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Integrative Approach for Studying Water Sources and Their Vulnerability to Climate Change in Semi-Arid Regions (Drâa Basin, Morocco)

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Abstract: The Drâa Basin at the south-east of Morocco covers a surface of ~115,000 km^2, it starts in the High Atlas Mountains and ends in the Atlantic Ocean. Surface water depends on rainfall (stormy events), melting snow and base-flow which help maintaining river discharge during the dry season. The Drâa Basin is characterized by a semi-arid climate with restricted surface water sources. However, this region possesses a relative richness in terms of groundwater flow whose functioning is required to be fully understood to achieve an adequate water management. Previous research in the region included a classical hydrogeology scope (aquifer unit theory and water-balance), which lacks a three-dimensional understanding of groundwater flow functioning. Groundwater represents ~97% of unfrozen freshwater in the continents, so a wide-view regional approach that allows a clearer perspective of groundwater dynamics in its geological context was applied: the groundwater flow systems theory (modern hydrogeology). Thus groundwater flows of different hierarchy (local, intermediate, regional) were identified. Conceptual modelling included both direct (hydraulic head and hydraulic properties of rock units) and indirect data (soil type, vegetation, geomorphology) in agreement with the physical-chemical and isotopic character of water. This model was implemented, calibrated and validated using the Modflow™ package. Initial water-table conditions were simulated during the 1939-1969 period, before construction of the Mansour Eddahbi dam. Obtained initial heads were subject to different recharge conditions representing contrasting climate scenarios. Model simulation reveals that the vulnerability to climate conditions (change in recharge) is related to groundwater flow hierarchy. In the High Drâa Sub-basin where local flows dominate, the water-table shows a difference in head of ~100 m between humid and dry recharge conditions (200 mm/year and 50 mm/year respectively). However, in Middle Drâa Sub-basin where evidence (physical and chemical groundwater properties, soil type and vegetation cover) of intermediate flow was identified, the water-table lacks immediate response to these variable recharge conditions. Results suggest local flows are more likely to be affected by different climatic conditions (recharge) than those of intermediate and regional nature. This knowledge could assist in defining appropriate strategies to manage local flows against drought conditions and to take advantage of intermediate and regional flows which are not directly affected by climatic conditions, but are subjected to concerns on their chemical quality and original recharge zone.

Key words: Groundwater・Discharge zone・Climate・Flow systems・Drâa Basin・Morocco

INTRODUCTION

An estimate of climate variability impact into water sources needs to integrate a wide view system approach as to help understanding surface-water and groundwater functioning. It has been recognized that any possible change in climate will directly affect recharge conditions. The behaviour of groundwater recharge and related processes will be difficult to be evaluated due to a number of factors as spatial and temporal variability in rainfall to track recharge rates and the uncertainty to extrapolate recharge estimates in time and space.

The hydrogeology of Drâa Basin has been the objective of several previous studies [1, 2, 3]. Obtained results were constructive but an understanding of the hydraulic continuity among aquifer units was not given

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the required importance. Indeed, these studies were based on the aquifer unit as the physical media that stores and permits groundwater transfer from the recharge to the discharge zone, making groundwater available to boreholes for its extraction. This concept, as implemented with the water-balance lacks a three-dimensional approach of groundwater dynamics needing to include other environmental components (geomorphology, basement rock, vegetation and soil type). A wide-system view that integrates these environmental components in a conceptual model is the Groundwater Flow Systems Theory, GFST [4, 5]. The GFST used in this work includes groundwater as an active agent which is manifested not only in hydraulic heads and groundwater quality, but in its interaction with external components of the environment; components that are in agreement with the systematized spatial distribution of flow. The GFST characterization was found to be a valuable tool to define groundwater vulnerability to climate change at local or global scale. This knowledge may assist in defining an appropriate strategy to sustain and protect related local flow sources and to take advantage and necessary precautions (natural water quality management) of regional and intermediate flow, which show the lowest response to climate variability. Therefore, the objective of this work is to characterize discharge zones, as a tool to define the hierarchy of groundwater flow systems (local, intermediate and regional); to identify groundwater flow paths, vertical inflows and outflows (recharge and discharge zones, respectively). Information to be used as a base to characterize the response of groundwater to contrasting recharge conditions (*i.e*., an alteration in climatic pattern).

General Description of the Study Region: The Drâa Basin includes a surface of ~115,000 km^2 in the south east of Morocco; the High and Middle Drâa Sub-basins (~30,000 km^2) are located (Figure 1) in a region characterized by arid and semi-arid climate conditions.

The climate of the Drâa Basin is influenced by orography (up to 4,000 m amsl, in the high Atlas Mountains) and a North to South altitude gradient. Precipitation is characterized by a spatial and temporal variability with the presence of extreme events due to tropical and extratropical interactions contributing to more than 40% of the mean annual precipitation of 100 to 300 mm•year^{-1}. Here, a complicated task has been the determination of the actual precipitation, since snow and rain are regionally variable [6]. Temperature reaches its maximum during July-August (40°C) and its minimum during January-December (-12.4°C). Due to the high prevailing temperature, the limited precipitation and the low air hygrometry, a measured Piche potential evaporation of 3,000 mm•year^{-1} was registered in the Drâa basin stations.

