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Importance of Vertical Groundwater Flow as a Discharge Component in Transboundary Chotts, Western Tunisia

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Abstract: The presence of groundwater discharge zones, locally known as Chotts, in the western border of Tunisia with Algeria is used as a case study to evaluate the current regional transboundary groundwater development status and the probable challenges of present groundwater trajectory, its regional flow patterns, water balance, and overall discharge-recharge features. The Tunisian Chotts Region constitutes the main discharge feature of groundwater flowing in the Continental Intercalaire and overlying Complex Terminal geological formations with their main recharge areas been claimed to be in the south Atlas Mountains of Algeria, the Tinrhert plateau of Algeria and the Dahar Mountains of Tunisia. The general direction of groundwater flow in the horizontal plane reaching El Djerid Chott is from West to East coming across the Algerian–Tunisian border seems to ensure hydraulic continuity of the Continental Intercalaire in the Djerid region. The affected territory covers some 7,000 km² with a surface elevation of 10 m amsl to –25 m bmsl; this land shears similar geographical location and elevation conditions as other chotts in Tunisia (ie., Gharza, Chtihatt Sighat, El Rahim, Majez Sfa). In the other side of the border, the main surface features in Algeria are characterized by chott Melrhir with 6,700 km² and –33 m bmsl, as well as the Merouane, the Kralla, Aslouj, Zhithif, Zebahir, Felrhir, out of which several are also located below main sea-level. A common feature from the groundwater perspective is certainly high salinity and water temperature as in Chott Gharza. Using Tóth's theory on groundwater flow systems, surface indicators were further analyzed to understand the systemic connection between recharge and discharge zones of regional groundwater flow identified from evidence on the land surface. Results suggest the need of further reviewing scientific data as well as to design a widespread education and training in groundwater flow systems understanding aimed to an increasing international interaction with shared information and common objectives in the management of transboundary groundwater systems. Without adequate and accurate scientific knowledge of groundwater flow characteristics in its 3D distribution, uninformed policy development could lead to unsustainable groundwater management. Current transboundary groundwater assessments would improve through a more solid scientifically management international scale plan. A road map towards a shared management of groundwater is described aiming to promote equitable and responsible groundwater allocation.

Keywords: Regional Groundwater Flow, Groundwater Discharge, Groundwater Flow System Theory

1. Introduction

The presence of Chotts, extensive and permanent groundwater discharge regions on the western border of Tunisia with Algeria and its eastern border with Libya (Figure 1) is investigated as a case study to evaluate the current territorial transboundary groundwater development status. Organisations such as the International Groundwater Resources Assessment Center [11] and UNESCO have inventoried 592 worldwide transboundary aquifers. Consequently, some states have begun their scientific evaluation. Evaluation is usually associated with the general expected and traditional nature of groundwater. Challenges to achieving a more precise groundwater flow trajectory among the countries involved appear critical in future economic development. Such challenge goes beyond the geological formational definition, horizontal groundwater flow patterns, a water balance, and political borders. Groundwater is the concept behind transboundary aquifers. The transboundary aquifer concept envisaged in the United Nations Resolution 63/124 [22] has significantly influenced the evaluation of groundwater issues in transboundary regions. Indeed, the review of groundwater functioning must be defined and tackle the lack of conceptual flow clarity [9]. Authors that contributed from a political geography and hydrogeology analysis based on scientific evidence and legal documents propose the current conceptual discrepancies between the scientific definitions of the transboundary aquifer and the nature of transboundary groundwater. These authors' results suggest the need to include a systemic vision of transboundary groundwater management issues. The hydrogeology of Chotts region has been the objective of several previous studies Dhaoui, Z. et al., Edmunds, W. M. et al., Kamel, S., Petersen, J. O. et al., Takuya, M. et al. respectively [4, 5, 12, 16, 19]. Obtained results were constructive but an understanding of the hydraulic continuity among aquifer units was not given the required importance. Actions supported by a homologation of scientific concepts and methodologies are foreseen to be applied by countries involved to guarantee an integrated transboundary water management with societal participation. Capacity building in groundwater flow systems is a relevant issue.

