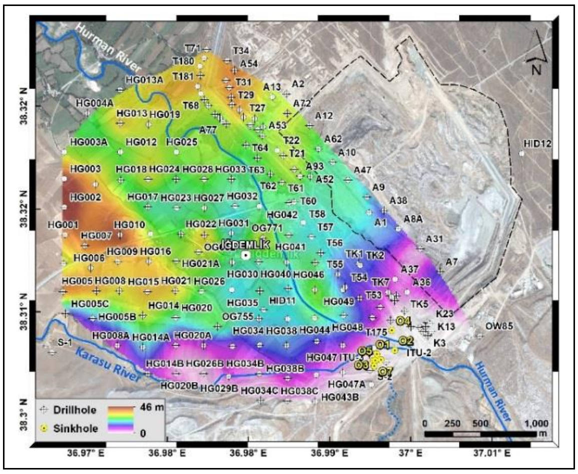
Layer	Parameter	Range of class (RC)	Rating Value (RV)	Weighted Coefficient (W)
K1	Plio-Quaternary Thickness (m)	>150	0	5
		150-100	1	
		100-75	3	
		75-50	5	
		<50	7	
K2	Thickness of Upper Clay (m)	>10	0	2
		10-5	1	
		5-3	3	
		3-1	5	
		<1	7	
K3	Thickness of Base Clay (m)	>20	0	4
		20-15	1	
		15-10	3	
		10-5	5	
		5-1	7	
		<1	9	
K4	Distance to Surface Drainage Network (m)	>100	0	1
		100-75	1	
		75-50	3	
		50-25	5	
		25<	7	
K5	Vertical Hydraulic Conductivity (m/sec)	$<3x10^{-7}$	0	3
		$3x10^{-7}$-$5x10^{-7}$	1	
		$5x10^{-7}$-$8x10^{-7}$	3	
		$8x10^{-7}$-$1x10^{-6}$	5	
		$>1x10^{-6}$	7	
K6	Hydraulic Head Loss in Confined Aquifer (bar)	>0.6	0	3
		0.6-0.9	1	
		0.9-1.2	3	
		1.2-1.5	5	
		1.5-2	7	
		2-3	9	

4.2 K1) The thickness of plio-quaternary cover

The coal-bearing Plio-Quaternary deposits in Afsin-Elbistan Coal basin are poorly cemented, fine grained (>% 80) and water-saturated. The isopach map of Plio-Quaternary deposits is given in Figure 3b. The inverse relation between the increase in thickness of Plio-Quaternary deposits and occurance of sinkholes is calculated by scoring in the assesment. The weight coefficient of this parameter is determined as 5 (Table 2).

4.3 K2) the thickness of upper (Blue) clay

One of the parameters that determine the occurence of sinkholes is the natural and artificial recharge of the cover layer, which are by precipitation and by infiltration in agricultural areas in Çöllolar site. There is a clay layer, which is blue in color and reaching up 20 m in thickness, below the cover layer (Figure 4a). The blue clay layer is named as "Upper Clay" in this study. It is observed that the Upper Clay layer was eroded and is missing in some areas and the cover layers (alluvium) are settled above the gyttja layer. In this case, the river Hurman, which runs through the south of the sector, directly feeds the gyttja layer. The inverse relation between the thickness of Upper Clay and the feeding of gyttja layer is taken into account in the analysis (Table 2).



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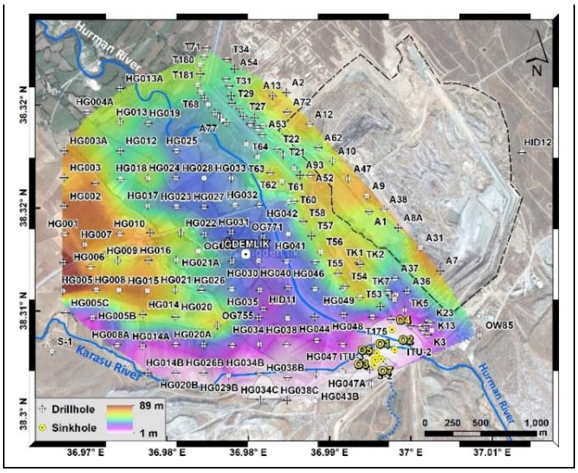

(b)

Figure 4. (a): Isopach map of the upper clay. (b): Isopach map of the base clay.