The oldest rocks that are found in the study region are those from Precambrian and Cambrian ages (Fig. 2), consisting in granite and rhyolite. These rock units are reported to be present in most of North Africa [7, 8]; related outcrops have been identified in the Anti-Atlas [2]. In previous studies granite and rhyolite were usually considered as basement rock; however, the highly weathered and fractured conditions of the top (~300 m) have been estimated as hydrogeologically active [9, 10]. Jurassic massif limestone rocks are present mainly at the High Atlas Mountains, the thickness of this unit has been reported to be of ~400 m. Basalt layers of Triassic age are found within limestone terrain. Quartzite rocks belonging to the Ordovician have been described mainly at the Jbel Bani escarpment (Fig. 2).

Tertiary and Quaternary sedimentary materials have been mainly described in the Ouarzazate basin (Fig. 2) and are dominated by detrital deposits, which partially cover the above indicated formations. A simplified representation of the outcropping geological units is presented in the map of Fig. 2.

Runoff has an important base-flow component which has been defined for major Drâa rivers, among these rivers are the Upper Dades (with an area of 1,525 km^2) with an average flow of 33 m^3/s; the M'Goun river has an average flow of 40 m^3/s; the Lower Dades (6,680 km^2) with an average flow of 76 m^3/s; the Ouarzazate river (3,507 km^2) with an average flow of 42 m^3/s. Springs flow is included in the registered runoff of these rivers. The Assif-n-Ait-Ahmed river joins the M'Goun river to form the Drâa River below its confluences with the Dades [11] at Iffre (1,500 m amsl) having an average discharge of 4 m^3/s (Figure 1). In general runoff is sporadic, extreme and varies according to snowmelt and precipitation. Infiltration dominates over surface discharge and is important for groundwater renewal especially in the High Drâa Sub-basin dominated by limestone rocks. This seems to be in agreement with the recession coefficient between 120-210 days reported by Schwarze *et al*. [12] for local river discharge. These authors also calculated a recession coefficient of 270-310 days for the Triassic basalts that are densely developed with fissures (transmissivity between 0.15 10^{-7} to 1.5 10^{-7} m^2/s). Modelled results by De Jong *et al*. [6] of the Drâa River runoff show that ~50% of the groundwater is transmitted into storage and base-flow. Available groundwater head values were restricted to some oases and major population centres [10].

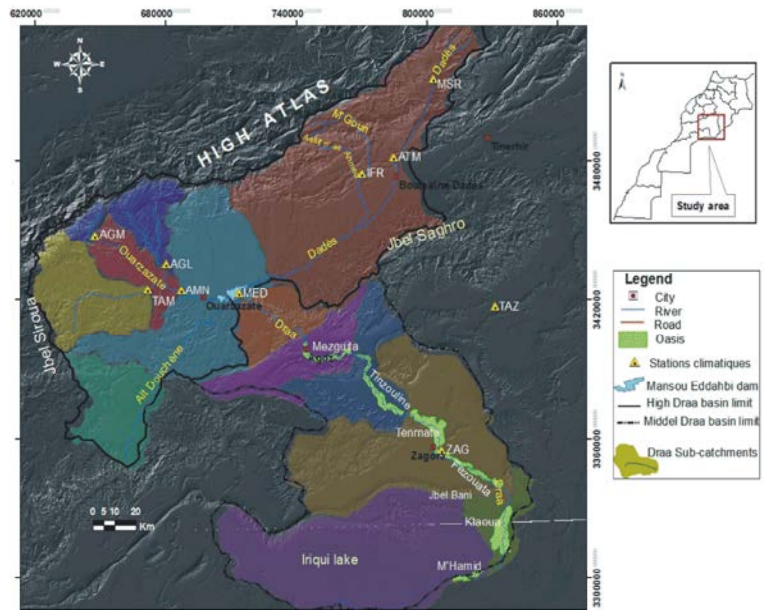

Fig. 1: Location of the study region showing specific geographical data

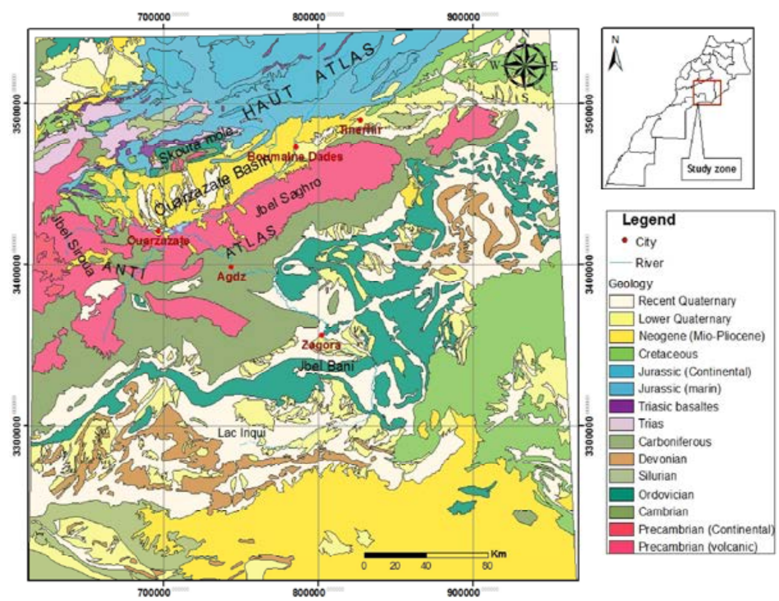

Fig. 2: Simplified geological map of the study zone (adapted from Ouarzazate map 1/500,000)

