Chapter

Identification and Assessment of Hazard of Development in Gypsum Karst Regions: Examples from Turkey

Sevda Özel

Abstract

This study includes natural hazards and environmental problems caused by gypsum on and near the soil, water, and structures. These are karst-specific deformations (caves, fractures, cracks) naturally occurring in gypsum areas, and the problems of salinization, corrosion, erosion, soil and water pollution that occur as a result of dissolution caused by the contact of gypsum with water. In particular, it has been determined that various transfer routes/lines that facilitate human life cause problems on substructures/superstructures resulting from their passage in gypsum areas or on substructures/superstructures (road, buried pipe, building) resulting from the spread of urbanization on this unit, and these have various risks. As a result of these events that have been proven by various studies, it has also been observed that gypsum causes natural hazards and has environmental impacts on human/plant/animal life and living environments and it has also been determined that the quality and sustainability of life/living environment decreased. Therefore, in this study, it has been put forward that gypsum areas pose a risk for the life of all kinds of living beings and that the choice of gypsum areas in the site selection for urbanization will always be risky with respect to natural hazards and environmental problems.

Keywords: gypsum, karst, Sivas (Turkey), natural hazard, environment

1. Introduction

The gypsum unit is one of the evaporite units that can be easily dissolved when it contacts with water in nature. Furthermore, gypsum units are geological environments with karstic characteristics as limestone unit, and all karstic structures can also develop in gypsum units. Therefore, gypsum areas are the sources for pollutants with inorganic characteristics, and geologically they also include geological structures that develop specifically to karstic areas. Moreover, gypsum areas are risky geological environments where natural hazards may occur in the case of the presence of settlement areas or human-made structures (building, road, substructure systems, etc.) on them [1–3]. For these reasons, gypsum is an important evaporite unit that should be taken into account in terms of both natural hazards and environmental problems and urbanization. Therefore, gypsum units cause negative effects on soil infertility and ground/surface water quality due to problems such as dissolution, salinization, erosion, and corrosion that directly occur in nature [4–6]. On the other hand, the rapid construction that comes with urbanization requires new settlement areas. Therefore, there are also constructions on gypsum units [3]. The reason why it is considered that gypsum areas will cause significant environmental problems in the future is natural hazards and environmental problems that will arise in the event when gypsum is mainly surfaced or very close to the surface especially in new places opened for settlement, as required by karst geology. This also suggests that there will be risks for the life of humans and living beings and that these risks will increase, especially in these kinds of areas in the future, along with the opening of an area consisting of evaporite units for construction. Geological structures specific to gypsum karst lead to the formation of caves/areas causing the danger of collapse under the ground of the building and also collapses along with the fact that dissolution caves and dissolution channels are merged over time and create large galleries. As a result of these events, concrete materials, pipes, and cable systems of buildings and substructure systems are damaged. This also means that substances that may leak liquid and gas are mixed into the soil, water, and even into the atmosphere or that there are energy losses. Thus, there will also be economic losses. For this reason, it was considered necessary to draw attention to the problems originating from gypsum, while they are examined with environmental problems and soil and water pollutions on the issues for environmental monitoring purposes, and these problems should not be ignored [5].

When natural-origin environmental problems described above are considered, it is essential to reveal the geological, engineering, hydrogeological, and environmental impact models of the environment in the site selection for settlement purposes and in the site selection of other human-made constructional areas [7, 8]. Therefore, various maps on different topics and scales that define the gypsum area from all aspects and geological/geophysical sections of various sizes are prepared by the relevant experts and scientists [3, 9–16]. Thus, gypsum areas can be defined in detail by using mineralogical-petrographic and structural properties of geologically lithological units, their degree of weathering, geophysical-hydrological-physicomechanical properties, and meteorological status, and other surface and underground research methods. With these studies, risky areas at the horizontal-vertical or shallow-deep dimensions can be determined by preparing reports and maps to take precaution for natural hazards and environmental impacts. According to the results found, new and future sustainable planning and preparations can be made for these issues. Then, human/plant/animal health and their living environments can be maintained in a sustainable manner. Therefore, the problems of erosion and pollution may be reduced more effectively with the measures to be taken. In conclusion, all these issues were examined in this study.

