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A Review of the Mechanism and Engineering/Environmental Problems of Subsidence Due to Groundwater Extraction (Withdrawal)

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Abstract
For decades, the increase in the exploitation of groundwater for agricultural and industrial development accompanied with successive droughts has seriously reduced the level of groundwater leading to land subsidence. The utilization of groundwater resources is of high importance and has become very crucial in the last decades, especially in coastal areas of arid and semi-arid regions. Groundwater withdrawal results in fluid pressure change in the layers. The pressure change in the layers induces both elastic and inelastic land compaction. The elastic compaction can be recovered if the water level rises again and inelastic compaction becomes permanent. Many major river deltas in the world are subsiding and consequently become increasingly vulnerable to flooding and storm surges, salinization and permanent inundation. The impacts of subsidence are potentially severe in terms of damage to surface utility lines and structures, changes in surface-water and ground-water conditions, and effects on vegetation and animals. Although subsidence cannot be eliminated, it can be reduced or controlled in areas where deformation of the ground surface would produce dangerous or costly effects. This study reviews the engineering and environmental problems of subsidence due to groundwater withdrawal.

Keywords: *Groundwater, Compaction, Subsidence, sinkholes, Extensometer*

1.0 Introduction

Land subsidence is the result of consolidation of subsurface strata caused by natural causes such as tectonic motion or man induced causes such as the withdrawal of groundwater, oil and gas (Abidin et al., 2013; Zeitoun and Wakshal, 2013; Galgaro et al., 2014).

The relationship between water level decline and the rate of subsidence has been observed for many years in various places (Hix 1995; Wilson and Gorelick 1996). This decline in water level of a confined aquifer system initiates a downward movement of the overlying layers in response to gravitational pull arising from the vacuum created by the volume of fluid withdrawal. If the downward pressure placed on the aquifer by the weight of overlying rock and water, remains constant, then, a reduction in upward pressure born by the fluid will result in an increase in the effective stress born by the aquifer. If pumping reduces the pressure head in a confined aquifer, the effective stress acting on the aquifer will increase and the aquifer will consolidate due to this increased stress. The hydraulic head drop in the aquifer will eventually result in the same amount of head drop in the confining layer as well. In response to this, the effective stress will increase, resulting in a commensurate volume reduction in the layer itself. If the solid and fluid in the confining layers are assumed to be incompressible, then, the volume of the fluid removed is equal to the volume of the subsidence (Jacob 1940; Galloway and Burbey, 2011).

The demand for ground water resources associated with rapid population growth and agricultural development has resulted in a serious lowering of ground water levels. Over 88% of water consumed is from ground water resources, the rest is from surface waters.
(Jalali, 2007). Over the past 25 years, groundwater exploitation strongly increased, resulting in a persistent drawdown of hydraulic heads (i.e. water pressure) throughout the entire delta subsurface. This process is known to trigger fine grained sediment consolidation in the subsurface, causing aquifer-system compaction (Galloway and Burbey 2011, Gambolati and Teatini 2015), expressed as land subsidence of the delta surface.

Land subsidence is a subtle process, affecting a large area and going on at a slow rate. Many do not realize that it is taking place until the impacts are felt. Increasing coastal floods, sea water intrusion, failure of well casings, differential settlements, cracks and other damages of buildings and infrastructures are some of the impacts of land subsidence.

2.0 Mechanism of Groundwater Extraction Related Subsidence

The principal causes of subsidence are aquifer-system compaction, drainage of organic soils, underground mining, hydro compaction, natural compaction, sinkholes, and thawing permafrost (National Research Council, 1991).
In general, subsidence includes contributions by other drivers (e.g. Tosi et al 2009). Apart from groundwater extraction, these include 1) shallow subsidence in the unsaturated zone triggered by phreatic groundwater level lowering, 2) natural and anthropogenic loading by for example buildings and infrastructure and 3) deeper rooted tectonics ((Galloway et al 2016).
More than 80 percent of the identified subsidence is a consequence of our exploitation of underground water, and the increasing development of land and water resources threatens to exacerbate existing land subsidence problems and initiate new ones. In many areas of the arid Southwest, and in more humid areas underlain by soluble rocks such as limestone, gypsum, or salt, land subsidence is an often-overlooked environmental consequence of our land- and water-use practices.