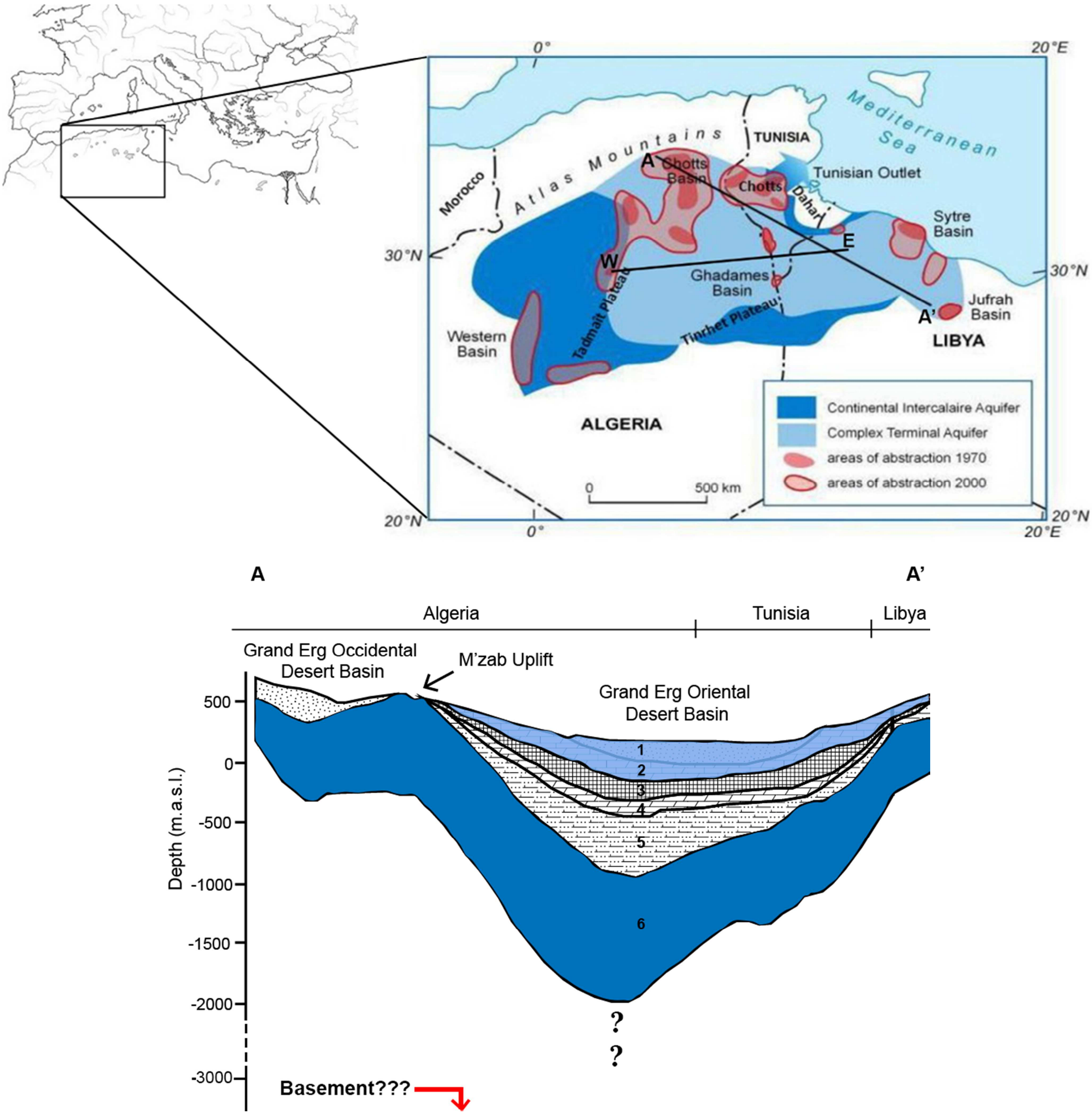

Figure 1. *Location of study region (inset) with outcropping formations map plus an A-A' cross-section showing the thickness of relevant geological strata where groundwater flow occurs; note a lack of basement rock definition. (Modified after Mamou, 1990; Kamel, 2012, respectively).*

Due to the Chotts arid setting, limited classic hydrogeological borehole data is available; studies carried out are also constrained to the aquifer concept with a restricted x, y, z domain of interest. Here, the natural continuity of groundwater flow from recharge to discharge needs to be reviewed using a conceptual 3D Groundwater Flow Systems Model as devised by Tóth, J. [20, 21]. In addition, the notion of hydraulic head proposed by Hubbert, K. M. [10] appears to be an essential parameter often mistaken by groundwater elevation. Finally, the reported total salinity, groundwater temperature and stable isotopes are neglected issues regarding their meaning from a groundwater flow perspective, presented in the following sections.

