Modeling the Irrigation system in Egypt

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Abstract

This paper partly describes the empirical part of the ongoing PhD thesis where we aim to incorporate the system dynamics methodology (approach) with the associated Geographical Information Systems (GIS) capabilities in Environmental modeling domain. We do not intent to describe the technical details of the synthesize process of the two software packages that dominating each technology. Rather, we will emphasize on the need for integration of SD and GIS, the significance of this approach (our new methodology), the potential mutually benefits, and, the framework we adopted to implement this integration.

Environmental systems are geographically (spatially) distributed, and GIS has been successfully used in addressing the environmental problems. For example, many forest resource companies and other environmental agencies such as EPA (U.S. Environmental Protection Agency), the National Parks Services, and the Bureau of Land Management had acquired GIS technology. Some of the greatest interest in the use of GIS for environmental problem solving has come from those who would apply the technology to translate the results of environmental modeling into policy. Post processing is essential if the results of a spatially distributed model are to be used for policy development. Results must often be aggregated by administrative unit, or brought into consistency with social and economic data for comparison and correlation. Displays must be developed to present the results of modeling in convincing form.

Modeling the environment with GIS, is not a new idea, but modeling the dynamics of space, time, and human choice is our main contribution. Our motivation is driven from three assumptions. First, the spatial representation is crucial to environmental problem solving, but GIS currently lack the predictive and related analytic capabilities necessary to examine complex problems. Second, SD Modeling tools typically lack sufficiently flexible GIS like spatial analytic components and are often inaccessible to potential users. Third, System dynamics approach and GIS technology can both be made more robust by their linkage and co-evolution. SD would benefit by the better engagement of the visual senses in evaluating the assumptions, operations, and results of the models. Doubtless many readers could recount experiences wherein the better mapping/visualization of spatial properties brought new and sometimes startling understanding to those previously confident that they fully understood a target system and methods for its analysis.

In this context, we have adapted a new methodology based on the Object Orientation to incorporate SD with GIS. We applied this methodology to model the irrigation system in Egypt. This paper describes the irrigation system from SD viewpoint. The scope of this paper is restricted to study the social implications of the water scarcity, and the water preservation policies. The issues of economic efficiency (in terms of water optimum utilization) and environmental efficiency (in terms of water quality) are beyond this study. The system dynamics approach is used to identify and characterize the relationships between social forces and physical variables (land and water) that escalate water scarcity conditions, and draw the water preservation polices. Moving from modeling to policy formulation, we examine four proposed policies for water preservation and ultimate utilization and discuss the feasibility of these policies in Egypt.

The analysis is partly based on materials obtained during the fieldwork that included interviews with officials of Egyptian government, NGOs and farmers in addition to the projects and reports published by the Ministry of Water Resources and Irrigation (MOWRI) and the Ministry of Agriculture (MOA) in Egypt.

Keywords: Environmental modeling, spatial dimension, dynamic systems.

Introduction

"As water is the font of life, irrigation has been the font of civilization. It underlay the rise of the first sedentary societies organized on a large scale, in Mesopotamia, Egypt, the Indus Valley and China. Irrigated agriculture appears to have been developed as early as the 7th century B.C." (Roger D. Norton, 2003). It has been estimated that "2.4 billion people depend on irrigated agriculture for jobs, food and income; and over the next 30 years, an estimated 80 percent of the additional food supplies required to feed the world will depend on irrigation."[1] In playing this fundamental role for food production, irrigation has become the world's largest user of fresh water, accounting for more than 80 percent of water use in Africa[2] and comparably high percentages in other developing regions of the world. In 1992 irrigation accounted for 91 percent of water withdrawals for low-income countries as a whole, and 69 percent for medium-income countries.[3]

In the past, many irrigation strategies tended to treat water as an inexhaustible resource, and the emphasis was placed on the construction and financing of new systems to serve farmers. Now the growing demands for water in all sectors (agriculture, urban, and Industry) have made it clear that water is a scarce resource, and former irrigation strategies are no longer viable in many areas.

Ever larger numbers of countries are seeing their annual renewable water supplies fall below the critical level of 1,000 m^3 per capita, below which they become a severe constraint on development prospects. Some of those countries, and their projected renewable water supplies (m^3 /capita) for the year 2000, are as follows: Saudi Arabia (103), Libyan Arab Republic (108), United Arab Emirates (152), Yemen (155), Jordan (240), Israel (335), Kenya (436), Tunisia (445), Burundi (487) and Egypt (934).[4]

The per capita fresh water availability in Egypt dropped from 1893 m^3 in 1959 to 934 m^3 in 2000 and tends to decline further to the values of 670 m^3 by 2017 and 536 by 2025 (UN CCA

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[1] FAO, "Water Policies and Agriculture," in: *The State of Food and Agriculture 1993,* Rome, 1993, p. 233, based on information from the International Irrigation Management Institute.

[2] The World Bank, *A Strategy for Managing Water in the Middle East and North Africa,* Washington, D. C., 1994, p. 69, on the basis of estimates by the World Resources Institute and The World Bank.

[3] World Bank, *World Development Report 1992,* Washington, D. C., 1992, p. 100, on the basis of data from the World Resources Institute.

[4] FAO, 1993, p. 238. These figures include river flows from other countries, some of which may not be reliable sources in the future.

2001; MOWRI 2002a; Abdel-Hai, 2002). The main reason behind this rapid fall is the predetermined quota of water from the Nile (55,5 billion m^3) and the raising pressure from population growth. The last is not the only reason; there are other significant driving forces escalate the water stress in Egypt. These driving forces fall into four categories: social, economical, and political forces and physical variables.

Social forces comprise the population growth impacts, poverty in rural territories, present cropping patterns, unequal distribution of irrigation water, and farmers' behavior. These forces influence ***physical variables*** (land and water) establishing enormous pressure for agricultural land expansion, which in turn exhaust current water resources, and boost the demand for water. The incremental demand for domestic water use due to population growth makes the situation even worse. ***Economical forces*** indicated that the annual freshwater withdrawals for agriculture sector in 2001 amounted to 83 percent. In spite of its high water consumption levels, its contribution to GDP accounts only for 16.5 percent versus the industry and service sectors contributing with 33.3 and 50.2 percent share in GDP respectively. Agriculture can be affected by increasing water scarcity due to growing demands from other sectors that seem to be more profitable. ***Political forces*** include government and farmers and their representatives who put pressure on the government to continue its policy of "*Irrigation water subsidies*". The government claims that there are positive social benefits such as employment and income increment. Through the "affordability" of free irrigation water, agriculture employ 50 percent of the labor force in rural Egypt, and prevents rural households from being pushed out of agriculture into the cities, which cannot provide shelter, jobs and food for millions.

Modeling the water scarcity problem

Regarding the fixed quota of water from the Nile (55,5 billion m^3), the impacts of population growth and improved life quality escalating the water scarcity conditions in the future, whereas poverty, unequal distribution, cropping patterns and consumers' behavior contribute to emerging water shortages in present. Water stress influenced by those factors has been monitored even within boundaries of one village.

Poverty in rural communities of Egypt is still a problem although a significant improvement in the standards of living have been made in the last three decades. Human Development Report (2003) estimated that 20.4% of total rural population is poor and 6.1% is ultra poor[5]. The distribution of the poor people in the country is quite uneven and shows significant differences among regions. For example, number of provinces in the Delta has higher poverty rates that reach 35.4% where 10.9% of the population is ultra poor. In other provinces in Upper Egypt, the proportion of the ultra poor population is as high as 41.9%. Often low-income levels and poverty in rural areas limits the farmers' ability to invest in agriculture pushing them to plant the low-cost crops that is water thirsty crops (i.e. rice, sugarcane). This shift in the cropping pattern triggers the increase in water use.