Extraction and drainage of ground water play direct roles in land subsidence by causing the compaction of susceptible aquifer systems and the dewatering of organic soils. The catastrophic formation of sinkholes in susceptible earth materials, although fundamentally a natural process, can also be triggered by ground-water-level declines caused by pumping, or by infiltration from reservoir impoundments, surface-water diversions, or storm runoff channels. Several other types of subsidence involve processes more or less similar to the three mechanisms just cited.
The following illustrate the three basic mechanisms by which human influence on ground water causes land subsidence—**compaction of aquifer systems, dewatering of organic soils, and mass wasting through dissolution and collapse of susceptible earth materials.**

Mining ground water

The relationship between a change in groundwater levels and the compression of the corresponding aquifer system is based on the principle of effective stress (U.S.D.I, 1999). When water is removed from the ground the pore water pressure is subsequently reduced. Without the water to hold up the weight of the soil above it, the land surface subsides and the aquifer layers become more compact resulting in an overall reduction in the pore space of the soils. Some aquifer systems can "rebound" if water is pumped back into it, however, more often than not, this vertical deformation results in permanent changes to the aquifer system. This is especially true when the compressed layer soils consist of very fine grained clays. In many aquifer systems around the country subsidence has led to the loss of groundwater storage capacity as well as other changes to the aquifer's hydraulic properties (Conway, 2011) including its ability to transmit water. Most current research suggests that the majority of aquifers experience only a small amount of reversible deformation, especially when subsidence has occurred over a long period of time.

Using fundamental effective stress soil mechanics (Terzaghi, 1925), the changes in effective stress, due to changes in pore pressure can be calculated.

$\sigma^{I} = \sigma_{I} – u$
$\sigma I = Z_{I} + Z_{2}\gamma_{sat}$
$u = Z_{2}Y_{w}\gamma_{w}$

Where: Z_1 is soil thickness above water table, Z_2 saturated thickness of soil below water table, γ bulk density of the aquifer above water table, γsat saturated density of the aquifer and γw density of water. Lowering the ground water increases effective stress and the stress due to the reduction saturation of the deposits above the groundwater. The resultant stress changes causes consolidation mostly in the interbedded clay. Much of the subsidence is permanent as there is little recovery even when the groundwater recovers to its original levels.

Drainage of organic soils

Land subsidence invariably occurs when organic soils—soils rich in organic carbon—are drained for agriculture or other purposes. The most important cause of this subsidence is microbial decomposition which, under drained conditions, readily converts organic carbon to carbon-dioxide gas and water. Compaction, desiccation, erosion by wind and water, and prescribed or accidental burning can also be significant factors. The total area of organic soils in the United States is roughly equivalent to the size of Minnesota, about 80,000 square miles, nearly half of which is “moss peat” located in Alaska (Lucas, 1982). About 70 percent of the organic-soil area in the contiguous 48 states occurs in northerly, formerly glaciated areas, where moss peats are also common (Stephens et al, 1984). Moss peat is composed mainly of sphagnum moss and associated species. It is generally very acidic (pH 3.5 to 4) and, therefore, not readily decomposed, even when drained. However, where moss peat is amended for agricultural cultivation, for example through fertilization and heavy application of lime to raise the pH, it can decompose nearly as rapidly as other types of organic soils.

