Modeling Tools for the Foum El Oued Groundwater Aquifer under Climate Changes Context: Geodatabase and Hydrological Model

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Abstract: Water resources management in arid countries requires the provision of all the necessary decision support tools, and implies taking into account the climate change component which becomes a structural reality. The Foum El Oued aquifer is one of the important water resources reservoir in the Laâyoune region, in the south of Morocco. It is facing the vulnerability problem to climate change, which is reflected in the fluctuating aquifer recharge and the risk of seawater intrusion due to the mean sea level rise. Our work focuses on effective groundwater modelling of this aquifer under a climate change context. In this paper we present results of the IT (information technologies) tools developed for this project, such as a regional geodatabase under a GIS environment and a hydrological model of the Saquia Al Hamra river floods, that mainly supply the aquifer recharge, and which was not taken into account in the past. These two IT steps provide the necessary inputs for the groundwater model which will be a key decision support system for the decision makers in water resources management, especially for water supply of Laâyoune population and irrigation of the Foum El Oued agriculture area.

1 INTRODUCTION

The Foum El Oued aquifer is an important water resources reservoir in the Laâyoune province, located in the west of the city on the coast of the Atlantic Ocean. Groundwater is used to supply Laâyoune and El Marsa cities with domestic and industrial water and to irrigate an agriculture area (250 ha) in the Foum El Oued plain. The main recharge of the Foum El Oued groundwater comes from the Saquia Al Hamra river floods, up to 90% (ABHSHOD, 2007), that occur three to five years. In this aquifer, groundwater has undergone significant pumping (6 Million m^3 in 2018 for drinkable water) confronted with a low rainfall and irregular aquifer recharge which has increased the risk of seawater intrusion from the Atlantic Ocean (El Mokhtar et *al*., 2018). Furthermore, climate change affects also the Foum El Oued groundwater management ranging from changes in recharge, increase of the mean sea level to the increasing water demand on groundwater pumping that leads to exacerbating the seawater intrusion into the aquifer freshwater. The objective of this research work is to develop a groundwater flow and hydrodispersif model for the Foum El Oued aquifer under the climate change context, with the aim of being able to assess the impact of the various groundwater abstractions on its potential as well as the evolution of the seawater intrusion extend due intensive pumping and increase of the mean sea level rise. In order to develop these models, we need to collect and process geological, climatic, hydrological, hydrogeological and socioeconomic data on the study area. Thus, a regional geodatabase is designed and produced under a geographical Information System (GIS) to allow data structuring, archiving and interrogation. This geodatabase makes it possible to produce various thematic maps and to provide the necessary inputs for the mathematical model of groundwater flow and seawater intrusion in the aquifer.

The Foum El Oued groundwater aquifer is located in the downstream of Saquia Al Hamra river, a long non perennial river, that only flows during the flood periods. These floods represent the main recharge of the Foum El Oued aquifer. The last flood occurring the October 2016 is the most important during these 50 years, recording a flow rate estimated to 3000 m^3/s (ABHSHOD, 2007). After the passage of this flood, significant increases of the piezometric level (more than 3m) were recorded in several monitoring wells. Hence, this situation motivated us to developed a hydrological model for simulating this last flood, in order to evaluate the possible future floods that could occur in the river with the same return period that will serve to assess future aquifer recharges.

In this paper, we focus on results obtained from the two IT tools of both Database/GIS, including climate change, and the HEC-HMS hydrological model as applied to our case study, with the prospects of exploiting these results for the preparation of inputs and the development of future models on groundwater flow and dispersive models in the aquifer of the study area (under progress).

2 METHODOLOGY AND IT BACKGROUND

2.1 IT Tools for Groundwater Modelling

Groundwater modelling is the mathematical representation of the flow system to solve the equations that constitute the flow model (USGS, 2005). For the Foum El Oued groundwater model, we are using several IT tools to process, produce and interrogate data for the project. The main used tools are the GIS, HEC-HMS and VISUAL MODFLOW softwares. The GIS is a framework that we use for gathering and processing data for the project and producing thematic maps relevant to the aquifer reservoir and the Saquia Al Hamra river basin. Additionally, the GIS-geodatabase provided specific data on climate change useful for hydrological and groundwater modelling, including the conceptual model. The HEC-HMS is used for the hydrologic simulation of the last flood of the Saquia Al Hamra river using regional data. The model will allow to evaluate future flow in the specific basin. These tools provide also the necessary inputs for the groundwater model under Visual MODFLOW to simulate and predict the groundwater flow conditions in terms of quantity and quality.