Unequal distribution of irrigation water is another factor involved in emerging water stress conditions. This is a result of water overuse at the head of the canal bringing less water

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[5] The poverty line used in HDR 2003 for rural area is 3963 LE (Egyptian Pound). Poor is defined person whose expenditure is less than specified poverty line. Those who are bellow food poverty line (3752.6 LE) are considered as ultra poor.

toward its tail. Thus, the farmers at the tail of the canal and downstream suffer from water shortages and are forced to abandon cultivation of some part of their land in order to avoid yield losses, whereas at the head of the canal peasants enjoy the abundance of irrigation water.

Unequal distribution of water can be linked to the bounded behavior of farmers who cannot see far reaching consequences of their actions (i.e. behavior such as mistreatment of irrigation infrastructure in order to get wider access to water, El-Khashab 2003). The low cooperation levels and low communication facilities preventing spreading the feedback of downstream farmers upstream is another aspect of this complicated issue. Farmers cannot always be blamed for their ignorance or low consciousness since the over-irrigation practices that lead to water shortages downstream often are induced by the unreliability of the water provision in canals. Uncertainty in water availability pushes them to over-irrigate, as they are not sure of the water delivery (volume and timing) next time (Holmen, 1991). Obviously, the water scarcity, in this sense, is not bounded in time or space. Water shortage can occur in present within one villages' boundary, hiding behind the abundant fresh water availability at the head of canal. But water scarcity definitely will intensify over time and expand over a larger space.

Cropping pattern plays a vital role in determining the irrigation water demand. During the 1950s, 1960s, and 1970s the agricultural sector was characterized by heavy government interventions in the production, trade and prices. The reform in the 1980s resulted in liberalization of prices and government control of the cropping was abolished. Consequently, some changes in cropping patterns occurred favoring production of high value added crops. Among them were the rice and the sugarcane with highest water requirements among the crops cultivated in Egypt. For example, the annual production of rice rose from 2.4 to 4.5 million tons (UN CCA, 2001) and fields of rice expanded almost by 50 percent (from 1 million feddan[6] to 1.5 million) (MOWRI 2002a). The cropping patterns that sometimes lead to water shortages serve the welfare interests of rural families. According to the UN CCA (2001), 57 percent of the population lives in rural areas, and a major part of them are engaged in the agricultural activities. As the agriculture is completely dependent on irrigation, it becomes the largest user of water with 83% share in water consumption (UN CCA. 2001).

Expanded fields of rice require additional amounts of water and therefore rice cultivation is restricted by the state. However, the fields of rice sometimes are out of control and there are observed violations of the quotas determined by the government. Even though official reports explain the increase in the cultivated rice areas by the increase in Nile flows during the 1990s (MOWRI, 2002a), the national survey (1998) shows that the main reason of crop choice is the profitability of crops. The explanation based on a profit driven cropping pattern, seems more relevant in this case if we take into account the poverty levels in rural Egypt. The rice is a high value crop and is likely to be an important contributor to raising the income (Poverty Reduction in Egypt. 2002). Thus, the fields of rice and sugarcane tend to expand and are driven by the welfare needs of farmers.[7]

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[6] One feddan is 0.42 hectare

[7] Here one can argue that not only the low-income farmers stand behind the rice filed expansions but profit driven motivation of big farmers can lead to the same result as well. However, here must be noted subsistence character of the farms in Egypt with and average landholdings of 2.6 feddans and 40 percent of farmers hold less than one feddan (Moharam, 2003). Therefore it has been assumed that main contributor to augmentation of high water demanding crop fields is the low income levels, beside the "free water" factor which will be discussed later on in Political forces.

Consumer’s behavior

The water stress conditions are also tied to the conscious behavior of the consumer, resulting from the level of education, accessibility and availability of information and cultural patterns.

A good example of the education level effect is the resistance of the farmers to use the new irrigation methods. Regardless of the presence of new irrigation systems in the new cultivated lands, farmers are still using the “surface flood irrigation method” (MOWRI, 2002a; Bishay, 2003). They prefer the old methods they had used to and resist the innovations.
Another example is the difficulties to expand fields cultivated with “the short-duration rice” in spite of its lower water requirement. One of the reasons is the taste of rice that Egyptian farmers do not like. Thus, they refuse to cultivate rice for taste preference reasons. A second reason is the lack of information about availability of such varieties. This behavior is also provoked by the accessibility to the inexpensive (almost free) irrigation water. Here we should consider another determinant of the farmers’ behavior that of awareness.

A national survey was carried out in 1998 intended to identify the farmer’s awareness, attitudes and practices concerning the water resource management. The study shows that about 61% of male and 29% of female farmers know that the available water resources in the country are fixed. The “Inexhaustible resource” perspective mentioned above is widely spread throughout the country. Only 21% of the farmers consider the scarcity problem that can emerge in the future as serious, whilst 23.6% do not see the problem at all. 57% of the farmers hold the hopes that larger water quota is negotiable. The response of the farmers differ significantly according to the education levels, pointing to higher awareness of the problem among higher-educated respondents. The low awareness can be explained with the low literacy level (53.1%) in the rural community (HDR, 2003), and the poor accessibility to the information.

Awareness about water preservation measures is low as well. Farmers are poorly informed about possibilities of how to decrease the water consumption. As the survey indicates, only 20% of male and 4% of female farmers had ideas about how to irrigate with less water, however about half of the respondents were aware of advantages of night-irrigation and almost all of the farmers use land leveling (El-Zanaty & Associates, 1998).

Quality of life

The standard of living has improved remarkably over the last 30 years due to accelerated economic growth. The main indicators of the social and human development programs and health services have made advances in life expectancy, from 55 years in 1976 to 67.1 years in 2001. Infant mortality was subjected to more than three fold reduction during the same period. The fraction of population who has access to the piped water has increased from 70.9% in 1976 to 91.3% in 2001. Almost 100% of urban households have access to sanitation facilities versus 78.2% in rural areas (HDR, 2003). However, in terms of access to piped water and sanitation, there is a great disparity between the regions behind the average figures. For example, in some provinces only 79.6% of the population are supplied with piped water and 18.6% do not have access to sanitation. These figures are among the lowest in the country leaving room for further improvements in life quality.

Improvements can impose additional constraints to the water supply in Egypt boost up the water consumption levels. Advancements in standards of living together with population growth have already been reflected in the expansion of water consumption levels for domestic use. Water consumption rose from 3.1 BCM[8] in 1990 (Abu-Zeid, 1991) to 5.23 BCM in 2000 (FAO Aquastate). Further augmentation of the life quality and the population growth will push up water demands up even further.

Physical variables

Physical variables include water resources and agricultural land. The Nile River is the main water resource in Egypt, the most fertile agricultural land lay on the banks alongside the Nile mainstream flow from the south to the north of Cairo where the diverge into two main branches formulate the Delta.

The Nile River provides more than 96 percent of all fresh water resources (UN CCA, 2001). The Nile originates from outside of the country boundaries and pass through nine countries. Among them Egypt, Sudan and Ethiopia are the main users. The international treaty of 1929 between "the Nile basin countries" has determined the quota of each country. The treaty entitled Egypt to 55.5 billion cubic meters (BCM) of Nile water annually and allotted 18,5 BCM to Sudan (Abu-Zeid, 1991).