Collapsing Cavities (Sinkholes)

This is associated with the sudden and sometimes catastrophic land subsidence associated with localized collapse of subsurface cavities—sinkholes. This type of subsidence is commonly triggered by ground-water-level declines caused by pumping and by enhanced percolation of water through susceptible rocks. Collapse features tend to be associated with specific rock types having hydrogeologic properties that render them susceptible to dissolution in water and the formation of cavities. Evaporate minerals (salt, gypsum and anhydrite) and carbonate minerals (limestone and dolomite) are susceptible to extensive dissolution by water. Salt and gypsum are, respectively, almost 7,500 and 150 times more soluble than limestone, the rock type often associated with catastrophic sinkhole formation.

Evaporate rocks underlie about 35 to 40 percent of the United States, although in many areas at depths so great as to have no discernible effect at land surface. Natural solution-related subsidence has occurred in each of the major salt basins (Ege, 1984) throughout the United States. The high solubility’s of salt and gypsum permit cavities to form in days to years, whereas cavity formation in carbonate bedrock is a very slow process that generally occurs over centuries to millennia. The slow dissolution of carbonate rocks favors the stability and persistence of the distinctively weathered landforms known as karst. Carbonate karst landscapes comprise more than 40 percent of the humid United States east of the longitude of Tulsa, Oklahoma (White et al, 1995). Human activities can facilitate the formation of subsurface cavities in these susceptible materials and trigger their collapse, as well as the collapse of pre-existing subsurface cavities. Though the collapse features tend to be highly localized, their impacts can extend beyond the collapse zone via the potential introduction of contaminants to the ground-water system.

3.0 Measuring/Monitoring Land Subsidence

Historically speaking, measuring land subsidence has not always been an easy task. With mostly everything in a given area subsiding together at an imperceptible rate, finding a reference point to see or measure the ground's deformation was often difficult. Fortunately today we have a number of technologies that can be used to accurately measure and monitor land subsidence.

Extensometers

An extensometer is a device that consists of a pipe or cable that is anchored to the surface below an aquifer. As the land subsides over time, the machine's recorder makes note of the change in relative distance between the bottom of the hole (preferably at the bedrock surface) and the ground surface above (Fulton, 2006). Extensometers are easy to set up (if you can find a good location) and require little oversight to operate. Similar to traditional surveying techniques, extensometers usually have an accuracy of about 1/100th of a foot.

Leveling Surveys

A leveling survey is a simple method of measuring subsidence that uses traditional surveyor's tools to complete. To complete the survey accurately the surveyors needs to measure the ground elevations of a subsiding area and reference those measurements to areas where no subsidence has occurred. Usually this means finding a benchmark that is connected to the underlying bedrock to ensure that it hasn't subsided. To improve accuracy surveyors typically increase the density of their measurements and also attempt to tie their survey to more than one benchmark. However accurate they may be, leveling surveys are typically very expensive and require a lot of time to complete for a relatively small area.

More recently, the advent of Global Position Systems (GPS) has augmented the abilities of surveyors to accurately measure ground subsidence. Though not as accurate as a tradition elevation surveying methods, GPS has allowed for the quick measurement of subsidence over larger scales than what was previously possible. Because of this, GPS is a great way to observe trends in elevation changes over time.

Interferometric Synthetic Aperture RADAR (InSAR) Measurement

InSAR is a relatively new technique that utilizes RADAR equipped satellites to measure changes in the earth's surface over time. This remote sensing technique can measure changes within a fraction of an inch and works best for areas of land that are not usually disturbed on a regular basis (such as farming operations) or where little vegetation that can skew the measurements exists. InSAR measurement can be expensive but when you consider the level of accuracy and amount of data that can be obtained, it usually turns out to be a bargain. An entire metropolitan area can usually be measured in a single satellite pass producing with millions of data points that can be analyzed. Because InSAR can measure such large areas, the technology has often helped scientist discover previously unknown subsidence features.

4.0 Implications of Land Subsidence

The impacts of subsidence are potentially severe in terms of damage to surface utility lines and structures, changes in surface-water and ground-water conditions, and effects on vegetation and animals. Although subsidence cannot be eliminated, it can be reduced or controlled in areas where deformation of the ground surface would produce dangerous or costly effects.

