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# **Development of a methodology for Integrated Water Resources Management in Mediterranean phosphate mine areas**

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**Abstract:** Mediterranean phosphate mine areas are located in semi-arid regions characterized by water scarcity and pronounced climatic variability. The increasing water demand, due to the development of the mining, agricultural and other socio-economic sectors, threatens groundwater resources. This situation represents a limiting factor to the sustainable development of these regions and it may result in conflicts between the water users. This raises the demand for an integrated water resources management (IWRM). This paper presents the methodology developed and applied in the European research project Elmaa to develop a tool for integrated water management in Mediterranean phosphate mine areas. This methodology consisted in carrying out water balances between resources and demands for the current year and for the next 20 years; identifying, defining and modelling solutions for reducing water deficit (water management options); and integrating all this information inside a unique tool, a Decision Support System (DSS). All these steps involved collecting specific data, which was performed through literature reviews, on-site measurements, surveys, socio-economic and technical studies and stakeholders meetings. The implementation of the methodology to the Gafsa mines influence area (Tunisia) showed that the DSS is a powerful tool for exploring the impacts of various water management strategies and the obtained results may substantially support decision makers in improving water management.

**Keywords:** integrated water resources management; methodology; Mediterranean phosphate mines.

## **1. INTRODUCTION**

The phosphate industry is a major economic sector for some Mediterranean countries (i.e. Morocco, Tunisia, Jordan) both in labour level and in trade balance worldwide. Therefore, even if this industry demands large volumes of water, its total fresh water consumption being evaluated in 2001 to 57, 20 and 15 million m<sup>3</sup> in Morocco, Tunisia and Jordan respectively, very few constraints regarding water consumption have been imposed to it for a long time. However, water is also needed for other sectors such as agriculture and drinking water supply. Since these countries have to face water scarcity due to their arid or semi-arid climate this situation results in competition for water resources. Moreover, the increasing water demand, due to many factors such as industrial, agricultural and socio-economic development, threatens groundwater resources in terms of quantity and of quality. This brings the need for an Integrated Water Resources Management. This approach deals with the management of water resources, demand and supply in order to achieve sustainable water resource uses [GWP, 2000a; GWP, 2000b].

In IWRM, the involvement of stakeholders, who are representatives of the major water users in the studied area, namely industry, agriculture, drinking water and sanitation and environment (water / basin) authorities, is essential in order to ensure that local community experience and views will be integrated into the development and management plan [Radif, 1999]. However, it also raises complexity since a whole host of intangible values and hierarchies emerges with the inclusion of different voices in the process [Lopez-Gunn and Martinez-Cortina, 2006]. This mainly implies that it is not always easy to assure convergence. Opposing factions may simply reflect different knowledge frames, interests, and beliefs among the participants. These factors may be complex to deal with [Sultana et al., 2007] but it is really essential to find a compromise for the relevance of the specific tools and actions plan developed to improve water management.

The IWRM approach was successfully used in several studies [Radif, 1999; Dungumaro and Madulu, 2003; Al-Omari et al., 2009; Martinez-Santosa et al., 2009]. In the specific case of phosphate mines influence areas, IWRM will allow a more efficient use of the existing water resources and a control of water demands without hampering the development of the mining sector.

This paper presents the methodology developed in the European project Elmaa for the implementation of an integrated water resources management tool. An application of this methodology to the Gafsa mines area in Tunisia is then given.

## 2. METHODOLOGY FOR INTEGRATED WATER MANAGEMENT

The main concept of the methodology consisted in implementing a multidisciplinary approach integrating technical, social, environmental and economic dimensions. This methodology is presented in Figure 1 and consisted in:

- Carrying out water balances between resources and demands for the current year (reference year) and for the next 20 years. For these steps, it was necessary to build the conceptual model of the socio-hydrosystem of the studied area, to define water resources and water demands and their evolution and to build and link specific models (hydrological, hydrogeological, water consumption by the industrial and agricultural sector).
- Identifying and defining solutions for reducing water deficit (water management options) and building a model to optimize their selection.
- Integrating all this information and models inside a complete tool.

