Groundwater Inrush Caused by the Fault Reactivation and the Climate Impact in the Mining Gafsa Basin (Southwestern Tunisia)

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Abstract

The Gafsa mining basin district in Southwestern Tunisia is one of the most important producers of phosphate in the world. The exploitation of this district started at the beginning of the twentieth century a few years after the first discovery of this valuable resource. The over-exploitation of groundwater to wash the phosphate caused water-level decline in the main aquifers and the corollaries of drying springs, loss of artesian condition, and water quality degradation, presumably due to mixing with relatively highly mineralized deep groundwater. The beginning of the Tunisian revolution bumped things up: total stopping of phosphate washing by groundwater during an important period. Following significant rainfall events, which regenerated the initial state of the natural and the artificial springs in the mining basin. The objective of the present work is to explain the process and the model simulation of groundwater inrush caused by reactivation fault in the Gafsa basin (Phosphate mining industry of the Company of phosphate of Gafsa) (Southwestern Tunisia-North Africa). The probability of the groundwater inrush caused by faults associated with the faults reactivation in deep underground is more than shallow underground. The climate impact (natural and anthropogenic) plays an important role in this neoformation of this lake in the Gafsa area.

Keywords: Groundwater; Reactivation Fault; Climate Impact; Gafsa Basin; Tunisia.

1- Introduction

After humanity, water is the most precious of God's creations. Groundwater resources are of great importance for industrial development in arid and semi-arid areas around the Mediterranean basin and specialty in North Africa; where surface waters are scarce or absent (Al Gamal and Hamed, 2014, Ayadi *et al.*, 2017; Attia and Hamed, 2017a; Hamed *et al.*, 2010, 2017; Hamad *et al.*, 2017). Continuously increasing abstraction of groundwater resources to meet rising industrial, agricultural and domestic needs, coupled with severe drought periods during the past decades leads to growing deficit of water. About 30% of land area on the Earth is arid or semi-arid where potential evapo-transpiration exceeds rainfall (McKnight and Hess, 2000).

These areas, collectively called “the arid and/or semi-arid zone”, constitute much of the Earth’s land between latitudes 18 and 40° north and south of the equator and include most of northern and southern Africa, the Middle East, western USA and the southern areas of South America, most of Australia, and large parts of central Asia and even parts of Europe (NOAA, 2010). In arid/semi-arid countries, issues related to water resources are of growing concern due to different environmental, economic and social factors. Continuously increasing abstraction of groundwater resources to meet rising industrial need, coupled with severe drought periods during the past decades leads to growing deficit of meteoric water.

The scarcity of surface water resources in southern Tunisia poses strategic difficulties for economic development. This situation was complicated after the construction in the neighbouring Algerian territory of several dams on non-perennial wadis (El Oudei and El Kebir), which provide regional agricultural areas with irrigation water. Thus, to secure water supply for agricultural and industrial needs, the demand for groundwater has greatly increased. Indeed, in the Gafsa mining basin, the number of deep wells has increased from 50 during the 1980s, to more than 1000 after the “Spring Revolution of Tunisia” (2011). This is due to an economic growth (phosphate industry and agricultural activity).

The drawdown of piezometric levels, progressing degradation of water quality, extinction of the artesianism are the main consequences of such intensive exploitation of the Complex Terminal (CT) aquifer (2,500 $l.s^{-1}$) (Hamed *et al*., 2010, 2013, 2014a,b). But after January 2011 (date of the Tunisian revolution “Arabian Spring”) the number of illegal wells is increased; the quantity of water discharge by exploitation is more 4,000 $l.s^{-1}$. But due to several problems there is a decrease of the overexploitation of pumping, to wash the phosphate in the mining basin.