Subsidence is a global problem that need serious attention. Groundwater is a valuable resource all over the world. Where surface water, such as lakes and rivers, are scarce or inaccessible, groundwater supplies many of the hydrologic needs of people everywhere. Groundwater depletion, a term often defined as long-term water-level declines caused by sustained groundwater pumping, is a key issue associated with groundwater use.

Pumping water out of the ground faster than it is replenished over the long-term causes similar problems. The volume of groundwater in storage is decreasing in many areas in response to pumping. Groundwater depletion is primarily caused by sustained groundwater pumping. Some of the negative effects of groundwater depletion include:

- drying up of wells
- reduction of water in streams and lakes
- deterioration of water quality
- increased pumping costs
- land subsidence

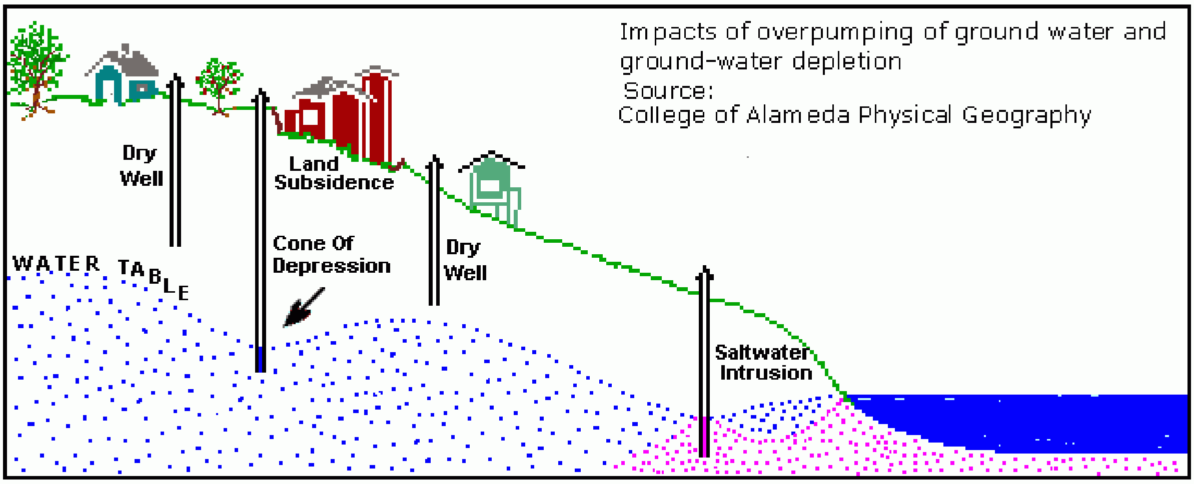

Fig 1. Illustration showing possible effects of groundwater depletion and over pumping (COA, Physical Geography, 2018)

Lowering of the water table

The most severe consequence of excessive groundwater pumping is that the water table, below which the ground is saturated with water, can be lowered. For water to be withdrawn from the ground, water must be pumped from a well that reaches below the water table. If groundwater levels decline too far, then the well owner might have to deepen the well, drill a new well, or, at least, attempt to lower the pump. Also, as water levels decline, the rate of water the well can yield may decline.

Increased costs for the user

As the depth to water increases, the water must be lifted higher to reach the land surface. If pumps are used to lift the water (as opposed to artesian wells), more energy is required to drive the pump. Using the well can become prohibitively expensive.

Reduction of water in streams and lakes

There is more of an interaction between the water in lakes and rivers and groundwater than most people think. Some, and often a great deal, of the water flowing in rivers comes from seepage of groundwater into the streambed. Groundwater contributes to streams in most physiographic and climatic settings. The proportion of stream water that comes from groundwater inflow varies according to a region's geography, geology, and climate.

