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Hydrogeological and hydrogeochemical investigation of the coastal area of Jifarah Plain, NW Libya

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Overexploitation of the groundwater has become a common issue along the coast where good quality groundwater is available. The shortage of good quality water from surface sources has made groundwater to be an important source in many urban areas. In regions where dry conditions prevail, water is ultimately precious. The issue of water shortage is likely to approach the crisis level in the arid countries where surface water resources are mostly scarce and groundwater resources are often non-renewable. The scarcity of water in Jifarah Plain, NW-Libya, is becoming more pronounced due to the increase of the population coupled with improvement of the standard of living over the last few decades. The coastal areas of the studied Jifarah Plain accommodate a high population with more than 50% of Libya's population; they live along 200 km of the Jifarah shoreline and are mostly concentrated in central Jifarah (along 105 km).

The main objective of this research is to characterize and assess the geology, hydrogeology, hydrodynamics and water quality of the Upper Miocene-Pliocene-Quaternary aquifer in order to identify the sources of high groundwater salinity. An additional objective is to construct, calibrate and develop a groundwater flow model that can be used in future development processes, and to assess and identify the hydraulic characteristics and stresses of the upper aquifer, groundwater flow regime, groundwater availability and quality. The study was based on data acquired from the General Water Authority (GWA) data base, previous studies and fieldwork campaigns conducted in 2007 and 2008.

The lithology of the upper aquifer varies widely and includes detrital limestone, gravel, marl, clay, silt, sand, sandstone and calcarenite. To the west of central Jifarah, in the southern Sabratah region, the lower part of the upper aquifer is composed of gypsiferous limestone and sandstone producing highly mineralized sulphate water in this area. The bottom of the upper aquifer varies between 30 and 180 m depth and depths of the wells that are utilized in this aquifer are between 30 and 160 m deep.

Water resources in the Jifarah Plain in 2005 consist of 3% surface runoff, 88% groundwater and about 9% desalinated and treated water and water from the Grat Man-Made River Project (GMRP). The climate in the study area is arid to semi-arid and typically Mediterranean, with irregular annual rainfall. The average annual rainfall and evapotranspiration rates are 250 mm/year and 1535 mm/year, respectively.

The estimation of groundwater exploitation for the upper aquifer for different purposes shows that the total amount of groundwater pumped in the Jifarah Plain for domestic, industrial and agricultural use amounts to 1201.30 Mm^3/year (2007). For drinking water supply and domestic wells, the overall amount pumped was 66.50 Mm^3/year, which is 5.55% of the total amount of groundwater extraction. The yield of irrigation wells was estimated to be 1123 Mm^3/year, which is equal to 93.47% of the total amount of groundwater extraction. The industrial sector pumps only 1% of the total groundwater utilization in the plain. There is also a considerable amount of water loss through sebkhas (78 Mm^3/year; Pallas, 2006), downflow leakage (151 Mm^3/year; Pallas, 2006) and a negligible amount of water discharge to springs (3.33 Mm^3/year). In total, the groundwater discharge in the Jifarah Plain amounts to 1433.33 Mm^3/year.

Several piezometers tapping the upper aquifer have been regularly monitored in the plain since 1970s. There are long term and, to some extent, seasonal fluctuations in groundwater elevations in the upper aquifer in the study area. Groundwater levels are directly proportional to rainfall in the area and inversely proportional to groundwater abstraction. The average fluctuation amplitude is high in the north of the plain, mainly due to higher average precipitation and pumping rates at the coast, and low in the south.

The general direction of groundwater flow in the plain is from the south – from the Jebal Naffusah mountains – to the coast. This was also confirmed in the developed groundwater model of the area. High heads were observed in wells in the south of the plain and in some wells in the north, located nearby a high topographic area.

Important storage withdrawal from the upper aquifer is causing continuous drawdown of the water level. The groundwater level is mostly low especially near the coast, where zero and negative heads are recorded for the majority of the wells. Depression cones in various places have dropped from 20 to 33 m below sea level, which testifies to the inversion of the hydraulic gradient and the intrusion of seawater.

This study analyzed 34 time-drawdown data sets from various wells penetrating all different aquifers in the basin. Hydraulic parameters were estimated, based on results from the constant rate pumping, and step-drawdown aquifer tests were interpreted with different methods such as the Cooper-Jacob equation, the specific capacity method, and type curve-fitting methods. An important advance of this study has been the development of new empirical relations between transmissivity and specific capacity for estimating transmissivity from specific capacity and successful application of the specific capacity method for the study area.

The final results show that for the upper aquifer, the transmissivities deduced from a specific well capacity range from 4.11 to 136.92 m^2/d with an average of 45.82 m^2/d, and 4.40 to 414.86 m^2/d with an average of 106.36 m^2/d for the deep aquifers. The curve-fitting results from the aquifer tests show the following parameters: an average transmissivity and hydraulic conductivity of 44.55 m^2/d and 0.89 m/d respectively for the upper unconfined aquifer. The semi-confined aquifer of Lower Miocene has an average value of 77.22 m^2/d and 0.64 m/d for transmissivity and hydraulic conductivity, respectively. The semi-confined Abu Shaybah aquifer has an average value of transmissivity and hydraulic conductivity of 182.94 m^2/d and 1.83 m/d, whereas the Al Aziziyah aquifer has average values of 82.31 m^2/d and 2.30 m/d for transmissivity and hydraulic conductivity respectively.