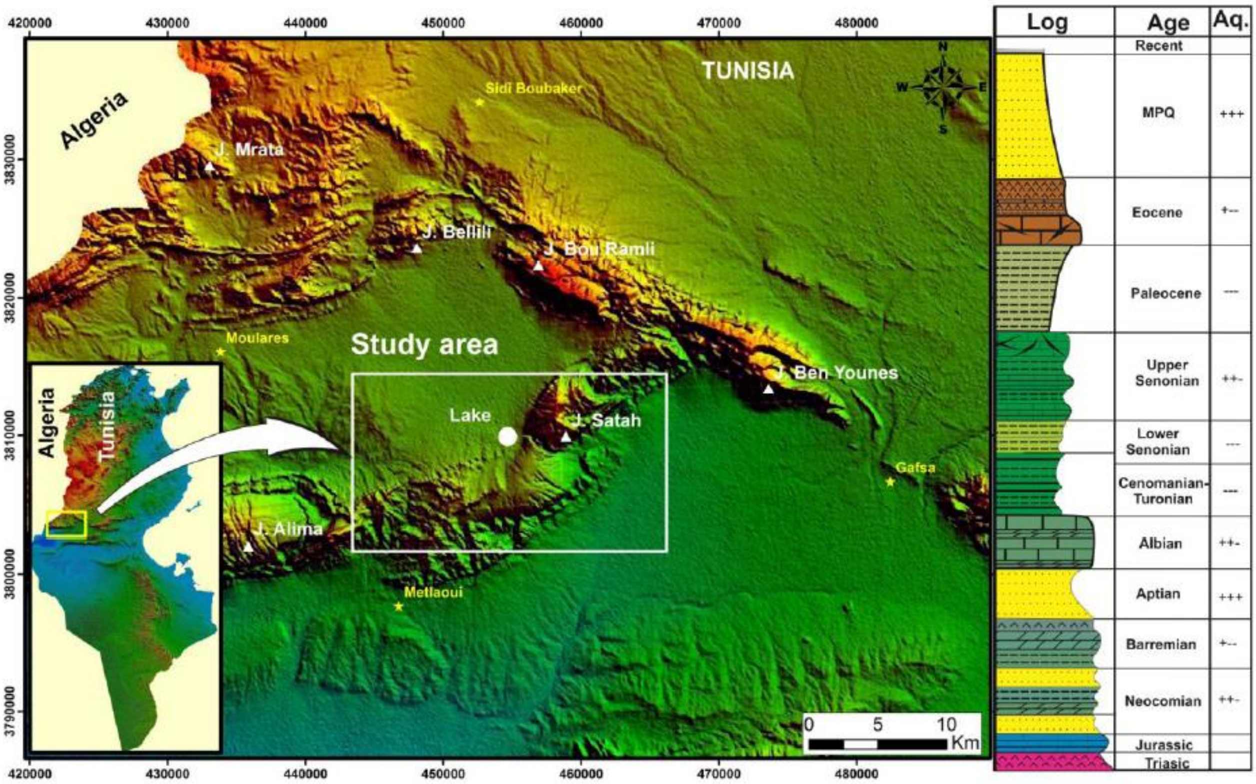

Figure 1) Geological localization of study area of Gafsa basin (Southwestern Tunisia).

2- Location and climate

Tunisia is characterized by an absence of high mountains and a relatively limited geographic extension, allowing the integration of Saharan air streams into the atmospheric circulation (Celle-Jeanton *et al*., 2001). However, due to its position in the western Mediterranean, it represents a climatic transition zone open to Atlantic and Mediterranean influences (Hamed, 2004, Hamed *et al*., 2012, 2013; Mokadem *et al*., 2016; Besser *et al*., 2017).

Indeed, regional hydrometeorological studies (Celle, 2000, Celle *et al*., 2001; Hamed *et al*., 2014, 2017) mention the existence of two major trajectories for dominant air masses (Fig. 1). These are the North Atlantic warm air masses that circulate from the Sahara Platform of the North Africa and the Mediterranean cool air masses that derive from the north (Hamed *et al*., 2014, 2017).

The study area, which is located in south western Tunisia, covers an area about 500 km2 and lies between the longitudes 6º30’–7°00’E and the latitudes 34°00’–34º30’N (Fig. 1). It corresponds to an anticline structure (≈650 m) limited in the North and in the East by the Gafsa Mountains (≈1000m), in the South by the Metlaoui Range (≈800m) and in the West by Algerian territory.