These steps involved collecting specific data, performed through literature reviews, on-site measurements, surveys, socio-economic and technical studies and stakeholders meetings.

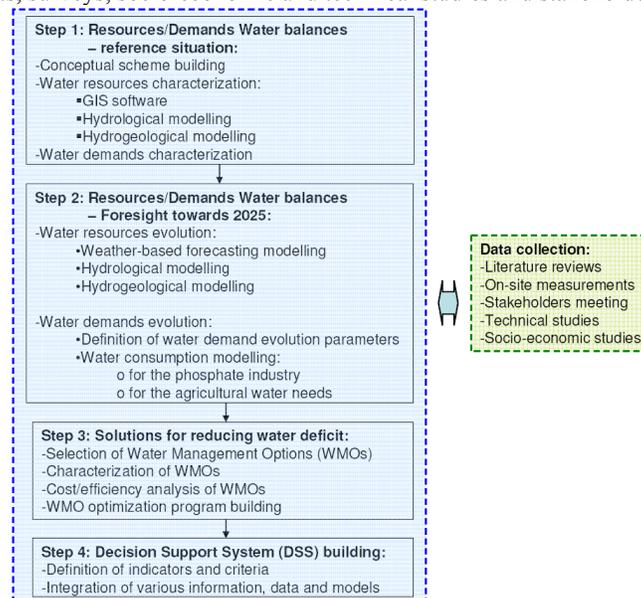


Figure 1. Integrated water management methodology

This methodology aims to build a customized software tool (Decision Support System or DSS) to help decision-makers to identify problems regarding water management and to explore the impacts of various water management strategies. Therefore, these results should help them in their decisions and to define relevant solutions according to their criteria.

## 2.1 Step 1: Resources/Demands water balances - reference situation

### 2.1.a Conceptual scheme building

A conceptual scheme is a simplified but realistic representation of the socio-hydrosystem of the studied area. It identifies and describes water resources called “Hydrological units” (climate, groundwater, surface water), water demands called “Socio-economical units” (agriculture, drinking water, mines, other activities) and water flow transfers between the different units. Wastewater treatment plants are considered as water resources (even if their quality is lower than the one of natural resources) which belong to socio-economic units [Bru et al., 2008]. The principle of the conceptual scheme is presented in Figure 2.

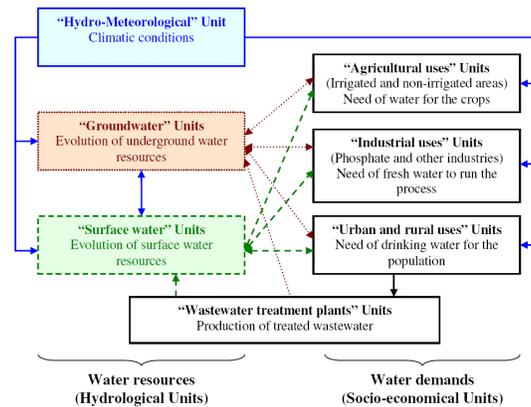


Figure 2. Principle of a conceptual scheme

### 2.1.b Water resources characterization

In order to have a better understanding of the main hydrological processes in the regions under study, a GIS database was produced and the main components of the water resources (groundwater, surface water) were characterized and modelled:

- Groundwater diffuse recharge (soil infiltrations), surface runoff and evapotranspiration were calculated with WetSpass, a spatially distributed and physically based water balance model [Batelaan and De Smedt, 2001]. This software, initially designed to be used on European regions, was specifically modified for a proper application to arid regions. These modifications consisted in particular to include specific arid regions parameters about land cover, soil texture and topography. Moreover, since arid regions are characterized by a strong irregularity of rainfall, evapotranspiration being higher than rainfall during the dry season, a seasonal time step assuming that the annual recharge is totally made up during the wet season had to be considered.
- Groundwaters systems and their interactions with surface waters (rivers) were simulated with MODFLOW, the well-known USGS hydrogeological model [Merritt and Konikow, 2000]. An extension of the MODFLOW model allowing combination with the WetSpass model was used here [Batelaan et al., 2003]. This coupling allowed considering not only diffuse recharge but also inflows from wadis and alluvial valleys, these latter being taken into account through boundary conditions.

