SUSTAINABLE DEVELOPMENT OF NON-RENEWABLE GROUNDWATER

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As water scarcity increases globally, the search for water resources becomes more pressing. Along with this, comes the overexploitation of existing water resources to sustain water supply for the ever increasing demand. Non-renewable groundwater is a vital source for domestic water supply, agriculture and industry in semi-arid and arid regions. Many groundwater-dependent ecosystems rely on non-renewable groundwater for their survival in desert oases. However, being a non-renewable water resource, or "fossil groundwater", as the term is commonly being used, deems it impossible to allow for sustainable development in absolute terms. This is due to the strong declines in groundwater levels and potentiometric heads that can result due to the exploitation of such non-renewable groundwater resources. This makes it inevitable to highlight the need to formulate guidelines and frameworks for proper management of these groundwater systems, to ensure the sufficient and equitable water supply from these aquifers, for longer periods of time and for future generations to come.

The meaning of sustainable development is thus slightly different when it comes to the use of non-renewable groundwater aquifers. Sustainable non-renewable groundwater development should focus on the socio-economic aspects of the population in need, the type of water use, the amount of use, and the availability of alternative water resources. As the type of water use plays a pivotal role in the sustainability of fossil groundwater resources, some argue that high water consumptive uses of non-renewable groundwater for agricultural and industrial production should be at a minimum. Others argue that the dire need for producing food locally or even for importing food (virtual water), demands the utilization of any available water resources, including fossil groundwater. This is specially the case when renewable water resources are scarce, and when financial resources that are needed to import food require, another water-consuming economic activity to provide for it. Some argue that fossil groundwater should be a strategic reserve and should be kept for future generations, but there is no standard criterion for when to start using such a reserve, or for when will future generations arrive. On the other hand, and although some detailed research may be needed to confirm the expected impact of the exploitation of fossil groundwater on the local and global climate, and on the hydrological cycle, one can also argue that the development of the entrapped fossil groundwater will increase the water budget, entering into the global hydrological cycle, leading to an overall increase in the global renewable water resources.

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Assuming the worst case scenario of negative impacts due to exploitation of non-renewable groundwater, this paper aims to explore, compare and analyze available guidelines and measures employed by different bodies that are managing non-renewable groundwater aquifers to reduce overexploitation and make fossil groundwater more sustainable. It recommends measures, regulations, and legislations on the supply-side, and the demand-side, for the quantity and quality protection of non-renewable groundwater resources, to come as close as possible to what may be considered “sustainable development of non-renewable groundwater”.

Introduction:

When assessing groundwater aquifers, the term “non-renewable” is totally relative. The term has always been associated with aquifers underlying arid areas where no surface recharge is applied. Many scientists believe that a state of “zero recharge” is extremely rare. Aquifers are also said to be non-renewable based on the replenishment period needed. In certain cases the period needed for replenishment is hundreds or even thousands of years which is very long in relation to the normal time-frame of human activity in general and of water resources planning in particular.

The international Glossary for Hydrology has no official definition for “non-renewable groundwater”. The closest term that is defined in the 1992 edition of the glossary is “Fossil groundwater”. It is defined as “water that infiltrated usually millennia ago and often under climatic conditions different to the present, and that has been stored underground since that time” (International Glossary for Hydrology, 1992).

The development of a non-renewable groundwater resource involves the extraction of the fossil groundwater in a process that is usually referred to as “Groundwater Mining”.

Non-renewable groundwater is not usually connected with ecosystems (which are dependent on them). Therefore, these resources are more like mineral or energy resources, such as ores or oil. Fossil groundwater is usually trapped in a geologic formation, either because of physical isolation of the aquifer from sources of recharge or impermeability of overlying strata. Typically, water in non-renewable aquifers is hundreds if not thousands (or millions) of years old.

Many areas of the world rely on nonrenewable ground water resources, globally defined as aquifer systems whose replenishment rates are so small that, for all practical purposes, their development is unsustainable and will eventually deplete the available water in storage.

Depletion of nonrenewable ground water resources typically manifests itself in declining water levels. Deeper pumping and static water levels may result in lower well yields, greater pumping costs, more wells needed to produce historic pumping rates and water quality changes. The economic life of the system may be finite. Future aquifer conditions and well yields are difficult to predict due to the changes in aquifer characteristics resulting from changes in aquifer storage coefficient, saturated thickness or available water level drawdown in a well.

The sustainable development of a resource that will be surely depleted is an extremely challenging process. The sustainable development in that case refers to prolonging the use of such resource as much as possible by applying relevant management tools and measures.

Much complexity is added when the non-renewable aquifer of interest is shared between different countries. The unwritten rule of shared resources will then be applied. The rule entails that what is left today will not necessarily be saved for tomorrow, but will be exploited by other partners. That concept alone is enough to corrupt any management plan for that common resource. Hence, proper enforced laws and legislations are essential to assure the equitable use of any shared groundwater aquifer. The same problem could also exist on the national scale if groundwater rights are not strictly identified.

Management plans should not only focus on prolonging the time period where the aquifer could be utilized, but should also consider preserving the quality of the water exploited. The two main factors that affect groundwater quality are pollution and saltwater intrusion. Many legislative measures and laws have been formulated to avoid pollution. The situation is different in case of saltwater intrusion, as it is a direct cause of overuse. In fact, saltwater intrusion, wherever reported, could be an indicator that a certain aquifer has reached a critical level of declining water levels. Therefore, management plans should allocate funds to field data collection and numerical modeling studies to predict saltwater intrusion.

International Examples of Non –Renewable Groundwater exploitation:

The potential for conventional water resources such as river water and renewable groundwater is extremely limited in the Arabian Peninsula and North Africa, excluding minor areas in the mountain ranges where annual rainfall exceeds 10 inches, or 250 mm. By overexploiting major rivers such as the Nile, Jordan, Tigris, and Euphrates, groundwater resources in deep sandstone aquifers, such as the Nubian sandstone aquifers and equivalent formations, could be regarded as a strategic reserve for development in the Middle East and North Africa. Groundwater in the deep sandstone aquifers, however, is non-renewable or "fossil" water which may offer an opportunity for short-term and emergency uses. Many Large-scale deep sandstone aquifer development projects were considered in countries like Egypt, Libya and Saudi Arabia. Currently, Jordan is embarking on a large scale fossil groundwater abstraction project from the Dissi Aquifer near the borders with Saudi Arabia where water will be transferred to Amman.