Groundwater pumping can alter how water moves between an aquifer and a stream, lake, or wetland by either intercepting groundwater flow that discharges into the surface-water body under natural conditions, or by increasing the rate of water movement from the surface-water body into an aquifer. A related effect of groundwater pumping is the lowering of groundwater levels below the depth that streamside or wetland vegetation needs to survive. The overall effect is a loss of riparian vegetation and wildlife habitat.

Land subsidence and Sinkholes

The basic cause of land subsidence is a loss of support below ground. In other words, sometimes when water is taken out of the soil, the soil collapses, compacts, and drops. This depends on a number of factors, such as the type of soil and rock below the surface. Land subsidence is most often caused by human activities, mainly from the removal of subsurface water. The formation of sinkholes involves natural processes of erosion or gradual removal of slightly soluble bedrock (such as limestone) by percolating water, the collapse of a cave roof, or a lowering of the water table brought about by over pumping of groundwater.

Fig 2. Land subsidence and Sink hole in Florida (WFTV Report, 2018)

Deterioration of water quality

One water-quality threat to fresh groundwater supplies is contamination from saltwater intrusion. All of the water in the ground is not fresh water; much of the very deep groundwater and water below oceans is saline. In fact, an estimated 3.1 million cubic miles (12.9 cubic kilometers) of saline groundwater exists compared to about 2.6 million cubic miles (10.5 million cubic kilometers) of fresh groundwater (Gleick, 1996). Under natural conditions the boundary between the freshwater and saltwater tends to be relatively stable, but pumping can cause saltwater to migrate inland and upward, resulting in saltwater contamination of the water supply.

5.0 Prevention /Control Measures

Methods to control or arrest subsidence include reduction of pumping draft, artificial recharge of aquifers from the land surface, and re-pressuring of aquifers through wells, or any combination of these methods. The goal is to manage the overall water supply and distribution in such a way that the water levels in wells tapping the compacting aquifer system, or systems, are stabilized or raised to some degree. In other words, at least manage the overall supply in such a way that effective stress in the aquifer system is not increased beyond the stress experienced to date. The local geologic conditions determine whether artificial recharge can be accomplished by regulated application at the land surface or by re-pressuring of aquifers by means of injection through wells. Both the artificial recharge of aquifers from the land surface and the re-pressuring of aquifers through wells normally require a supply of potable surface water.

Some of the control measures include:

Reduction of Pumping Draft

Reduction of pumping draft may be accomplished to some degree by one or more of the following methods:

1. Import of substitute surface water.
2. Conservation in application and use of water: (a) through improvement of irrigation methods, such as change from ditch and furrow or flood irrigation to overhead sprinkler irrigation or to drip irrigation. (b) through change from crops requiring heavy duty or demand to crops requiring less duty, such as from cotton to orchards.
3. For overdrawn ground-water basins, adjudication (equitable distribution) of available supply.
4. In urban areas, by recirculation and reuse of treated water by industrial plants.
5. By decreasing irrigated area or industrial plants using large quantities of water.
6. By moving the well fields to tap more permeable (less compressible) deposits. .
7. By changing the depth range of perforated intervals in well casings or screens to tap less compressible deposits.
8. By legal control.

Whether any one of these remedies is economically justified depends on its cost compared with the costs of continued subsidence. The first requirement for estimating costs is an estimate of the magnitude of subsidence that would occur (1) if the artesian head was maintained at the present level, and (2) in response to an assumed additional decline in head

Artificial Recharge of Aquifers from the Land Surface

Land subsidence usually results from compaction of compressible confined aquifer systems due to intensive withdrawal of ground water and consequent decline of artesian head. Because confining beds restrict the vertical downward movement of water from the land surface, artificial recharge of confined system(s) by application of water at the land surface directly overhead ordinarily is not practicable. However, the geology of the system may be such that the confined aquifer system may crop out at or near the margins of the ground-water basin; this outcrop area may be near enough to the subsiding area so that artificial recharge on the outcrop area will raise the local water table and also the artesian head in the confined system.