### 2.1.c Calculation of water balances

Each unit of the conceptual scheme was described with quantitative information: (i) resources were characterized by their exploitable volume of water and (ii) users were characterized by their water consumption expressed in volume per year for each resource unit. Therefore, water balances for the reference year were performed. These water balances aimed to highlight the water resources which are overexploited or nearly overexploited (indicating a risk in coming years).

## 2.2 Step 2: Resources/Demands water balances - foresight towards 2025

### 2.2.a Foresight of water demand : What evolution of water uses towards 2025 ?

Several social, economical, industrial and agricultural driving forces that have an impact on water demand were identified, namely population and its growth rate, drinking water consumption ratios (per habitant, dependent on habits and living conditions), irrigated area, crops grown, irrigation techniques, and phosphate level production and technologies. For each of them, a set of probable values for 2025 were defined with literature and expert advices. Crossing all the possibilities leads to a set of potential water demand values for each use for the next 20 years. These parameters were used for building the scenarios of water demand evolution.

Moreover, specific models were built to simulate the water consumption of the mining and the agricultural sectors. Regarding the mining industry, it was necessary to develop a tool simulating the whole washing plant, from the beginning of phosphate processing to the storage of water in tailing dams. Water flows between tailing dams and groundwater were also modelled and quantified. For the agricultural sector, a routine was developed to calculate the real agricultural water needs related to specific crops, corresponding area, type of irrigation system, efficiency of the distribution system and soil characteristics. This routine allows estimating excess irrigation water which flows to groundwater and it could also help farmers to optimize their withdrawals for irrigation.

### 2.2.b Water resources evolution

Water resources evolution over time was simulated with the hydrological (WetSpass) and hydrogeological (MODLOW) models previously developed. These models take into account the foresight of water demand and of climate. For climate evolution, a weather-based forecasting model was built based on statistical analyses of rainfall, temperature, humidity and wind speed time series data on the study area. Statistical properties include temporal characteristics (periodicity, trend, etc.), frequency characteristics (auto-correlogramm, return period of rainy events, etc.), and the identification of the law of frequency division. By combining all these information, the forecasting model allowed simulating climate evolution over the next 20 years with a monthly time step.

It was then possible to perform resources/demands water balances for the projected year. As for the reference year, this water balance aimed to highlight potential problems on water resources balance i.e. water resources that would be overexploited or nearly overexploited.

## 2.3 Step 3: Water management options (WMO) - Solutions for reducing water deficit

To overcome water deficit and to solve, at least partly, the problem of water scarcity, water management options were selected and described carefully. This selection was performed with stakeholders (mine and state representatives from the drinking water supply, agricultural and sewage sectors). These options aimed at either increasing the available water resources or reducing the water demand. Increasing resources can be reached with the groundwater desalination or the use of non-conventional water resources such as treated municipal wastewaters or phosphate mine washing water. Even if only uses which require low water quality can use these waters (no drinking water), complementary treatments can still be necessary and acceptability problems can be faced. Reducing the demand can be obtained with the implementation of technological innovations for water saving in the mining, agricultural or drinking water supply sectors. For some WMOs, a technical study was performed in order to characterize them and to evaluate their feasibility. For example, laboratory and field tests about using phosphate washing water for forage crops irrigation led to positive results with no significant contamination of soil, groundwater and plants under the particular soil and climatic conditions. Then, for each WMO a table was built in which the technical description, the opportunities (extent to which the option could be implemented) and the different types of constraints regarding their implementation (sanitary, social acceptability, organizational, etc.) were described in detail. The cost of each option was also integrated in this table. An economical evaluation was conducted to analyze these options and to compare their global cost to their efficiency through the establishment of a cost-efficiency ratio (CE expressed in € per saved m<sup>3</sup> of

fresh water). This cost-efficiency ratio enables to rank WMOs depending on economical criteria and therefore is a support to decision makers for their choice. This cost efficiency ratio was then integrated into the decision tool. Moreover, it was also used to develop an optimization routine aiming to find the best combination of WMOs which allows minimizing costs by reaching the water balance for each concerned resource. This routine was developed using Microsoft Excel (solver).