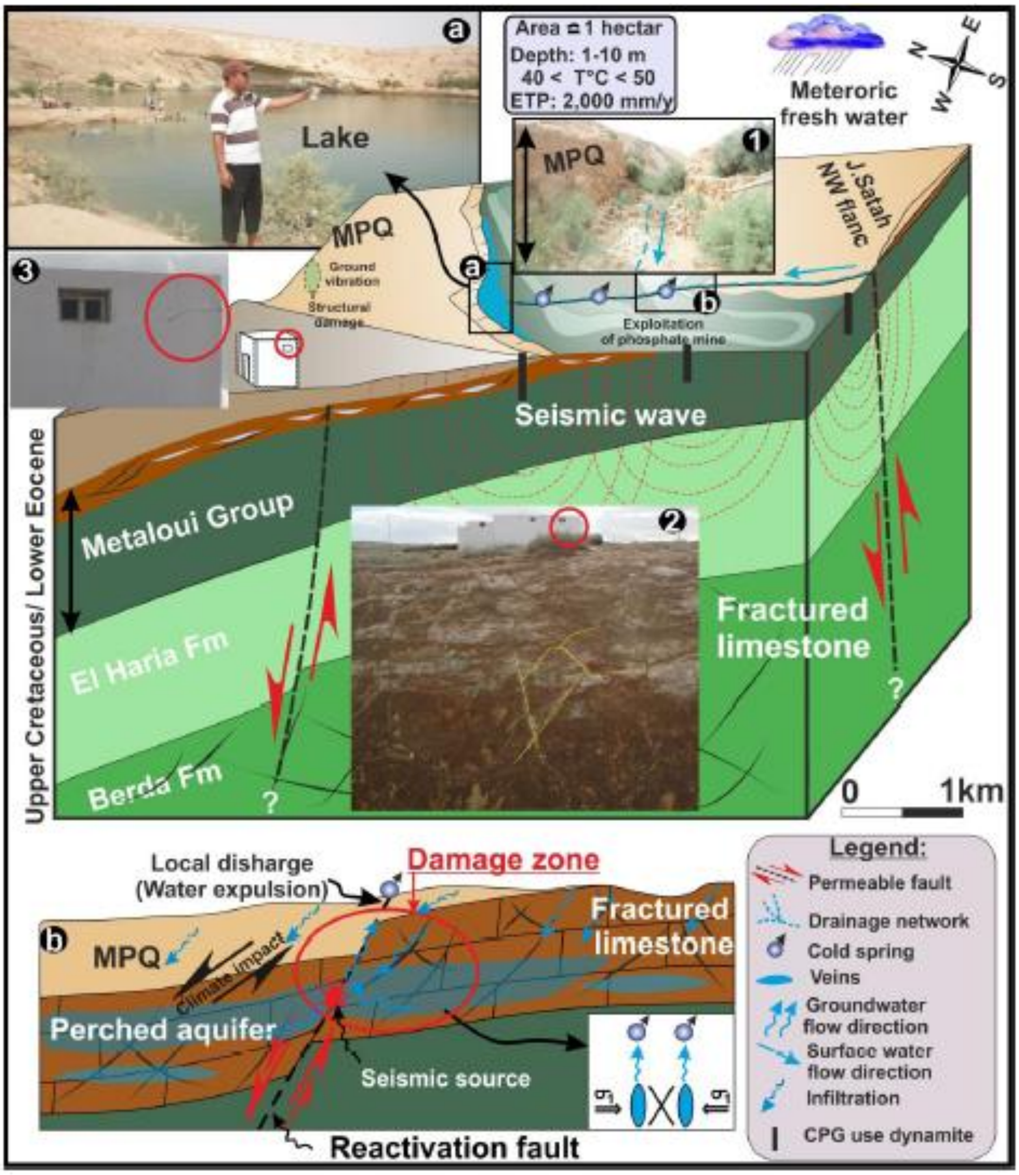

Figure 2) Conceptual model showing the hydrodynamic and the anthropogenic impact in the Gafsa mining basin.

The study area has a temperate Mediterranean climate, with moderately hot summers (38<T<50°C) and cold winters (-5<T<15°C). It shows a mean annual rainfall of about 350 mm. year^{-1} (data based on observations from 1964 to 2017) (Hamed *et al*., 2014, 2017) with a maximum amount of rainfall from November to January. Several authors (Yermani *et al*., 2002; Hamed, 2009, 2015, 2017a,b; Mokadem *et al*., 2014, 2016; Melki *et al*., 2017) estimated a potential evapo-transpiration varied between 1700 and 2000 mm.year^{-1}.

The hydrostratigraphic units in the Gafsa region are shown in Figure 1. These units consist of three main aquifer systems, namely, from the bottom to the top, the Continental Intercalaire (C.I), the Complex Terminal (C.T: Cretaceous and Mio-Plio-Quaternary) and the shallow aquifers (SASS). The fractured limestone (outcrop in the study area) and the MPQ aquifers are recharged during the rainfall events (Fig. 2).