The Nubian Sandstone Aquifer System (NSAS) is a transboundary groundwater basin in the North Eastern Sahara of Africa. The international waters of this regional aquifer are non-renewable and shared between Chad, Egypt, Libya and Sudan. The area occupied by the Aquifer System is 2.2 million square km; 828,000 square km in Egypt, 760,000 square km in Libya, 376,000 square km in Sudan, and 235,000 square km in Northern Chad. The volume in storage represents the largest freshwater mass in the whole world. An estimate of the storage capacity is shown in Fig.1. The total recoverable volume of about 15000 cubic kilometers is also shown, where it was assessed based on 100m drawdown in the unconfined aquifer and 200m drawdown in the confined aquifer (AbuZeid, 2003).

Fig.2 reflects the increasing dependence on the aquifer, represented in the increasing amounts abstracted over the years. The increasing demographic growth and the lack of renewable water resources in this arid region have resulted in an increasing attention to the groundwater potential represented by the NSAS (AbuZeid, 2003). Geologically, the area of the Nubian Sandstone

Aquifer System is composed of different water bearing strata that are differentiated into two systems, namely the Nubian Aquifer System (NSAS) and the Post Nubian Aquifer System (PNSAS) (AbuZeid et.al, 2006).

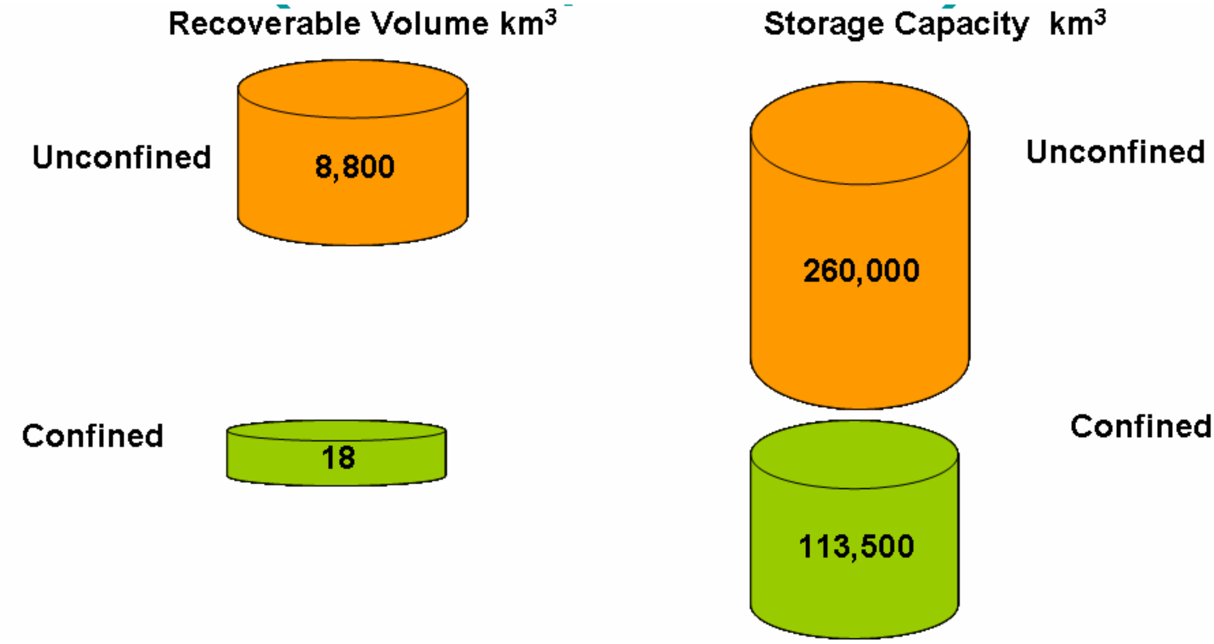

Fig.1a NSAS Storage capacity and Recoverable volume (AbuZeid, 2003)

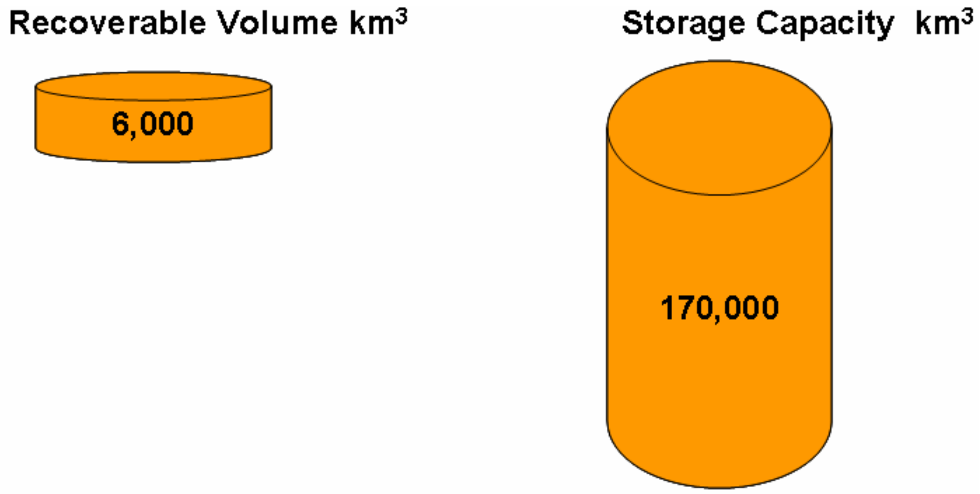

Fig.1b Post NSAS Storage capacity and Recoverable volume. (Unconfined) (AbuZeid, 2003)