The Anti-Atlas domain shows poor groundwater storage capacity and low groundwater renewability; however, the folded Liassic limestone and dolomite of the High Atlas, covering 20% of the Upper Drâa catchment, represent a main aquifer system in regard to its aquifer characteristics, its volume and its recharge [3]. This classical view of aquifer unit needs to include an explanation of the regional hydraulic connection of the various groundwater systems found in the Drâa Basin. Therefore this paper, based on Ouysse [10] results, pursues to apply a wide-view system approach that will connect groundwater in Drâa Basin to its environmental components.

MATERIALS AND METHODS

Groundwater represents ~97% of unfrozen freshwater in the continents; a wide-view regional approach that allows the understanding of groundwater dynamics in its geological context was applied [10]: the Groundwater Flow

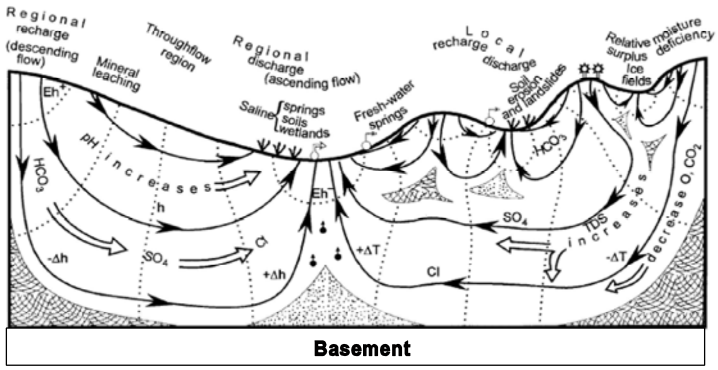

Fig. 3: Interdisciplinary representation of local, intermediate and regional flow systems; adapted from Tóth [13].

Systems Theory (modern hydrogeology) as represented in Figure 3. Thus available data were analysed with an interdisciplinary wide-view system interpretation of the GFST [5]. The defined methodology included the final modelling with Modflow™ package. The incorporated groundwater hydraulics represents field conditions implicit in the evidence of indirect groundwater flow response such as vegetation, soil and, water salinity and temperature. Such evidence is considered to be agreeable within prevailing geomorphology. A final control key was to use recharge/discharge conditions as defined in the field, to be in agreement with groundwater flows of different hierarchy, *i.e.,* local, intermediate, or regional [10].

Model Construction

Flow Systems and Environmental Response

Groundwater Chemistry: The chemical response of rainfall-water after its recharge occurs has been clearly established by Tóth [14, 5]. This author showed the expected anion chemical evolution in groundwater along its flow path in both, distance and depth of travel, from recharge to discharge (Figure 3), evolution that provides an inside of the reaction between water and rock units, making it possible to differentiate groundwater belonging to different flow systems.

The chemistry of groundwater in the Drâa Basin has been studied by several researchers among whom Chamayou *et al*. [2] and Cappy [3] represent published relevant data. An interpretation of accessible data from the perspective of groundwater flow systems theory provides an alternative view for water management purposes as well as to characterize the hydrogeological response of the study basin permitting to evaluate sources and related processes as well as mechanisms of salinization.

Chamayou *et al*. [2] described different chemical groundwater types in the Drâa Basin; however, a link between water type and its presence from a *3-D* perspective incorporating the geological framework was not attempted. One type was classified as Ca-HCO_3 with total dissolved solids (TDS) lower than 1,000 mg/l, these authors indicate that water of this type accounted for less than 10% of points studied in Middle Drâa. Water with this quality is considered according to GFST to belong to local flow and therefore, is related to recently infiltrated precipitation in a nearby recharge zone [10]. Chamayou *et al*. [2] indicated that groundwater in about 50% of the points they studied in the Middle Drâa was mainly SO_4-Ca type presenting an alkaline nature, Mg^{2+} component was reported to be not uncommon; TDS were reported to be from 1,000 to 10,000 mg/l. These characteristics suggest the presence of groundwater that has travelled from a short to a lengthy path and could be related to local and intermediate flows [10].