2. Natural hazards environmental problems in gypsum karst regions

2.1 Regional features of gypsum karst morphology in the study area and its surroundings: examples from Sivas (Turkey)

Karst is a morphological term and it is important to analyze karst morphology in terms of natural hazards, because the gypsum unit is a type of karst and can be solved if it contacts water. Gypsum can transform to anhydride as a result of geological and atmospheric processes in near-surface karsts, or vice versa. In other words, with the introduction of water into the anhydrite structure through these processes, an anhydrite unit can transform into a gypsum unit. These transformations also occur in the Hafik Formation, in Sivas (**Figure 1a**). The Hafik Formation is an Oligo-Miocene aged unit presenting wide spread in the Sivas evaporite basin and mostly consisting of massive gypsums [17–19, 20]. Upon examining **Figure 1a**, it is observed that the Sivas tertiary basin shows a northeast-southwest extension [21]. On the other hand, this basin starts from Gemerek in the southwest of Sivas and extends along the Sivas center, Hafik, Zara, and Imranlı. In **Figure 1a, b**, the study area is located in the Sivas basin and occurs from the Hafik Formation. This basin is one of the largest Central Anatolia basins, which was formed in the collision zone and is located in the most important gypsum karst area of Turkey. However, the areas of gypsum outcrops occur in Central and Eastern Anatolia, and gypsum formations are found mostly in Ankara, Çankırı, Çorum, Kırşehir, Kayseri, and Sivas regions (**Figure 1a**). In addition, dissolution dolines are found in the youthful karst areas between Sivas and Zara; some of the most important collapse dolines are found in the mature karst area between Hafik and Zara [15, 20, 22, 23, 26, 27]. The dolines on gypsum have solution and collapse characteristics, and it was observed that population rates were low in these areas [24]. According to the study by Hadimli and Bulut (2000) because of the dense surface karst in these gypsum areas is observed; these areas do not offer suitable environments for human life. Therefore, in Turkey, in areas where macrokarst structures (poly, uvala, doline) are observed, even despite a continuous population, it has been observed that the areas with microkarst structures (lapya) observed are used periodically [24]. Furthermore, in karstic fields, karstic structures (such as doline bases) are used for agricultural area needs (due to need), although they do not show high agricultural potential. In particular, large doline-based areas around

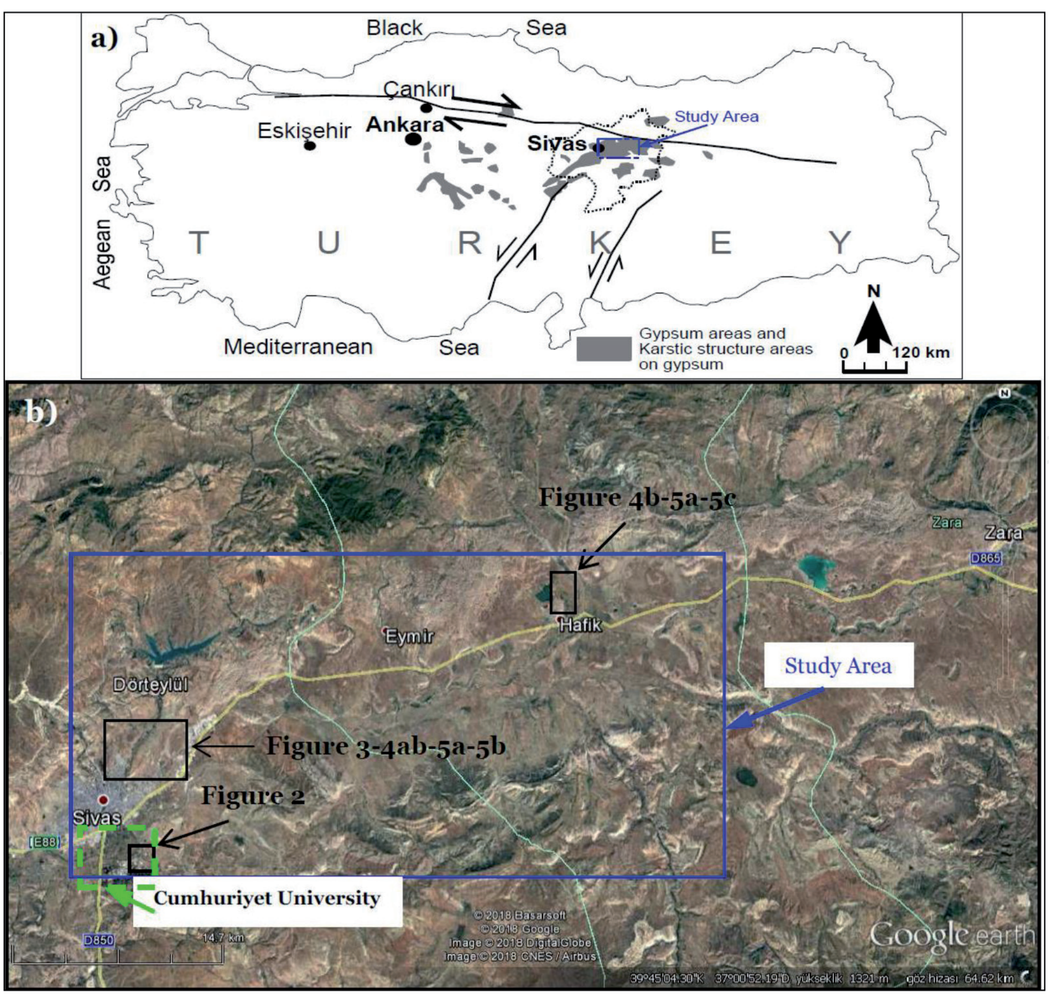

Figure 1.
(a) Study area (rearranged from [23, 25], and (b) the locations of figures (arranged from Google Earth, 2018, August 12, 2018)).

Hafik (Sivas) and Zara (Sivas), developed in different sizes and gypsum formation, are used for agricultural production [24, 25]. However, these lands are also used as settlement area, forest area, pasture area, natural parks, natural sports and tourism resort area, raw material acquisition (e.g., plaster, cement industry), and mining area [24].