2.2 IT for the Geodatabase

Groundwater modelling requires the conceptualization of both the aquifer reservoir and physical groundwater flow and solute transport. For this purpose, we need to collect and process several types of data on the study area. This is ensured by developing a database to facilitate the organization, processing and editing of the project data. Hence, we developed a geodatabase under GIS; designed to store, manipulate and interrogate geographic information and spatial data. This geodatabase is a source of geographic information, within a GIS, systematized into geographic data sets built on top of relational database management systems (RDBMS) such as Microsoft Access, Oracle, or Microsoft SQL Server that are customized for storing spatial data structures.

Data collected from several sources are digitalized and geo-referenced; the spatial reference coordinate system used for the representation and projection of the geographic data in the study area is the WGS 1984 UTM Zone 28N.

These necessary data for the implementation of the project were collected from national and regional organizations involved in the water sector (Saquia Al hamra and Oued Dahab Hydraulic Basin Agency ABHSHOD, Laâyoune Regional Agriculture Direction DRA, the National Office of Water and Electricity-Water Branch / Direction of Saharan provinces, the Regional Direction of Meteorology of Laâyoune DMN, Mohammadia school of engineers EMI, the Direction of Planning and Research of Water DRPE). For different needs and data use, processing of the collected data started by controlling their homogenization and their format, as well as their coherence, completeness and quality.

The project's geodatabase is named "FEO_GDB", and it includes features, feature classes, feature data sets, relationships and rasters. Features are spatial vector objects (e.g., points, lines, polygons, and multi-patches) with attributes (fields) to describe their properties. The "FEO_GDB" is designed with a thematic hierarchical architecture, including all hydrogeological topics: geography, administration, infrastructure, geology, hydrogeology, hydrology, water uses, models, seawater intrusion, and allowing producing thematic maps (Figure 1).

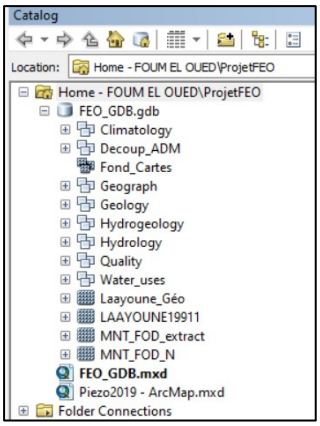

Figure 1: The thematic structure of the geodatabase.

The FEO geodatabase is used all among our project to prepare and interrogate data for each project thematic, to produce inputs for the groundwater model and to use the results from this model to produce others outputs. The interaction between the geodatabase and all the other project steps is continuous and interactive (Figure 2).

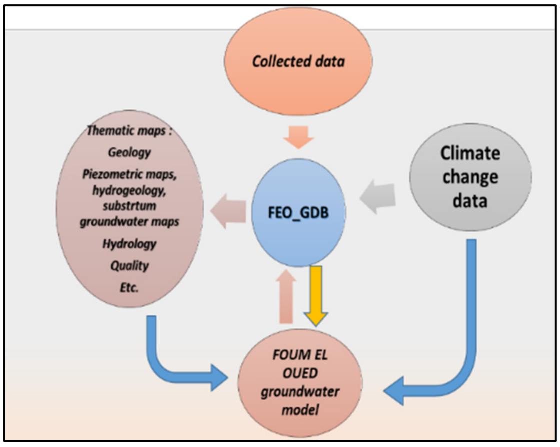

Figure 2: Database objective's organizational scheme.

2.3 Hydrological Modelling

The hydrological model is a mathematical representation of the hydrological processes in a watershed, such as the saquia Al Hamra river, involving all the hydrologic cycle (rainfall, evaporation, runoff, etc.).