The present work seeks to understand groundwater discharge identification to propose a regional continuity of flow from recharge to discharge conditions and their relation to groundwater functioning. Such flow is beyond the aquifer concept, which is explained as the couple: formational rock+saturation water. Groundwater flow, which undoubtedly has a 3D distribution, is naturally over-imposed on the regional geological formations outcropping from western Libya, southern Tunisia, and the central part of Algeria, reaching as far as their border with Morocco. Although the Continental Intercalaire and the Complex Terminal (Figure 1) Mamou, A. and Kamel, S. [13, 12] have been extensively studied [17] from their geographical distribution to their hydrogeological characterisation, groundwater flow systems understanding awaits further interest. The objectives of this work are i) to find evidence that the Chotts in the central-western region of Tunisian constitute a main vertical upward discharge feature of regional groundwater flow; ii) to demonstrate the importance of discharge areas (Chotts) as a key to understanding recharge areas, and iii) to recognise the hydraulic response of the Chotts within the context of regional groundwater flow and the importance of vertical flow in hydraulic head distribution.

2. Materials and Methods

The methodology adopted in this paper is the Groundwater Flow Systems Theory (modern-Hydrogeology) Figure 2. This theory proposes understanding flow patterns in 3D by applying the gravity-driven flow concept that differentiates three significant flow systems (local, intermediate, and regional), travelling from shallow to deep conditions. To further achieve such a differentiation, available surface evidence of the groundwater flow systems was included, such as the nature of discharge areas. Here, the systemic connection between recharge and discharge areas of local and regional groundwater flow systems plays a significant role in their systemic understanding. Generally, regional flows have high temperature and saline water (i.e., total dissolved solids)), and local flows have lower temperature and salinity water. Such attributes allow identifying the nature of the groundwater arriving at the Chotts and nearby extraction wells.

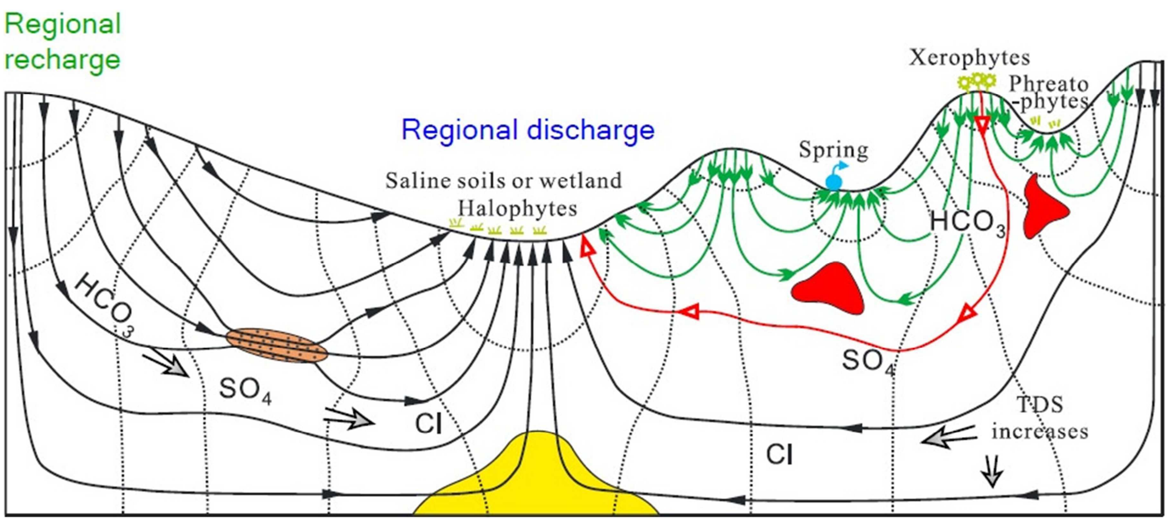

Figure 2. *Schematic diagram of groundwater flow systems (after Tóth, 1999).*

The methodology included the conceptual modelling of the hydraulic head, which is determined using (1) devised by Hubbert, K. M. [10]. The hydraulic head is the main driving force for groundwater flow.

$$h = z + p / (\rho \cdot g) \quad (1)$$

Where h is the hydraulic head; p the gauged pressure measured at the elevation datum z (basement rock); ρ water density, varying on total dissolved solids and temperature; g the gravitational acceleration.

3. Groundwater Flow Systems

3.1. Groundwater Flow Direction

The presence of the Chotts relates directly to permanent groundwater circulating in the Continental Intercalaire and

Complex Terminal formations Figure 1. These formations constitute the Northwest Sahara Aquifer System (NWSAS) [17]. The NWSAS forms part of one of the world's largest and most arid deserts containing at least one significant aquifer system plus any other aquifer unit below the base of the Continental Intercalaire formation.