The sudden generation of collapse dolines in areas underlain by gypsum constitutes great danger for both lives and property. Karst features, such as sinkholes, near-surface caves, and collapse structures, which are formed in water-soluble rocks, constitute potentially serious hazards. Groundwater in karst areas is an important resource, which needs to be developed and protected [23]. Water percolates over or through gypsum and dissolves the highly soluble rock; and this causes the formation of sinkholes, caves, natural bridges, disappearing streams, and springs. Thus, natural hazards include damage and/or collapse of houses, buildings (such as dams, bridges, highways, and farmlands) [26, 28]. Such events can cause great economic hardship, disruption of lives, and even loss of life. Conclusively, the study area is located on the gypsums on the Hafik Formation and geologic units with gypsum intercalation (**Figure 1a**). Therefore, karst structures such as fractures, cracks, dissolution caves, and deterioration areas specific to karstic areas are very extensive in these units. Moreover, the geological formation of the study area does not change, the Hafik Formation and karstic structures in this formation continue throughout the study area [3]. The full ranges of gypsum-karst features are present in the region, and there is a number of striking examples of karst hazards and environmental problems [26, 28, 40].

Therefore, collapses in karst terrains constitute very serious geological hazards and can damage engineering structures and cause groundwater contamination [29]. In these areas, very shallow soil could develop, or there is no soil development, and the outcropped karstic area is open to external factors and processes. Therefore, this unit mainly consisting of massive gypsum and gypsum interfingered fractured rocks has a structure that is easily dissolved under the impact of atmospheric processes [6]. Thus, cracks and intense joint systems in various directions have developed in gypsums of the Sivas basin. These are causing the fall of rocks (blocks) in parts where bevels are steep at rocks [13]. These natural hazards and their environmental problems are common in Sivas.

2.2 Natural hazards and environmental problems caused by gypsum areas

Natural hazards and environmental problems that occur in gypsum areas depending on the karstic characteristics of a gypsum unit and the geochemical, hydrogeological and atmospheric characteristics of its mineralogical composition may lead to different effective problems in human/plant/animal health and their living environments. Every detail is important in urban planning since the selection of gypsum areas as new settlement areas will cause problems in planning studies that increase with urbanization. These problems can be listed as foundation and drainage works in unplanned/out-of-plan construction works, constructions, which cannot be completed on time, safety problems that may arise due to the wrong material selection, and enabling the formation of new pollution areas [5, 30, 31]. While making site selection in these cases, if there is an area, which is zoned or will be zoned for construction, planning will be different according to them in the works to be done. Therefore, the reduction of costs and the correct orientation of investments can be ensured by examining the issues related to site selection and very large-scale events. Another important issue is related to carrying out scientific studies because different preparations will be made with different studies in site selection depending on the geological characteristics of gypsum, the parcel size of the building to be constructed, and building types. First of all, since the size of the area where the structure will be placed is different or the load to be imposed on the ground will be different depending on the size/number of floors of the buildings to be constructed, methods are selected accordingly and survey studies are initiated. If works are completed with correct planning when it comes to site selection, the gains brought along by them will be too much. However, in gypsum areas, the following natural hazards and environmental problems are generally observed.

2.2.1 Leachate waters

Surface waters or groundwaters contacting with gypsum lead to the dissolution of gypsum. Thus, the concentration of ion dissolved in water increases, and the water transmitted threatens the soil fertility and the life of living beings by leaking into the soil in the areas where it transmits. Furthermore, the waters brought by precipitation through washing the surfaced gypsum impair the quality of potable or tap waters and soil quality by mixing into surface waters and leaking into underground waters. In urban areas, corrosion, salinization, mineral transformation, and dissolution cause damage to the ground and structures in places where building foundations and substructure systems exist. As a result of this, safety problems arise in buildings or on the ground (**Figures 2–5b,c**). For example, hazardous leachate waters or gases in buried pipes damaged by corrosion erosion may mix into the soil and then underground waters, which means the formation of a source of pollution [5, 6].

2.2.2 Subsidence/collapse/rock (block) fall

If site selection is made or construction areas are selected for settlement purposes without getting engineering service, the problems of ground subsidence in gypsum areas, and rockfall in collapse areas and slope areas can be observed (**Figures 2a, b, 3b** and **5b, c**) [3]. They have a negative impact on human life and lead to material and moral losses. For example, subsidence and cracks occur in foundation ground due to dissolution in the gypsum unit (with the contact of leachate water), and this may cause damage to buildings. However, the rockfall constitutes a safety problem (e.g., in road, highway, and railway routes) [13] (**Figure 3b**). Consequently, various structural damages (cracks, dissolution, collapse, sinkholes,

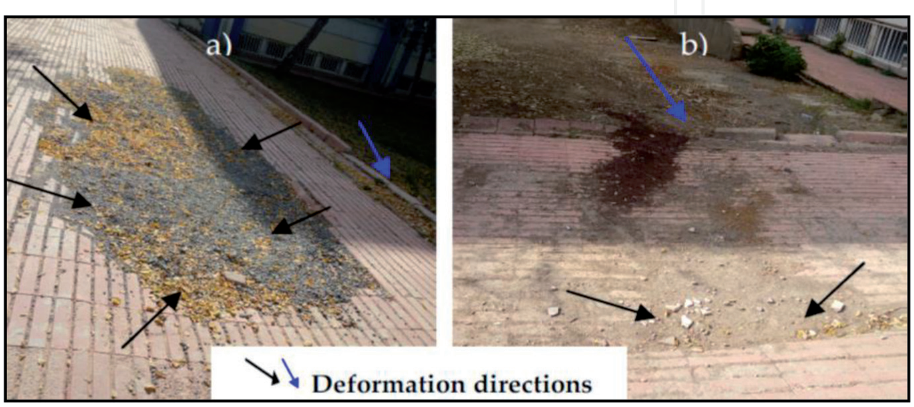

Figure 2.
Gypsum-based ground deformations in the southeast Sivas city (Turkey) (photos: Sevda Özel, 2018). (a) As the setting-collapse increases, the cavity (~1.0 × 2.5 m²) is filled with fill material (as a temporary measure) and (b) a newly formed dissolution area under the pavement (~0.3 × 0.5 m²).