Simulation of the last flood of the Saquia Al Hamra river basin was made by applying the Hydrologic Engineering Center's Hydrologic Modeling System HEC-HMS. It is designed to simulate the rainfall-runoff processes of watershed systems. The process used for our simulation is the Soil conservation service (SCS) Curve Number (CN) model that estimates the precipitation excess as a function of cumulative precipitation, soil cover, land use, and antecedent moisture, using the following equation (1):

$$P_e = \frac{(P - I_a)}{(P - I_a + S)} \quad (1)$$

where P_e=accumulated precipitation in time t, P = accumulated rainfall depth at time t, I_a= initial loss, and S= potential maximum retention.

We also use other processes, the Clark unit hydrograph for the transformation and a meteorological model for the weather data used for the simulation. For this latter simulation, we used and applied the inputs provided from the data collected from the National Direction of Meteorology (for rainfall) and the Direction of Research and Planning of Water (for flow rates).

3 GEODATABASE/GIS EXPLOITATION FOR SITE CHARACTERIZATION

3.1 Site Location

The Foum El Oued coastal aquifer is located in Laâyoune province, in the south of Morocco, 20 km west of Laâyoune city (Figure 3). It is a fresh groundwater system that supplies the Laâyoune city with drinking water and irrigation of an agriculture area extended on the Foum El Oued plain. The study area is located in an arid zone with a severe water scarcity, exacerbated with the climate change impact and increasing water demand, due to the socio-economic development of the Laâyoune region.

Drinking water supply is ensured by both the Laâyoune seawater desalinization unit (2/3) and the Foum El Oued fresh groundwater aquifer (1/3) from a pumping well field.

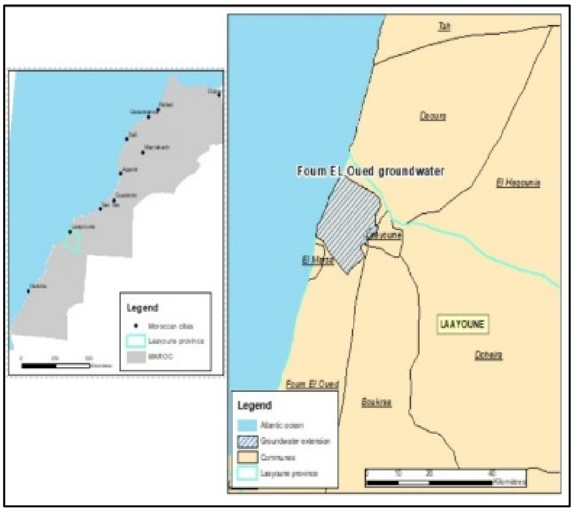

Figure 3: The Foum El Oued coastal aquifer location.

3.2 Geological Context

The Foum El Oued aquifer corresponds to the units from the permeable late Miocene to Plio-Quaternary geological formations. It is formed of a fluvio-lake sediment, composed of complex sedimentary, detrital, biochemical and chemical alternations. These formations lie on an impervious substratum composed of clay sediments from late Cretaceous to late Miocene (Figure 4).

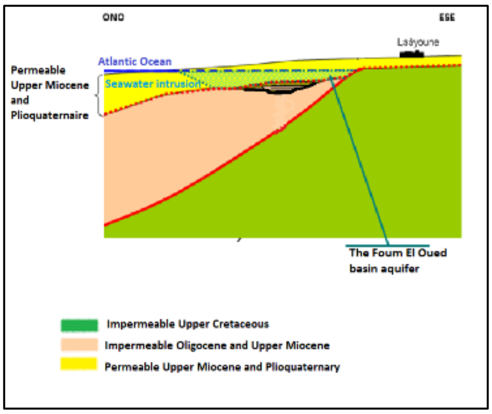

Figure 4: Geological schematic section of the Foum El Oued area (DRHS, 2003).