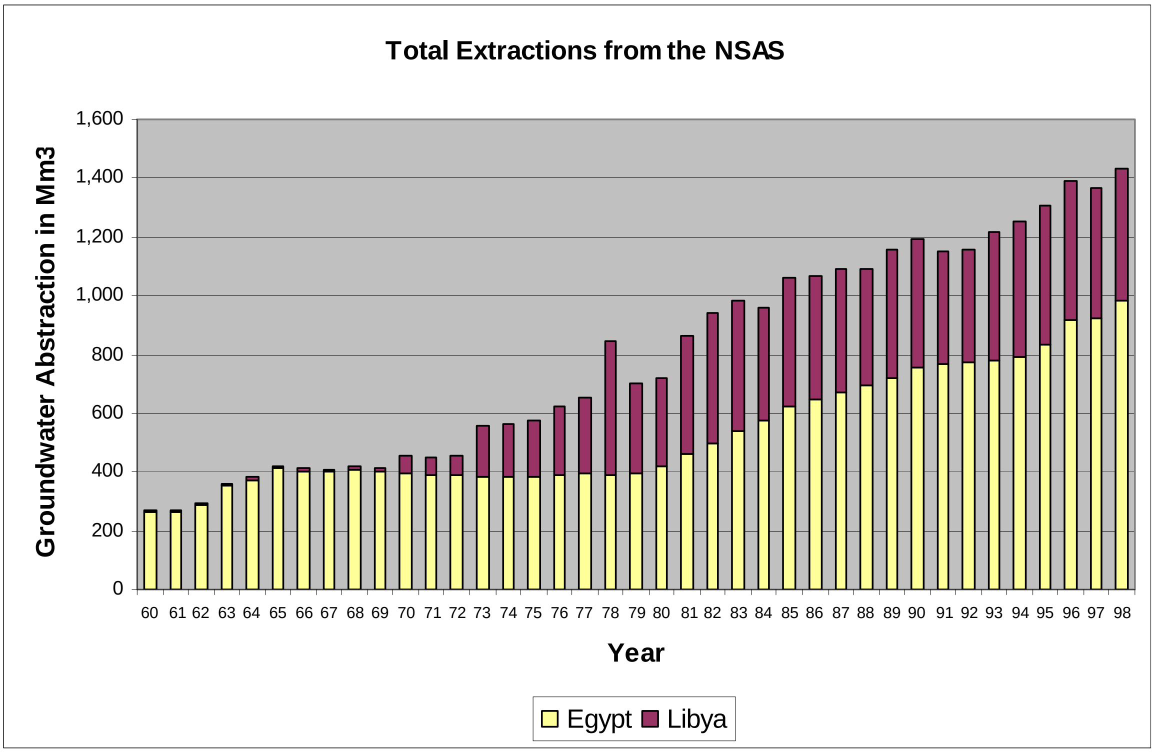

Fig.2 NSAS annual abstractions (CEDARE, 2002)

The four countries sharing the NSAS represented by their National Coordinators adapted a regional information network aiming for cooperation and knowledge exchange in order to achieve the best scenario for sustainable development, and agreed to continue the monitoring of the aquifer through a mechanism specified in two agreements. Regional thematic maps, regional mathematical model, and a regional information system were developed. Also, a regional strategic was developed based on extensive data collection and Numerical Modeling (CEDARE, 2002). Throughout the regional programme as well, the role of the Joint Authority for the Study and Development of the NSAS was revitalized. The countries agreed to update the information by continuous monitoring and sharing of the following information; Yearly extraction in every extraction site, Representative Electrical Conductivity measurements (EC), and water level measurements (AbuZeid, 2002).

The North Western Sahara Aquifer System (NWSAS) covers more than a million square kilometers, 60% of which are in Algeria, 10% in Tunisia, 30% in Libya (OSS, 2008). It has been shown that abstractions has exceeded recharge in the recent year, which makes the aquifer partially non renewable.

Groundwater in Saudi Arabia is found almost entirely in the many thick, highly permeable aquifers of large sedimentary basins of the Arabian Shield. The estimated groundwater reserves down to a depth of 300 meters below ground surface are about 2,185 billion cubic meters. The average annual recharge is about three orders of magnitude less than that, or about 2,762 million cubic meters. Groundwater is supplemented by desalinated water and treated wastewater. Saudi Arabia has become the largest desalinated water producer in the world. The total annual water Production from desalination plants has increased from about 200 million cubic meters in 1980 to over ١،٠٠٠ million cubic meters in 2002 which represented about 50% of the total domestic and industrial demands of that time, and most of the rest is met from groundwater resources. (Abderrahman, 2006).

Saudi Arabia was one of the world's leaders in the production of wheat for self-sufficiency in food until early 2008, when the 30 years programme for self sufficiency in wheat was abandoned to save water. The production of wheat is dependent almost wholly on the mining of non-renewable groundwater resources. The most commonly used method of irrigation in Saudi Arabia is the central-pivot sprinkler system, which loses a significant amount of water through evaporation. Moreover, salt accumulations in surface soil layers and/or underlying aquifers, which is a typical and difficult problem for groundwater irrigation in the arid region, cannot be neglected in any long-term development project. In Saudi Arabia this has already caused a substantial depletion of non-renewable groundwater resources (Murakami, 1995). The large abstraction of groundwater has led to high levels of salinity in some of the important coastal aquifers such as Alat aquifer and khobar aquifer (Kobeissi and Abdulrazzak, 2002). The total consumed volume of nonrenewable groundwater resources for agricultural, domestic and industrial purpose from 1980 until the end of 2000 was about 260,000 million cubic meters which accounts to 11.5% of the total groundwater reserves in the top 300 meters below ground level (Abderrahman, 2006).

The kingdom's first initiative to conserve non-renewable groundwater resources was expressed in the Fifth Development Plan (1990-1995), according to that plan; total water use in Saudi Arabia was to be reduced by 8%. The reduction in water consumption was planned to be the result of a projected decline in annual agricultural consumption. This change in the consumption rate was expected to take place through changing crop patterns, the intensification of water-saving techniques, and other appropriate measures, all of which were not meant to affect the desirable growth rate of agricultural production or its value added (Murakami, 1995).

Recently, Saudi Arabia has attempted, with varying levels of success, to manage the use of groundwater resources by controlling aquifer development, well licensing and control of drilling, agriculture policy modification, and production of non-conventional water resources (Abderrahman, 2006).

