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Model development for integrated water management in the influence area of phosphate mines

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Abstract: The phosphate industry is a major contributor to the economy of some Mediterranean countries such as Morocco, Tunisia and Jordan. Large volumes of water are required by the mining industry in areas where water resources are scarce or limited. The increasing water demand, due to many factors such as industrial, agricultural and socio-economic development, combined with a pronounced climatic variability threatens groundwater resources in terms of quantity and of quality. This water scarcity is alarming as it represents a limiting factor to the sustainable development of these regions and it may result in conflicts between the water users. This paper presents the methodology currently applied in the European research project Elmaa to develop a Decision Support System (DSS) in two case studies, one in Tunisia and one in Morocco. The main objective of these DSS is to help water managers in improving water resources management at a regional scale. To achieve this objective, an integrated approach is implemented. This approach includes a realistic description of the socio-hydrosystem of the studied area, definition of scenarios for water resources and water demands evolution for the next 25 years, results of hydrologic and hydrogeologic modelling and results of socio-economic studies. By comparing water scenarios, it allows determining ways to optimise water consumption and to improve water resources conservation.

***Keywords**:* Integrated water management; DSS development; Phosphate mines; Mediterranean countries.

1. INTRODUCTION

The phosphate industry is a major economic sector for some Mediterranean countries (i.e. Morocco, Tunisia, Jordan), with a contribution between 3 and 5% of their Gross Domestic Product. This industry demands large volumes of water, its total fresh water consumption being evaluated in 2001 to 57, 20 and 15 million m^3 in Morocco, Tunisia and Jordan respectively. An increase of fresh water used by the phosphate industry is expected for the next years due to the fast-growing phosphate production. Combined with the population growth, the drinking water access improvement and the extension of irrigated areas for agriculture, this leads to a continuous increase of water demand in countries which have to face water scarcity due to their arid or semi-arid climate. The pressure on water is so serious that it results in competition between drinking water supply and economical activities such as phosphate industry, agriculture and tourism. This brings the need for an integrated water resources management including a more efficient use of the existing water resources, a control of water demands, and the search of new water resources.

The European project Elmaa aims to reduce tensions on water resources around phosphate mines at regional scale through the development of a Decision Support System (DSS). A 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]. Regarding water management, it generally involves at least two building blocks among [Denzer, 2005]:

- Integrated models able to simulate the behaviour of socio-hydrosystems, coming from different fields of science such as water sciences (hydrology, hydrogeology), agronomy (crop needs, irrigation), hydraulic (drinking water supply network), socio-economy (human activities), etc;
- Geographical Information System (GIS);
- Database management system (data, information, results);
- Scenario evaluation module (multi-criteria analysis, economical analysis (cost-effectiveness and cost-benefit analysis), etc);
- Convivial Graphical User Interface (GUI).

Some examples of DSS are ‘WaterWare’ [Jamieson and Fedra, 1996], the ‘MULINO’ DSS [Mysiak et al., 2005], and more recently ‘WaterStrategyMan’ DSS [Maia and Schumann, 2007].

After a description of the methodology adopted in the Elmaa project to develop a DSS, this paper briefly presents the work performed to implement it for two case studies namely the Gafsa mines area in Tunisia and the Khouribga mines area in Morocco.

2. METHODOLOGY FOR INTEGRATED WATER MANAGEMENT

2.1 Overview

Integrated water management involves evaluating the evolution of the water resources and the satisfaction of the water demands on the studied area for the next years. For this purpose, an integrated model has been proposed in the Elmaa project, which consists in:

- a conceptual model,
- scenarios of water resource evolution and water demand evolution,
- a calculator which performs water balance and gives useful information for water management.

This model constitutes the heart of the final Decision Support System (DSS) which aims at defining and ranking the most pertinent actions regarding water management. In the Elmaa project, DSS building is carried out with the support of stakeholders who are representative of the major water users in the studied zones, namely drinking water and sanitation, agriculture and industry (here mainly mining).

2.2 The conceptual model

A conceptual model 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 the water flow transfers between the different units. Wastewater treatment plants are considered as water resources which belong to socio-economic units. The principle of the conceptual model is presented in Figure 1.