The current water demand in Egypt is estimated at 67.47 BCM per year, where 55.5 BCM of this quantity is provided from the Nile. Therefore the Nile becomes the almost exclusive source of water for the country. The rest of the water demand is met by: the renewable groundwater (4.8 BCM), the drainage water reuse (4.5 BCM), and the treated municipal (0.7 BCM) and industrial wastewater (6.5 BCM) which returns to the closed system. About 3 BCM out of the 55.5 BCM is lost in the surface evaporation and the irrigation system network (MOWRI, 2002a). Water demand is expected to rise up to 87.9 BCM by the year 2017. It has been planned to meet the rapid growth of water demand "partly" from additional water resources that can be obtained from nonrenewable groundwater aquifers in Sinai and the Eastern and Western deserts (UN CCA, 2001).

Table 1 indicates the present and the projected water resources. The water balance for year 2017 can meet the demand if the Irrigation Improvement Plan, drainage water reuse, and treated wastewater reuse achieve the target figures. The objectives provoke some consideration regarding its feasibility. In particular, the prolonged conflict concerning the Jonglei project in Sudan, and the drainage water reuse (4.7 BCM in 1990) which should reach to 7.00 BCM in year 2000 (according to the study of Adly Bishay). Unfortunately the figure has remained almost the same since that time.

Table 1: Present and projected water resources in BCM based on CCA materials

Source	**2001**	**2017**
The Nile	52.5*	55.5**
Renewable ground water	4.8	7.5
Agricultural drainage water	4.5	8.4
Treated domestic waste water	0.7	2.5
Treated industrial waste water	6.7	6.7
Desert aquifers	0.57	3.77
Rainfall and flush harvesting	-	1.5
Saving from management	-	1.5
Total	69.77	87.37

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[8] BCM stands for Billiom Cubic Meter.

* 3 billion cubic meters of surface evaporation is subtracted.
** Including the 2 BCM possibly yield from Jonglei project. Jonglei project in Sudan intended to increase the availability of the Nile water, and reduce the evaporation from Sudan's Sudd swamps. Project has not been completed due to the conflict in the region.

Land expansion

Due to the present development of the manufacturing sector and the land reclamation projects, a considerable increment in demand is emerging in the agriculture and industry sectors. Despite the present conditions of continuous declining "per capita crop area" and "per capita crop production", the current population growth rate (2.1%) obliges the agriculture sector to provide food for a larger number of people.

The problem of "limited land resources" is not only restricted to the food security issue, but also linked to the employment issue as well. The rural area accommodate 57% of the population, 50% of them are engaged in the agricultural sector (HDR, 2003). The food demand, the habitation requirements, and the increment demand for jobs, enforce the government to adopt "horizontal land expansion" plans. The last has been considered as the available solution for generating jobs to meet the population growth problem. The Plans promise to add 3.4 million feddan of desert land to the cultivated land area (UN CCA, 2001). This means that, given the present water use practices, land expansion would place an enormous strain on water supply. The causal relationship between the described forces and variables in focus in this study are portrayed in Figure 1.

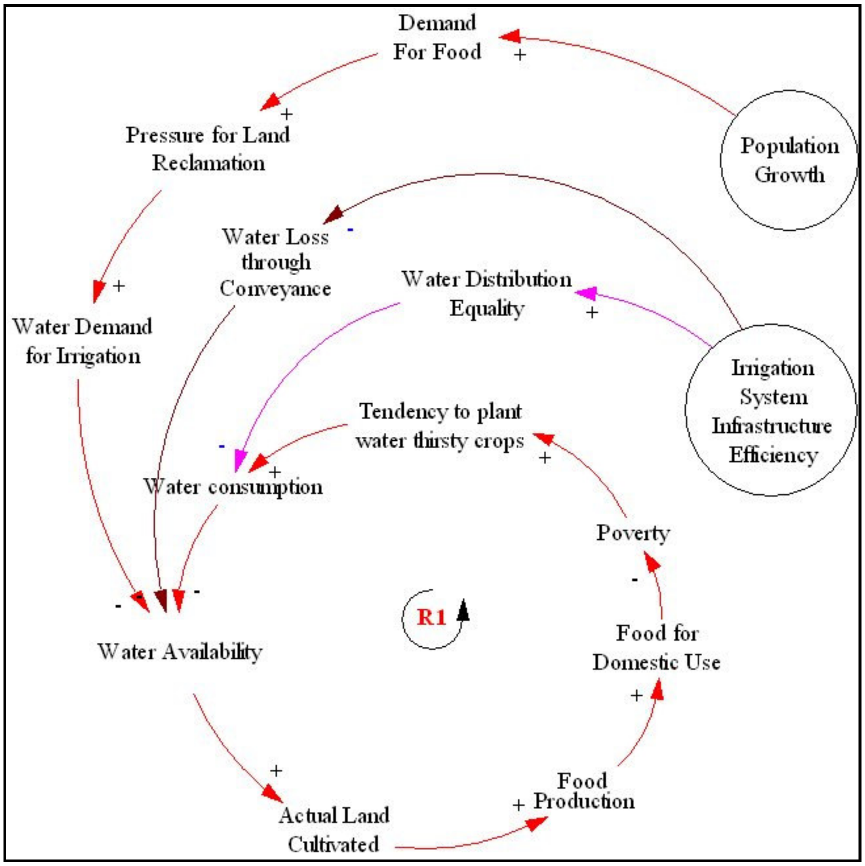

Figure 1: The population growth increases the demand for food, which put pressure to reclaim more land. Such reclamation projects raise the demand for irrigation water and exhaust the current water resources. At the same

time, the inadequacy of the present irrigation system infrastructue leads to unequal water distribution service, and large quantities of water are lost throughout conveyance process. This waste of water decreases the chances to cultivate even the present agricultural land, which suffer from land-yield deterioration, as a result, the food production slows down. This will increase the poverty, leading to inadequate cropping patterns, and inefficient farming. As a consequence, the water consumption boost adding more stresses and shortages.

Economic forces

As supplies fail to catch up with the growing demand, competition for water will intensify and the agriculture being the largest water-consuming sector might loose its existing supplies. Table 2 illustrates the present water distribution among different economic sectors.

Agriculture is the largest consumer of water resources worldwide and so it is in Egypt as well. The annual freshwater withdrawals for agriculture sector in 2001 amounted 83 percent (UN CCA, 2001). In spite of its high water consumption levels, its contribution to GDP accounts only for 16.5 percent versus to industrial and service sectors with 33.3 and 50.2 percent share in GDP respectively. As some analysts point out, agriculture can be affected by increasing water scarcity due to growing demands from other sectors. It has to compete with high value users; this in the long run would lead to the release of water from agriculture to the other sectors (Engelbert et al, 1984). The consideration about water reallocation becomes relevant taking into account the Egyptian government's support to the development of the industrial sector (MOWRI, 2002a).

Water Users	**Worldwide** (In percent)	**Egypt** (In percent)		
	1999	**1990**	**2001**	
Agriculture	65	84	83	***78***
Industry	25	7.8	10	***14***
Domestic use	10	5.2	6	***8***
Total water use in BCM	-	59.2	67.47	***68.67***

Table 2: Water allocation among the water users. (Based on the data obtained from Abu-Zeid, 1991. and UN CCA, 2001. Figures given by FAO Aquastate are indicated in italics).

The water demand for the industry sector has increased in the last 10 years from 7.8 to 10 percent (to 14 percent according to FAO), which was mainly compensated by a declining the share of other water-consuming sectors. The water demand for the domestic use has increased as well from 5.2 to 6 percent (8 percent according to FAO), whereas, during the same time, the water use in agriculture declined by one percent (6 percent according to FAO). So the impacts of intensifying competition between sectors are already becoming evident. It is important to emphasize the fact that for economic reasons the water reallocation may shift towards higher productivity use of water. This may lead to the emergence of a water scarcity condition in the agriculture sector being the low value water user. Adding the economic forces to the pervious causal loop diagram (Figure 1), the results can be seen in Figure 2.