Historically, Bahrain has utilized groundwater for both agriculture and municipal requirements. Natural fresh-water springs used to flow freely in the northern part of Bahrain, but, with increased demand, spring flow has decreased and pumped boreholes became the normal means of obtaining water. Faced with rising demand and the contamination of the aquifers by seawater intrusion, Bahrain turned to desalination of seawater to provide for the increasing demand for water supply (Murakami, 1995). Another development measure adopted in Bahrain is the reverse Osmosis brackish water desalination, which is a practical solution to combat salinity in many of Bahrain's aquifers such as the Dammam Aquifer.

Botswana is an arid to semi-arid country with scarce surface and groundwater resources. Despite the increase in use of surface water schemes, most villages and a few towns continue to rely on groundwater resources for water supply because of the limited or no supply surface water resources. Indications are that groundwater mining is inevitably taking place over large areas in Botswana that receive little if any recharge because of low and unreliable rainfall. The Jwaneng Northern Wellfield (JNW) has been operated since 1979 when Jwaneng Diamond Mine started operation, producing approximately 9 million cubic meters of water per year. Groundwater abstraction in 1984 was 5,262,205 m3 while in 2000 it was 8,929,220 m3. The cumulative abstraction from 1979 through 2000 was 130,790,082 m3. In an effort to try to manage the wellfield sustainably, Modeling is continually carried out to estimate optimum drawdowns and the safe yield (Phofuetsile, 2006).

The Great Artesian Basin, underlying 1.7 million km2 of semi-arid regions of Australia, is one of the larger artesian basins in the world. It is Australia's largest and most important groundwater resource. The mining of the artesian pressures and groundwater in storage during the last 125 years has affected the Basin to varying degrees. It has produced large-scale drawdowns and reduced discharges from flowing artesian water boreholes and spring which has directly affected the pastoral industry. It is estimated that water bores supply on average 0.01 million L/day per borehole, and produce a total of about 300 million L/day. The Great Artesian Basin Sustainability Initiative, begun in 1999. This program accelerates borehole rehabilitation and borehole drain replacement programs to achieve partial recovery of artesian pressures in strategic areas of the Basin. Its goal of replacing the open bore drain distribution system with polyethylene piping combined with float valve controlled tanks and trough systems will substantially reduce water wastage. This in turn will reduce the demand for water produced by the bores, thereby leading to increased artesian pressures and artesian flows from water boreholes and possibly re-establishing flows from some water boreholes and springs that have ceased flowing (Habermehl, 2006).

Strategies and Guidelines:

“Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

The previous international definition of sustainability that was set by the Brundtland commission in 1987 focuses on two main points: the needs of the poor are to be urgently satisfied and the natural limits of economic development must be taken into account during planning (BMZ, 2007).

The application of this principle is often set equal to not using non-renewable groundwater at all, since, once extracted, water cannot be used by future generations. This assumption follows the classic rule for groundwater management, which is to use only those quantities which can be replenished by natural sources of recharge. In fact, the use of non-renewable groundwater leads to a decrease of the groundwater level and, thus, of the resource availability if all other boundary conditions remain constant (BMZ, 2007). However, some might argue that this fact does not contradict the principles of sustainable development. Because of its history of formation and its generally deep location in the underground, non-renewable groundwater is rarely associated with ecosystems. The use of these resources, therefore, normally has considerably less adverse effects on the environment than over-use of other renewable resources, which very often form the means of existence for valuable ecosystems (BMZ, 2007). The focus on sustainability should, therefore, be primarily focused on the affected population, i.e. on their social and economic development. A just distribution of benefits from the use of non-renewable groundwater between today's users and those of future generations appears to be the actual challenge for sustainable management. In many countries, particularly in North Africa and the Middle East, the intense use of non-renewable groundwater is a reality today. This region is one of the most water-poor regions in the world and faces a significant increase of population which will lead to an even higher demand for drinking water. The problem is further aggravated by increased agricultural uses for the available water and plans for industrial production (BMZ, 2007). Some argue that development of the entrapped fossil groundwater will increase the water budget, entering into the global hydrological cycle, leading to an overall increase in the global renewable water resources. Some research is needed to study the regional impact of the increase in the global water budget.

Meeting the requirements of social sustainability in respect of development of the nonrenewable groundwater resource is conditioned on applying a positive balance between the short-term socio-economic benefits and longer-term negative impacts. It should be recognized that predicting the longer-term evolution of any given case of groundwater mining will be subject to significant uncertainty. This is due to the uncertainty associated with most of the components involved in the process of groundwater development and future predictions. The lack of a complete hydrogeological understanding along with other factors like innovations in water technology, changing global agriculture and food markets, and accelerated climate change, place limits on conventional resource management. This dictates the need to incorporate more flexible and adaptive risk-based approaches, which need to find political acceptance (UNESCO, 2006).

As for future predictions, the uncertainty associated with aquifer modeling is also unquestionable. Developing a near perfect numerical model requires accurate stratigraphy data which in turn requires intense electric logs which is not affordable on many levels. Although, there are many indirect statistical methods that adopt the inverse problem theory to estimate aquifer properties, traditional methods such as pumping tests remain the better option and they are equally expensive.

Although the statement sounds so "cliché", it is worth repeating that the objective must be to achieve a change from uncontrolled exploitation towards planned management of groundwater use. Proposed plans should focus on the rational use of the deployable resource and achieving inter-generational equity (UNESCO, 2006). At the same time, within the foreseeable period of groundwater use, technical alternatives for substitution must be developed and examined with respect to their economic and ecological feasibility. Examples here include sea water desalination or desalination of saline groundwater as well as wastewater purification and re-use. (BMZ, 2007).

(Foster et.al, 2003) indicated that for the utilization of non-renewable groundwater to be managed effectively, special emphasis must be put on aquifer system characterization to facilitate adequate predictions of groundwater availability, the distribution of wells to abstract it over a given time horizon, the impact of such abstraction on the aquifer system itself, and finally the anticipated groundwater quality changes during the life of intensive aquifer development.