The Chotts represent the main discharge area of the groundwater circulating through the Continental Intercalaire and Complex Terminal formations. "Chott" is a North African term for a flat salty terrain within a surface hydrologically closed basin [7] and [18]. Although the NWSAS covers a surface of 1.1 million km², only comparable with the Guarani Aquifer in South America, having 1.2 million km², it has groundwater storage estimated by Baba Sy, O. [1] and Petersen, J. O. et al. [16], in 31,000×109 m^3 using an effective merely 5% porosity. Similarly, the Guarani Aquifer has water storage of 30,000×109 m^3 [6]. However, intense water abstraction in the 1970s for domestic and agriculture decreased observed water levels in the NWSAS; further withdrawal reached a reported 75 m^3/s in 2000 [16], increasing the drawdown effect.

The general direction of groundwater flow in the horizontal plane reaching El Djerid Chott seems to be from West to East, flowing across the Algerian–Tunisian border, establishing a hydraulic continuity of the Continental Intercalaire to the Djerid territory (Figure 3). The affected discharge part covers +7,000 km² with a surface elevation of 10 m amsl to –25 m bmsl; this land shares similar geographical location and elevation conditions to other Tunisian Chotts (ie., Gharza, Chtihatt Sighat, El Rahim, Majez Sfa). In Algeria, the main surface features are characterised by Chott Melrhir with 6,700 km² and –33 m bmsl, as well as the Merouane, the Kralla, Aslouj, Zhithif, Zebahir, Felrhir Chotts, several of them located below the main sea-level. A common feature is a high salinity and water temperature in Figures 3 & 4, as in Chott Gharza. Features suggest water density requires to be considered in the hydraulic head for flow direction evaluation; however, groundwater flow is usually defined horizontally utilising the water-table elevation. This consideration implies using the theoretical properties of water with 20°C and 1,000 mg/L of salinity instead of the Hubbert, K. M. [10] approach. As a result, some misleading scenarios could develop. These scenarios might represent opposite groundwater flow processes. For instance, it could be argued that an expected salinity increase will occur along the supposed flow pattern deduced from the water table distribution, which is not observed in the reported field conditions, as shown in the maps in Figure 3. Similarly, the groundwater flow has a different temperature at different depths, making it necessary to impose corrections for the actual pressure of the water column. The effect in water density by temperature and salinity requires knowledge of their distribution on the vertical scale.

Regarding the temperature and the chemical signature in Table 1, borehole 22 near Chott El Djerid, tapping Continental Intercalaire, has the highest temperature, 85°C; other nearby boreholes 14-15-29 reported in the same formation have 46 to 54°C. Chloride in borehole 22 is 3,427 mg/L, others from 798-1,188 mg/L [16]. Such contrasts suggest the presence of crucial vertical flow components. It is to note that boreholes 19-20-27 show lower Chloride but higher temperature than boreholes 14-15-29 whose water is reported to travel to depths from 1,926 m to 2,078 m [16]. On the other hand, according to Edmunds, W. M. et al. [5] borehole 109, with a reported depth of 2,257 m tapping the Continental Intercalaire, near Chott El Djerid, has the lowest temperature, 38°C, and other nearby boreholes have 66 to 71°C. The reported Chloride value measured at borehole 109 is 442 mg/L, others from 356 to 1,600 mg/L. Consequently, borehole 109 suggests the presence of vertical flow downwards from the water of a local flow with lower temperature and salinity.

According to several sources Meyer, D. F., Kamel, S. and Guendouz, A. et al. respectively [14, 12, 8], the basement rock is usually not given further consideration. The stratigraphy column information ends at the base of the Continental Intercalaire (see Figures 1 & 5) [15]. The Tóth Groundwater Flow System (Figure 2) requires the position of basement rock; vertical inflows and outflows would provide further groundwater functioning identification to establish the natural conceptual hydrogeological model. The model would benefit by proposing recharge, transit and discharge areas.

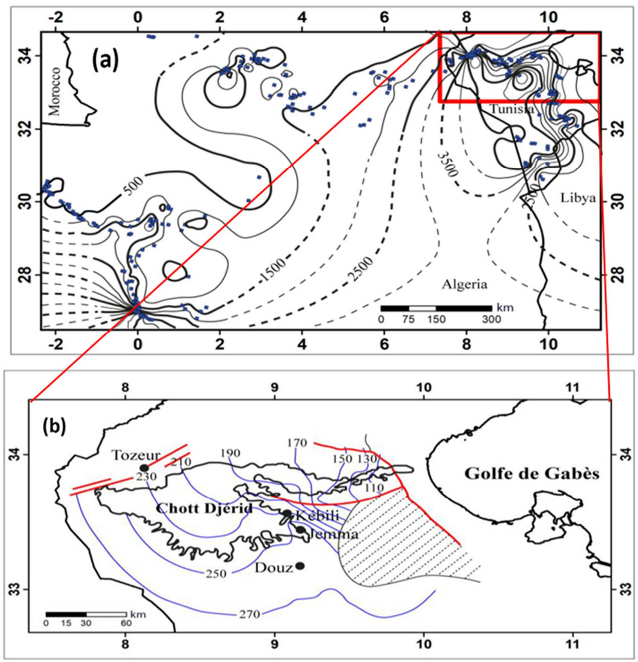

Figure 3. A representation of Total Dissolved Solids (a) and water-table distribution (b) of the Continental Intercalaire Aquifer. Adapted from (Meyer, 2016).