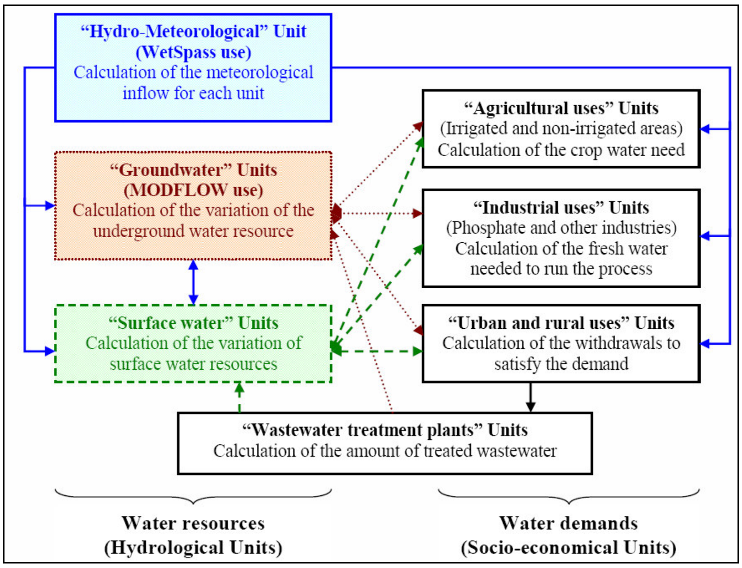


Figure 1. Scheme of the conceptual model

2.3 The scenarios

Scenarios of evolution of water resource and water demand, called here "user scenarios", were defined in the Elmaa project for the next 25 years. They are composed of one climatic scenario, one scenario for water demand evolution and one water management option.

A climatic scenario consists in 25 years-long sequences of daily precipitation and evapotranspiration which show the same statistical properties (auto-correlogramm, return period of rainy events, etc.) as historical series. Three climatic sequences were created (average, dry and wet). Each of them was simulated with "Wetspass", a physically based water balance model for the estimation of long-term average spatial patterns of groundwater recharge, surface runoff and evapotranspiration [Batelaan and De Smedt, 2001].

For the *scenario of water demand evolution*, several social, economical, industrial and agricultural parameters which could impact the water demand were identified (e.g. population growth rate, drinking water consumption, irrigated area and phosphate production…). For each of them, a limited set of potential values is listed according to literature review, prospective exercise and expert opinion. Crossing all the possibilities leads to a set of potential water demand values for each use for the next 25 years.

Lastly, *water management options* were defined by the stakeholders of the project to face the problem of water scarcity. A wide range of options was proposed such as modification of the water allocation scheme, use of non-conventional resources (treated wastewater for example) or technological improvements in the mine process. An economical study has been conducted to analyse these options and to evaluate their global cost, their efficiency (in term of saved m^3 of fresh water) and their potential environmental and sanitary impact.

The choice of one scenario of water demand evolution and of one water management option determines the total withdrawals needed to satisfy each use and their links to a given resource (according to the supply scheme which can be defined by the management option). Using these data and the Wetspass results as recharge input, the evolution of groundwater levels and base flow to the rivers are simulated for each user scenario with a groundwater flow model developed with MODFLOW [Merritt and Konikow, 2000]. An extension of the MODFLOW model allowing combination with the WetSpass model is used here [Batelaan et al., 2003]. For a given user scenario, each "Groundwater" and "Surface water" unit is then associated to a dataset describing its inflows and outflows whereas each "Socio-economical" unit is associated to a dataset describing its water demand and its water supply.

2.4 The calculator

By integrating all the information described above, the calculator gives an overview of the evolution of water resources and the satisfaction of water demands on the studied area for the next 25 years. For this purpose, it performs water balances at a monthly time step for each unit. Since the calculator is statically linked to the unit models of the conceptual model, calculator running on a user scenario involves simulations with the WetSpass and Modflow models are completed for this scenario. For resource units, this water balance aims to estimate the available water (storage or river flowrate) by difference between inputs and outputs and for demand unit it aims to compare water demand and water supply. The calculator computes four variables to describe the results of these water balances:

- the water volume available in each groundwater V:

$$V = \varepsilon \cdot S \cdot H \quad \text{with} \quad \begin{array}{l} S\text{: groundwater area } (m^2) \\ \varepsilon\text{: storage coefficient of the groundwater} \\ H\text{: piezometric level (m)} \end{array} \tag{1}$$

- the flow of the main downstream river $Q_{dowstream}$ (if the case study has a perennial river):

$$Q_{downstream}(m^3) = Q_{upstream}(m^3) - \sum surface\_withdrawals(m^3) \tag{4}$$

- the satisfaction of the total needs (monthly and annually) S_T:

$$S_T = \frac{\sum withdrawals(m^3)}{\sum needs(m^3)} \tag{2}$$

- the satisfaction of the needs per use (monthly and annually) S^i:

$$S^i = \frac{withdrawals(m^3)}{needs(m^3)} \tag{3}$$

The calculator also gives data and information concerning economical, environmental and sanitary aspect relating to the chosen water management option.