3- Geological and Tectonic setting

The sedimentary series in the study area range from the Triassic sandstone and evaporite (Jebel Ben Younes) to Quaternary siliceous deposits (center of the basin). The Upper Cretaceous series begin with a thick Cenomanian-Turonian dolomite and claystone unit, locally interbedded with gypsum levels, belonging to the Zebbag Formation. This unit is overlaid by the Aleg Formation deposits constituted of thick Late Turonian-Early Campanian marly and calcareous claystone, locally intercalated with fossiliferous thin limestone layers that increase in thickness and frequency to the top (Burollet, 1956). On the Aleg Formation reposes the Early Campanian-Late Maastrichtian limestone and dolomitic limestone of the Abiod Formation, which represents the end of the Upper Cretaceous series. The lower and the middle parts of this formation are dominated by clayey and marly thin layers, while, the upper part is distinguished by a fissured feature (Ahmadi, 2006). Above the Abiod Formation reposes the Late Campanian-Paleogene claystone of the El Haria Formation, which represents the Cretaceous-Tertiary transition. This formation is overlaid by shallow marine to shore-face Paleocene-Early Eocene series belonging to the Metlaoui Group. This latter consists of thin gypsum, clay and highly fossiliferous dolomitic intercalations belonging to the Selja Formation, which is overlaid by the phosphatic carbonates and claystone series of the Chouabine Formation and the massive limestone layer of the Kef Eddour Formation. On these formations reposes the Late Eocene thick gypsum rich dolomite of the Seugdal Formation that constitutes the last marine facies. The oldest continental Neogene Formation is represented by the Sehib clayey and silty conglomerate, which is overlaid by the Middle-Late Miocene sandstone of the Beglia Formation. This latter is made up of loose to locally friable well-sorted sands (Burollet, 1956). The uppermost deposits in the study area belong to the Segui Formation of Late Miocene-Pleistocene age (Hamed, 2009, 2015).

From the tectonic point of view, the sedimentary series of the oriental Atlas, particularly in the study area, have been controlled by extensive tectonics during the Mesozoic age leading to the setting up of normal east–west and northwest–southeast fault networks (Zouari, 1995; Ahmadi, 2006). During the Cenozoic age, the Gafsa foreland basin was affected by compressive deformation events producing fault-related fold belts in relation with a thin-skinned mechanism (Ahmadi *et al*., 2006). These compressive tectonic events, mainly acting during the Quaternary age (Ahmadi, 2006) and controlled by inherited fault directions, created east–west fold belts such as Mratta-Bellil and Satah-Alima- Bliji (Ahmadi, 2006; Hamed, 2009, 2015; Hamed *et al*., 2010).

4- Materials and methods

The data used in the present study are the geophysical profils, lithostratigraphic logs of boreholes, direct observations and the hydrochemical study of surface water (lake). Water samples for Laboratory analyses were collected at the arid season (June-July, 2014). TDS, Temperature, pH, and specific electrical conductance (SEC) of the discharge water were measured *in situ* using a Consort C535 multi-parameter analyzer. After that, sample bottles were filled and kept in a refrigerator (4 °C) upon collection. Samples revealing relatively high salinity (exceeding 3 $g.l^{-1}$) were diluted before analysis. The ionic balance for all samples is within ± 5 %.

5- Results and discussions

Tunisia is one of the largest phosphate producers in the world (more than 10 million tons per year since the early nineties). In the mining Gafsa basin, the phosphorites formed during the Paleocene/Eocene were found to be composed of apatite, calcite, dolomite, clay minerals (illite, smectite, sepiolite and kaolinite), quartz, opal-CT, and gypsum (occasionally) (Chaabani, 1995; Tlig *et al*., 1987; Tlili *et al*., 2012). In Tunisia, phosphorite deposits occur in several areas, such as the North-South Axis (Nosa) and in the Gafsa-Metlaoui region. Gafsa basin is one of the most geologically investigated areas in southern Tunisia (Hamed *et al*., 2014).

Since 2003, stripping the surface layers in the study area by the CPG industrial sector to discover a new phosphate stock has resulted in the emergence of artificial lakes. These lakes have been recharged by the meteoric water, water leaks of MPQ aquifers and by the springs of small perched of Eocene aquifer due to the explosion dynamite that caused the reactivation fault (expulsion of deep groundwater of these perched small reservoir) (Fig. 2).