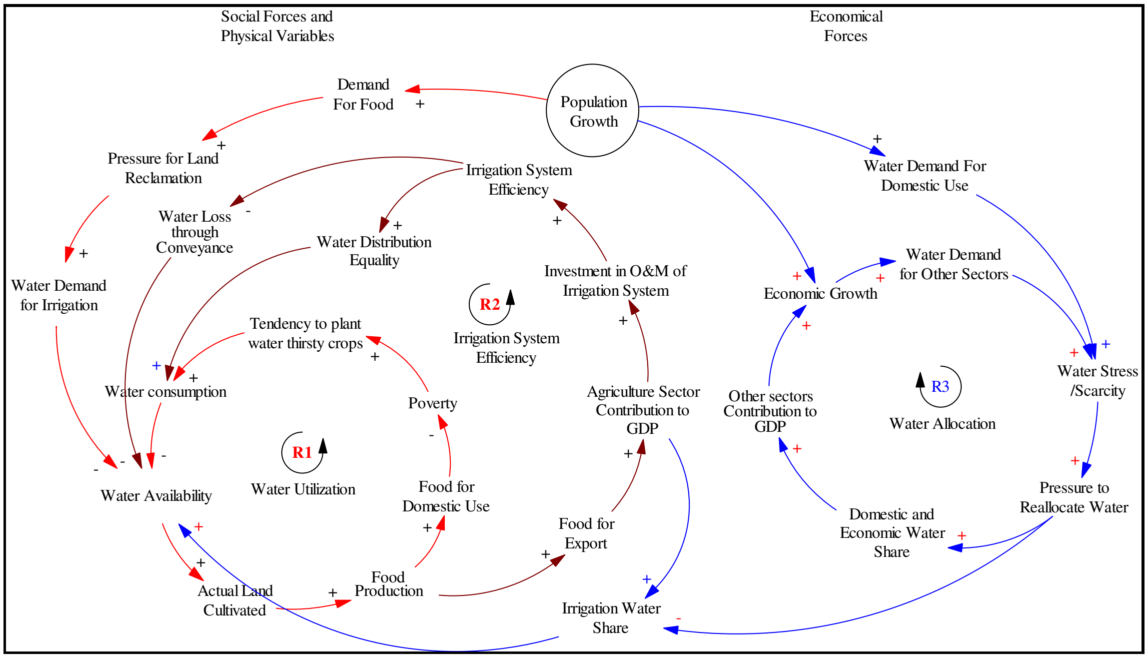

Figure 2: improving the irrigation system and water distribution services are driven from the investment in the operating and maintenance processes. The later raising the efficiency of the irrigation system and minimize the losses, providing more water for cultivation and reclamation processes. That will provide more food for export, which will help in cost-recovery and magnifying the contribution of agriculture sector to the GDP, encouraging for more investment, and above all, helping in water preservation.

Political forces

Although water is a critical component for development in Egypt, the limited water resources are not treated as a scarce commodity. On the contrary, the government is heavily subsidizing it. That unintentionally promotes wasteful practices and hinders the emergence of rational use of resources (Ahmad, 2000). "Subsidy" Issue involves many factors and its removal would have a wide spread effects on the whole society. The interactions of subsidy-attached variables are shown in figure 3. The main reason behind the irrigation subsidies lay in the social and economic objectives the government is aiming at: to provide the water for farmers regardless of their disparate income levels (Johansson, et al., 2002). It has been used to promote growth in agriculture and other sectors of the economy as well (Rogers, et al, 2002).

The subsidies in the irrigation sector have aimed at sustaining the agriculture economy, ensuring the self-sufficiency of farmers. Almost free accessibility to the irrigation service boosted water demands and discouraged farmers from investing in efficient technologies and carrying out water saving practices. (Postel, 1997; Rogers, et al, 2002)

Different sources give diverse information about the price for irrigation water delivery. Postel (1997), Wickelns (1998), Ahmad (2000) stated that the provision of water in irrigation canals is free of charge, whereas the representatives of NGOs operating in some provinces indicate that farmers are charged for irrigation service through land tax. However, from my experience, the land tax is 20 LE per feddan per year with an exception of new lands, which are not subjected to land tax whereas the annual investment budget for operation and maintenance of the irrigation and drainage system (including main canal system/distribution works) amounts to 100 LE per feddan/year (MOWRI, 2002b). The figures give evidence that water and irrigation service is extremely subsidized regardless of the operating costs.

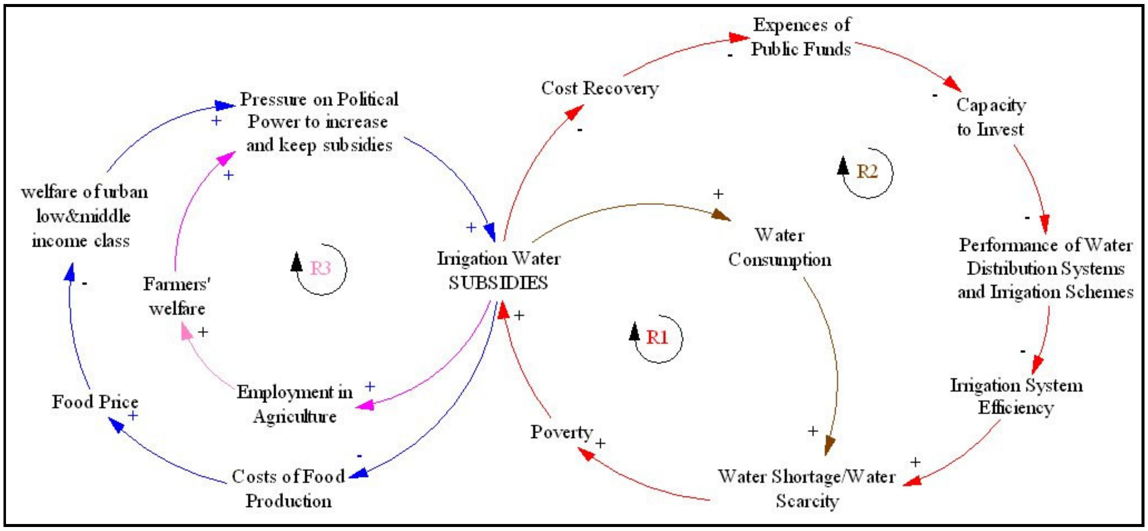

Figure 3: subsidies means to grant water for free. That strengthens the present political power, which aims to provide more employment in agriculture and improving farmers' welfare. The higher is income the more are farmers satisfied which facilitates to retaining the present political power. From subsidy benefit the urban low and middle-income classes as well, as the last are provided with cheap food. However, on the other hand the higher are subsidies the lower is cost recovery and less is expense of the public funds. Therefore the capacity to invest is lower. It negatively affects the performance of irrigation system and decrease it's efficiency. Low efficiency has negative contribution in emerging water stress/scarcity conditions. The subsidies also promote water intensive crops, which aggravate the water scarcity problems even more. Scarcity leads to the lowering the incomes and poverty. The higher is the poverty the more is need for subsidies. The relations here are negatively reinforcing.

The main justification behind the subsidiary reasons pointed out by the government officials and NGO's representatives was the *affordability* (Malashkhia 2003). However, the affordability is not the single driving force for the government policy. There are other social benefits of irrigation water subsidy. From a food security viewpoint, irrigation subsidies hold absolute explicit significance since food production is completely dependant on irrigation. Produced food is cheep enough to benefit the urban poor and middle class. (El-Quosy, 2003).