Cappy [3] proposes chemical and isotopic response of groundwater in various Sub-basins that are included in the Drâa Basin such as the Assif-n'Ait-Ahmed, Ouarzazate, Iffre, Jbel Saghro and High Atlas. However, a wide-system view proposing underground hydraulic interconnection among Sub-basins, acknowledging the presence of local, intermediate and regional flow systems was not an objective of his research [10]. Evidence presented by this author, when interpreted from the flow systems perspective, suggests water with high Cl^- and Na^+ concentration as well as with high temperature propose the presence of groundwater flow that has travelled a deep and lengthy path [10]. In the context of the Drâa Basin, groundwater with high salinity content including high HCO_3^- (and salinity) in wells has been reported some 10 km to the NE of Ouarzazate. The high salinity content (6,610 μS/cm) of this water suggests that it has a long

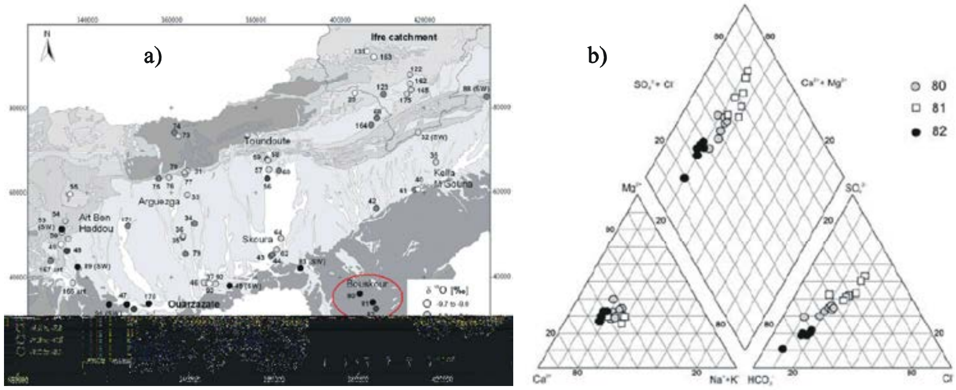

Fig. 4: Chemical characteristic of groundwater extracted in wells 80, 81 and 82 at the Jbel Saghro, Bouskour test-site. a) location of wells, b) Piper representation [3].

residence time; the high HCO_3^- shows a response to CO_2 emanating from the Earth's mantle [3], which also is evident by a low pH (6.29) [10].

Further, the identification of the presence of different groundwater flow systems induced into an extraction well may be defined as proposed by Carrillo-Rivera and Cardona [15] from data presented by Cappy [3]. For instance reported chemistry (and isotopic behaviour) for extracted water from wells 80, 81 and 82 (Fig. 4) in the Jbel Saghro (Boskour site) located to the eastern part of the Ouarzazate Sub-basin vary in its anion content, with extraction time, from HCO_3^- to SO_4^{2-} or vice-versa. This suggests that each well is extracting groundwater with contrasting residence time, representing younger and older groundwater from local to intermediate flows, respectively [10].

Groundwater temperature could be used as indicator of groundwater hierarchy and travelling depth and time; in the vicinity of Tinzouline just in the Anti-Atlas region a reported thermo-mineral water (>30 °C) ($Na\text{-}HCO_3$) emanating from the Acadian Formation with TDS of 2,700 mg/l suggests that it has travelled to a depth of about 1,500-2,500 m and cooled down on its way out. Therefore this water shows evidence to belong to a regional flow [10].

Soil and Vegetation: The landscape in the study region is that of contrast, from high snow covered mountains (High Atlas and Anti Atlas, *ie.* Jbel Saghro and Siroua, respectively) to a gentle sloping quasi-flat sandy desert terrain in the south (Lake Iriqui). Most high terrain is covered by *Leptosol* which has a very shallow profile depth resulting from little influence of soil forming processes. It contains mainly gravel [16]. The more to the south the more that *Anthrosols* (soil modified by human activities, including burial, partial removal, cutting and filling, waste disposal, the application of manure and irrigated agriculture) are found in oases, where an increase in salinization is also observed. *Anthrosols* in Mezguita are non-saline and in Fezouata are slightly-saline. In Ktaoua the *Anthrosol* is strongly-saline, land covered by this soil has been out of use for some time. The Drâa River is ending in the former Lake Iriqui shows the presence of a strongly-saline *Solonchak* and *Sierozem* soil (*Aridisols*). According to GFST, such contrasting soil types suggest the presence of potential recharge (*Leptosol*) and discharge conditions (saline soil) at high and low topographic landscape, respectively.

According to literature [17], the *Aridisols* (*Solonchak*, *Sierozem*) dominate largely in the oases and the desert plains (Iriqui Lake) where alkaline soils are strongly present. This type of soil (Figure 5) was used as indicator of discharge zone of intermediate and regional flow systems [10].

Natural vegetation is mainly represented in the lowlands [18] by *Acacia genus*, while in the highlands shrubs and few *Juniper* (*Cypress* family) trees are not uncommon. A strong vegetation gradient with altitude in the catchment shows *Hamada* from 400-1,500 m amsl; *Artemisia* steppes 1,500-2,000 m; *Junipers* shrub-lands 1,800-2,400 m amsl; Cushion shrubs >2,400 m amsl and *Acacia Wadi* communities are located in rivers beds and in dry river beds. Finckh and Poete [18] reported that the forest cover, as well as that of wetlands, represents about 2% of surface of the study territory (~1% each).