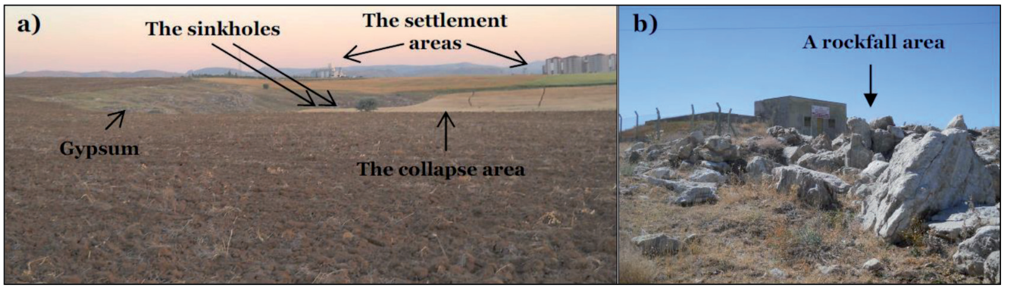

Figure 3.
Gypsum-based karst deformations in Sivas (Turkey) (photos: Sevda Özel 2013, 2015). (a) The collapse area, sinkholes, and the gypsum clastic soils in the east and northeast of Sivas. (b) The rockfalls in the northeast of Sivas.

doline, erosion, corrosion, rockfall, etc.) arise and are observed in the structures of the building (**Figures 2–5b, c**).

2.2.3 Health and living environment of living beings

Vegetation losses also occur with soil salinization occurring with leachate waters containing the high amounts of dissolved ions mixing into the water from gypsum as a result of the contact of gypsum with water in cover units on the edges or on gypsum. In this case, erosion may occur in these regions over time (**Figures 4a** and **5b, c**). Therefore, all living beings including humans, and their living environments are damaged by these losses. Hence, low water-soil quality decreases and destroys the nutritional sources of living beings; soil-water pollution, as well as inadequate nutrition conditions, affect the health of living beings, and plant species may become extinct or decreased due to erosion (**Figure 4a, b**). Similarly, living beings may have to migrate to living environments where healthier and better opportunities exist. The health and living environments of living beings are impaired with these exposures in the dimension of the environmental problem.

While discussing the dimensions of environmental impacts in terms of the settlement by reviewing the detailed characteristics of the environment, hydrogeological and hydrogeophysical investigations are important in this regard. In particular, it is necessary to perform well-planned field studies that determine shallow and deep geological/geophysical, hydrogeological and environmental impact characteristics of the gypsum karst region. Whether the Environmental Impact Assessment (EIA)/Strategic Environmental Impact Assessment (SEIA)

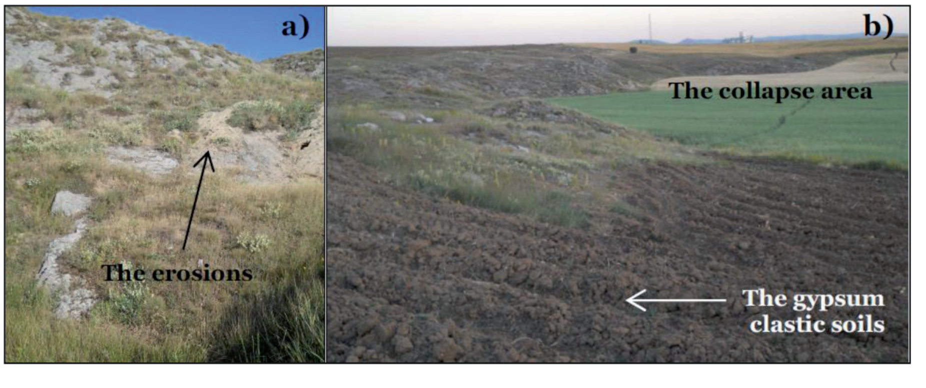

Figure 4.
(a) The erosions in the east of Hafik-Sivas (Turkey) (photo: Sevda Özel, 2013). (b) The gypsum clastic agricultural soils in the east and northeast of Sivas city (Turkey) (approximately 1–2 km away from the city) (photo: Sevda Özel, 2013).

is required, the identification of aquifers, the calculation of aquifer hydraulic parameters, and underground water-surface water information (feeding-discharge zones, the rate and direction of the flow of underground water, underground water level, the amounts of seasonal variations, hydrogeochemical properties of underground water and leachate waters, and underground water level maps) are necessary.