In the Figure 2 we present the impact of the CPG dynamite to exploit the phosphate. The wave propagation caused the reactivation of fault located at depth of about 1000 m in J. Satah area. Since 2011, the increase of meteoric water (March, 2014) and the decrease of the overexploitation of groundwater especially in Douara area (Channoufia boreholes) because the political problems during the Tunisian revolution; caused an inversion of groundwater flow direction from West to the East along the permeable fault. Also there is water expulsion of the perched Eocene aquifer “Karst aquifer” (lumachellic limestone) (Figs. 2 and 3g).

The reactivated fault has all kinds of damaging effects under the water pressure and water rising along the fault plane. In these cases there are damage of buildings of the entire of the Gafsa basin (Moulares, Metlaoui, Redayef and M’Dhilla areas). We refer to the damage zone as the portion of the fault zone in which the protolith has been variably fractured during fault-related deformation.

The permeability of the Eocene rock is increased by the effects of the rock pressure, solid-fluid coupling. Then the pathway is formed and the groundwater inrush occurs. The permeability of the fault area will be changed when the permeability coefficient changed. The process of a pathway formed by the fault reactivation and variation rules of the permeability are described by the formulas 1 and 2 of (Yaoqing, 2003):

$$K=K_0\, e^{\alpha t} \ ; t<t_0 \quad (1)$$

$$K=K_{max} \ ; t\geq t_0 \quad (2)$$

K_0: permeability coefficient of original fissures in the fault area;

K_{max}: maximum permeability coefficient of original fissures in the fault area;

α: coupling parameter;

t_0: time of inrush pathway fully formed;

t: time of inrush pathway formed;

Finally, in this study we demonstrated for a synthetic case of inrush of perched groundwater that contaminated by the recent meteoric water and/or the shallow aquifers of the MPQ. In Tunisia, there are several different stages of the researches of the groundwater inrush caused by the fault reactivation.