Re-pressuring of Aquifers through Wells

Re-pressuring of confined aquifer systems by artificial recharge directly through wells, although expensive, may prove to be the only practical way to slow down or stop land subsidence in a particular area. The Wilmington oil field in southern California is a classic example of subsidence control by injection of water through wells. Re-pressuring of the oil zones to increase oil production and to control subsidence began on a major scale in 1958. By 1969, when 175 x $10^3 m^3$ (1.1 x 106 barrels) of water per day was being injected into the oil zones, the subsiding area had been reduced from 58 to 8 km^2, and locally the land surface had rebounded as much as 0.3 m (Mayuga and Allen, 1969).

In 1975 about 80 x 106 m^3 (500 x 106 bbls) of water was injected into the oil zones to (1) control subsidence, (2) produce 10 x 106 m3 of oil and (3) utilize 67 x 106 m^3 of water produced with the oil. According to Gates et al (1977), the injection of this great quantity of water from diverse sources created many problems which were controlled by various chemical and physical treatments. Replenishing ground-water supplies by artificial recharge through wells and pits has been practiced in many areas.

6.0 Case Study

Land Subsidence Due to Excessive Ground Water Withdrawal: A Case Study from Stavros - Farsala Site, West Thessaly Greece (Rosos et al, 2010)

In this study, Rosos et al, (2010) described the Stavros – Farsala study area as part of West Thessaly basin. Thessaly basin is lowland in Central Greece, with an extent of 4,520km^2, mainly drained by Pinios River. According to his study, Thessaly basin is subdivided by a group of hills, in two subbasins, the westerner and the Eastern. Stavros-Farsala study site is located in the eastern part of the western subbasin. These subbasins are two main individual hydrogeological units, developing high potential aquifers. The overexploitation of these aquifers led to the manifestation of extended damages due to land subsidence phenomena.

Geological setting

From the field mapping conducted during the study (Rosos et al, 2010), Mesozoic Alpine formations outcrop in the margins of the study area, while, post alpine deposits are presented in the lowland of the basin. The Mesozoic Alpine formations belong to the Pelagonian (Subpelagonian) geotectonic zone and they constitute the bedrock of Quaternary deposits of Stavros – Farsala area. These formations consist of Schist–chert formation, Ophiolites, Limestone’s and Flysch sediments (Mariolakos et al., 2001; Rozos & Tzitziras, 2002).

Hydrogeological conditions

The hydrogeological conditions as described by Rosos et al (2010) has been summarized thus. From their study, the quaternary deposits contain the main aquifers of the wider study area. The aquifers constitute a system of unconfined shallow aquifers, extending in the upper layers, and successive confined artesian aquifers developing in the dipper permeable layers (Marinos et al, 1995; Marinos et al, 1997). This system besides the percolated surface water is also supplied by water through the lateral infiltration from the karstic aquifers of the alpine carbonate formations, outcropping in the margins of the basin. In general, the authors noted that the richest aquifers are developed in the western subbasin of Thessaly plain, due to their rich supply both from the big infiltrating part of the surface runoff and the lateral infiltration. The exploitable water potential of the above described system is about 400x10.

In order to study the ground water fluctuation in Stavros – Farsala region, Rosos et al (2010) used thirteen (13) water wells which were monitored from 1972 to 2007. The piezometric level monitoring data proved that during the years a sufficient drawdown of the ground water level took place, reaching up to values of 67m. It appears that even if a small recharge of aquifers takes place every year during the rainfall period, the final tendency is a stable drawdown. The mean piezometric level drawdown exceeds the 40m and the mean annual drawdown rate was estimated to be 60 cm/year. It was noticeable that the changes of the ground water level were not caused by a corresponding reduction of the mean annual rainfalls. According to the meteorological data from three local stations, namely Farsala, Domokos and Myra, the mean annual rainfalls were nearly stable during the last thirty years, with a small exception during the period 1977 to 1984.

