An overview of the land subsidence phenomena occurring in Greece, triggered by the overexploitation of the aquifers for irrigation and mining purposes

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Abstract. Land subsidence caused by overexploitation of aquifers manifests with an increasing frequency in several regions of Greece. The first signs of land subsidence have been identified since 1965 at the west side of Thessaloniki (broader Kalochori village region), in the form of a progressive marine invasion. Since then several areas have been investigated and proved to be affected mainly by the overexploitation of the aquifers. The multidisciplinary nature of the subsidence mechanism combining the geological, hydrogeological and morphological setting of the areas with the human activities and the land use data makes their study complicated and require the intervention of multiple scientific specialties. Furthermore, at several sites, beside ground truth data, the land subsidence trends and extends have been also identified via multi-temporal InSAR techniques, such as PSI and SBAS techniques. Among the sites to be presented in the current paper is the wider area of Kalochori village in the eastern part of Thessaloniki plain, the east and west Thessaly plain in central Greece and the region extending to the west–southwest of the Amyntaio opencast coalmine in West Macedonia.

1 Introduction

Several sites in Greece are affected by the manifestation of land subsidence phenomena triggered by various mechanisms. For example the oxidation of organic soils triggers land subsidence at the Xiniada plain, Central Greece as well as at the Filippoi shoal extending at East Macedonia and Thrace prefectures. The natural compaction of under-consolidated soil formations triggers deformations at the Gianitsa plain, extending at the West of Thessaloniki. The collapse of old mining tunnels threatens a wide area of the Anthoupoli municipality at the city of Athens and the collapse of karstic cavities is responsible for the occurrence of several sinkholes at the Ionian Islands and in several other areas in Greece.

Among the land subsidence mechanisms, the one affecting the most extended areas and is clearly triggered by human activities is the one related to the overexploitation of the aquifers. Unlike most of the large plain areas of Greece are affected by those phenomena. As presented in the location map of Fig. 1, the major plain areas affected are: (1) the wider Kalochori – Sindos plain area at the west of Thessaloniki, (2) the Anthemountas basin at the east of Thessaloniki, (3) The Amyntaio basin hosting the homonymous open pit coal mine, Florina prefecture, (4, 5) the West and East Thessaly plain, central Greece and (6) the Messara basin, Crete Island. Beside them, there are several other smaller plain areas filled with normally consolidated or even slightly over-consolidated soil formations effected by over-pumping.

An intriguing output of the studies conducted at the above mentioned sites is the uplift – rebound motion trend identified at the Kalochori site after the recovery of the aquifers. The aquifers recovered after the pause of the industrial activities due to the financial crisis in Greece.

The extensive depression cone at the perimeter of the Anargiroi opencast coalmine and its relation with the manifestation of intensive land subsidence phenomena, damaging at list two densely populated villages, is also an intriguing case study.
Aiming to provide an overview of the land subsidence phenomena occurring in Greece due to the overexploitation of the aquifers, the most characteristic case studies and the most intriguing results will be briefly presented at the current paper.

2 Characteristic case studies

2.1 Wider Kalochori-Sindos plain area at the west of Thessaloniki

Land subsidence in the broader Kalochori-Sindos region has been recorded since 1964 in the form of seawater invasion (Stiros, 2001; Loupasakis and Rozos, 2009). In 1965 an intensive rainfall took place, causing seawater inundation to threaten the houses of Kalochori. As a countermeasure, in 1969 the government built the first embankment to protect the area from the sea. Now, the maximum land subsidence values can be identified along the embankments where clearly the sea level is over the inland surface for more than 3 to 4 m (Fig. 2).

The wider area is founded over Quaternary deposits (Rozos and Hatzinakos, 1993) and despite the intensity of the land subsidence phenomena no differential displacements or surface ruptures have been reported. This phenomenon is unique, at least in Greece, and it can only be attributed to the absence of faults intersecting the top layers and the bedrock within the narrow limits of the study area. It is a fact that the faults’ offset creates intensive variations at the thickness of the compressible formations leading to the manifestation of differential displacements in case of ground water drawdown (Loupasakis et al., 2014).