According to the GFST, the presence of vegetation such as *Acacia and Tamarix* as well as the presence of alkaline soil and a shallow water-table suggests potential sites where discharge conditions are not uncommon (Fig. 6).

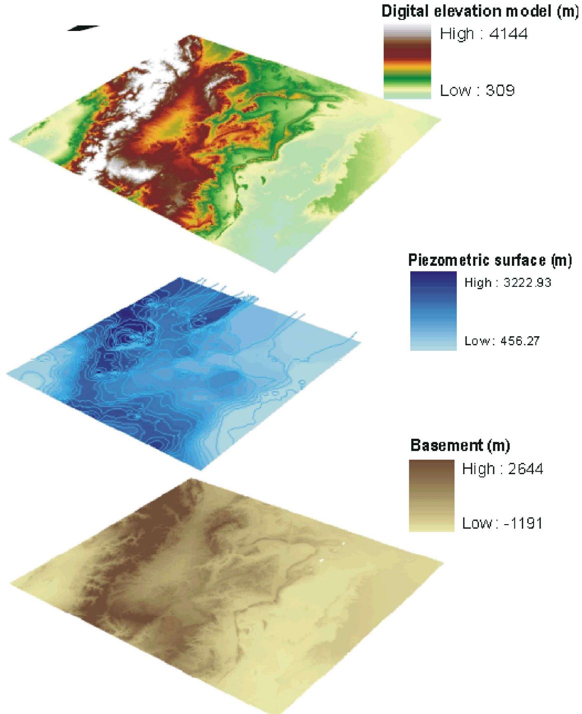

Fig. 5: Boundary conditions (terrain elevation, initial hydraulic head and basement elevation used in constructing the Model

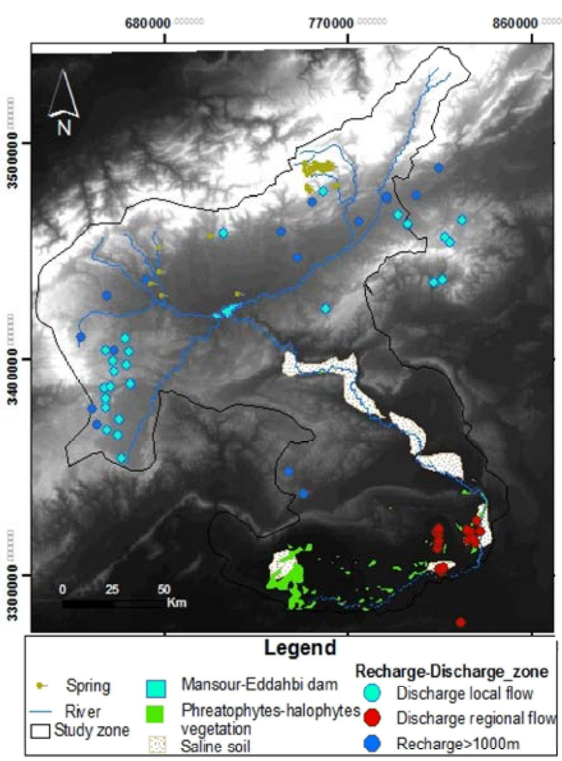

Fig. 6: Manifestation of flow systems and indirect indicators in the study zone

Soil and vegetation were used as direct indicators of recharge/discharge conditions to construct the conceptual model executed by ModFlow™ (Fig. 6).

Groundwater Modelling: Modflow [19] was used as a tool to understand the original initial conditions of groundwater flow in the territory related to the Drâa Basin prior to any important development such as the construction of the Mansour Eddahbi dam [10]. These conditions are considered as a starting point to define the original conceptual functioning of the groundwater system. The aim of using this tool was to define how different scenarios of future evolution of climate conditions, such as a reduction in precipitation, would potentially affect the groundwater flow system in the Drâa Basin [10].

A representation of the initial conditions of the water-table was chosen due to uncertainty of relevant data to achieve a representative model of the Drâa Basin under present unsteady (transient) state conditions, as these conditions are affected by groundwater extraction, inflows from the Mansour Eddahbi Dam, change in land use, input from precipitation (rain and snow) among others [10].

Modflow model solves the following equation that represents groundwater flow in three dimensions (3D) incorporating anisotropic and heterogeneous conditions under non-equilibrium conditions with water flow under equal density, temperature (isothermal at 21°C) and salinity (˜1,000 mg/l, TDS) characteristics. The equation is as follows:

$$\frac{\partial}{\partial x}(Kxx\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(Kyy\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(Kzz\frac{\partial h}{\partial z})-W=Ss\frac{\partial h}{\partial t}$$

where:

K = Hydraulic conductivity in the horizontal (x, y) and vertical (z) directions
h = Hydraulic head
W = Volumetric flow per unit volume, representing source or sink of water
Ss = Specific coefficient of storage and
t = Time.

Conceptual modelling included both direct (hydraulic head and hydraulic properties of rock units) and indirect data (soil type, vegetation) in agreement with the physical-chemical and isotopic character of water present within the prevailing geomorphology and in agreement with the GFST.