The geological stratification status (thickness, depth, slope, topographic changes of layer limits, geological and geophysical parameters) should be calculated. In the detailed investigation of karst geomorphology, the necessary attention should be paid to the seismic activity status, seismic activity history, and meteorological and morphological characteristics of the region. With these studies, the limits of hazardous areas and the risks can be determined after geological-hydrogeological-hydrogeophysical characteristics of the environment are determined in site selection. Therefore, it is important to define geological environments well and choose the right calculation method in terms of the environmental impact analysis and the measures to be taken. In addition to these, these regions are also monitored periodically by monitoring network and sampling methods designed based on the success and environmental impact of measures taken according to detailed engineering geology/geophysics and environmental geotechnical inputs, and engineering properties of the field, as a result of the environmental impact assessment [4–7, 32]. Thus, control mechanisms, management style, and other plans/projects can be prepared to take measures against risks and dangers within a scientific framework. Furthermore, site selection, natural hazards, environmental problems, and the monitoring studies of them show that it is necessary to maintain joint research with the relevant engineering and other disciplines and that the increase/improvement of environmental protection laws is important. Therefore, it will be important and useful to ensure that studies are not limited only with the top surface and subsurface studies and that necessary attention will be paid to shallow and deep investigations. Based on this idea, the examples of the creation of living environments that are less affected by gypsum-induced events will increase. Moreover, it should be taken into account that natural hazards and environmental impacts caused by gypsum are not only those that appear on the Earth's surface and that there may also be ongoing problems under the ground. Accordingly, when natural hazards and environmental impacts specific to gypsum areas are examined, environmental problems and natural hazard/risk situations caused by gypsum in the site selection for settlement purposes and in the site selection of other human-made construction structures are listed below:

2.2.3.1 Mineral transformations

These transformations constitute an important environmental problem for deformations resulting from volume expansion and especially for settlement areas (such as structural damage) and agricultural-water areas. In addition to gypsum ($CaSO_4 2H_2O$), which is one of the minerals of the evaporite group, anhydride ($CaSO_4$) and other minerals of the evaporite group are easily soluble when they contact with water (**Figure 5a–c**).

In the event of the loss of water in the environment, these minerals may be recrystallized, new minerals may be formed by the displacement of ions, or minerals may transform into each other. For example, as gypsum ($CaSO_4 2H_2O$) absorbs heat (as temperature increases) depending on climate conditions, it loses water and may transform into gesso ($CaSO_4 \frac{1}{2} H_2O$) and anhydride ($CaSO_4$) units, respectively [3]. On the other hand, the melting temperature of gypsum is very high (about >100°C or about 700–1500°C), the dissolution temperature of gypsum

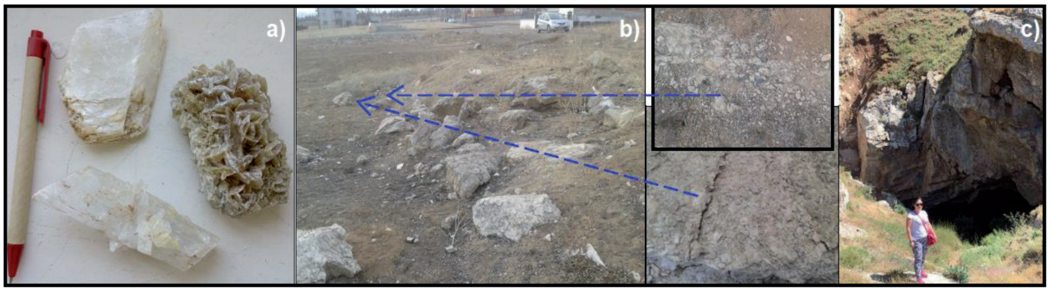

Figure 5.
(a) Gypsum samples collected from the northeast and south-southeast of Sivas (Turkey) (photo: Sevda Özel, 2005, 2007, and 2010). (b) Surfaced gypsum in the northeast of Sivas (Turkey) (photos: Sevda Özel, 2015) (c) Gypsum karstic deformation structures (cave, fracture, crack, collapse) from Hafik Formation in Sivas (Turkey) (photo: Sevda Özel, 2017).

is very low (about 0–50°C) [33–35]. For example, the solubility of gypsum in pure water at 20°C is 2.531 g/L [34, 36]. Gypsum is about 10–30 times more soluble than limestone, and it commonly has a lower mechanical strength [3, 15, 23, 33, 34]. However, between 0 and 30°C, the range encompassing most natural waters, the solubility of gypsum increases by 20%, reaching a maximum (about 2.66 g/L) at 43°C [34]. Therefore, sudden collapses in gypsum areas are a great danger for both life and property [3]. Therefore, the quality of water in the basins where the rock types formed by these minerals dominate is easily impaired, and surface and underground waters in which evaporite group minerals are dissolved are naturally polluted [4, 6, 38]. These polluted waters also pollute fertile soils if they leak into the soil.