Table 1. Data used by Petersen et al. (2018).

Borehole	Cl (mg/L)	Temp°C	Aquifer
22	3,427	85	Continental Intercalaire
14-15-29	798-1,188	46-54	Continental Intercalaire
19-20-27	259-536	68-76	Complex Terminal

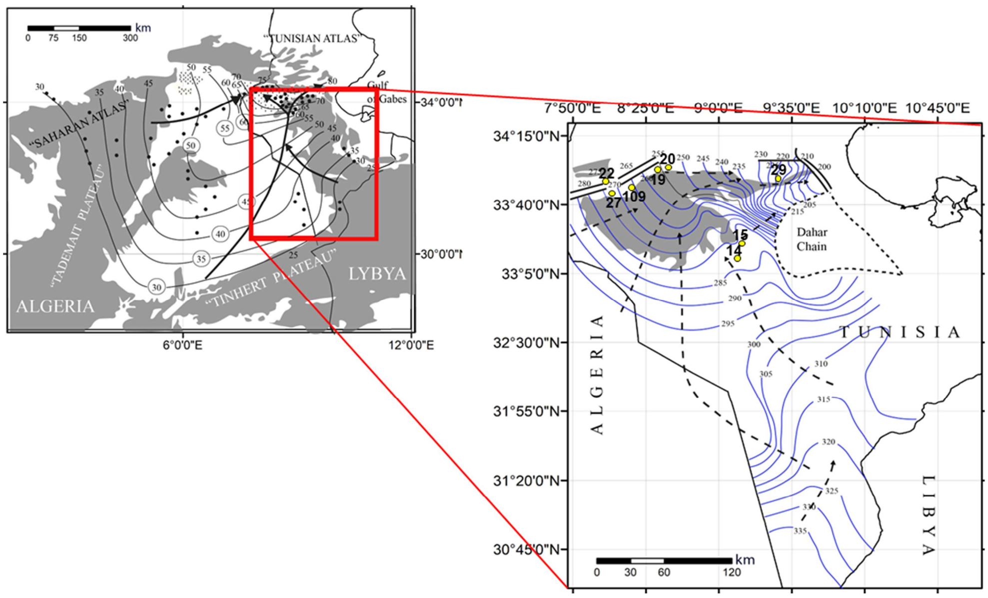

Figure 4. Groundwater temperature at the base of the Continental Intercalaire, as well as reported water-table elevation for the same formation (after Kamel, 2012).

3.2. Groundwater Recharge-Discharge

Indeed, reported discharge conditions have been present since historical times; in theory, the source of this outflow is constantly replenished to permit the discharge yield conditions to prevail over time. Considering Djerid and Gharsa Chotts only, they cover a surface of ≈8,000 km^2; with the potential evaporation adding to ≈2 m/year, a precise discharge quantity implies a continuous flow of ≈500 m^3/s. This estimate excludes other Chotts, direct water evaporation by shallow water level zones, current groundwater extraction and natural discharge into the Mediterranean sea. Therefore, the extensive water storage allows for thousands of years for groundwater to show any depletion effect; as Bredehoeft, J. D. et al. [2] suggested, actual recharge is a questioned concept in groundwater management.