Employment and income increment are other positive social benefits. Through affordability of irrigation water, agriculture employ 50% of labor force in rural Egypt (HDR, 2003) and prevents rural households from being pushed out of agriculture into cities that cannot provide shelter, jobs and food for millions. Thus, the subsidies on irrigation avert cities from increasing poverty, crime and social unrest that can lead to political instability. As Young (1992) notes, farmer serves as an instrument of public policy "the farmers and the public are in food producing and employment creating partnership and the government's (taxpayer's) part of the bargain is to provide the water." Here one can assume that the retaining the power is part of the bargain as well. There is very little determination for cost recovery (Young, 1992) and concerns regarding the farmers' welfare might be not the only reason behind the low political will. Removal of subsidies becomes politically infeasible for the political elite as it might threaten with change in the political power and stability.

There are other aspects of subsidy that, in the long run, will result in harmful effects on the environment, the economy and the society. "Water free" conditions contribute to the rising demand against the limited supply options and therefore are considered to be one of the driving forces of water scarcity (Meyers & Kent, 1999. Rogers, et al., 2002). As discussed in the paragraph on social forces, some wasteful practices and growing of high water demanding crops are deeply rooted not only in income levels or behavior as such but are fed by the subsidy. A “free” resource sends misleading signals and serves as an incentive to grow water inefficient crops and overuse the water imposing water scarcity conditions to future generations. Moreover, this also gives the rise to negative environmental effects such as drainage problems, water logging, declining groundwater tables, and salinization (Sur, et al., 2002).

There is need for investments in improving the maintenance of irrigation schemes. Because of very low cost recovery, the main source for the operation and maintenance (O&M) is the public fund placing on it additional pressure and diverting the financial sources from other social or human development programs that might have a higher priority if the agriculture would fully recover its costs. Tight public funds do not allow carrying out improvement plans, resulting in further deterioration of the system. This leads to lower efficiency rates and to fostering the water shortages. The last has direct negative impact on the farmer’s welfare. The relations are illustrated in figure 3 and show the negative reinforcing character of subsidies on farmers’ welfare in the long run imposing the problems if not only to the present generation but to the future generations as well.

Water Preservation Policies

Based on the causal relationships that have been identified from analyzing the problem, a system dynamic simulation model was developed using the PowerSim software. The model consisted of four modules where each module portrayed one of the following sectors:

The population sector containing the urban population, the rural population, and the labor force.
The agricultural land sector: including the old agriculture land, the reclamation process, the investment in agriculture, and the agriculture contribution to GDP.
The water sector: representing the water supply/demand, and the irrigation system.
The food sector: including the food production process and the land yield/fertility.

Running the model through sensitivity analysis revealed that the model is most sensitive to the water sector. Water is essential to cultivate land, which in turn yields food that is vital for the life of the population. As Roger Norton stated: “water is the font of life… irrigation has been the font of civilization.” Thus the emphasis should be on that sector and since the water resource is predetermined, the emphasis would be on the water conveyance and utilization process, in plain text, on the structure of the irrigation system.

Scarcity, by definition, is a function of demand and supply. Water preservation strategies work on either the demand side or the supply side. The demand side encompasses policies such as cropping patterns and water pricing, whereas policies like water allocation, water release, and improving the irrigation system efficiency come under the supply side. From a broader perspective, the concept of demand management implies that any increase in a specific sector demand must be met with an equivalent reduction in other sectors (industry and domestic). From an agricultural viewpoint, as indicated above, subsidies of irrigation have contributed to the emergence of water scarcity conditions. Free resources send a misleading message about abundance of water to the water-users. The illusion of affluent resources finds its confirmation in a high fraction of farmers (43 percent) who simply do not know whether there is likely to be a problem with sufficient water supplies in the future (El-Zanaty, 1998).

Although, in the long term, there is little doubt that attention needs to be focused on demand management strategies, there is sufficient evidence to indicate that significant savings can be made by improvements in the control and management of existing irrigation supplies. Thus, we will start by explaining the policies that can be applied on the supply side, and then address the other policies in the demand side.

Improving the efficiency of the present irrigation system

From supply side, most studies focus on ***efficiency***. The irrigation efficiency improvements are seen as an effective tool for increasing the water supply sources. "Increasing the *efficiency* of the irrigation system has two different meanings. Technically, it refers to the reduction of water losses (at each level of the irrigation system). In a broader sense, it refers to increasing net economic returns for the system users, taking full account of externalities."(Norton 2003).

Efficiency can be carried out through irrigation improvement plans and better land management. Externalities include a wider set of factors that comes into play. Therefore, the concept of efficiency can be only viewed in its broad meaning which entails the technical and environmental efficiency aspects and water reuse as well. First, we discuss the limitation of the efficiency definition applied to Egypt; later on the constraints that accompany implementation of preservation measures will be identified with regard to their social and economical impacts. Although environmental impacts are beyond this study, we will mention them briefly.

The simple scheme of irrigation in Egypt can be visualized in the following way: Water is released from the Nasser Lake reservoir (through the High Dam gates) flow to the Nile mainstream that contains barrages on certain locations, mainly on the head of the main distributor canals. The water from the mainstream flows into the main canals. The irrigation canals enrich their water flow with water extracted from aquifer and groundwater, drainage water and discharge from industrial and domestic users. From the main canal water is delivered to the farms passing the secondary canals and water distribution system, which itself, consists of tertiary canals and mesqa[9], see figure 4 (Holmen, 1991; Tiwari & Dinar 2002). A part of the water carried by irrigation schemes is lost to seepage and percolation as a result of the poor technical condition of the distribution system and topography. Some water evaporates during conveyance.

After transmission, water is applied on the fields. Plants for crop production consume part of it, another fraction ends up in the drainage network and the third is lost to seepage. Thus taking into consideration the structure of water distribution scheme, the water use efficiency can be split into conveyance (or distribution) and application efficiency. Whereas the conveyance efficiency points to the ratio "between water storage facilities and delivery systems at farm level"(Martinez, 1994), and the application efficiency refers to the water use at the farm level (Tiwari & Dinar, 2002).

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[9] Mesqa - name for irrigation ditches.

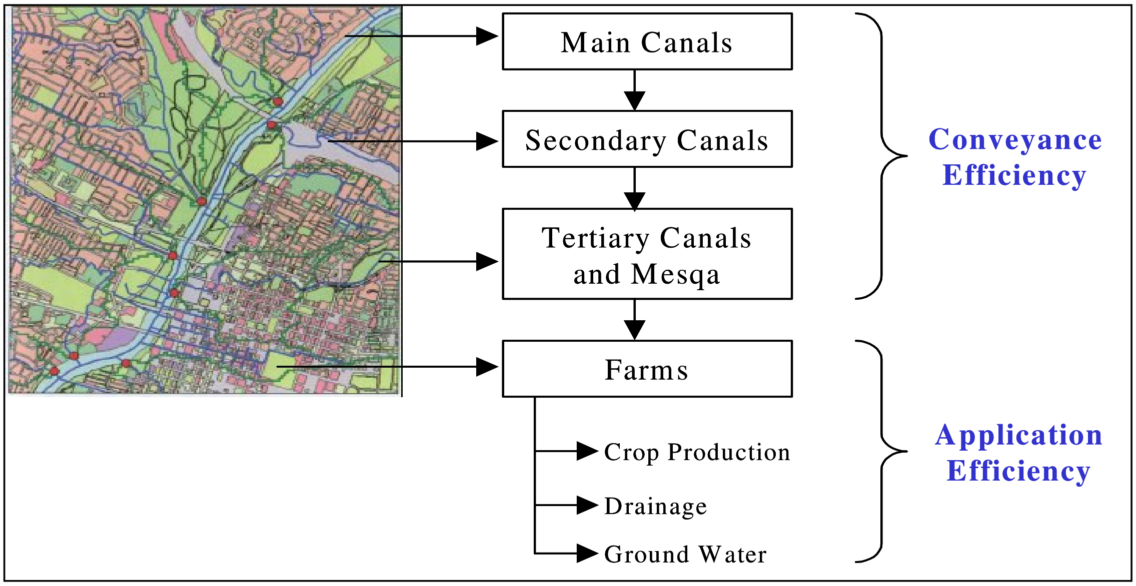

Figure 4: Irrigation water distribution scheme (based on Tiwari & Dinar, 2002)

The *worldwide* figures for the (overall) efficiency of the surface irrigation are estimated at 37-50 percent (Carruthers, et al.1997; Tiwari & Dinar, 2002). Conveyance efficiency is around 60 percent (Martinez, P. 1994), application efficiency accounts 40 percent for traditional methods of irrigation, and 60 - 70 percent for advanced systems show high performance with efficiency (Martinez, 1994; Myers & Kent, 1997).