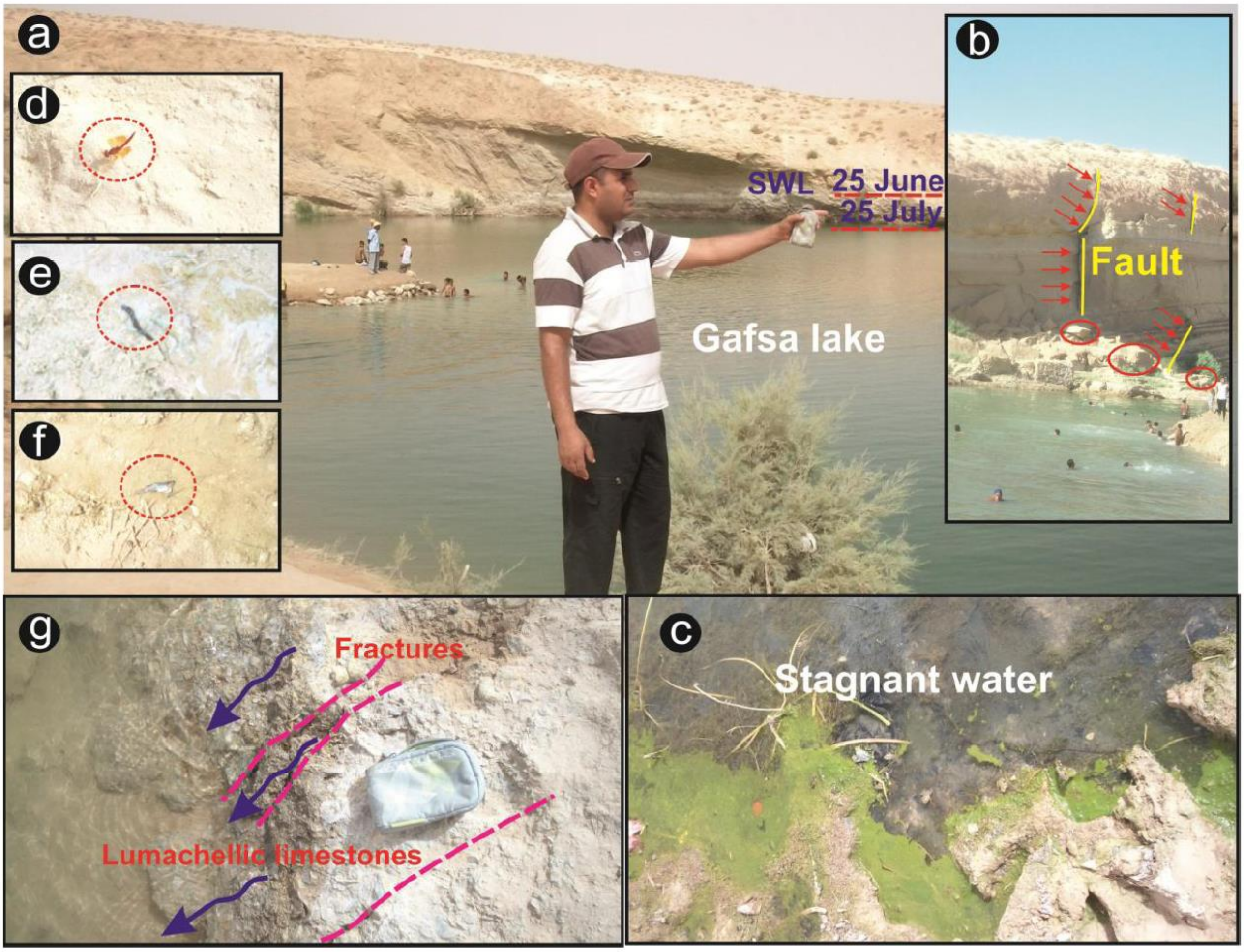

Figure 3) Actual characteristics of the Gafsa lake (Hamed et al., 2014)

The appearance of this lake (area about 1 hectar and the depth varied between 2-15 m) in the Gafsa mining basin (Phosphate mining industry of the Company of phosphate of Gafsa “CPG”) (Southwestern Tunisia-North Africa) caused many health problems (Fig. 3). The high evaporation and the absence of the rate of water renewal in the study area caused the decrease of the surface water level (SWL ≈ 1m in one month) (Figs. 3a and 3b), alagaire green layer in the limit of this lake (Fig. 3c), proliferation of insects (Fig. 3d) and nemathodes (Fig. 3e). Fortunately, the neoformation of this humid area in this arid basin, there are the migratory birds bring the fish to minimize these insects (Fig. 3f) there is even the insect of leishmaniosis well very known in the Gafsa basin.

The TDS (total dissolved solids) range from 2.2 to 3.94 g.l^{-1}. This parameter ranges from fresh to brackish/poor water. Groundwater salinity in the study area varies probably both in the vertical and lateral directions. The salinization of the groundwater would be expected to result from the ionic concentrations increasing due to both evaporation of this stagnant water, to the effects of interactions between the groundwater and the fall blocks and the anthropogenic effect of human activities (swimming) (Figs. 3a and 3b).

The figure 4 shows the photo-satellite localization of the transboundary area of Gafsa mining basin, or the significant releases of phosphates washing resulting from heavy exploitation of groundwater from the Complex

Terminal "CT" system aquifers. Current recent studies show that these releases have catastrophic damage to the ecosystem and human health in the study area (atmospheric, pedologic and hydrogeological desertifications). The questions that always arise: Are there any valorization of geo-resources of the mining area? How to adapt in this mining environment of phosphate mining?.