Evaporite units tend to expand and swell depending on their origin, and these unites may also involve areas where underground waters are collected, and the sources where underground waters rise to the surface [3]. Upon examining **Figure 1** it is observed that, a shallow or deeper ground cover may develop or soil development may not occur at all in these areas. If the karstic area is surfaced, these areas are open to external factors (e.g. precipitation, wind, temperature) and processes (e.g. dissolution, erosion, deterioration). In this case, cracks in various directions, dense joint systems, melting areas, and various karstic structures begin to occur in gypsum areas. Moreover, larger fractures or new faults may occur as a result of seismic activity and collapse events. Furthermore, rock (block) fall events may also occur in rocks where slopes are perpendicular [12]. According to all these geological characteristics, significant ground problems are encountered in the existing buildings in the area or during and after new construction with the use or selection of gypsum areas as settlement areas (**Figure 1a,b**). These areas should be included in the class of areas with risky areas, especially if such areas continue to be selected as new settlement areas.

2.2.3.2 Pollution

There is always a risk of pollution in soil and underground/surface waters in gypsum areas. This pollution problem takes place as a result of salinization. Gypsum units may lead to salinization by ion decomposition resulting from the contact with water. Waters with the intense ion content formed during salinization threaten underground waters, surface waters, soil quality, and the life of plants, animals, and humans in the places of their passage, as leachate waters. In other words, leachates are the waters containing inorganic pollutants, and they also interact with other materials. This also reduces the existing underground/surface water quality and decreases the soil fertility, plant diversity, and the acquisition of fertile product [5, 6, 24, 27, 29]. The pollutants mixed in the soil also affect living beings in the soil, plants that grow/are grown in the soil, or living beings fed with these plants.

2.2.3.3 Ground damage

Since gypsum units geologically have swelling-expansion characteristics due to their mineralogical structure, they cause swelling in the ground. Thus, ground and structure deformations caused by the swelling of gypsum grounds, and material damages occur on superstructure grounds and in substructure systems (**Figures 2a,b** and **5b**). In these situations that endanger the safety of buildings, the life of human and living beings will also be under risk due to the safety problem (**Figure 2**). On the other hand, gypsum units may also be covered with alluvial units in some places. In this case, similar ground swelling problems may occur if units with swelling properties like clay are found in the alluvial filling material. Therefore, it is necessary to control leachate and underground waters in the construction areas in both cases.

2.2.3.4 Corrosion

Corrosion may occur on the grounds of gypsum areas and in the immediate vicinity of them, and in structures (**Figure 5b**). In particular, there is a corrosive effect on installation, building foundation, and substructures. It leads to rapid deterioration, and rusting and corrosion of materials in buildings and substructure pipe systems. Underground corrosion results from chloride (Cl) dissolved from the evaporite units in the caves in the soil, sulfate salts (SO_4), and dissolved gaseous oxygen (O). As a result of the fact that these dissolved ions cause stress difference in metal and electrolyte, they are oxidized to the metal ion in the anode or realize the corrosion (on the micro- or macroscale) event by passing into the solution as a metal ion [39]. Therefore, corrosion is one of the environmental problems arising from the gypsum unit since it causes damage to structures, building systems, and soil.

2.2.3.5 Karst structures

They pose a threat to people and structures or to agriculture and water areas in and near settlement areas in places where karst-type structures such as fractures/cracks, dissolution caves, and dissolution channels develop [28, 40] (**Figures 2–5b,c**). In the regions with intense collapses, hazardous areas that cause a safety problem for human and other living things emerge. Furthermore, agricultural areas, water resources, road routes, as well as settlement areas are also damaged. Therefore, a safety problem exists not only in settlement areas and in the immediate vicinity of them but also outside of them, and it affects the lives of all living beings. Furthermore, these problems also pose risks to national economies.

2.2.3.6 Seismic activity

It is also important to monitor seismic activity in and around these areas. In a region which is active in terms of seismicity, fractures, faults, and subsidence dissolution caves/areas in gypsum units, and changes in underground water levels should be monitored because new deformations may develop over time and new dissolution caves/areas may also occur (**Figures 1a** and **5b, c**).

New problems will be added to the existing problems if all these natural and environmental factors that have an impact on the sustainability of the environment and the quality of life of all kinds of living beings are not determined, and hazards, risks and other problems that may arise are not kept under control in time. Therefore, the attempts of regional or local authorities to maintain environmentalist works, as well as at the dimension of countries, and the compliance with the EIA/SEIA reports in constructions are important for the sustainability of the quality of life.

3. Conclusions

In this study in which geological and geomorphological and natural and environmental risks in gypsum areas were examined, natural hazards, environmental problems, and risk situation were dissociated and discussed. In other words, upon evaluating the available data, it was suggested that the problems arising from the gypsum karst may occur and may increase over time with the contributions of the intense seismic activity, geological units specific to karstic environments, heavy rainfall due to erosion, and occasional human interventions. On the other hand, all events such as soil and water pollution caused by gypsum in evaporite areas, salinization in the soil, and underground/surface waters as a result of the dissolution of gypsum, corrosion on the ground and structures, swelling and collapses on the ground, and the development of various karstic structures (dissolution/erosion/collapse areas, caves, fractures, cracks, etc.) underground were described as environmental problems. The hazards, environmental problems, and risks that may arise in gypsum areas, in the site selection of settlement areas due to urbanization and population growth were also emphasized.