2.5 The Decision Support System (DSS)

The DSS is the final tool which will be used by the actors of water management to explore the impact of various water management strategies combined to climatic scenarios by comparing them against a baseline scenario. The baseline scenario is defined as the current state of the water system under the assumptions 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 calculated from data given by the integrated model. These indicators are related to water resources characteristics, effectiveness in water demand coverage, 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, satisfaction of the total water demand, satisfaction of the water demand per use, evolution of the total water consumption with respect to the consumption in 2005, costs, etc.

A Graphical User Interface (GUI) will be created to facilitate the interactions of the DSS user with the integrated model, namely the selection and setup of the simulated scenario, and to provide him with different forms of results presentation, including tables, graphs, maps, etc.

By evaluating different ways to optimise the water consumption and its re-use and by measuring the potential impacts of changes in the mining and agricultural practices related to technological innovations or evolutions in the institutional or regulatory framework, this DSS will help water managers to adopt plans to improve water availability, its conservation and its sharing between the different users in the influence area of phosphate mines.

2.6 Stakeholders involvement

Stakeholders were involved from the early stage of the project within the ‘stakeholders committee’ in order to create and to keep a permanent link between research consortium and local water management actors. While the ‘resource’ part of the system is knowledge and project research based, the ‘user system’ is defined with the support of a stakeholder committee. Three types of consultations were organized. The first type consisted in their participation to meetings of the consortium for them to express their opinions and validate the work of the working groups (all case studies together). The second type, which was individual consultation, aimed at collecting their point of view and above all their indicators for a good water management, these indicators being a major component of the DSS. The third type of consultation is to gather them in workshops (stakeholders of the same case study together) in order to induce discussions for a common validation of management options. The objective was not to select management options accepted unilaterally but to sweep across a majority of possible management options to evaluate their impact and then to find a consensus among them. This appears to be a real distinct task for which the results of the modelling platform should be useful (i.e. the assessment of the impact of each management option should help for decision making). The different forms of consultation experimented are complementary in the sense that they bring all different information, thus they should not be neglected.

3. CASE STUDIES

The following sections present the implementation of this methodology to develop a DSS for a Tunisian and a Moroccan case study, namely the Gafsa mines area and the Kouribga mines area.

3.1 Gafsa mines area, Tunisia

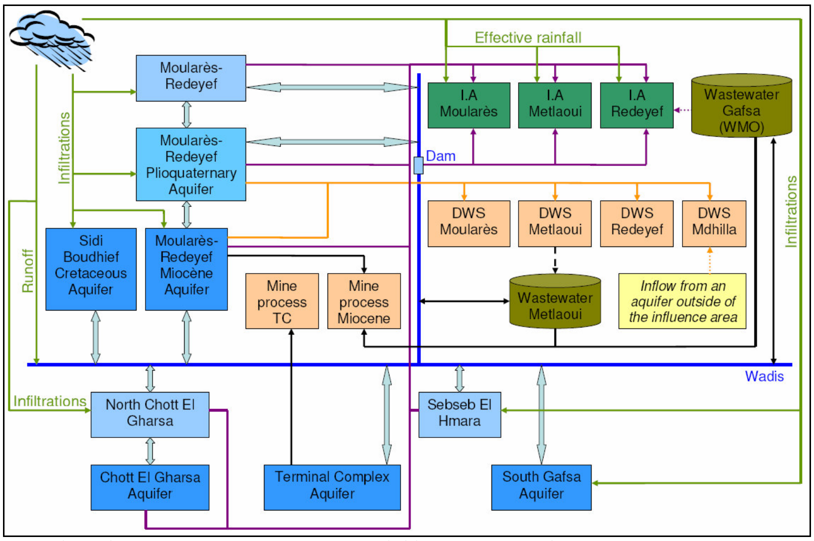
The Gafsa mines influence area is situated 350 km south of Tunis near the north-eastern part of the desert. This region is known for its industrial activities related to phosphate (extraction, production of phosphoric acid and of fertilizer) and farming which both compete for water resources. The influence area has a population of 323,709 inhabitants, including 73% living in urban zones and 27% in rural zones. It has a complex hydrographic network mainly made of small non-perennial rivers. It contains 9 aquifers including 3 water tables (Moularès-Redeyef, North Chott El Gharsa and Sebseb El Hmara) and 6 deep aquifers (Moularès-Redeyef Plioquaternary and Miocène aquifers, South Gafsa aquifer, Sidi Boudhief Cretaceous aquifer, Terminal Complex aquifer and Chott El Gharsa aquifer).