3.3 Climate Context (past)

The prevailing climate in the study area is of the desert type and very influenced by oceanic effects. The temperature variations recorded in Laâyoune weather station shows that August is the hottest month of the year, with a maximum average of 27.7 °C, and December is the coldest month with a minimum temperature of 15.2°C. The rain is very rare in the study area, the annual rainfall values, recorded in the Laâyoune weather station, between 1976 and 2018, range from 155 mm recorded in 1989 to 10.7 mm recorded in 1992 with an average value of 54.89 mm (figure 5).

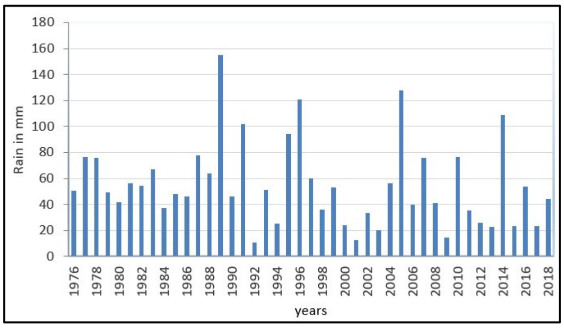

Figure 5: Evolution of annual rainfall at Laâyoune weather station, 1976-2018.

3.4 Climate Change Projections

In order to assess climate change at the regional level, and with the objective of taking them into account in the analysis, we worked with the regional climate models (RCMs), which are the most suitable for the project, in particular those from RICCAR, specific to the Arab region (ACSAD and ESCWA, 2017). Thus, we examine the projections of the two parameters, temperature and rainfall, extracted from several regional climate models and choose the most appropriate results for RCP4.5 (moderate) and RCP8.5 (extreme) scenarios (figures 6 and 7). The extracted projections are relevant to two main local weather stations (namely Laâyoune and Smara) which are located respectively in downstream and upstream of the Saquia Al Hamra basin.

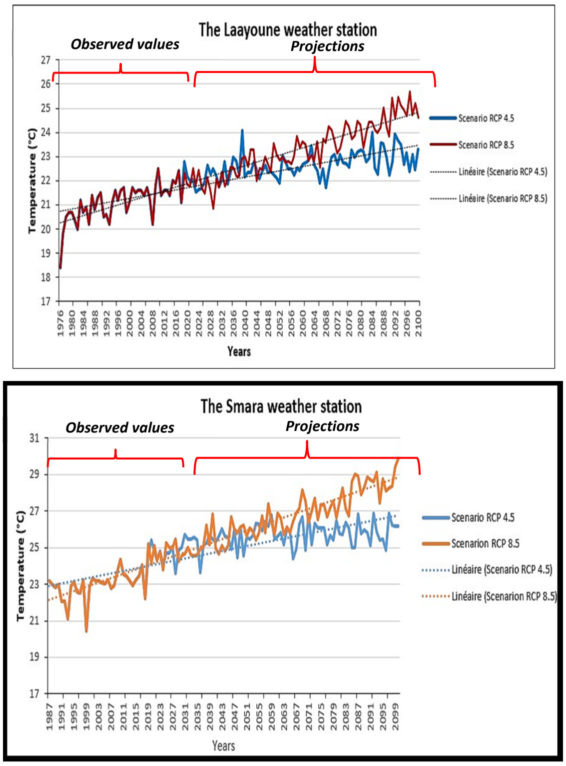

Figure 6: Temperature projections for Laâyoune and Smara weather stations until 2100.

These two figures show a trend of increase in temperatures for both weather stations and for both scenarios. However, these projections predict more increase in temperature values for the Smara weather station, exceeding the maximum of the recorded averages (24.4 °C). The increase is obviously greater for scenario RCP8.5 than that of RCP4.5, where temperature will exceed 24 °C before 2050. The temperature projections for Laâyoune station show also an overall increasing trend in mean temperature, but it is more marked for RCP 8.5 than for RCP4.5.