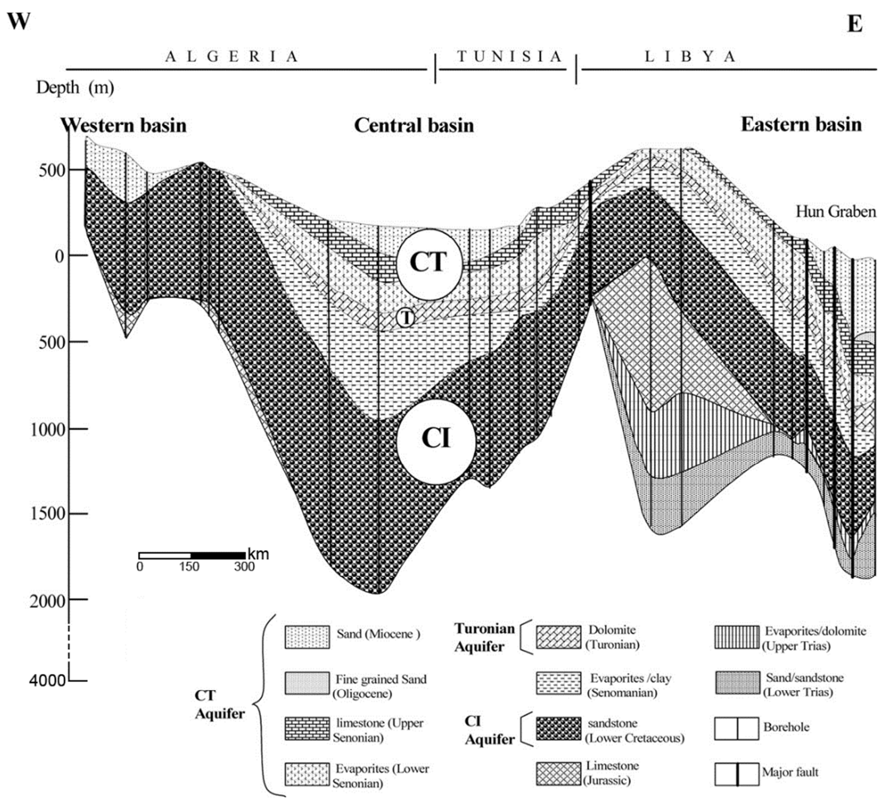

Figure 5. East-West section across of the Continental Intercalaire, CI, and the Complex Terminal, CT, named as NWSAS (after OSS, 2003) (Section location in Figure 1 as W-E).

The principal modern recharge areas in the Continental Intercalaire and overlying Complex Terminal formations have been claimed to be in the south Atlas Mountains of Algeria, the Tinrhert plateau of Algeria and the Dahar Mountains of Tunisia. However, most analyses ignore the importance of recharge occurring in Algeria's Tademait plateau and generating the regional groundwater inflow travelling from Libya. Most of these inflows discharge as transboundary groundwater in the chotts. The lengthy path the recharging water must follow to reach the chotts suggests that the inflow water originated under contrasting climatic conditions. Therefore, discharge groundwater is expected to have a different isotopic signature from current recharge conditions.

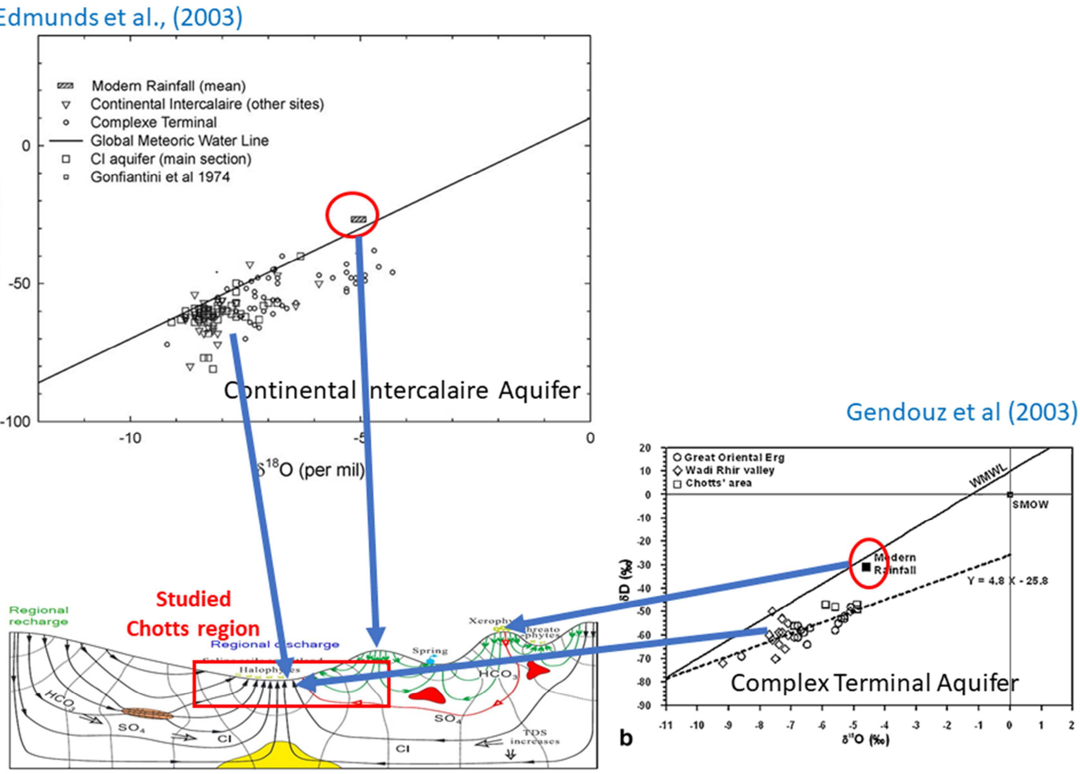

Figure 6. *Proposing interpretation of $^{2}H/^{18}O$ diagram for Continental Intercalaire groundwater in Southern Tunisia (a) (Edmunds et al., 2002) and Complex Terminal groundwater (b) (Gendouz et al., 2003).*