## 2.4 Step 4 – DSS building

A Decision Support System (DSS) is an interactive computer-based system intended to help decision-makers in using data, documents, knowledge and/or models to identify and solve problems [Power, 2004]. In the Elmaa project, the DSS which was developed is designed for water management stakeholders to explore the impact of various water management strategies by comparing them to a baseline scenario (“Do nothing” scenario) and then to rank and evaluate the different WMOs. The baseline scenario is defined as a state of water resources and water demands in 2025 assuming that in the coming years water availability and water demand will follow the currently observed and forecasted trends. The comparison between simulated and baseline scenario is made through indicators which are related to water resources characteristics, water consumption evolution, environmental impacts and costs. Examples of indicators are the following: amount of withdrawals and available water resources, piezometric level of each aquifer, total water consumption in 2025, costs, etc.

The global architecture of this DSS is given in Figure 3. Exploration of the impacts of a given scenario needs the following steps:

1. Choice of a user scenario (defined for the projected year). Each scenario takes into account a climatic evolution, a water demand evolution and a combination of WMOs. A specific WMO optimization program, based on the cost-efficiency approach, could be used to optimize the choice of WMOs and to design a global water saving plan.
2. Calculations of water balances and indicators. These calculations are performed in the integrated model which integrates all the information relative to the user scenario to run models describing water resources and demands evolution.
3. Presentation of the results. This module helps to present final results by means of synthetic tables, charts and graphics.

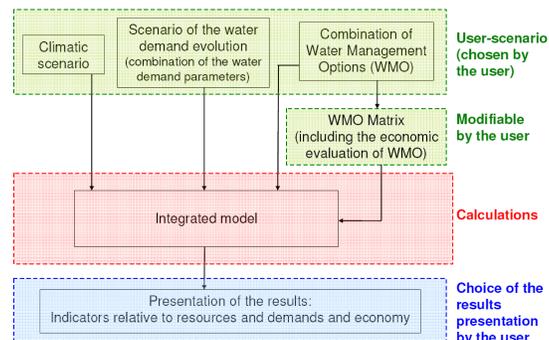


Figure 3. Global architecture of the Decision Support System

## 3. An application to the mining area of Gafsa (Tunisia)

This section presents the implementation of the methodology to a Tunisian case study, namely the Gafsa mines area.

The Gafsa mines influence area is situated 350 km south of Tunis near the north-eastern part of the desert next to the Algerian border. This region is known for its industrial activities related to phosphate ores (extraction, phosphoric acid and fertilizer production) which makes Tunisia the fifth main phosphate producer worldwide with a production of merchant phosphate of 8 millions tons in 2007 [Republic of Tunisia, website]. Phosphate industry has a strategic importance within the Tunisian economy both in terms of labour and in terms of trade balance worldwide. The Tunisian state owns the companies related to this activity, namely Gafsa Phosphate Company (CPG) for phosphate extraction and

Tunisian Chemical Group (GCT) for its processing. Therefore, even if this industry demands large volumes of water, very few constraints regarding water consumption have been imposed to it so far. However, the Gafsa arid region has other water users such as agriculture and drinking water supply which results in competition for water resources. These other water users are also confronted to water related impacts from the mining industry (discharges polluting water and soils) and other types of impacts (noise, tremors). Gafsa region, which is classified in the bioclimatic arid level, has a dry subtropical climate characterized by cold winter, dry hot summers and low and irregular precipitation. These unfavorable climatic factors combined with the continuous increase in water demand due to the fast-growing mining activities, the extension of irrigated areas and the population growth result in depletion and degradation of the water resources. The previously described methodology was implemented to this case study in order to improve the situation of water scarcity without hampering the development of economical sectors such as mining and agriculture.