The status of fossil and other non-renewable ground water resources under international law is a much neglected topic in international legal discourse and regulatory development The UN 1997 convention on the non-navigational uses of watercourses is one of the recent and authoritative effort to codify international law applicable to fresh water resources, directly omits such waters from its scope. Under the Convention, a watercourse is defined as: “a system of surface waters and groundwaters constituting by virtue of their physical relationship a unitary whole and normally flowing into a common terminus.” While considered broad in its application to surface bodies of water, the definition limits the treaty’s applicability to certain types of ground water resources, and excludes fossil and non-renewable aquifers (Eckstein, 2007). However in the first draft for the international law of transboundary aquifers, a differentiation between renewable and non-renewable groundwater has been strongly suggested.

A Vision for the Future (The case of the Nubian Sandstone Aquifer System):

A clear future vision is essential in resources planning; estimating the recoverable volume of each aquifer is the compulsory first step in future planning. It is also useful to consider different utilization schemes.

An example considering different utilization scenarios for the NSAS is hereby illustrated. The goal is to estimate the life expectancy of the aquifers under each scenario. It is assumed in all scenarios that the shares of different countries are proportional to the area of the aquifer located within their boundaries. As shown in figures 1 and 2, the total recoverable volume is approximately 15000 cubic kilometers. As 36% of the total aquifer area is located in Egypt, the total allowable recoverable volume for Egypt is calculated to be 5425 cubic kilometers, while that for Libya is 4149 cubic kilometers which corresponds to approximately 28% of the area. Similarly, Sudan's share of the total recoverable volume is 4787 cubic kilometers, and Chad's is 638 cubic kilometers.

For reasons related to data availability, the scenarios will focus mainly on Egypt. The final abstraction record of 1998 will be the initial record for Egypt in the following future scenarios. As shown in Fig.2, the annual abstraction in Egypt was 980 million cubic meters.

The first scenario will assume a 2% annual population increase in Egypt, and will honor the global limit for water poverty which is 1000 cubic meters per capita per year. The total annual water volume available to Egypt is considered 57 billion cubic meters (BCM) which consists of the 55.5 BCM from the River Nile and 1.5 BCM from precipitation. This scenario assumes that the excess volume to meet the water poverty limit which is 1000 cubic meters per capita per year will be met from the NSAS. It was found that NSAS could sustain the remaining volume to reach up to the limit for water poverty for 60 years as shown in Fig.3a, with a total of 5323 cubic kilometers abstracted from NSAS. The starting year of that scenario is 2008 and the end year is 2068. Based on the assumption that the industrial and domestic needs will add up to 20 % of annual abstractions, and agriculture will consume 80% of these abstractions, and the fact that one feddans needs 5000 cubic meters of water per year, the expected number of feddans (acres) irrigated by 2068 is 39,372,369 (Fig.3b) where the population is estimated to be 246,000,000 which means that the expected per capita share of agricultural land is 0.16. By 2068 the per capita share of renewable water resources is estimated to be 309 cubic meters per year, which means that by that time NSAS will be responsible for 691 cubic meters per capita per year to reach the water poverty limit.