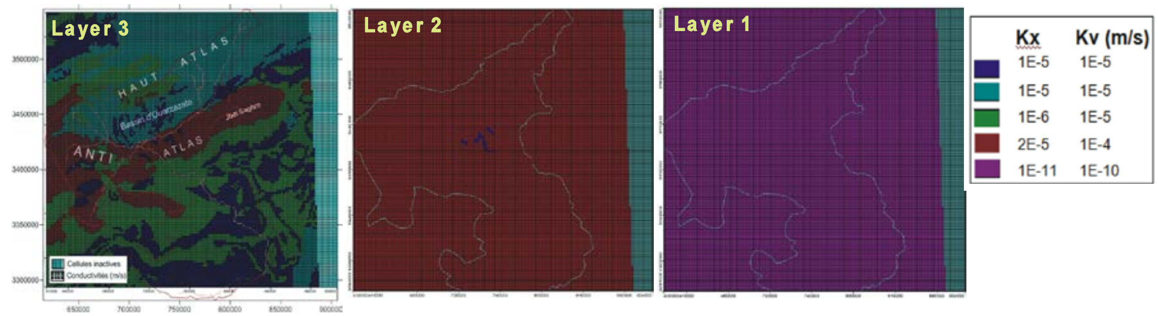

Fig. 7: Mesh and distribution of hydraulic conductivity (Kx/kv) in the modelled domain [10]

Geometry of Modelling Domain: The model consists of a horizontal mesh with cells of 2,000 by 2,000 m representing 17,856 cells; they are included in 144 lines (cells) in the west-east direction and in 124 columns in north-south direction.

The model geometry was achieved using as top boundary the digital elevation model that incorporates a surface extension of 71,424 km^2 presented in X and Y UTM Coordinates system (Figure 5). The bottom boundary (basement) was defined by subtracting the thickness of upper layers and a layer of 300 m of weathered and fractured Precambrian units from the value of elevation. Obtained digital map (grid format) of the basement was used as input for the conceptual model and was adjusted inside the model to be in agreement with natural conditions (avoiding errors in iteration process).

The classification of the geological formations according to their hydraulic properties in the studied domain was based on the geological map of Ouarzazate 1/500,000; five main lithological units finally included in three layers after a simplification of the original geological map content (Figures 2 and 7). The hydraulic properties values (K_v, K_x, K_y, S_s, S_y and porosity) used in the first version of the executed model were chosen in agreement with the values recommended by Freeze and Cherry [20], Domenico and Mifflin [21], McWorter and Sunada [22] and Morris and Johnson [23]. The final values were adapted after successive runs of the numerical model and through a strategy of trial and error [10].

Initial Conditions: The initial head defined the position of the surface of the hydraulic head ("observed" in Figure 8) that is meant to exist before the start of any artificial groundwater alteration (human extraction, artificial recharge) in the study area. The model represents the elevation of the water-table (surface hydraulic head) with respect to sea level altitude. The definition of initial heads was used to estimate the position to the water-table surface measured in wells, springs and observed in some piezometers before establishment of Mansour Eddahbi Dam in 1972 (Ouysse, 2012). An initial map with the water-table distribution was obtained by spatial interpolation (inverse distance weighted) of available data in ArcGis (9.3).

Boundary Conditions: The conditions of head potential were represented by the River module which indicates a possible exchange between heads in the river and the groundwater system. The General Head Boundaries (GHB) module was incorporated to acknowledge the possibility of having lateral groundwater connection equivalent to water flow entering from, or leaving, constantly to/from neighboring surface basins.

In the present investigation, a simplification made incorporated a lack of significant difference in both temperature and salinity in groundwater. This permitted to assign hydraulic heads considering that there is no density variation along the thickness of the water column regarding temperature and salt content in the analyzed space of any cell.

The recharge and evapotranspiration module were used to illustrate the conditions of IN/OUT flux. According to literature [3] the recharge zones of springs located in High Atlas were estimated to be located between 2,400 and 2,900 m amsl. In this work recharge was consider positive up to 2,000 m amsl (the recharge potential in the Anti Atlas was included) [10]. As, there is lack of direct field measurement of the recharge rate, it was estimated from values from the literature [3] at 10% of the mean annual rainfall. In the Drâa Basin, the rainfall is variable with altitude (orography effect). In the High Atlas Mountains (up to 3,500 m amsl) the climate is humid where a value of 900 mm/y has been registered. However, at low altitudes (Ouarzazate basin, Middle Drâa Basin), the mean annual rainfall is between 100 to 300 mm/y. This heterogeneity in the rainfall was taken into consideration during model simulations.