Surface subsidence ruptures in Stavros – Farsala site

In the eastern part of Thessaly basin the land subsidence's phenomena was reported for the first time in1996 (Soulios, 1997). With a time delay, in Farsala site, west Thessaly, these phenomena, with the form of surface ruptures, were firstly manifested in 2002. The overexploitation of the ground water resulted to the activation of the subsidence mechanism in the discharged aquifers and subsequently led to the manifestation of the accompanying phenomena on the surface, apart from the land depression.
Therefore, along the margins of the basin were the bedrock outcrops and generally in areas were the thickness of the deposits is small, fractures of the ground occur, as a result of the tensile forces action.

On the contrary, Rosos et al (2010) noted that in the parts of the basin with thick deposits the compaction of the formations can become noticeable by the extraction of the water well pipes from the ground. They noted that the variations on the geotechnical behaviour of the foundation formations lead to the manifestation of numerous tensile fractures, in several sections of the town. Precisely, in the centre of the town, an area extending 50 m x 360m was intensively damaged. The road pavements present multiple fractures, redisplayed afterwards any repair works. Also, several buildings, intersected by the ruptures, were intensively damaged requiring expensive reconstruction works. Small ground ruptures have been also presented in the northern part of the town in an area covering 180 m × 200 m. Also, beyond the south western limits of the town and at the west of the railway line, two more extensive ruptures were observed with total length 1,000 m and 2,500 m respectively.

In Stavros small town, the main ground rupture was found westwards the railway line. This tensile rupture has a total length of about 2,100 m, an azimuth of 105° and a vertical displacement at a rate of 60 cm. The trace of the rapture affects road pavements and numerous buildings, they observed. The buildings founded along the trace of the ruptures present several damages, such as cracks in the stonework, distortions in doors, windows, stockyards and pavements. Also, several ground ruptures are located at the south of the town, intersecting cultivated areas.

Correlation of land subsidence's with overexploitation of ground water

In order to correlate the land subsidence's phenomena in the wider study area of Stavros - Farsala with the overexploitation of the aquifers, the loggings of water wells were evaluated. From the evaluation, Rosos et al (2010) observed that the loggings from Farsala region (water well PZ6), the first aquifer is located at a depth of 10.3 m to 14.8m, and consists of sand and gravel. The second aquifer consists of conglomerates and is located at depth 33.3 m, with a mean thickness 5.2 m. Respectively in Stavros site, the logging of water well34 revealed that the first unconfined aquifer starts from the surface up to a depth of 2.6 m. The second confined aquifer is located at a depth from 5.6m to 8.7 m, while a third aquifer, consisting of quaternary deposits, appears from 13.3 m to 15.8 m.

The diagram of Figure 5.2 correlates the water tables fluctuations in respect to time in Farsala site. It reveals that from 1984 until 2005 the ground water level was dramatically decreased. The first aquifer was completely drained, at September 1991, as the ground water level reached the depth of 15.82m, and the second one at September 2005, as the water level reached the 38.5 m in depth. Respectively, in the case of Stavros site, the first and second aquifers were drained in September 1976. The drawdown of the ground water level kept on going until September 1978 (depth of groundwater level 15.45m). Finally, at September 2001, with only a few recharges the ground water level reached the depth of 22.15m and all three aquifers were drained. The thorough examination of the data referring to ground water level and rainfall reveals that the mean annual drawdown is roughly constant for all water wells in the study area with a value of 60 cm/year.

From the above discussion Rosos et al (2010) suggested that the biggest part of the aquifers in Thessaly plain is under a status of over exploitation, following by a continuous lowering of the ground water level year by year. What differs locally is the intension of overexploitation and the time of the beginning of the ground water table lowering.