Persistent Scatterer Interferometry (PSI) (Ferretti et al., 2000, 2001) and Small Baseline Subset (SBAS) multi-temporal Interferometric approach (Berardino et al., 2002) have been applied for the analysis of 20 years ERS 1/2 and ENVISAT datasets. The velocities estimated for the ERS datasets present subsidence, for the narrow area of Kalochori, with magnitude up to 35 mm yr\(^{-1}\) (Raspini et al., 2014), fitting perfectly with the ground-truth data. Also, according to the interferometric data the phenomena extend to the north affecting Sindos. At this point it should be noted that the fact that the phenomena also affect Sindos was first recognised after the evaluation of the first Interferometric data. The uniform subsidence of the site and its great distance from the coastline did not provided any indications to suspect the occurrence of such phenomena so far north in the mainland.

Nevertheless, the intriguing output was provided by the ENVISAT data archive covering the period 2003–2010, showing that there was a change in motion trend, from subsidence to uplift (Fig. 3) (Svigkas et al., 2016). The uplifting trend of the second decade is well correlated with hydrogeological data following a synchronous rise of the aquifer water level, but with an offset of 1.5 years. Furthermore, by examining the graph of Fig. 4, it is clear that the synchronization is so perfect that since 2007 the uplifting signal becomes smoother, following the smoother recovery of the aquifers.

2.2 East and west Thessaly plain in central Greece

The Thessaly plain, located in central Greece, is a large plain further divided, by hills, into two parts the East and the west plain. At the east Thessaly plain, the land subsidence phenomena have been observed since 1986 when numerous ground raptures appeared causing extensive damages to lin-
ear infrastructure and settlements (Fig. 5). The fact that the surface raptures are parallel to the Quaternary faults crossing the plain led some scientists to correlate the differential deformations with a so called “aseismic tectonic creep” along the faults (Kontogianni et al., 2007). A careful study of the kinematics of the ground fissures, and a correlation of the deformations with the ground water depression piezometric surface revealed that they are related to the over-pumping of the aquifers. As indicated by piezometric level measurements, since the early 80’s (1982–1983), the aquifer systems of the study area have been subject to excessive over-exploitation.

At the west Thessaly plain, the land subsidence phenomena have been intensified since 2002. In the Quaternary deposits of the plain, constituting of Pleistocene sand and gravel horizons with brown and grey clayey silt to
silty clay intercalations, highly productive aquifers are de-
veloped. These alternations of permeable coarse-grained de-
posits (aquifers) with impermeable to low permeability strata
(aquitards) create shallow unconfined aquifers and a number
of successive semi-confined to confined aquifers, sometimes
artesian (Ilia et al., 2018). A great number of wells exploit
the unconfined aquifers for irrigation purposes triggering the
land subsidence phenomena. Concerning the reported dam-
ages due to land subsidence, the majority of them have af-
fected roads and private buildings in the town of Farsala and
the villages of Agios Georgios, Stavros and Anochori. Simi-
lar to the East Thessaly plain, the surface raptures are parallel
to the Quaternary faults crossing the plain. Figure 6 presents
the spatial distribution of the surface raptures following the
tectonic lines as well as the distribution of the deformations
at the town of Farasla. It is clear that the deformations affect
only parts of the town that are founded on the Quaternary
formations, while the parts located over the limestone of the
bedrock remain, as expected, stable.

2.3 The perimeter of the Anargiroi opencast coalmine,
Florina Prefecture, West Macedonia

The land subsidence phenomena caused by the dewatering of
the mines are listed among the mining-induced catastrophic
geo-hazards slowly affecting extensive areas around the open-
casts, causing irreversible damages.

The site under investigation is the area extending west–
northwest of the Amyntaio opencast coal mine, located at
the homonymous basin at Florina Prefecture. This mine will
be active for several more years, and currently a second mine
(Filotas mine) is excavated within the limits of the basin, as
a replacement source of coal.