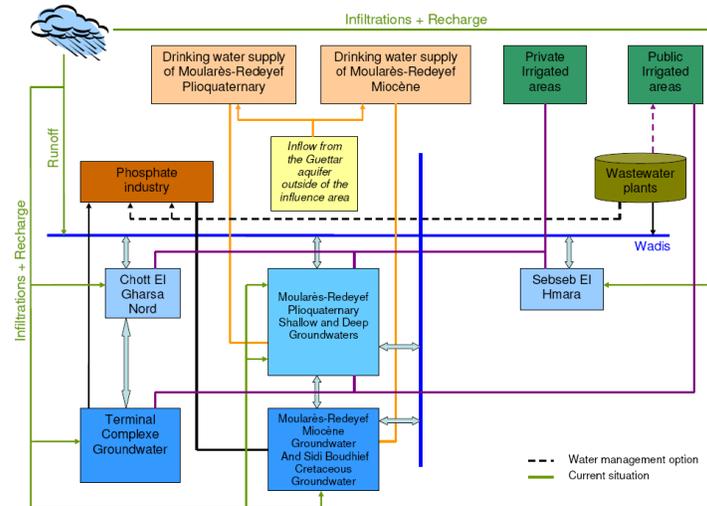


Figure 4. Conceptual scheme of the Gafsa mines influence area (Tunisia)

The conceptual scheme derived from the analysis of the Tunisian studied area reveals the complexity of the hydrology of the region and of the links between water demand units and water resource units. As it can be seen in Figure 4, the socio-hydrosystem is made of five groundwater resources units interacting with one another and several units related to drinking water supply, wastewater treatment plants, industrial activities (phosphate mining processes) and irrigated areas for agriculture. One surface water unit was also identified but since it is not a permanent stream (wadis) it was not considered thereafter.

Water demands and water resources were characterized for 2005. A specific attention was given to characterize water resources in terms of water quality (mainly salinity) to identify for which use it could be used. In particular, drinking water can only be supplied by the Miocene and Plioquaternaire groundwaters because it requires a high water quality level such as a salinity level lower than 1.5 g/L. Moreover, hydrological and hydrogeological simulations showed that groundwater diffuse recharge is very low in this arid regions compared to inflows from wadis and alluvial valleys: for the Miocene groundwater for example, the recharge from wadis is  $0.3\text{m}^3/\text{s}$  and the diffuse recharge is  $0.017\text{m}^3/\text{s}$ .

Then, evolution of water demands was evaluated up to 2025. This was mainly performed with literature reviews and stakeholders meetings. However, since several assumptions were made to estimate the evolution of the driving forces (population, water consumption, network losses, irrigated areas etc.) up to 2025, there are some uncertainties about the water demands foresight. In order to account for these uncertainties several scenarios (with high and low values for these driving forces) could be built. Regarding water resources, their evolution was simulated up to 2025. In particular, it was assumed that the water quality and the exploitable volume (water volume which is renewable by natural recharge) of groundwaters will not change over these 20 years. These assumptions were mainly

motivated by the fact that the “exploitable volume” parameter does not take into account artificial recharge systems although each system can induce a recharge up to 0.1Mm<sup>3</sup>/year. For example, 19 artificial recharge systems are built on Sebseb Elhmara so they could overcome the overexploitation observed in 2005. However, more studies are needed to precisely estimate their recharge and their evolution over climate conditions.

These works allowed performing water balances for the current year and for the projected years. Results of these water balances are presented in Table 1 and Table 2. Table 1 shows that the pressure on shallow groundwaters is very high due to the agricultural sector’s water needs. Indeed, Sebseb Elhmara is currently overexploited and the exploitation level of Chott El Gharsa has reached its exploitable level. On the other hand, deep groundwaters have a positive balance, their exploitation rate being lower than 80%. These groundwaters are mainly used by the mining industry (66%) but also for agriculture (21%) and for drinking water supply (13%).