4.4 K3) The thickness of base (Green) clay

The calcereous bedrocks and Eocene clastics are widespread and rich confined aquifers and overlained by a clay layer which is green in color and reaching up 90 m in thickness (Figure 4b). This clay layer is named as "Base Clay" in this study. Base Clay is the bounding layer for the anaerobic conditions which ease the coal formation and maturation within the Plio-Quaternary layers. It also forms a boundary condition as an impermeable layer above the confined aquifer at the bottom. Moreover, the Base Clay causes a delay in the possible hydraulic connection between the lower and upper aquifers during the pumping studies for reducing the hydraulic head of the karstic aquifer in the region. The Base Clay is absent in the region where the sinkholes occured following the dewatering studies on February-2015. This region corresponds to the basin edge where the unconfined upper aquifer (Alluvium) and Hurman River interference with confined lower aquifer directly. An increase in the thickness of the Upper Clay, which forms the critical boundary condition, would decrease the interference. So, this situation has been taken into account in susceptibility assesment (Table 2).

4.5 K4) Distance to surface drainage network

Hurman River and Karasu River controls the surface water drainage in the study area (Figure 3a). Both rivers are fed by precipitation in the basin and by karstic carbonate rocks that are wide-spread exceeding the basin boundaries. Surface water feed the alluvium aquifer in lowlands [16] and [17]. However, the flow rate of Hurman River exceeds 10 m^3/s in rainy season. During the flood, there is a loss of water from the surface flow in the sections where the stream bed consists of permeable geological units [18].

In this study, depending on the level measurements in observation wells (during pumping tests) in karstic system it is determined that there is a flow from surface water to the sinkhole area (karstic system) in ground water [12].

4.6 K5) Vertical hydraulic conductivity

The flow and velocity of groundwater depends on the porosity of hydrogeological system, hydraulic conductivity and hydraulic gradient rather than the properties of water. The vertical hydraulic conductivity, as well as the horizontal conductivity, has an importance in numerical groundwater flow models and in analysis of sinkhole occurance. The hydraulic parameters of the lithologic units in the study area has been compiled from previous studies [18] and controlled by the pumping tests which were performed during this study. The vertical hydraulic conductivity has been taken into considaration as another parameter in sinkhole susceptibility analysis of Çöllolar Sector (Table 2).

4.7 K6) Hydraulic head loss in confined aquifer

It is known that the sinkholes in the study area occured after the operation of the wells (labelled with K in Figure 5) which were drilled in order to decrease the hydraulic head of the karstic aquifer. Depending on this, the hydraulic head loss has been used as one of the parameters of sinkhole susceptibility analysis. The hydraulic head loss between the primary piezometric levels, which were measured in karstic wells before pump tests, and the lowest piezometric level on 30th June 2015 were calculated and equal hydraulic head loss map is prepared depending on these calculations. Figure 5 shows the groundwater level and flow direction in June 2015.

The weight coefficients and impact degree of class ranges of above parameters in sinkhole occurence is given in Table 2.

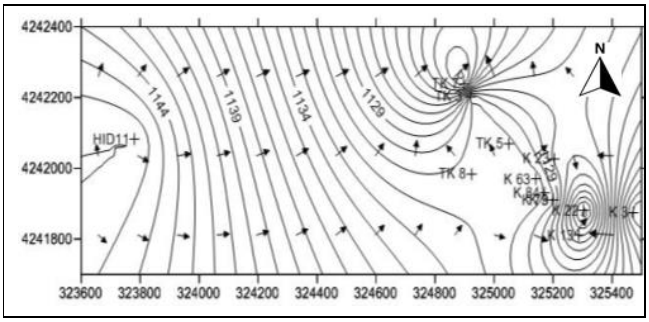

Figure 5. Groundwater equipotential map in June 2015.