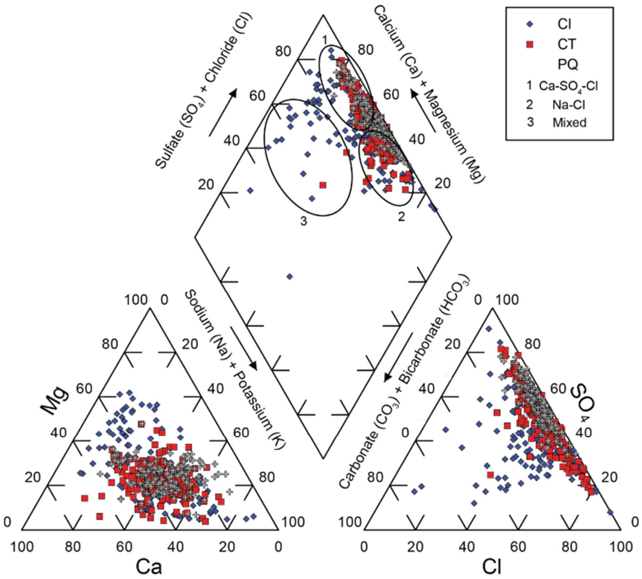

Figure 7. *Overall major-ion data for samples collected at different times from different groundwater sources (after Meyer, 2016).*

The stable isotopes tell a temperature-related history of the travelling water in both Complex Terminal and Continental Intercalaire, suggesting the water has been strongly evaporated and/or indicates an isotopic signature when recharge occurred (Figure 6). However, groundwater has been collected in discharge areas, often utilising boreholes. As a result, the actual flow path of arriving water is unknown; recharge areas require a review. Evidence suggests groundwater samples show other than actual recharge conditions (see Figure 6). Therefore, the Tóth groundwater flow systems could guide further related studies toward the original recharge conditions. That implies most samples collected close to the chotts provide information on the discharge condition on water recharged in ancient times. Data collected represent the recharge conditions when the discharging regional flow system occurred.

On the other hand, the main chemical elements and compounds in sampled water suggest groundwater's development characteristics. Figure 7, after Meyer, D. F. [14], shows the prevalence of water to have higher SO_4 than HCO_3 and a high tendency to have Cl as the main component.

Based on Figure 2, these results propose that samples belong to relative ancient water as suggested by the development of $HCO_3 < SO_4 < Cl$.

Regarding to the meaning of the sampled water, Figure 8a after Carrillo-Rivera, JJ. et al. [3] establish a critical reference for the sampling time when the vertical upward components of flow are present. The lithological nature of this borehole in fractured rock is considered to play a significant role in the flow response towards the extraction time. Collecting representative samples in abstraction boreholes becomes crucial when vertical flow components are present in the site of interest. On the other hand, the uniform water quality and temperature response observed in Figure 8b, suggests a nil response of these components after one day of continuous pumping, opposite to Figure 8a. The proposed flow regime to the late abstraction borehole is controlled by a lithology represented by granular material, where horizontal flow regulates the inflow. The knowledge and understanding of the presence of different flow systems in the site of interest become essential in data collection and interpretation.