In Egypt, the average leakage during conveyance is 25 percent between the main canals and the outlets, and 11 percent from the outlets to the fields (Tiwari & Dinar, 2002). About 10 billion cubic meters are lost in canals (Imam, 2003). These figures indicate poor performance of distribution systems, brings us to the suggestion that improvements in efficiency rates leave a significant potential for water preservation. However, the data obtained from the field (to calibrate our model) show a scene, which is completely different.

Irrigation efficiency figures in Egypt seem surprisingly high, taking into account the fact that the most common method used in farms is the surface flood irrigation. According to the information obtained from MOWRI the average (overall) efficiency rate of irrigation system is around 75%, which makes it highest in the world. Much the same applies to the conveyance and application efficiency. The conveyance efficiency on the old lands is 70% and on new lands it reaches 80%. Application efficiency rates are higher – 80% and 90% on the old land and the new land respectively. Keller (1992) argues the same. He points out the fact that efficiency rates in Egypt are considerably high (89%). These high efficiency levels create much confusion taking into account the *worldwide* irrigation efficiency rates.

The significant difference between the *worldwide* average and the country figures can be explained by the different methods applied to calculate the efficiency rates (Nino 2003).

The first method, which refers to the ratio between the amount of water discharged at the root zone (used by plant) and the amount of water delivered, produces low irrigation efficiency rates (Tiwari & Dinar, 2002).

The second method, which considers the natural water-recycling factor in its equations, produces higher efficiency rates. This method, which is drawn from the so-called "IWRI paradigm"[10]- claims that water lost to seepage and percolation during conveyance and application cannot be considered as loss. Water diverted from the reservoir and other sources is partly evaporates. Some fraction of water is taken up by plants and used for evapotranspiration. The other fraction of water is lost to seepage from canals and fields. This fraction percolates to the deep aquifers and groundwater where recaptured and recharge the ground water and aquifers. Thus, the lost water is reused as additional source of supply later on, obtaining it from wells or aquifers. The drained water, which is collected in drains, is returned into the irrigation system as well. So the water can be returned to the system again and go through the same cycle until almost all of the water is consumed. (Keller, 1992; Perry, 1999) Therefore the efficiency rates still go high despite the great losses during the conveyance and field application.

The calculations of efficiency suggested by IWRI, which include the natural recycling factor, lead to very controversial conclusions. In fact it diminishes the importance of efficiency improvement measures. So the study of Keller concludes that due to high irrigation efficiency rates in Egypt, the potential for improving the system performance from a physical water use efficiency standpoint is limited. So does Seckler in his article (1992) when stating " The benefits of investing in on-farm efficiency in such systems are substantially reduced by system wide effects, perhaps even to zero".

The logic of the paradigm is convincing unless we do not pay any attention to the deterioration of water quality that accompanies each cycle of reuse. Going through the continuous recycling phase water picks up considerable amounts of salt from the soil, saline sinks, fertilizers, and pesticides (Keller 1992). The reused water quality becomes so deteriorated that it is questionable whether water can be used for irrigation or not (Martinez, P. 1994). The issue of water quality will be discussed in the discussion part later on. Here we just want to emphasize the fact that estimate offered by the "IWRI Paradigm" leaves out such important factor as an environmental efficiency[11].

As mentioned earlier, the concept of efficiency could be only viewed in its broad meaning that entails the *technical* and *environmental* efficiency aspects and water reuse as well. It seems more appropriate to save water trough increasing *technical* efficiency of irrigation system so the high quality fresh irrigation water from river is not lost. Here we suggest (in application efficiency on-farm level) converting "gradually" from the surface flood irrigation methods to the modern irrigation methods like low-pressure sprinklers and/or drip-emitters systems (with 90% efficiency for both systems). The funds to build modern irrigation system (to replace the old one) may be provided form subsidies budgets. The government (MOWRI)[12] may use part of the O&M funds for this purpose. The benefits, in short term they will save water, and in long term they will leave up subsidies and increase the agricultural capital (in terms of advanced irrigation system network).

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[10] IWRI – stands for International Water Resources Institute. The Paradigm was based on studies of Keller. D and Willardson, L.S.

[11] The paradigm has some other objections as well (Tate, 1994): Brooks questions the assumption of natural recycling. He finds that the idea about effective natural recycling must be proven and cannot be just assumed. Another point is considerably inefficient use of capital, as the less efficient on-farm consumption needs larger supply and effluent facilities.

[12] MOWRI stands for Ministry of Water Resources and Irrigation.

Unfortunately it is impossible to carry out further studies in limited time to study the feasibility of this proposal. However, technical and environmental efficiency must be considered together in order to draw picture closed to reality and consider all side effects.

The adjustment of water supply to match the actual water demand.

The flood season starts usually in July when water rush from the Ethiopian highlands. The floodgates of the High Dam are left open[13], as well as the main barrages. By the first of December, the muddy flow (caused by the rainy season in Ethiopia) is practically ceased, and the Nile is now dependent in the main continuous flow from the region of Lake Victoria through the White Nile. The floodgates are closed to accumulate water behind the Dam. The sluices are closed gradually in order to allow the sufficient water for irrigation to escape. Ordinarily the dam is filled to capacity by the first of March. The river may be so low by April that it is necessary to supplement its flow with storage water from Nasser Lake. From this time until the flood season in June, (sometimes later), irrigation is carried on largely with dammed-up water.[14]

The Egyptian agricultural year is divided into three seasons; Summer from April 1st to August 1st; the Flood Season from August 1st to December 1st; and winter from December 1st to April 1st. The chief crops of the summer are corn, cotton, sugarcane, and rice. Corn and rice are cultivated in the flood season too. Wheat, barley, beans, and clover are the most important winter crops. Winter has formerly been the principal agricultural season, following the rise of the Nile as it did before building the High Dam. But under perennial irrigation, crops can be grown all the year round. It must be remembered that the seasons sometimes overlap; crops are frequently sown before those of the previous season are harvested. In this way, about one-half of the Delta is made to produce two crops a year. Some soil is made to yield three crops annually, if carefully selected crops are planted.

The flood cycle fall into the supply side while the agriculture seasons cycle fall into the demand side. The two cycles are - to large extent - correlated and there is a lag shift between them. In fact, the agricultural cycle is depending on the flood cycle. Any slight disturbance in the flood inflow will result in a magnified disturbance in the agricultural rotation. In other words, farmers would not be able to cultivate land if the water inflow is ceased, or they may miss the opportunity to cultivate the desirable crops if water inflow delayed, enforcing them to plant alternative crops. This mandatory shift in the cropping pattern fluctuates the water demand.