Precipitation is the main source of recharge with an amount of 268.20 Mm^3/year. There is also a considerable amount of recharge coming from the return flow from irrigation and domestic supply (131.80 Mm^3/year), while a smaller fraction of recharge is coming from wadi beds at the southern and eastern borders of the plain (66.59 Mm^3/year). The inflow from the southern border is negligible and amounts to 0.76 Mm^3/year, whereas the inflow from the sea amounts to 166.10 Mm^3/year (Mott-MacDonald, 1994). In total, the groundwater recharge of the upper aquifer is 633.55 Mm^3/year.

Groundwater budget calculations results show that the total extraction of 1433.33 Mm^3/year is more than two times higher than the recharge. This clearly shows an unbalanced situation which leads to important water level decline and water quality deterioration.

Understanding the geochemical evolution of groundwater is important for sustainable development of the water resources in the plain. Water samples were collected from 137 sampling points in the study area and analyzed for the major cations and anions (Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-, HCO_3^-, CO_3^{2-}, Fe^{2+}). The analytical process is mainly based on water type classification according to Stuyfzand (1986), graphical illustration methods (Piper diagram, scatter diagram, ionic ratios diagram, Durov diagram and Van Wirdum diagram), maps and hydrogeochemical profiles showing the spatial and vertical distribution of water quality parameters in the study area.

The major hydrogeochemical processes occurring in the upper aquifer are: mixing with seawater end member; cation exchange during salinization; dissolution of gypsum and sebkha sediments, carbonate dissolution and agricultural pollution.

Lower ratios of Na^+/Cl^- than the seawater ratio indicate seawater encroachment. The ionic ratio of Na^+/Cl^- shows a higher value in the upstream direction, where most of the water types are classified as CaMix, MgMix and to some extent $CaSO_4$ to the south of Sabratah. In the downstream direction, the Na^+/Cl^- ratio is decreasing, where NaCl and CaCl water types are developed.

Stuyfzand's classification clearly shows the significant geochemical differences between the coast and the inland part, where the groundwaters follow paths of hydrochemical evolution, from Ca/MgMix water types in the south via Ca/MgCl types evolving to the NaCl type close to the seaside. This pattern indicates that groundwater chemistry is changed by the increasing admixture of seawater. The NaCl and CaCl waters indicate a strong relationship with seawater.

Ca/MgMix (HCO_3Cl) and Ca/MgMix ($ClHCO_3$) are probably transitional types from freshwater to saltwater. In the Sabratah area, the $CaSO_4$ type is found inland, pointing to gypsum dissolution.

Towards the recharge area, less influence of seawater is observed; the positive cation exchange code indicates the presence of Mg^{2+} due to dissolution of dolomite and/or Mg^{2+} bearing calcite in the freshwater end member. Towards the discharge area near the coast, the negative and equilibrium cation exchange codes are resulting from the salinization phenomena.

The saturation index shows mostly a tendency to precipitation for calcite and dolomite in the aquifer system. Gypsum and anhydrite are undersaturated, but with higher SI values in the area south of Sabratah, where the dissolution of gypsum has increased the concentrations of SO_4^{2-} and Ca^{2+}.

Results show that water samples do not compare favourably with WHO standards (1993); many samples exceed the maximum admissible concentration. Of the sampled coastal groundwaters, 61% exceed the recommended Cl^- value for standard drinking water (250 mg/l) and 26% have Cl^- greater than the highest admissible level of 600 mg/l.

The groundwater flow model of the upper aquifer was successfully constructed and developed. The model was calibrated and used to ascertain the aquifer hydraulic parameters, specifically, hydraulic conductivity, groundwater flow regime and groundwater budget. It was also used as a tool to assess the impact of abstraction.

The steady state simulation has indicated that the groundwater flow direction is from higher topography in the south to the north, towards the Mediterranean Sea in the north and the sebkha drains in the northwest of the plain.

The non-steady state simulation has indicated that groundwater levels in the upper aquifer are most sensitive to discharge from wells. Groundwater flow direction is from south to north, towards the depression cones and reduced heads on the coast.

The hydraulic conductivity value of 6.10 m/d and specific storage of 0.20 give the best results for steady state and transient calibrations. The transient state confirmed that under the current discharge conditions (1201 Mm^3/year), exploitation from the upper aquifer is unsustainable, where the discharge is much higher than the recharge.

Finally, the study recommends the following:

- Reduce the pumping rate, especially near the coast to avoid seawater infiltration.
- Obtaining comprehensive meteorological records on the study area and recharge areas based on daily observations will provide more accurate estimation of recharge in the region.
- The need for the installation of a representative monitoring well network for the observation of both piezometric heads and water quality is high. A network of monitoring wells should cover the whole area equally. The observations of water levels should be taken regularly.

- Conducting more reliable aquifer tests distributed over the whole plain, where drawdown measurements should ideally also be taken in observation wells.
- Confirmation of the origin and composition of the freshwater end member coming from the recharge area is also required.
- A detailed study about current land use activities and locations of possible point sources of contamination (e.g. pollution from agriculture) should be prepared.
- The construction and running of a comprehensive transient and transport model for the upper aquifer including the recharge area.