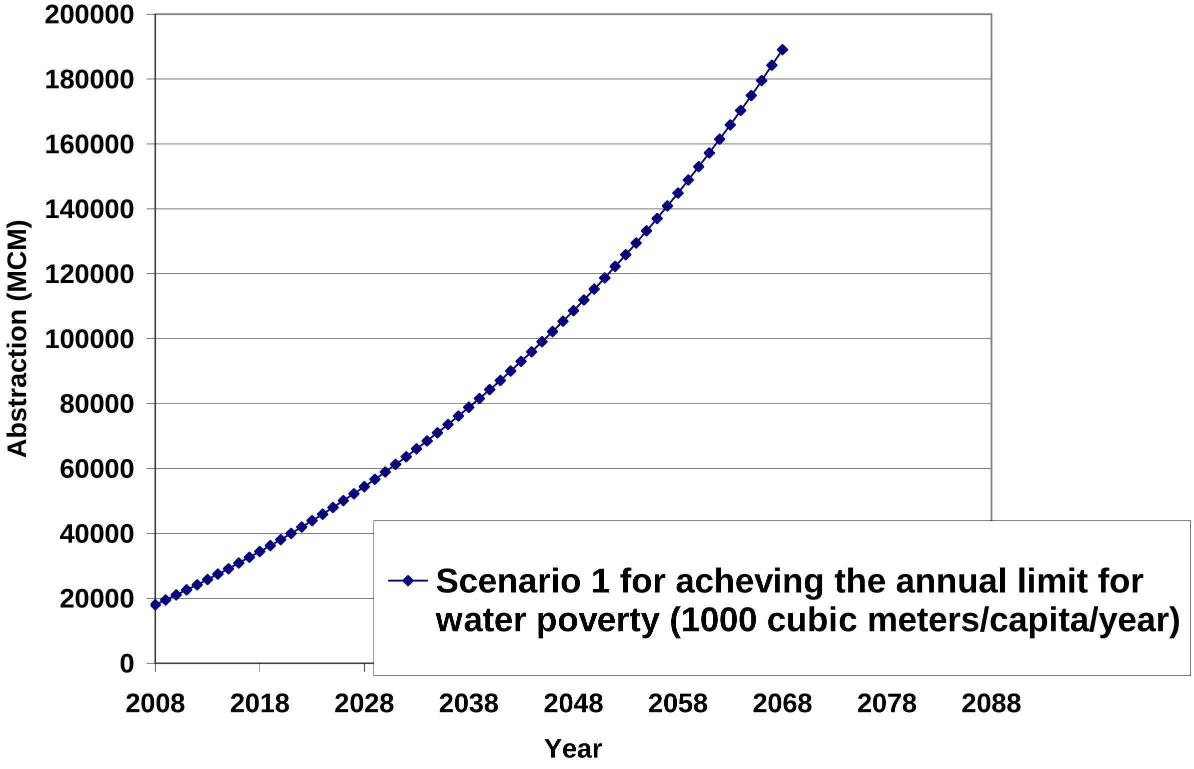

Fig. 3a NSAS Scenario 1

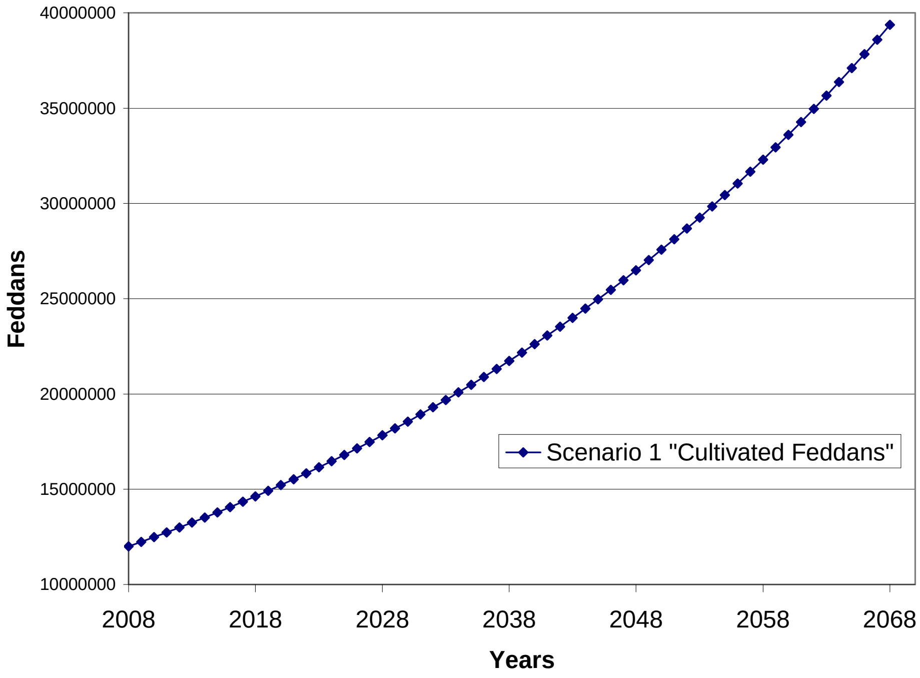

Fig.3b NSAS Scenario 1 Cultivated feddans

The second scenario will assume that the annual increase in population in Egypt which is 2% will be fully diverted to the currently uninhabitable western Egyptian desert and that Agriculture will be their main activity. It is also assumed that they will totally rely on NSAS for their agricultural needs and all other needs. The inclusive number that refers to all the community needs will also be 1000 cubic meters per capita per year. It was found that the aquifer will last for 67 years under this scenario, the starting year of the scenario is 2008, the end year is 2074, and a total of 5459 cubic kilometers will be abstracted from NSAS as shown in Fig.4a. The total number of cultivated feddans is estimated to be 32,579,683 (Fig.4b) where the population is estimated to be 209,000,000 residing in the new proposed community, in addition to 75,000,000 which is the starting population of 2008, the total country population should reach 284,000,000 capita under this scenario, which makes the per capita share of agricultural land 0.15. This scenario assumes total dependence on NSAS.