The projections of rainfall in Laâyoune station indicate that for the RCP4.5 scenario there will be increasing trend, which is unlike the prediction for the north-eastern regions of Morocco where there will be an overall decrease in the rainfall. While, the RCP8.5 scenario will expect a precipitation decrease in the global trend (Figure 7). However, for Smara weather station, the projections predict an increasing of rainfall for both scenarios. This will result in a positive impact on the Foum El Oued aquifer recharge, as the main recharge comes from the Saquia Al hamra river floods of upstream sub-basins covering the Smara area (Figure 8).

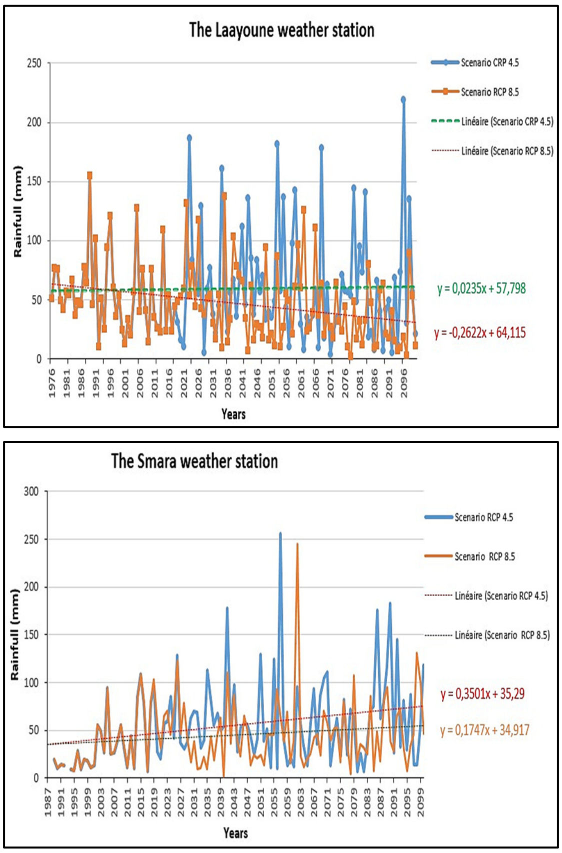

Figure 7: Rainfall projections for Laâyoune and Smara weather stations.

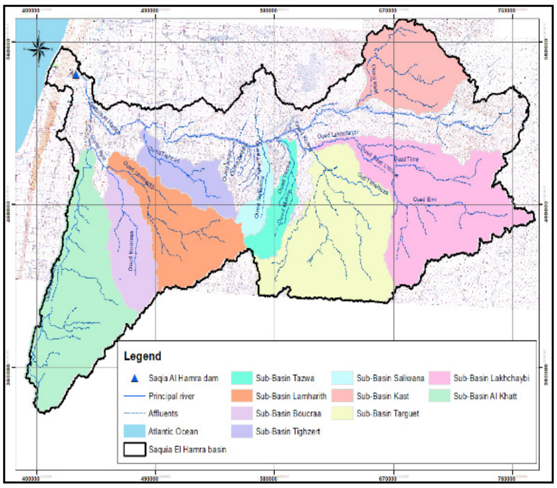

Figure 8: Saquia Al Hamra watershed and its sub-basins

3.5 Characteristics of the Hydrological Basin

The Saquia El Hamra is the main river of the Sahara watershed which crosses the whole basin in its northern part from east to west and having its outlet in the study area (Figure 8), where floods are spreaded over the plain before reaching (very rarely) the Atlantic Ocean. The river length is 400 km and the watershed is extended on a total area of 82 000 km^2. The river is characterized by a wide bed which can reach 2 to 3 km in some sections, and the flow occurs during heavy floods from upstream sub-watersheds.

The hydrographic network of the watershed includes many rivers, the most important ones are those of the left bank of the stream; El Khatt, Boucraa, Tizert, Target, etc. (Figure 8). Table 1 below provides some characteristics of the Saquia Al hamra river.

Table.1. Saquia Al Hamra river characteristics.