**Table 1.** Resources/demands water balance for the reference situation (2005)

		Situation in 2005						
		Exploitable volume (Mm <sup>3</sup> )	Extracted volume (Mm <sup>3</sup> )	Water balance (Mm <sup>3</sup> )	Exploitation rate (%)	Agriculture (Mm <sup>3</sup> )	Drinking water supply (Mm <sup>3</sup> )	Mine (Mm <sup>3</sup> )
Shallow groundwaters	Chott El Gharsa	1.7	1.7	0.0	100.0	1.7	0.0	0.0
	Sebseb Elhmara	0.6	0.7	-0.1	116.7	0.7	0.0	0.0
Deep groundwaters	Plioquatenaire	10.0	5.7	4.3	57.0	3.4	2.3	0.0
	Miocène	18.8	14.7	4.1	78.2	0.7	1.9	12.1
	Terminal Complex	15.2	11.5	3.7	75.7	2.7	0.0	8.8
<b>Total</b>		<b>46.3</b>	<b>34.3</b>	<b>12.0</b>		<b>9.2</b>	<b>4.2</b>	<b>20.9</b>

In 2025 (Table 2), it is expected that the water demand for each sector will increase. In particular, the mining water demand is expected to increase by 6 Mm<sup>3</sup> (+ 24.9%), and the irrigated water and drinking water demands are expected to increase by 2 Mm<sup>3</sup> (+ 21.7% and + 42.9% respectively). This will lead to a deterioration of the water scarcity situation observed in 2005. In particular, two water resources units will be overexploited in 2025 according to the calculations: Sebseb Elhmara (shallow groundwater) and Miocène (deep groundwater).

**Table 2.** Resources/demands water balance for the projected year (2025)

		Situation in 2025						
		Exploitable volume (Mm <sup>3</sup> )	Extracted volume (Mm <sup>3</sup> )	Water balance (Mm <sup>3</sup> )	Exploitation rate (%)	Agriculture (Mm <sup>3</sup> )	Drinking water supply (Mm <sup>3</sup> )	Mine (Mm <sup>3</sup> )
Shallow groundwaters	Chott El Gharsa	1.7	1.7	0.0	100.0	1.7	0.0	0.0
	Sebseb Elhmara	0.6	0.7	-0.1	116.7	0.7	0.0	0.0
Deep groundwaters	Plioquatenaire	10.0	6.8	3.2	68.0	4.0	2.9	0.0
	Miocène	18.8	21.4	-2.6	113.8	2.0	3.1	16.3
	Terminal Complex	15.2	12.6	2.6	82.9	2.8	0.0	9.8
<b>Total</b>		<b>46.3</b>	<b>43.2</b>	<b>3.1</b>		<b>11.2</b>	<b>6.0</b>	<b>26.1</b>
<b>% increase from 2005</b>			<b>25.9</b>			<b>21.7</b>	<b>42.9</b>	<b>24.9</b>

Therefore, alternative water management options could be implemented to reduce the pressure on water resources. For the Gafsa mines influence area, twelve water management options (WMOs) were identified; these WMOs were either related to the agricultural sector (3 WMOs) or to the mining sector (6 WMOs) or to the hydrologic engineering (1 WMO) or to the drinking water supply (2 WMOs). Definition and characterization of water management options, carried out with the support of stakeholders, includes an exhaustive description of each option (technical aspects, implementation, constraints and incentives) and an evaluation of its potential impacts for the environment, the economy and its acceptability. Socio-economic evaluation of these options showed that the maximum water volume which can be saved (i.e. if all WMOs are implemented) is about 28.3 Mm<sup>3</sup>; the mining sector representing the highest water saving potential with a maximum volume of 18.3 i.e. 64.7% of the total water savings.

All these elements will be integrated into the final DSS. Depending on assumptions chosen by the user, this DSS will allow evaluating and comparing various water management strategies. The regional stakeholders will then be provided with a tool for a better water

management in the Gafsa mines influence area, this tool being adapted to their specific needs.

#### 4. CONCLUSION

The methodology developed for the building of an integrated water resources management tool is presented in this paper. This methodology, implemented in close collaboration with stakeholders, consisted in carrying out water balances between resources and demands; identifying and modeling solutions for reducing water deficit (water management options); identifying indicators and criteria for results presentation; and integrating all these elements inside a complete tool, the Decision Support System (DSS). Its application to the case study of Gafsa mines influence area (Tunisia) showed that it constitutes a powerful way for helping decision makers in improving the situation of water scarcity without hampering the development of economical sectors such as mining and agriculture. However, this work also highlighted difficulties to collect detailed data and to develop a tool which perfectly fit local stakeholders needs i.e. taking into account their knowledge about computer science and their feelings about modeling results.

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