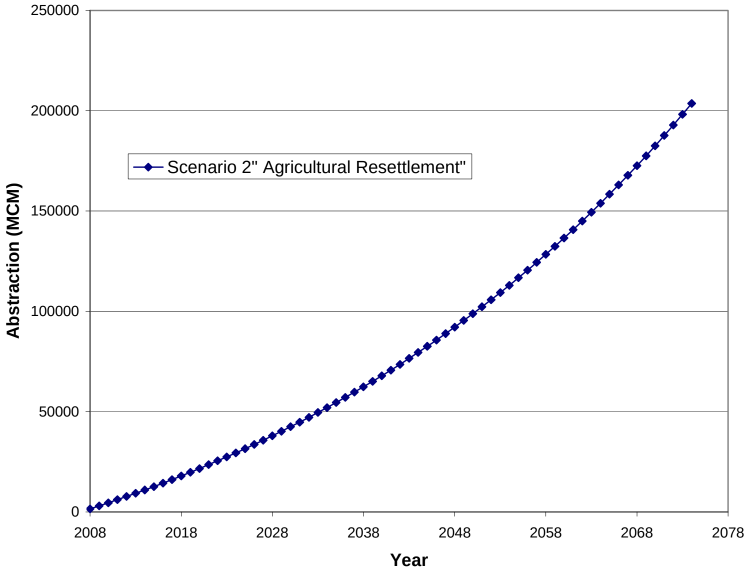

Fig.4a NSAS Scenario 2

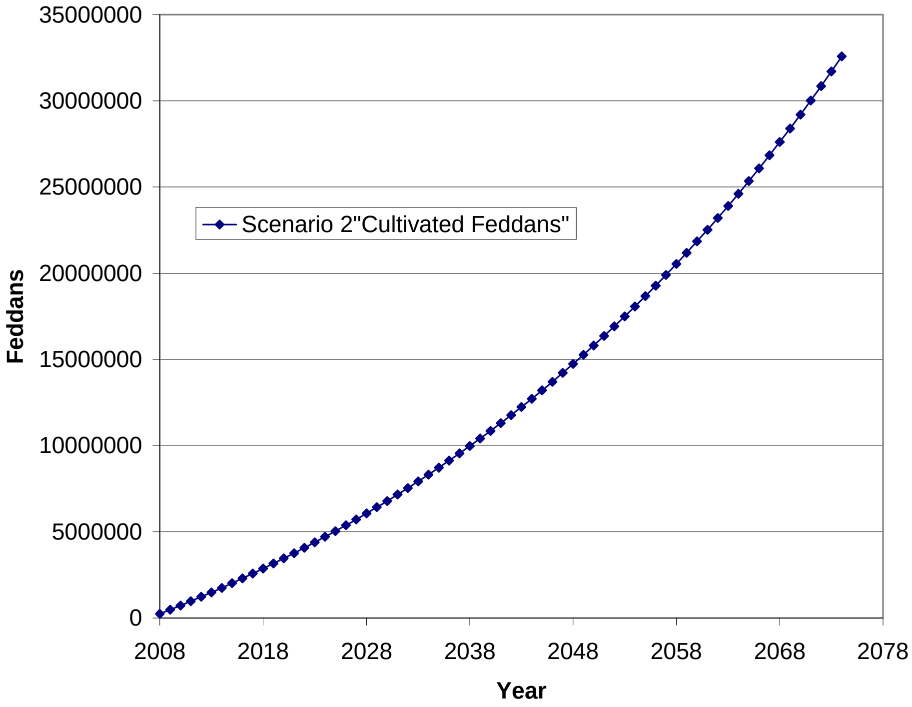

Fig .4b Scenario 2 Cultivated Feddans

The third scenario assumes that the annual population increase will move to the western desert and industry will be the main activity, Domestic and industrial needs will be abstracted from NSAS. The waste water resulting from both the industrial and domestic sector will be used for agriculture and aquifer recharge. The domestic and industrial uses will be estimated based on the semi fact that 200 cubic meters per capita per year will be enough for both sectors as it is globally accepted that 100 cubic meters per capita per year is the average domestic water use, and the same for industrial use. The waste water resulting from both sectors are estimated to be 80% of the initial amounts and will then be used for agriculture. Under this scenario, with restricting agriculture to treated wastewater only, NSAS will last for 119 years as shown in Fig.5a. The starting year is 2008 and the end year is 2126. The total number of cultivated feddans is expected to be 22,481,000 by 2126, while the population would be approximately 777,000,000 which result in a low per capita share of agricultural land of 0.03 feddans. The total volume abstracted from NSAS by the end year will be 5420 cubic kilometers.

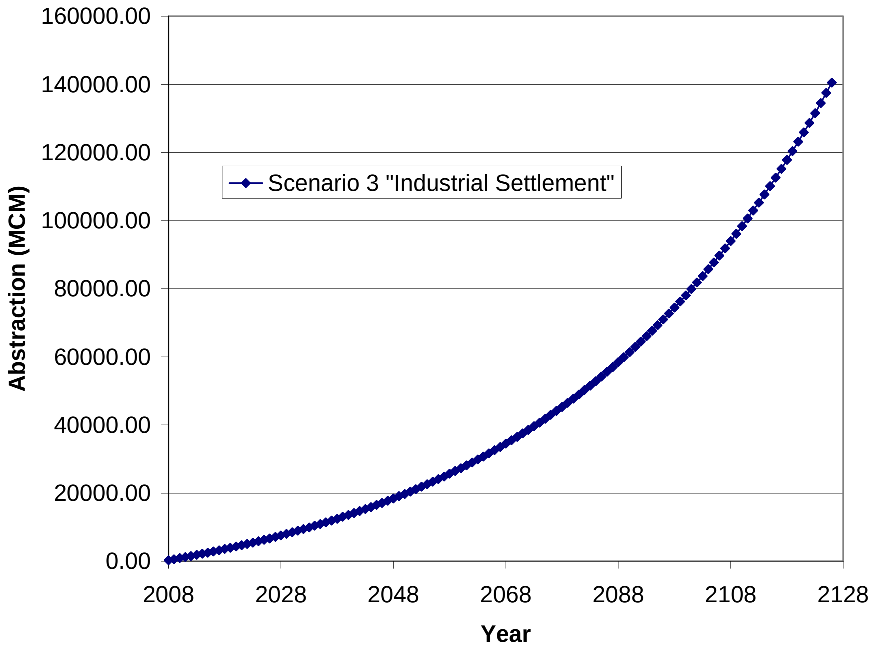

Fig. 6a NSAS Scenario 3

Assuming that 80% of the abstracted water will be used for agriculture after being treated, and knowing that one feddan (acre) needs 5000 cubic meters every year, the number of cultivated feddans for each year can be calculated as shown in Fig 5b.

It could be noticed that scenario 3 will achieve the highest sustainability; but it has the least agricultural benefit which is natural in a supposedly industrial community.

The main advantage of scenario 3 is that it sustains the needs of the growing population from NSAS for 119 years, leaving the renewable resources to a population close in number to that of 2008.

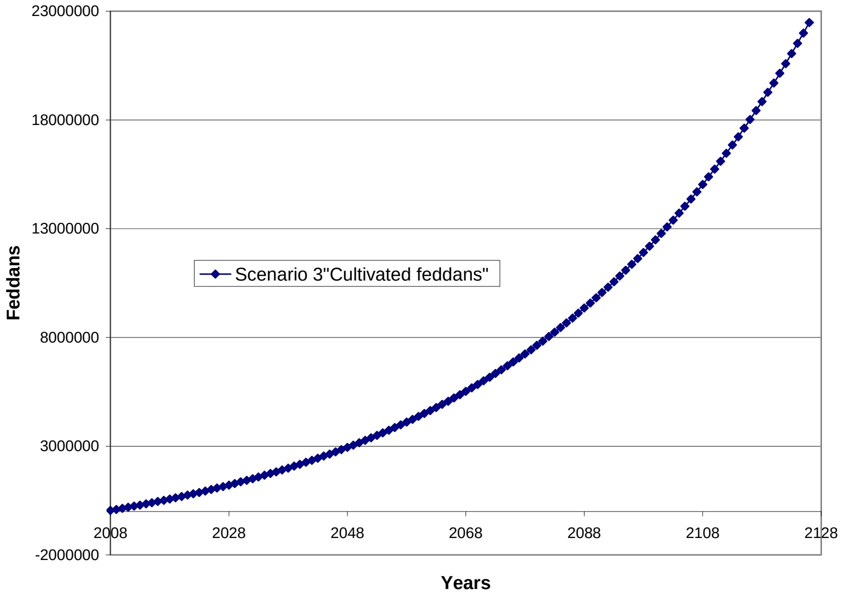

Fig.6b NSAS Scenario 3 "Cultivated Feddans"

In a future research, scenarios 1 and 2 will include recharging the aquifer with treated waste water which will significantly enhance the sustainability.

One of the impacts that might be positive in all scenarios is the evapotranspiration produced from the irrigable areas that might act as an input to the hydrological cycle causing some precipitation in the region; however, this precipitation may not enhance NSAS directly in a form of surface recharge.

It should be noticed that all scenarios have assumed that aquifer abstraction follow a uniform distribution, which is practically untrue. In fact, recoverable volumes may be reduced by concentrated well fields. Abstraction rates might also vary from one area to another. Therefore, the sustainability discussed in the previous three scenarios is subject to increase or decrease.