Gafsa region, which is classified in the bioclimatic arid level, has a dry subtropical climate characterized by very cold winter, dry hot summers and low and irregular precipitation. The continuous increase in water demand combined with these unfavourable climatic factors result in depletion and degradation of the water resources. Indeed, water demand is increasing due to the population growth, the extension of irrigated areas and the fast-growing mining exploitation. Currently, the phreatic aquifers, which are entirely allocated to agriculture, are entirely overexploited with an exploitation rate of 113%, while the exploitation rate of the deeper aquifers reaches 80%. The withdrawals in deep aquifers are mainly used by industry (76%), the rest being divided between agriculture (13%) and drinking water (11%) [DGRE, 2001a; DGRE, 2001b; DGRE, 2005a; DGRE, 2005b].

The objectives of the DSS developed for the Gafsa mines influence area are to allow a better allocation of the water resources between all the water users and to improve water management, e.g. by proposing technological innovations for water savings. The DSS is still under construction but several steps have already been performed: building of the conceptual model, definition of the parameters for the water demand scenarios and description of the water management options.

The conceptual model 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 2, the socio-hydrosystem is made of one unit of surface water, nine units of groundwater resource interacting one another and several units related to water drinking supply, wastewater treatment plants, industrial activities (phosphate mining processes) and irrigated areas for agriculture.

Parameters influencing the water demand in Gafsa area were defined during workshops with the stakeholders (Table 1). For each parameter, two or three values were fixed: a “low value” corresponding to a decrease in water consumption, a tendency value (following the Business As Usual) and a “high value” corresponding to an increase in water consumption. Combination of all parameters fixed at the tendency value defines the baseline scenario. The set of scenarios of water demand evolution which will be included in the final DSS will be constructed by combining all the possibilities of these parameters.



Legend: I.A = Irrigated Area DWS = Drinking Water Supply
TC = Terminal Complex WMO = Water Management Option

Figure 2. Conceptual model of the Gafsa mines influence area (Tunisia)

Table 1. Parameters table

Parameters	**Low value for the water consumption**	**Tendency value (Business As Usual)**	**High value for the water consumption**
Population growth rate	- 0.3% per year	0.51% per year	1.21% per year
Drinking water consumption	BAU decrease of 2% i.e. 4.1 Millions m^3/year	4.2 Millions m^3/year	BAU increase of 2% i.e. 4.3 Millions m^3/year
Efficiency of the waterworks system (Efficiency * wear rate)	Improved efficiency: 90 %	Current efficiency: 80%	
Connection rate with the wastewater collection system		82%	100%
Irrigated area (ha)	Current value: 3371 ha	Projected value: 6027 ha	
Cropping pattern		Current cropping pattern: Perennial crops: 55% Cereals: 3% Fallow: 18% Vegetables: 22%	Other cropping pattern with a higher water consumption
Irrigation efficiency	Improved irrigation system: Improved furrow irrigation: 70% Sprinkle irrigation: 80% Drip irrigation: 90%	Current irrigation system: Furrow irrigation: 50%	
Phosphate production		8 Millions tons/year	BAU increase of 30% i.e. 10.4 Millions tons/year
Volume of fresh water used to produce 1 ton of phosphate		2.25 m^3/ton	
Water recycling rate in the washing phosphate plant	60%	40%	
Water consumption by the other industries		3 Millions m^3/year	BAU increase of 2% i.e. 3.1 Millions m^3/year

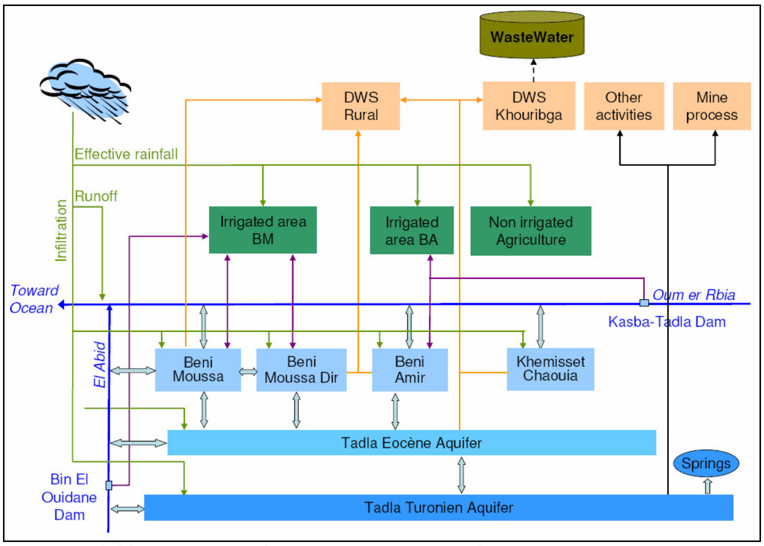
Definition of water management options, carried out with the stakeholders, includes an exhaustive description of each option (technical aspects, implementation, constraints and incentives) and an evaluation of its potential impacts for the environment, the economy and its acceptability. For the Gafsa mines influence area, 9 water management options were defined:

- 2 management options regarding the hydrology:
  - construction of groundwater recharge systems,
  - generalization of water spreading systems.
- 3 management options regarding the agricultural uses:
  - use of water saving systems in the agricultural areas,
  - use of treated wastewater for irrigation,
  - use of phosphate schlamms for agriculture.
- 3 management options regarding the industrial uses:
  - use of treated wastewater for phosphate washing,
  - improvement of the water recycling in the mine process,
  - increase of the charge on the water used in the mine process.
- 1 management option regarding the drinking water supply
  - use of systems to decrease household water consumption.

3.2 Khouribga mines area, Morocco

The influence area of the mining site is located 140 km southeast of Casablanca and covers three provinces: Settat, Khouribga (region of Chaouia Ourdigha) and Beni Mellal (region of Tadla Azilal). The zone extends over 21,075 km^2 which represents about 3% of the national surface area. It is included in the Oum Er Rbia large river basin. Even if this area is characterized by an arid climate with extreme variability of precipitations, the Oum Er Rbia is a very regular stream, its lowest water flow being about $40m^3/s$. Two main aquifer systems can be distinguished on the influence area (see figure 3):

- Tadla multilayer system which comprises 3 aquifers partly confined. Only two of them are exploited, due to the poor capacitive properties of the second one.
- Plioquaternary phreactic aquifers (Khemisset Chaouia, Beni Moussa, Beni Moussa Dir, Beni Amir).



Legend: DWS = Drinking Water Supply BM = Beni Moussa BA = Beni Amir

Figure 3. Conceptual model of the Khouribga mines influence area (Morocco)

The Khouribga mines influence area comprises 111 towns including 101 rural and 10 urban towns. Its density is 80 inh./km^2 for a population of 1,300,000 inhabitants. Drinking water is distributed in cities whereas the rural districts are not yet all equipped. The drinking water access rate is about 60% in Khouribga and Settat provinces and 90% in the Beni Mellal province. The studied region is characterized by diversified activities: agriculture (65% of the area) including rainfed areas (69%) and irrigated areas (31%), drinking water supply (urban and rural), mining industry, agro-food industries (sugar industries) and tourism. All these activities are dependant on water resources. Behind the evident problem of water quantity, the water resources quality is also a major issue since agricultural intensive practices (use of fertilizers and pesticides) and lack of treatment for most of the domestic and industrial wastewater threatens the water resources of this area [M'Hamdi et al., 2007].

Similar to the Tunisian case, the DSS regarding the Khouribga mines influence area aims at improving water availability, its quality and its sharing. The development of this DSS is still in progress but the conceptual model (Figure 3) and the description of the water management options have already been carried out. The defined water management options are the followings:

- 4 management options regarding the industrial uses:
  - improvement of the water recycling in the washing plant of Daoui,
  - use of water from dams for phosphate plant,
  - use of nitrated water for phosphate washing plant,
  - use of urban wastewater for phosphate washing plant.
- 1 management option regarding the drinking water supply
  - use of water from dams for drinking water supply.
- 1 management options regarding the agricultural uses:
  - use of water saving systems for irrigation.

4. CONCLUSION

The methodology implemented to develop a Decision Support System (DSS) is presented in this paper. This DSS aims at improving water management on the influence area of two phosphate mining sites considered in the Elmaa project, namely the Gafsa mines area in Tunisia and the Kouribga mines area in Morocco. These DSS building, developed with an integrated approach and in collaboration with stakeholders, has involved performing a realistic description of the socio-hydrosystem of the studied area, defining scenarios for water resource and water demand evolution for the next 25 years, performing hydrologic and hydrogeologic modelling and conducting socio-economic studies. Several water management scenarios will be simulated with these DSS and will be compared through the indicators given by each simulation. Even if these DSS are still in progress, it can already be concluded that they will constitute a powerful tool for helping water decision makers in improving water availability, its quality and its sharing between the different users.

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