Basin/sub -basin	Area (Km^2)	P* (km)	CC*	CT* (hours)
Saquia Al Hamra	82 000	2346	1,43	95

P*: Perimeter
CC*: compactness coefficient
CT*: Concentration time

3.6 Hydrogeology of the Foum El Oued Aquifer

3.6.1 The Aquifer Substratum and Thickness

The aquifers lie uncomfortably on an impermeable substratum composed of predominantly clay sediments from the Upper Cretaceous to Upper Miocene (silto-sandy clays and marls of gray, green, blackish or whitish colors). This substratum is shallow to sub-outcropping to the east of the Foum El Oued area, few kilometers west of the town of Laâyoune (Figure 10). Based on the elevation digital model (DEM) and the substratum map, we could produce the thickness map of the Foum El Oued groundwater aquifer, which shows that the aquifer thickness varies between 20m (east of the basin) to 190m along the Atlantic coast (Figure 9).

3.6.2 The Piezometric Fluctuations

The Foum El Oued groundwater table is monitored since 1977 via a network of observation wells made up of 32 piezometers, which do not show continuous records of measurements over the time. Based on the time series data collected from ABHSHOD for the Foum El Oued aquifer, structured and processed in the geodatabase, we were able to plot the piezometric level evolution in observation wells as illustrated in Figure 11. This latter clearly shows a decrease of the groundwater level during 2011 due to operated groundwater pumping by the National Office of Drinking Water of Laâyoune (ONEE) and followed by shutdown of some pumping wells. On the other hand, we can clearly notice the groundwater level increase during 2016 due to the Saquia Al hamra river floods which have a positive impact on the groundwater aquifer recharge.

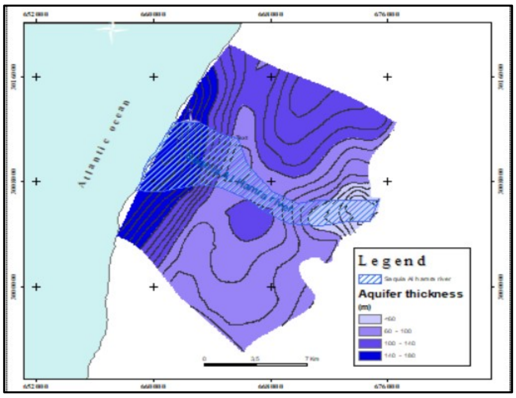

Figure 9: The Foum El Oued aquifer thickness.

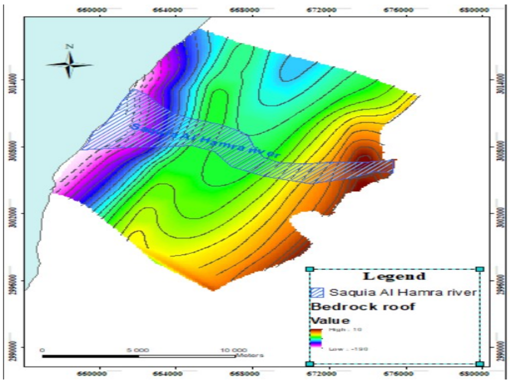

Figure 10: The Foum El Oued aquifer substratum.

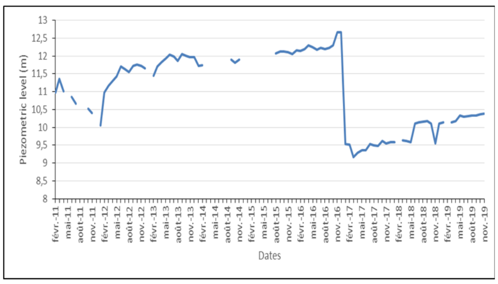

Figure 11: Piezometric time series for a monitoring well installed in the aquifer.

4 HYDROLOGICAL MODEL

4.1 The Saquia Al Hamra Floods

The hydrographic network of the watershed includes many rivers and streams as illustrated by figure 8. Surface water flow of the Saquia Al Hamra river is controlled by a downstream dam, located just upstream of the study area, and the only major dam reservoir of the basin, with a storage capacity of 410 Million m^3 (Mm^3). In the downstream of this dam, the river's bed is represented by large sand dunes at the level of Foum El Oued aquifer, which contribute favourably to the aquifer recharge.