In conclusion, it was strongly emphasized that gypsum areas with all types of features specific to karstic areas are risky areas in terms of natural hazards and environmental problems and that they would also maintain various environmental problems in the future. Accordingly, it was proposed for countries and regional and local authorities to prepare various risk maps showing the limits of hazardous and safe areas for the prevention of economic losses and the sustainability of all living things, to be always sensitive to environmental hazards within these limits, and to carry out monitoring studies. Furthermore, since the amount of dissolution and damaged area in gypsum may increase under the effect of water over time, these areas are defined as risky areas for settlement in geological engineering studies. Therefore, it will be useful always to pay the necessary attention to foundation engineering because, in the future, corrosive areas that will cause damage to the structure and ground in the foundation of the structure may occur and decompose concrete and building systems, and grounds may collapse by dissolution. Therefore, it would be useful to be cautious in geologically gypsum areas since natural hazards and environmental problems will always pose risks in these areas.

Author details

Sevda Özel
Department of Geophysical Engineering, Cumhuriyet University, Sivas, Turkey

*Address all correspondence to: sozel@cumhuriyet.edu.tr

References

[1] Sevil J, Gutiérreza F, Zarrocab M, Desira G, Carbonela D, Guerreroa J, et al. Sinkhole investigation in an urban area by trenching in combination with GPR, ERT and high-precision leveling. Mantled evaporite karst of Zaragoza city, NE Spain. Engineering Geology. 2017;**231**:9-20. DOI: 10.1016/j.enggeo.2017.10.009

[2] Carbonel D, Rodríguez-Tribaldos V, Gutiérrez F, Galve JP, Guerrero J, Zarroca M, et al. Investigating a damaging buried sinkhole cluster in an urban area (Zaragoza city, NE Spain) integrating multiple techniques: Geomorphological surveys, DInSAR, DEMs, GPR, ERT, and trenching. Geomorphology. 2015;**229**:3-16. DOI: 10.1016/j.geomorph.2014.02.007

[3] Darıcı N, Özel S. Examination of the structural characteristics arising in gypsums by the GPR and MASW methods (Sivas, Turkey). Natural Hazards. 2018;**93**:1-16. DOI: 10.1007/s11069-018-3320-1

[4] Atmaca E. Examination and replanning of solid waste manegement of Sivas citiy center [thesis]. Sivas, Turkey: Cumhuriyet University Graduate School of Natural and Applied Sciences Department of Engineering; 2004

[5] Özel S. Investigating with Geophysical Methods of Spreading Inside the Underground of the Leachates of the sivas city solid waste disposal area [thesis]. Sivas, Turkey: Cumhuriyet University, Graduate School of Natural and Applied Sciences Department of Geophysical Engineering; 2010

[6] Özel S, Yılmaz A, Candansayar ME. The Examination of the spread of the leachates coming out of a solid waste disposal area on the ground with geophysical and geochemical methods (Sivas, Turkey). Journal of Applied Geophysics. 2017;**138**:40-49. DOI: 10.1016/j.jappgeo.2017.01.013

[7] Yılmaz A. Çevre Jeolojisi. Sivas, Turkey: Cumhuriyet Üniversitesi Mühendislik Fakültesi Yayın; 2008.Vol. 107. 379 p

[8] Yılmaz A. Çevre Jeotekniği. Sivas, Turkey: Cumhuriyet Üniversitesi Mühendislik Fakültesi Yayın; 2009a.Vol. 116. 276 p

[9] Duvarcı E. Rejyonal Jeoelektrik Haritaları Projesi: Sivas Tersiyer Havzası Özdirenç Etüdü. Report no: 9701, 20. Ankara, Turkey: General Directorate of Mineral Research and Exploration (MTA) Publications; 1994

[10] Toshioka T, Tsuchida T, Sasahara K. Application of GPR to detecting and mapping cracks in rock slopes. Journal of Applied Geophysics. 1995;**33**:119-124

[11] Tanıdır R, Karlı R. Türkiye Rejyonal Elektrik Haritalar Projesi. Report no: 9868. Ankara, Turkey: General Directorate of Mineral Research and Exploration (MTA); 1996

[12] MTA. Sivas ve civarının mühendislik jeolojisi haritası. Sivas, Turkey: General Directorate of Mineral Research and Exploration (MTA) Publications, MTA Orta Anadolu I. Bölge Müdürlüğü; 1996

[13] MTA. Sivas kentinin çevre jeolojisi ve doğal kaynakları. Sivas, Turkey: General Directorate of Mineral Research and Exploration (MTA) Publications, MTA Orta Anadolu I. Bölge Müdürlüğü; 1997

[14] Xavier D, Odile A. GPR and Seismic imaging in a gypsum quarry. Journal of Applied Geophysics. 2000;**45**:157-169

[15] Waltham T, Cooper A. Features of gypsum caves and karst at Pinega (Russia) and Ripon (England). Cave and Karst

Science. Transactions of the British Cave Res Assoc. 1998;**25**(3):131-140

[16] Xu C, Butt SD. Evaluation of MASW techniques to image steeply dipping cavities in laterally inhomogeneous terrain. Journal of Applied Geophysics. 2006;**59**:106-116. DOI: 10.1007/s12665-018-7660-7

[17] Yılmaz A. Tokat (Dumanlıdağı) ile Sivas (Çeltekdağı) dolaylarının temel jeoloji özellikleri ve ofiyolitli karışığın konumu. Maden Tetkik ve Arama Dergisi. 1984;**99**(100):1-18. Ankara, Turkey