5 Susceptibility analysis

Depending on the defined parameters (K1-K6), thematic maps of the study are were prepared in ESRI ArcGIS software. By using the raster math tool of ArcGIS, Sinkhole Susceptibility Map was composed based on the calculations of overlapping thematic maps (Figure 6).

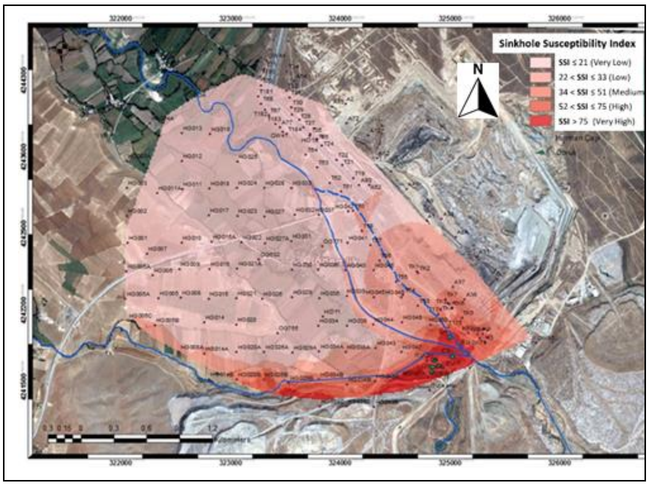

Figure 6. The Sinkhole Susceptibility Map of soutwestern part of Çöllolar Open-pit Mine (12).

The Sinkhole Susceptibility Index (SSI) was calculated by using all parameters which were classified and weighted. The SSI refers to the susceptibility of sinkhole formation (Table 3).

Table 3. The sinkhole susceptibility Index of Afşin-Elbistan coal basin.

SSI index	Susceptibility	Area (km^2)	Area (%)
SSI ≤ 21	Very Low	4.7	68.18
22 < SSI ≤ 33	Low	0.88	12.51
34 < SSI ≤ 51	Medium	0.82	11.69
52 < SSI ≤ 75	High	0.31	4.41
SSI > 75	Very high	0.22	3.20

The higher value of the SSI means that the risk of potential occurrence of a sinkhole is high. In other words, high SSI indicates that the susceptibility of sinkhole formation is also high. Calculated SSI in the study area ranges from 9 to 110 and the higher values were obtained for the area corresponding to the margin of the basin where the sinkholes occurred.

The red areas on the map in Figure 6, presents the areas that has a high susceptibility in terms of sinkhole formation. This region also corresponds to the areas of the basin edge where there is no Upper Clay or Base Clay and the thickness of the Plio-Quaternary units are low. The assesment reveals that the susceptibility is low in the regions where the Upper Clay and Base Clay is thickest and the loss of hydraulic head is low.

6 Results

In this study, a GIS-based analysis was performed to identify potential areas of sinkholes to occur in case of a decrease in piezometric head of the karstic system which is located on the southwestern boundary of Çöllolar Open-pit Mine in Afsin-Elbistan Coal basin. Analytical Hierarchy Process (AHP) approach, which is one of the multi-criteria decision-making analyzes, has been adopted in determining the impact and weight coefficients of each effective parameter which plays a role in formation of the sinkholes. Sinkhole Susceptibility Index (SSI) were calculated by assessing all parameters which were classified and weighted. Calculated SSI indicates the susceptibility of the location to sinkhole formation. The higher SSI means that the risk for sinkhole formation is high. Increase in SSI refers to an increase in susceptibility of sinkhole formation, and decrease in SSI refers to a decrease in susceptibility of sinkhole formation. In this study, the calculated SSI of Çöllolar Open Mine site ranges between 9 and 110. The highest SSI in the study area were calculated in the southern part which also correponds to the basin margin. In this region, the thickness of Plio-Quaternary units are low and the Upper Clay-Base Clay is missing in the stratigraphical sequence.

As a result of this study; it is determined that the susceptibility of sinkhole occurence is low in the areas where the thickness of Upper Clay, Base Clay and Plio-Quaternary units are high and the hydraulic head is gradually low in Afsin-Elbistan Coal Basin.

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