Based upon cropping patterns submitted by MOA, the national irrigation demands (the “normal” water demand in the model) are calculated by the MOWRI, who set the correspond schedules for water release (water supply). However, regarding the cropping pattern plans prepared by MOA, the process by which the data is gathered at the cooperative level can lead to significant over-estimates of cultivated land area and inaccuracies in cropping patterns.

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13 Floodgates are left open for the double purpose of keeping the reservoir free from silt and allowing the sediment to enrich the lower country land, as it has done for centuries.

[14] It is estimated that a flow of 905 cubic meters of water per second throughout the year is necessary to provide perennial irrigation. Since the river supplies a constant flow of only 226.4 cubic meters per second, while the flood flow of from 8490 to 14150 cubic meters per second, the High Dam making up the deficiency in constant flow by storing a surplus in flood season.

Evasion of regulations concerning land use is commonplace, particularly in the transferal of agricultural land to residential use, and it is estimated that arable land area may be over-estimated by up to five percent (Radwan, 1997).

In addition to the overestimation of available land, MOA makes only a general overall recording of farmers' cropping patterns, covers only the principal crops (maize, wheat, clover, cotton). The minor vegetable crops were not recorded, nor the short season *corn fodder* crop grown from October to December. This imprecision is a legacy of the enforced quota system which, has led farmers to supply inaccurate data about their cropping patterns and encouraged cooperative officials to concentrate on recording areas for only a narrow range of specified crops. Such inaccuracies give rise to important variations between the actual and officially calculated crop water requirements. This is most significant, for example, for the *corn fodder*. If official calculations were to be applied precisely, there would be a deficit during that period (from October to December) of 22% of the water requirements. Furthermore, the use of regional cropping patterns, as a basis for deciding water requirements, ignores requirements caused by the canal/mesqa level variations. Finally, it was noted that the optimal planting and harvesting dates were assumed to be valid across the various regions, yet observations in the field indicated that farmers' actual planting and harvesting dates would often be delayed or put forward up to one month as a result of various localized factors.

Lutfi Radwan 1998 studied the water flow patterns along the ditches and the main distributor canal in the Monofia province (in the Delta center)[15]. Measurements of flows indicated that the inflows to the majority of ditches were above the demand during the whole year (see figure 5).

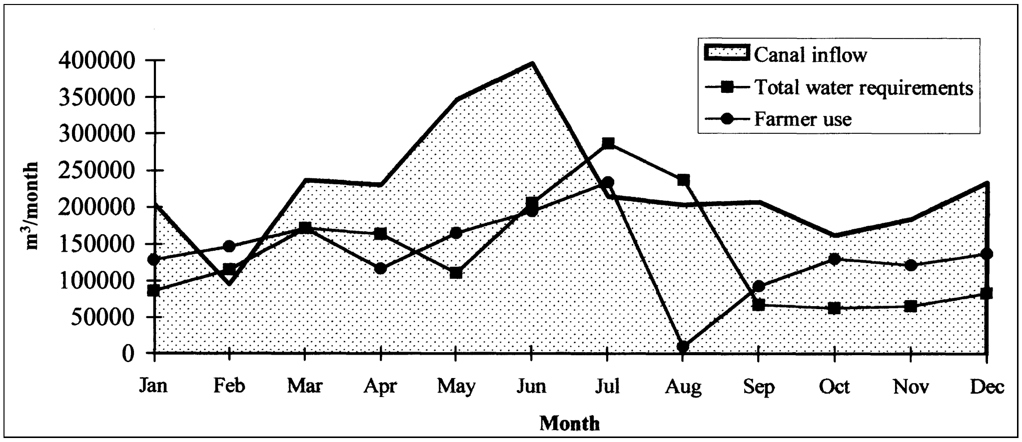

Figure 5: Total water requirements, farmer use and canal inflow at Um Aisha Mesqa.
Source: Lutfi Radwan 1998.

He compared the actual inflow into one mesqa (Um Aisha) to observed farmer use patterns and both were contrasted with: 1) the total water requirements calculated from local data of cropping patterns, 2) planting/harvesting dates and conveyance efficiency. He found that whilst farmer use patterns exhibited a high degree of correlation with estimated total water requirements, the actual releases into the canal were 64% higher than total water requirements for this period (including all conveyance requirements). He concluded that this pattern of over-supply was largely the result of the mismatch between the supply and demand, and there is a need to ensure that sufficient water is available when farmers need to irrigate.

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[15] Monofia province is one province out of 12 provinces in Delta region.

The irrigation department officials defend such behavior (over-supply patterns) by claiming that individual farmers at the head of the canal are over-using and wasting water. Therefore, additional water is supplied to ensure that sufficient water reaches farmers located further along the canal (tail-enders). In reality, field observation have indicated that this argument could not be applied to most of the ditches where tail-end water levels were generally high and few tail-enders mentioned any serious occurrences of shortage.

Most of the discrepancies between supply and demand are a result of the variance between the officially estimated cropping patterns, planting/harvesting dates, and those actually observed. Briefly, the origin of the problem lays in the *lack of integration* between the MOWRI -administered rigid patterns of supply and the informal farmer patterns of demand.

Throughout the simulation, we found out that if supply patterns more closely matched the demand patterns, canal levels would be constant. It would then be possible to obtain a reduction in total inflow and the surplus wastage could be reduced. However, it is unlikely that demand patterns be greatly modified and the change must, therefore, occur in the supply pattern. The reason for that is: it would be difficult to impose a rigid structure of patterns of demand as these are variable in response to a wide range of social, physical and other influences. Planting and harvesting dates can be delayed or brought forward for any number of reasons and similarly rotational and daily irrigation patterns will be affected by a variety of factors. It is necessary, therefore, that the supply patterns be in some way modified to match more closely the demand pattern. This is only likely to be effective if farmers are involved in defining the agricultural water requirements.

Cropping Pattern Policy

Historically, the single most important change in the cropping pattern in Egypt's modern history was caused by the introduction of cotton during the reign of Muhammad Ali (1805-1849), because it led to the transformation of irrigation methods. Cotton requires a good deal of water in summer when the Nile water is low, and it must be harvested before the flood season. This necessitated the regulation of the Nile flow and brought about a shift from basin (flood) to perennial (roughly, on demand) irrigation. Perennial irrigation not only made cotton growing possible, it also permitted double and even triple cropping on most of the arable land. Furthermore, it enabled farmers to switch the crop cycle from a three- to a two-year cycle. The original three-year cycle included clover and cotton in the first year, beans and fallow in the second, and wheat or barley and corn in the third. The two-year rotation consisted of clover or fallow followed by cotton, and the second year, crops of wheat or barley and beans followed by clover and corn. By 1890 about 40 percent of the land was put on a two-year rotation. The biennial rotation was believed to be harsh on the land, and the government tried to eliminate it in 1950s. In 1990 farmers resorted to both rotations flexibly.

The model simulation exhibit significant change in the water demand when we assigned different crops for agriculture lands. That inspired questions like: What will happen if we concentrate the cultivation of a certain crop (wheat for example) in one region. Is there optimum cropping pattern that achieve 1) the ultimate utilization for irrigation water and agricultural land, 2) high profitability for farmers' welfare and country economy.

M. Saleh and Bayoumi 2004 have conducted a remarkable study. They stated that the current cropping pattern is not economically efficient in the utilization of the available water resources and major improvements should be done. They suggested a targeted agriculture policy to achieve the best economic utilization of water resources. They built an "optimization model" to find the optimal cropping pattern in Egypt, which maximizes the net income return per cubic meter. Their results can be seen in table 3.