[18] Yılmaz A, Yılmaz H. Characteristic features and structural evolution of a post collisional basin: The Sivas Basin, Central Anatolia, Turkey. Journal of Asian Earth Sciences. 2005;**27**:164-176

[19] Aktimur T, Atalay Z, Ates S, Tekirli ME, Yurdakul ME. Geology of Area in the Between Çavuşdag ile Munzur Mountains. Ankara, Turkey: MTA (Mineral Research & Exploration General Directorate) Report; 1988. Vol. 8320 p. 102

[20] Dinçer H, Zeybek Hİ. Doline topography on the northeast of Sivas city. SOBİDER. Journal of Social Sciences. 2017;**17**(4):531-542

[21] Ayaz E. Sivas yöresinin karmaşık jeolojik yapısına bağlı olarak gelişen önemli maden yatakları ve MTA'nın Sivas yöresindeki yeni bulguları. MTA Doğal Kaynaklar ve Ekonomi Bülteni. 2013;**16**(13):65-87, General Directorate of Mineral Research and Exploration (MTA) Publications, Ankara, Turkey

[22] Doğan U, Özel S. Gypsum karst and its evolution east of Hafik (Sivas, Turkey). Geomorphology. 2005;**71**:373-388. DOI: 10.1016/j.geomorph.2005.04.009

[23] Hadimli H, Bulut İ. The land use, its problems and organisation in karstic areas. Ankara University TUCAUM 5. National Geography Symposium), 16-17 October 2008, Proceedings Book, Ankara, Turkey. 2009:39-48

[24] Doğan U, Yeşilyurt S. Gypsum karst south of İmranlı, Sivas, Turkey. Cave and Karst Sciences. 2004;**31**:1

[25] Günay G. Gypsum karst, Sivas, Turkey. Environmental Geology. 2002;**42**:387-398. DOI 10.1007/s00254-002-0532-0

[26] Karacan E, Yılmaz I. Collapse dolines in miocene gypsum: an example from SW Sivas (Turkey). Environmental Geology. 1997;**29**:(3/4)

[27] Ulugergerli E, Akca I. Detection of cavities in gypsum. Journal of Balkan Geophysical Society. 2006;**9**:8-19

[28] Darıcı N. Investigation of in gypsum developing structural features with ground penetrating radar (GPR) and multi channel analysis of surface waves (MASW) methods [Master Thesis]. Sivas, Turkey: Cumhuriyet University, Institute of Science, Department of Geophysical Engineering; 2015

[29] Yılmaz I. GIS based susceptibility mapping of karst depression in gypsum: A case study from Sivas basin (Turkey). Engineering Geology. 2007;**90**:89-103

[30] Martínez-Moreno FJ, Galindo-Zaldívar J, Pedrera A, González-Castillo L, Ruano P, Calaforra JM, et al. Detecting gypsum caves with microgravity and ERT under soil water content variations (Sorbas, SE Spain). Engineering Geology. 2015;**193**:38-48. DOI: 10.1016/j.enggeo.2015.04.011

[31] Zini L, Calligaris C, Forte E, Petronio L, Zavagno E, Boccali C, et al. A multidisciplinary approach in sinkhole analysis: The Quinis village case study (NE-Italy). Engineering Geology. 2015;**197**:32-144. DOI: 10.1016/j.enggeo.2015.07.004

[32] Gutiérrez F, Parise M, DeWaele J, Jourde H. A review on natural and human-induced geohazards and impacts in karst. Earth-Science Reviews. 2014;**138**:61-88. DOİ: /10.1016/j.earscirev.2014.08.002

[33] Yılmaz A. Çevresel Etki Değerlendirme. Cumhuriyet Üniversitesi Mühendislik Fakültesi Yayın No: 110, 275p,Sivas, Turkey; 2008b

[34] Bögli A. Karst hydrology and physical speleology. Springer, Berlin, p284; 1980

[35] Klimchouk A. The dissolution and conversıon of gypsum and anhydrite. Int J Speleol. 1996;**25**(3-4):21-36. DOI: 10.5038/1827-806X.25.3.2

[36] Brandt F, Bosbach D. Bassanite ($CaSO_4$ $0.5H_2O$) dissolution and gypsum ($CaSO_4$ $2H_2O$) precipitation in the presence of cellulose ethers. Journal of Crystal Growth. 2001;**233**:837-845

[37] Gutiérrez F, Parise M, DeWaele J, Jourde H. A reviewon natural and human-induced geohazards and impacts in karst. Earth-Science Reviews. 2014;**138**:61-88. DOI: /10.1016/j.earscirev.2014.08.002

[38] Waltham T, Cooper A. Features of gypsum caves and karst at Pinega (Russia) and Ripon (England). Transactions of the British Cave Res Assoc, Cave and Karst Sci. 1998;**25**(3)

[39] Yılmaz A, Atmaca E. Environmental geological assessment of a solid waste disposal site: a case study in Sivas, Turkey. Environ Geology. 2006;**50**:677-689. DOI: 10.1007/s00254-006-0241-1

[40] Candansayar ME, Demirel C. Boru hatları ve korozyon etütlerinde jeofizik çalışmalar. Antalya, Turkey. TMMOB Jeofizik Mühendisleri Odası Ali Keçeli Jeofizik-Jeoteknik Çalıştayı Bildiriler Kitabı; 2015