The hydrological regime of the Saquia El Hamra river is marked by a strong seasonal and inter-annual irregularity. The maximum inflow occurs during major floods from upstream sub-watersheds, when the rainfall is very important in the upstream of Smara region (Figure 12). The flood frequency of the Saquia El Hamra river is about two to five years at Laâyoune dam (Figure 13).

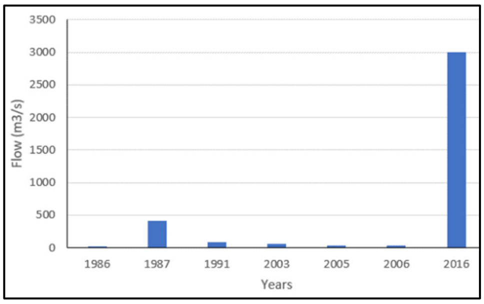

Figure 12: Historical floods of Saquia Al Hamra river

The last flood of October 2016 has recorded a pick flow of 3000m^3/s. This flood whose flow has caused the rupture of the dam and carried away the dike, has never been recorded before in the catchment.

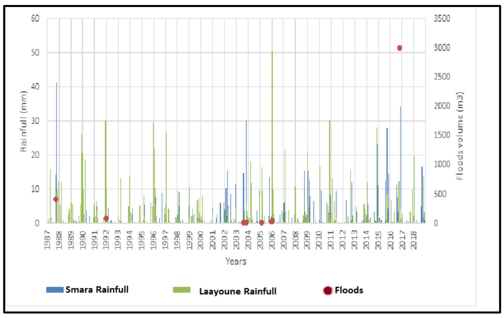

Figure 13: The occurrence of Saquia Al Hamra floods within the rainfall upstream (Smara) and downstream (Laâyoune) of the basin.

4.2 Last Flood Simulation (2016)

The simulation is made by applying the Hydrologic Engineering Center's Hydrologic Modeling System HEC-HMS. For this purpose, we used data collected from the DMN and the observed flow rates of the Saquia Al Hamra river at the level of Smara-Tantan bridge, as recorded by the DRPE (DRPE, 2016). The model was then calibrated in order to find out the parameters allowing adjusting the observed values to those obtained by simulation. Several parameters have been calibrated such as the CN and the storage coefficient. Figure 14 gives the preliminary results obtained after several tests. These results will be improved by the calibration and by introducing others relevant parameters to the study area, and by using other modeling tools taking into consideration the topographic characteristics variation in the basin. The modelling part is going on to improve these results and to assess the aquifer recharge from floods as main input in the groundwater flow model. The natural aquifer recharge from precipitation for 2020 – 2100 is already evaluated based on the DMN and RICCAR time series of projected rainfall, but it would not be so significant compared to the flood recharge (Larabi et *al.* 2020).

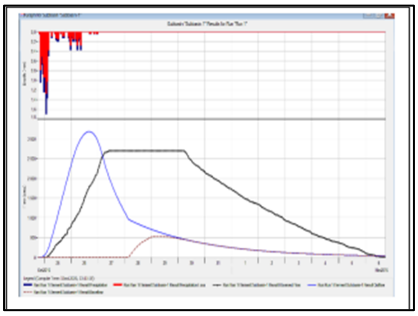

Figure 14: Simulated results by HMS hydrological model.

5 CONCLUSION

The results of the IT tools developed for this project, such as the regional geodatabase /GIS and the hydrological model of the Saquia Al Hamra river floods that mainly supply the aquifer recharge, and which was not taken into account in the past, are of great importance for developing the groundwater models. The geodatabase and hydrological modelling have led to important results on climate change, hydrology and groundwater characterization for the Foum El Oued aquifer and the Saquia Hamra river basin. This helps also the decision maker to monitor, control and mange water resources in the site. Additionally, these two IT steps provide the necessary inputs for the groundwater model which will be a key decision support system for the decision makers in water resources management, especially for water supply of Laâyoune population, irrigation of the Foum El Oued agriculture area and protection of the aquifer from seawater intrusion. This management should take into consideration the climate change adaptation, especially when the projections show positive evolution of the rainfall in the upstream basin.

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