According to recent measurements, the ground water-table
drawdown close to the mine is more than 70 m (Tzampoglou
and Loupasakis, 2017, 2018). Actually; the overall excava-
tion including the surrounding draining wells acts as an in-
finity operating deep well with a diameter of approximately
4km, draining most of the basin. At this point, it should be
noted that besides the mining activities, the overexploitation
of the aquifers in the wider basin is also amplified by an in-
creasing number of farmers’ irrigation wells. But from the
form of the overall depression cone is clear that the domi-
nant braining activity is the mining. The overexploitation of
the aquifers has triggered, since 2005, extensive land subsi-
dence phenomena. These phenomena extend 2–3 km around
the mine causing damages to three villages so far: Anargiroi,
Valtonera and secondarily Fanos. The surface raptures were
initially reported at 2001 in the urban area of the Anargiri
village and by 2006 the damages affected the entire plain; in-
cluding the distant village of Fanos, located 4 km away from
the mine.

The orientation of the surface raptures is clearly related to
the orientation of the main tectonic lines forming the plain
(Fig. 7). The differential vertical displacements across the
fractures are inversely proportional to the distance from the
mine. The maximum values are recorded right next to the
mine’s crest, reaching up to offset values of 0.5–1 m, while
the fractures gradually faint moving away from the mine
(Loupasakis et al., 2014).

At the Valtonera village, a single fracture intersects the
entire village causing differential vertical displacements up
to 30 cm (Fig. 8). On the contrary, at the Anargiri village,
which is much closer to the mine, the deformations distribu-
tion is more complicated. Multiple fractures’ directions are
recorded following both the tectonic lines directions as well
as the ground water depression cone contour lines.

A farther investigation of the phenomenon was conducted
by applying numerical simulations (Loupasakis et al., 2014;
Tzampoglou and Loupasakis, 2018). The simulations were
aiming to the study of the phenomenon at the most heavily
damaged area of the villages and to the parametric simulation
of the influence of the geological profile’s geometry on the
surface deformations.

The parametric simulations proved that the faults’ offset is
the main parameter affecting the differential displacements
of the surface and the occurrence of the surface raptures.
Also, the common result of the simulations was that the
ground water drawdown affects intensively the surface rap-
tures offset. So as verified by the ground truth data the sim-
ulations also proved that the vertical displacements decrease
moving away from the crest of the mine.

3 Discussion

Land Subsidence triggered by the overexploitation of the
aquifers is a quiet natural hazard, evolving very slowly, and
sometimes taking place for decades before it gets noticed. As
an example, the deformations at the narrow area of Sindos,
due to the lack of deferential deformations, were first realised around 2010, more than 50 years after they were triggered.

Reviewing all above case studies, it is clear that besides the ground water drawdown, the factor affecting the most the occurrence of differential deformations is the existence of tectonic faults at the base rock formations of the plain. The alterations on the thickness of the compressible soil layers, imposed by the faults’ offset, allows the manifestation of differential displacements along the projection of the fault on the surface of the plain.

At all above described case studies, differential deformations, and as a result surface raptures, were recorded only at

**Figure 6.** The spatial distribution of the surface raptures and PSI data (modified from Ilia et al., 2018).

**Figure 7.** Intensive Distribution of the surface ruptures at the Amyntaio basin. A. Anargiroi, B. Valtorera and C. Fanos villages (Tzampoglou and Loupasakis, 2017).
the plain areas where the base rock formations were inter-
sected by tectonic lines.

To the direction of the mining risk management, is clear
that the intensity as well as the extent of the land subsi-
dence can be predicted using hydrogeological and geotech-
nical studies to determine mechanisms of the phenomena by
combining ground truth data and modeling procedures. So,
mining project managers can make proper decisions to pro-
tect natural and urban environments by reducing impacts of
the mining hazard.

An also interesting conclusion is that due to the grate ex-
tend of the phenomena and their low deformation rates the
Interferometric techniques has be proved to be a valuable tool
for their study.

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