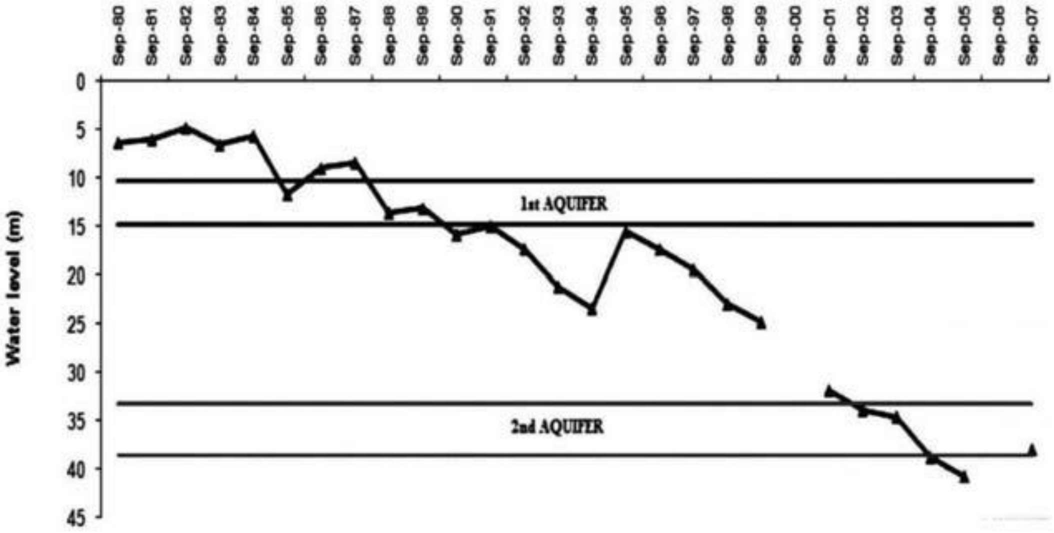

Fig. 3: Ground water table fluctuations with time in Farsala site (Pz46 borehole) (Source<Rosos et al, 2010).

7.0 Conclusion

Groundwater over drafting could result in a slow but cumulatively significant amounts of land subsidence. The subsidence includes the elastic consolidation of the aquifers and the inelastic consolidation of the confining layers. The elastic consolidation of aquifers is related with compressibility, which can be estimated from the fluctuations of water level in response to atmospheric pressure variations. The inelastic, permanent consolidation resulted from the fluid withdrawal is mainly due to the rich clay contents in the confining layers.

The mechanism of land subsidence, as it is, is due to the reduction in ground water level, increases in effective stress leading to the consolidation of the soil.

8.0 Recommendations

The following policy objectives must be advanced simultaneously to ensure groundwater sustainability.

1) **Avoid or Minimize Subsidence**. In areas where groundwater pumping is resulting in subsidence at levels causing damage or risk of damage to overlying infrastructure that affects parties outside of an existing management area, additional land use planning, engineering, capital improvement and monitoring and reporting requirements -- including possible pumping restrictions in the impacted area -- should be implemented by the local or regional groundwater management agency.
2) **Assess Groundwater Connection to Surface Waters**. GMPs should include an

evaluation of the relationship the surface water source has to groundwater levels and quality in the subbasin or basin and identify the impacts, if any, on the surface water source and its related public benefits.

3) **Increase Groundwater Storage**. Storing surface water in underground storage basins is necessary to optimize use of the state's limited and highly variable water supplies. This need will only increase with climate change. California must take aggressive steps to develop significant new groundwater storage and conjunctive use projects, including potential state funding for local project capital costs.
4) **Remove Impediments to Recharge**. Coordinated and planned use of surface water, recycled water, storm water and groundwater resources to maximize the availability and reliability of water supplies is an essential management method. Policies that are impediments to groundwater recharge should be evaluated and revised as necessary.
5) **Provide State Financial and Technical Assistance**. The government, through agencies, should provide significant new financial assistance and technical support to local and regional agencies for improving or developing Groundwater management policies. Developing management capacity in currently unmanaged areas should be the first priority.

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