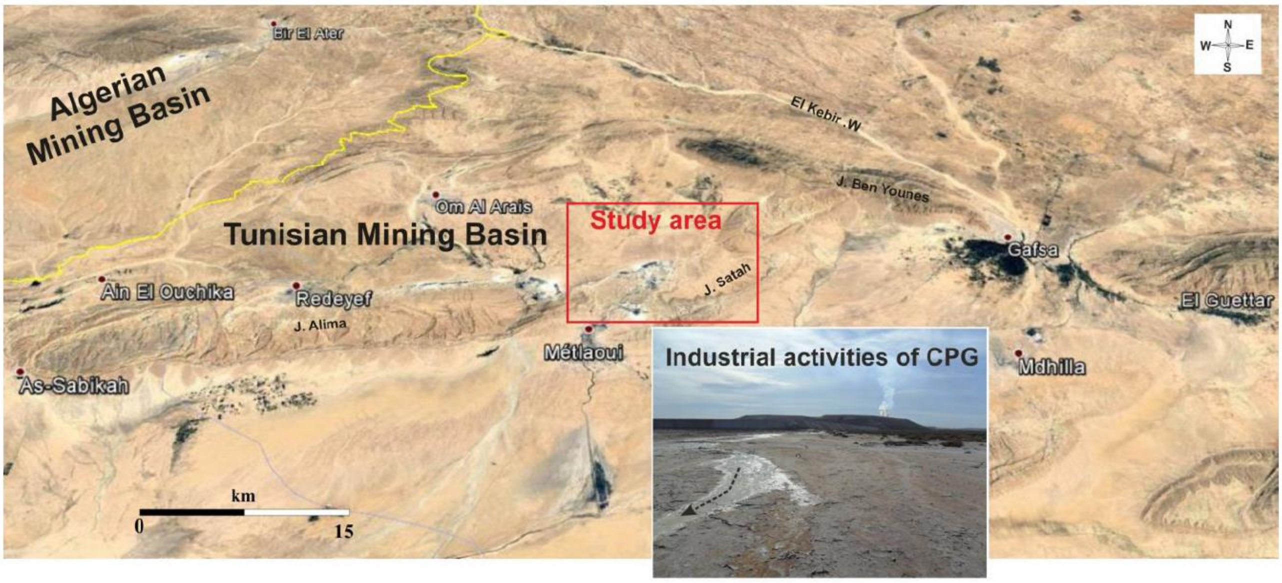

Figure 4) Photo-satellite map showing the localization of the transboundry area of Gafsa mining basin.

6- Climate effect on groundwater in the study area

Climate change has a multitude of immediate and long-term impacts on water resources (surface and groundwater) in Arab countries and in the Southern Mediterranean Basin. These include flooding, drought, sea-level rise in estuaries, drying up of rivers/wadies, poor water quality in surface and groundwater systems, precipitation and water vapor pattern distortions, and snow and land ice bad distribution. These effects, when compounded together, have devastating impacts on ecosystems and communities, ranging from economic and social impacts to health and food insecurity, revolutions, migration...all of which threaten the existence of many regions in Arab countries (Al Gamal and Hamed, 2014; Redhaounia *et al*., 2015; Attia and Hamed, 2017, Hamed *et al*., 2010, 2013, 2017; Hadji, 2017; Hadji *et al*., 2017).

In our case of the mining basin of Gafsa, the mismanagement of the water molecule "the Blue Gold" has been the main cause of the Tunisian revolution that has been started since 2008 in the mining region of Rédayef (unemployment due to the absence of agricultural projects, deterioration of air/soil/water caused by the phosphate sector, bed economic situation...).

Currently the over-exploitation of groundwater in the mining basin (Tuniso-Algerian transboundry basin) will aggravate the situation especially in these arid to desert climate conditions and also in these global socio-economic conditions. In my opinion, the international cooperation and the internal collaborations (political, university, academic, industrial...) are needed to improve the current state. Training of current generations to allow and to have beautiful future situations through future understandable and well-formed generations (economic, political, climatic sectors ...).

7- Conclusions and perspectives

The objective of this study was to assess the respective impact of climatic and anthropic pressures on groundwater resources in the mining basin of Gafsa (SW Tunisia). Our main results showed that water management modifies the hydrogeological response at short and large-time scales. We assume that the reason why large-scale rainfall component do appear in the spring discharge is that groundwater storage is highly affected by over-pumping (washing phosphate and agricultural sector). This result shows that possible long-term impacts of rainfall variability due to climate change may be masked by a high pumping rate. In this case an increase of the pumping rate from the 1960s, the stress on the groundwater resource does increase from year to year (hydrogeological desertification). This indicates that the aquifer is currently over-exploited. This study highlights the effectiveness of wavelet analysis in characterizing the response variability of karst systems (Eocene Fm.) where the hydrogeological regime is modified by pumping. In order to establish water management scenarios under climatic changes, our approach may be useful to help decompose time series, extracting frequencies in which climatic and anthropogenic components are mainly localised, before their use in modelling approaches.

Currently, several scenarios to avoid the problems of groundwater degradation mainly by the industrial sector (CPG/GCT-Tunisia) (Hamed, 2017b):

1. Ovoid the overexploitation of groundwater;
2. to move towards the unconventional waters (wastewater of phosphate, wastewater of ONAS);
3. Phosphate washing by seawater (pilot project ERAMED developed by Hamed in 2017);
4. to move towards "Green Chemistry" (renewable energy) (pilot project ERASMUS developed by Moussaoui in 2017);
5. to move towards the intelligent irrigation in the agricultural sector;
6. Manage the surface water (rainwater mainly: surface and/or sub-surface dams, hill lakes, CES);
7. to move towards new technology (smart technology) to adapt to the impact of climate change in arid land (South Mediterranean basin).

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