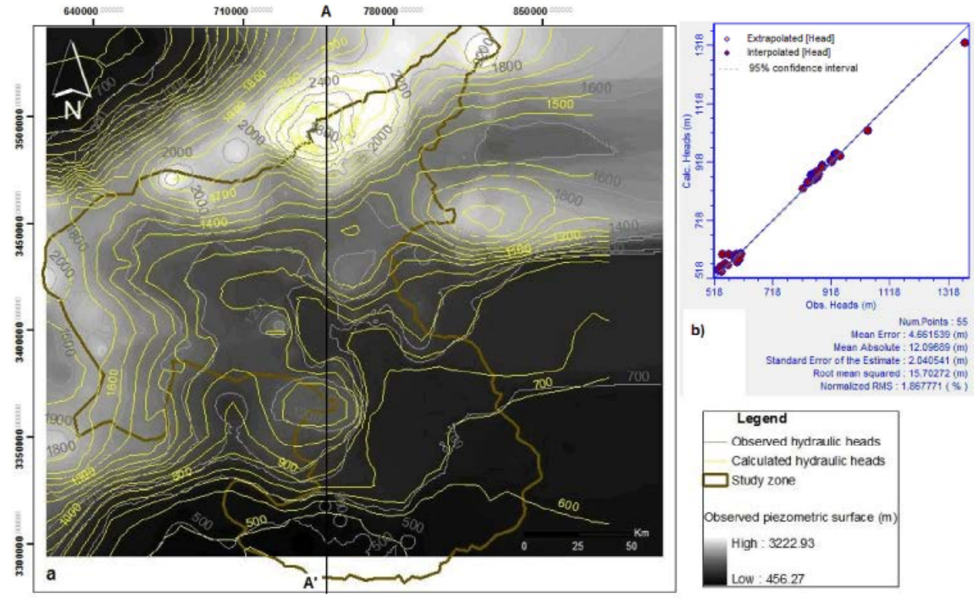

Fig. 8: Comparison between observed and calculated heads; (b) hydrodynamic calibration of the model in unsteady state conditions (10 years of iteration) [10]

The evapotranspiration module in this model was used to present the discharge zone of intermediate and regional flow systems [10]. As cited above, the saline soil (*Solonchak, Sierozem*) and vegetation cover (*phreatophytes* and *halophytes*) were used as indicators of discharge zone where actual evapotranspiration was estimated at 500 mm/y [10].

RESULTS AND DISCUSSION

Initial Conditions, Flow Hierarchy and Vertical Flow (Recharge/Discharge Zones): The implemented calibrated model was used to correlate observed and calculated hydraulic heads in observation wells. Computed heads were also validated using different proxies, which represent actual environmental conditions (soil type, vegetation and springs). Initial conditions were simulated for the water table during the period (1939-1969) before construction of the Mansour Eddahbi dam. Results of Figure 8 were obtained for 10 years of simulation with a normalised *RMS* error of 1.8% where values are aligned. For 10 years of simulation, the modelled hydraulic heads shows a similar representation of observed initial heads for the period (1939-1969) (Fig. 8).

Cross-section AA' of hydraulic head (Fig. 9) shows that the High Atlas constitutes a zone of main recharge represented by downward vertical flows reaching to a depth of more than 2,500 m; these flows travel cross the Drâa Basin and show a hydrogeological continuity towards nearby surface basins (Tafilalet, Haouz) 1[0]. Recharge occurs at levels of up to 3,000 m amsl.

In the Dades river the model shows the confluence of flows (Figure 9) resulting from the High Atlas and Anti Atlas which have travelled for a distance of ~40 km and ~10 km, respectively. According to previous analysed data, the karstic formations of the High Atlas mountains include a relative number of springs (Fig. 6); the model was able to reproduce the presence of these springs (for example, S28, S29) (Figure 9) depicted by upward vertical flow reflecting a discharge zone of local flow [10]. A local flow has a shallow path and its discharge is manifested at short distance; this flow is the origin of springs in Liasic formations of High Atlas which discharge in rivers and valleys [10].

In the Drâa River, the model suggests (Figure 9) a contribution from the Anti Atlas and from the Bouazzer-El Graara massif. Each of these input waters present different chemical quality, as the Anti Atlas is essentially volcanic, while the massif of El Graara is characterized by the Acadian Formation (quartzite) [10]. Chamayou [2] and Margat [1] proposed the contribution of groundwater from the quartzite formations into the Drâa River alluvial Quaternary deposits. Results of the present modelling validate this hypothesis and reveal that these geological units located in the Anti Atlas and Bouazzer-El Graara contribute positively to the groundwater flow systems of the Drâa Basin [10].