In all scenarios, it is essentially important to assess an alternative plan after the end year. Many technical measures can be considered as will be presented in the following section.

Technical Measures:

While sustaining fossil groundwater sounds more like a problem of quantity rather than quality, enhancing the water quality is equally essential for sustainable development. Some technical measures are globally adopted for the dual purpose of preserving quantity and quality.

One of the important measures is setting the distance between wells so that the allowable draw downs are not exceeded. Such a measure requires a strong law enforcement policy.

Saltwater intrusion in non-renewable coastal groundwater aquifers is one of the significant issues in water resources over the last decades. Its negative impacts include drinking water shortage and aquifer contamination. Moreover, it also leads to land subsidence and estuary ecosystem destruction. Mitigation of saltwater intrusion requires an appropriate ground water management strategy, which involves optimization techniques to deal with the conjunctive use of surface water and ground water.

One method to manage the saltwater intrusion without affecting needed water quantity is the development of a hydraulic barrier (saltwater intrusion barrier) via surface water injection. Injection of surface water into aquifers intuitively leads to several advantages and has minimum to no impact on natural environments. However, the barrier efficacy and economy rely on a well-planned design over a set of injection wells (Elrawady and Tsai, 2006).

A basic hydraulic barrier consists of an infiltration basin and a recharging well. These elements contribute to the formation of a groundwater mound under the recharge areas which results in a high gradient than the surrounding which counterbalances the movement of the freshwater/groundwater interface.

Developing a saltwater intrusion barrier (SIB) management model requires optimizing the design by finding the least number of injection wells and minimum injected surface water amount such that human-built saltwater intrusion is efficiently mitigated and ground water availability is enhanced. The SIB management model involves optimization of injection well selection, injection rate scheduling, and injection rate optimization. The objective of the SIB model is to minimize the overall pumping rates while the desired ground water heads and chloride levels in the intruded areas are met (Elrawady and Tsai, 2006).

The SIB model could only be efficient if it is well optimized. However using freshwater is not essentially a practical solution in the scope of sustainable development. Using treated brackish water or treated wastewater will be the best option to use the SIB as an enhancement tool for both the quality and quantity of non-renewable groundwater.

Another method to mitigate saltwater intrusion is the physical barrier. It involves the construction of sheet piles and filling up deep trenches with clay, cement, concrete or asphalt. This method is widely criticized due to its various limitations along with its high costs (Kobeissi and Abdulrazzak, 2002).

Seawater desalination is one of the options for sustaining the fossil groundwater dependant developments. The biggest disadvantage of that measure is the high cost, and in some cases the long travel distance to transport the desalinated water from the coast to the development site.

Desalination of brackish groundwater is another common measure. Reverse osmosis is currently the fastest growing technology and is applied not only for desalination of seawater but also for treatment of brackish water and to produce high quality production water for industrial use and even to treat domestic waste water or drainage water (Allam,2002).

Another important technical measure is wastewater recharge. It is being applied successfully in Orange County, California in what is referred to a 'Groundwater Replenishment System"(GRS). It has many positive impacts, such as decreasing the amount of waste water discharged to the ocean. Waste Water is treated through advanced techniques, including microfiltration, reverse osmosis and ultraviolet disinfection and hydrogen peroxide. The resulting water will be so pure; it will actually improve the overall quality of the groundwater basin by lowering the mineral content (www.gwrsystem.com).

Conclusions and Recommendations:

The importance of sustaining the use of non-renewable groundwater aquifers has been portrayed. Some global strategies and technical measures for sustainability have been shown.

The proposed scenarios have proved that NSAS could be utilized for up to 120 years. Although not all non-renewable aquifers have the huge recoverable volume of NSAS, similar approaches could elongate their utilization period.

It could be indicated that the optimum management plan to achieve the maximum possible sustainability of non-renewable aquifers could be divided into two main parallel axes, the first is decreasing the consumption, and the second is recharging the aquifers. Extensive research is needed to optimize both functions.

As for decreasing the consumption, among all water use sectors, the domestic sector has the highest priority; it should be the only sectors using abstracted fossil groundwater. Other sectors can rely on other water sources such as treated waste water which is the more affordable option in many countries or desalinated water. Using treated waste water in agriculture will make a significant difference towards sustainability, as the agricultural sector is usually the highest consumer.

Artificial recharge with treated waste water and/or brackish water is highly recommended to enhance water availability. The GRS project in California could be taken as a good model to be followed. Governments should invest funds in similar projects for their obvious necessity and future strategic importance. Opening such a project to stakeholders might be differently accepted according to the norms and customs of each community.

Applying the use of treated waste water on the agricultural sector should be designed so as not to incur any additional charges on land owners, which may be practically difficult if a private firm is responsible for the waste water treatment. The government should insure that private firms are only making profit from the treating process not from the treated water. After all, it would be best if the government controls the whole process.

Extensive research is needed for future planning. Development of numerical groundwater models along with urban models will be essential in any planning phase. The continuous flow field modeling will keep authorities updated on the aquifer status, and will give decision makers many important inputs about the life expectancy of the aquifer which might affect their decisions in applying or removing restrictions. Groundwater transport modeling will give decision makers the same insight with respect to the status of water quality and would affect their decision in developing one of the technical measures. Urban models can predict the needs for different water use sectors, and when crossed with Groundwater models, a semi realistic image of the sustainability of the non-renewable aquifer with respect to the urban needs can be obtained.

The future development plan for non-renewable aquifers has to clearly identify the life expectancy and accordingly, the maximum yearly drawdown. Alternative plans on utilizing other water resources such as seawater desalination should be set up and ready for execution before the end of the aquifer's life expectancy.

Non-renewable shared aquifers should be subject to international agreements specifying the maximum permitted yearly drawdown; all well locations should be subject to inspection by all the sharing countries and international organizations.

A groundwater abstraction rights system including permits and licenses has to be clearly defined, it also has to be consistent with the hydro geological reality of continuously-declining groundwater levels, potentially- decreasing well yields and possibly deteriorating groundwater quality.

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