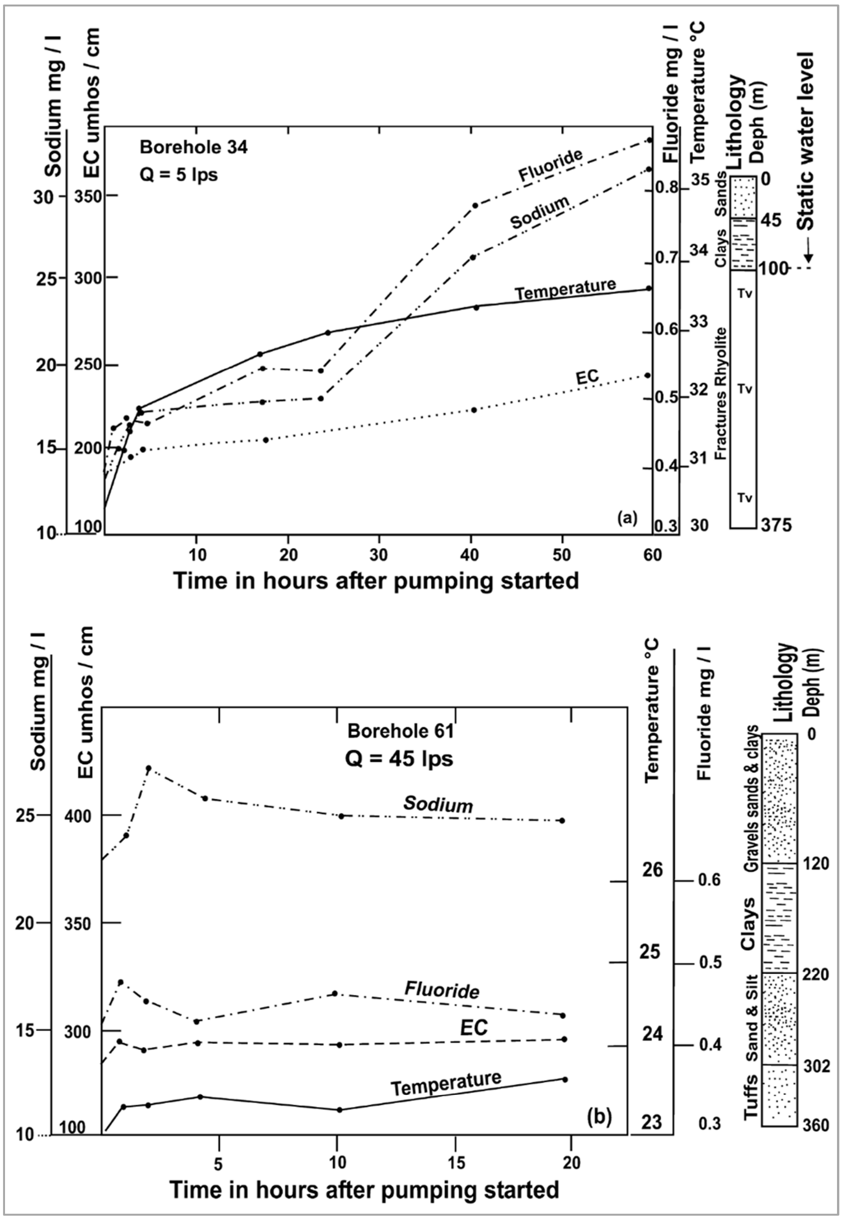

Figure 8. *Chemical and temperature responses to pumping time in boreholes suggest the presence of upward flow (a) and horizontal flow (b) (Carrillo-Rivera et al., 2002).*

4. Conclusion

The definition of groundwater flow functioning is a step beyond the formational aquifer facing transboundary groundwater issues. Such characterisation will benefit from a 3D Tóth flow system-view of hydrogeological data analysis that could provide the best logical definition of the observed nature of the flow. Overall analysis that becomes more significant when considering discharging groundwater in the chotts originated not only from the other side of the political border but from beyond a distant source. Hydrogeological studies would gain from including hydraulic head correction, leading to a more precise assessment of the groundwater flow direction and the proposed water balance. Indeed, vertical groundwater flow components need additional recognition to pure horizontal flow, including inflows and outflows above or below the formational strata of interest. Concepts that become crucial in regions under intensive extraction. Such a component would modify any calculations or groundwater flow considerations. Related countries in shared groundwater would benefit from capacity building in transboundary groundwater issues from a flow systems perspective. The gain in defining, understanding, and highlighting the nature of inflows related to the chotts from Algeria, Tunisia, Morocco, Libya and beyond will enable management proposals according to the nature of the discharging flow. Further capacity building would acknowledge the need to standardise relevant data collection and applied methodology.

Such standardisation could account by emphasising that pumping boreholes may represent a mixture of groundwater flows with abstraction time. The relevance of the nature of the groundwater flows on the vertical scale in terms of temperature and quality would require extra attention. The hydraulic connection across formational units becomes a relevant challenge to be clearly established. Here, the position of the basement rock becomes crucial. In flow systems investigation, the nature of the boundary conditions is paramount similarly to any hydrogeological study for both groundwater flow modelling and hydrochemical researches. Capacity building on groundwater management will benefit from a 3D regional flow understanding to avoid unnecessarily jeopardising the international environment where groundwater and related users are involved. Recharge concerns will benefit from understanding the groundwater flow systems involving their discharge and transit conditions supported by isotopic and chemical signatures within the geological framework of reference.

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