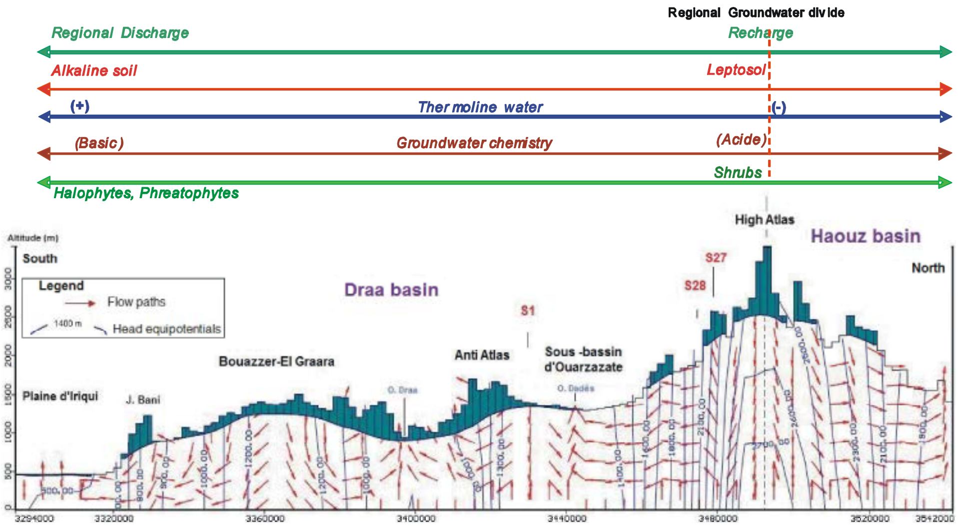

Fig. 9: Cross-section AA' showing head equipotentials, groundwater flow hierarchy and indirect validating evidence and vertical flux (recharge/discharge zones). The location of the Cross-section AA' is in Figure 8 [10]

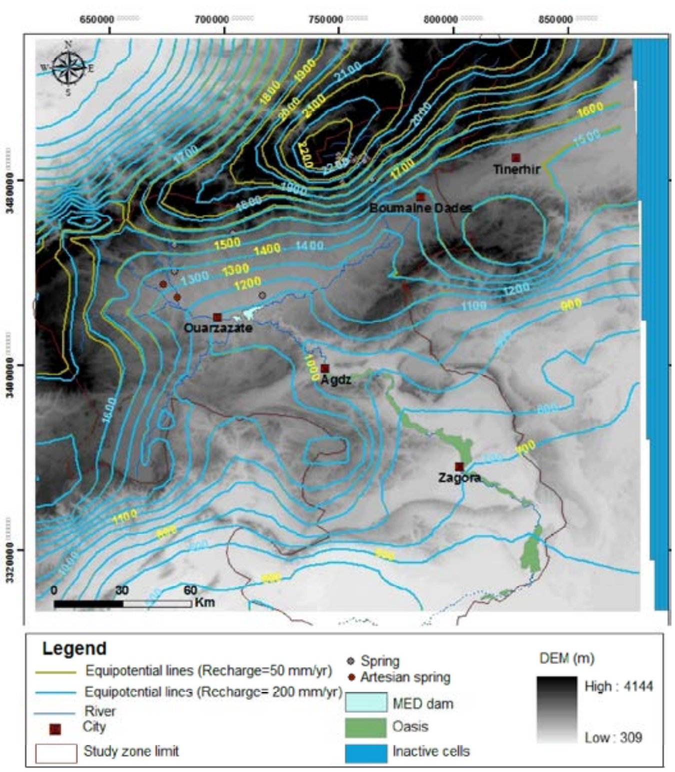

Fig. 10: Water-table behaviour as related to change in recharge conditions [10]

There is no enough information related to thermal and highly alkaline groundwater in Iriqui Lake, this regional groundwater flow discharge zone of the Drâa Basin is identified by the presence of the botanical species (*halophytes, phreatophytes*) which are adapted to certain conditions of salinity [10]. In Iriqui Lake the model indicates a discharge zone with upward vertical flow which can preliminarily be related to a regional system outlet [10].

Groundwater Response to Variability in Recharge Conditions: Obtained initial heads were subject to alternative recharge conditions, which represent contrasting climate scenarios. Model simulation reveals (Figure 10) that the vulnerability to climate conditions (change in recharge) is related to groundwater flow hierarchy.

In the High Drâa Sub-basin where local flows dominate, the water-table shows a positive response of the hydraulic head of ~100 m when humid (high recharge) conditions of 200 mm/year where modelled, as when compared to 50 mm/year. However, in the Middle Drâa Sub-basin where the presence o f intermediate flows (and regional) was identified the water-table lacks an immediate response to this variable recharge conditions.

CONCLUSIONS

The constructed groundwater flow conceptual model executed by Modflow™ reproduced results which represent implicitly field conditions according to the interdisciplinary analysis proposed by the GFST. This analysis includes groundwater (hydraulic head, physical, chemical and isotopic signature), vegetation cover, soil type and lithology (geomorphology and hydraulic properties). The model was also partially validated by the identification of the relationship among the obtained model results and the existing data in terms of local, intermediate and regional groundwater flow systems.

The use of the Modflow™ model was directed to understand the original initial conditions of groundwater in the Drâa Basin by defining its flow hierarchy and flow paths. Different scenarios of future evolution of climatic conditions, such as a reduction in precipitation (variability of recharge conditions), that would potentially affect the groundwater flow system in the Drâa Basin were identified. Results suggest that local flows as in the High in Drâa Sub-basin) are more prone to respond to recharge conditions as compared to the intermediate and regional flow systems that are present in the Middle in Drâa Sub-basin.

These findings could assist in defining an appropriate strategy to protect local flow water users against drought conditions and to take advantage of intermediate and regional flows which are not directly affected by climate variability and change, but are subjected to concerns on their quality and original recharge zone location. Furthermore, the model here introduced will require updated information concerning aquifer-test to adjust the hydraulic properties for better representation of field conditions, as well as to define the relation of extracted groundwater to hydraulic head in time and space. Tests that would require incorporating water quality response to define the nature of the flow system (or systems) that is captured by the extracting well.

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