Table 3: ***Optimal Results of the FPP (thousand feddans)***
Source: M. Saleh and Bayoumi M. 2004

	Crop	**Land planted** in year 2002	**Optimal Land indicated**	
			Local Scenario	International Scenario
1	Wheat	2450	2869.4	2400
2	Barley	79	72	72
3	Broad bean	303	165	165
4	Chickpeas	17	11	11
5	Fenugreek	16	3	20
6	Lupine	9	6	6
7	Lentil	5	4	4
8	Sugar beet	300	300	300
9	Winter clover	1960	2000	1800
10	Flax	21	21	21
11	Winter onion	64	25	80
12	Garlic	21	30	30
13	Winter tomatoes	173	173	173
14	Winter potatoes	77	77	77
15	Maize	2078	2078	2078
16	Sorghum	382	251	251
17	Rice	1340	811	811
18	Peanut	151	78	82.957
19	Sesame	68	52	52
20	Soya bean	13	9	9
21	Summer onion	24	15	30
22	Sunflower	46	32	32
23	Summer potatoes	113	130	130
24	Summer tomatoes	273	300	300
25	Cotton	731	600	600
26	Sugarcane	312	222	222
27	Summer clover	44	50	17

The proposed improvements would save around 4.2 BCM of irrigation water. However the net agriculture income would decrease by 100 million pounds. Nevertheless, the 4.2 BCM water saved can be used to cultivate new reclaimed land, which in turn will generate an additional agriculture income. This newly reclaimed land can be planted by wheat in the winter season and by maize in the summer season (M. Saleh and Bayoumi 2004).

Despite the significant results of this study, it does not consider the geographical distribution of the crops, which is affected by many factors such as the land availability in different zones, the local climate variation between north and south, land fragmentation, and soil quality and fertility in different regions.

The Nile banks in the south range between 4-18 kilometers span and surrounded by plateaus and mountains unlike Delta land, which widely open, flat and have no barriers for expansion. The climatic differences between north and south have some impact on the geographical distribution of crops. For example, humidity in the Delta suits long-staple cotton. The drier, hotter climate of the south favors the planting of sugarcane, onions, and lentils.

Cropping patterns and crop yields differ depending on the farm size. It is difficult to describe farming patterns in more detail, however, because the scarce information available is inconclusive and sometimes contradictory. A survey of three Delta villages in 1984 found that farmers who cultivated one *feddan* or less were more likely to grow cotton than those with holdings greater than ten *feddans*, a conclusion that contradicted findings of an earlier study. It also revealed that yield levels of different-sized farms varied by crop. For instance, wheat yields were higher on small farms, while the opposite was true for rice. The reasons were not clear, and the findings contradicted a large body of evidence from other countries that showed yields were invariably greater on small farms. There was agreement, however, that larger farms produced proportionally more fruit crops, probably because the high capital investment and the long-term commitment required would be prohibitive to small farmers, who needed more flexibility.

Yet, the study is still valuable and may be feasible if it considers the geographical distribution of the crops.

Water pricing policy

The irrigation water pricing is one of the widely recognized measures for demand regulation. The main objective of the water pricing policy is maximizing efficient allocation of water resources, promote conservation but at the same time it should not compromise the social objectives such as affordability of water resources (Rogers, et al., 2002).

According to Rogers, the full price of water consists of operation & maintenance cost together with capital charges, adding economic and environmental externalities. Different methods have been used for pricing, which can be placed in four major categories: volumetric pricing, non-volumetric pricing (based on land size or crop cultivated on land), quotas, and water markets (Johansson, et al., 2002). During the fieldwork, I have focused on the first two pricing mechanisms leaving out the quota and market considerations.

Ahmad, 2000; Bazza & Ahmad, 2003; Massarutto, 2003 argued that charging farmers for water, would induce incentives for eliminating wasteful irrigation practices and alter the cropping patterns, shifting it towards crops that consume less water but have high values.

In view of the water scarcity threats in Egypt, limited and almost exhausted sources for supply and heavily subsidized irrigation service begs the question why this economic instrument has not been implemented in country?

Water pricing has many constraints. First of all it is the cultural perception, believes sanctioned by religion and tradition, which perceive water not as commodity but one of the basic human needs. Thus the perception of water as a non-commodity resource averts the introduction of charging for irrigation services (Abu Zeid, 1998; Rogers, et al., 2002).

Water pricing was unacceptable for Egyptian reality in most of the interviews that were conducted during the fieldwork. The representatives of MOWRI, Ministry of Social Affairs, and farmers confronted the idea of imposing the irrigation service charge due to affordability reasons. However, there were some respondents who do recognize the significance of water pricing policy for valuing water, to convey the main massage to the users regarding the water scarcity problem, and to reduce the burden of subsides.

Rogers, et al., 2002 argued that water pricing policy as an effective measure for water conservation provokes some doubts, as the practice (in various countries) does not confirm emergence of water saving habits among farmers if the prices fixed per hectares. In this situation the cost for maintenance and operation might be recovered but the main target of water saving is not achieved, as farmer does not have the motivation for optimizing the water use. Only high prices would result in substantial water saving levels but will compromise the social welfare of user groups.

From personal point of view, high charges for water will increase farmer's expenses and negatively affect their income levels. This makes farmers more vulnerable as their affordability is decreasing. This means that farmer has to reduce the water consumption.

Decreased water application leads to lower yields and further worsening the farmer's income status as net-returns is dropping down. This is a reinforcing loop. Poor yields limit the ability for proper farm management, this leads to abandon the agriculture and immigrate to the cities with hope for better life. Overpopulated cities cannot bear large numbers of immigrants from rural areas and will cause problems, which would have negative consequences for national interests.

Declining water consumption levels enhanced by imposed user change will negatively contribute in emerging soil salinity problems, which has harmful effects on yield and farmer's income as well. Under such conditions the gloomy scene perspective make the water pricing policy unacceptable for the negative social implications.

Discussion

Considering the analysis and policies suggested above, we recommend applying the policies described in the following order: first applying the appropriate cropping pattern that achieves the best economic utilization of water. The appropriate cropping pattern will lead to more accurate determination for irrigation water demand. Second, adjusting the supply to more closely match the demand will save large amount of water. Then, converting –gradually- the old irrigation methods (surface flood) to modern irrigation systems will increase the water availability that can be employed to cultivate (reclaiming) more land. Water pricing policy is not an option that can be applied in Egypt since imposing the water charges at this stage might face inevitable problems.

GIS and SD meet in a new paradigm

System dynamics approach has been employed to analyze and understand the water scarcity problem. Irrigation system (the physical structure) is one of the basic components playing a significant role in establishing the water stress/scarcity conditions. This physical structure, which include canals, channels, drainage network, barrages, control-gates, and various irrigation structures, is spatially distributed. It covers hundreds of square miles, and span over broad geographical regions each of them characterized by different topology and hydrology system. Therefore, to deal with these components (their location, surrounding, and spatial relationships), we need a distinctive information system that is designed to work with data referenced by spatial or geographic coordinates. We need the geographical information system (GIS) that includes both the database system with specific capabilities for spatially referenced data, as well as the set of operations for analyzing this data.

From a broader view, GIS may be used to capture, analyse, and display spatial data, while the SD models provide the tools for complex and dynamic analysis. Input for spatially distributed models, as well as their output, can be treated as a map overlays and topical maps (Fedra, 1994). The familiar format of maps not only would support the understanding of model results, but also will provide a convenient graphic user interface (GUI) to the spatially referenced data, and to the simulation models.

From a GIS perspective, the irrigation system (for example) is represented by a way of linear, point, and polygon features. Utilizing ArcGIS 8.3 software (combined with Arc Hydro and Spatial Analyst tools), enables us to develop the adequate themes such as: irrigation network (polylines theme), control-gates, barrages, and irrigation structures (point theme), water bodies such as lakes and reservoirs (polygon theme), and agriculture lands and farms (polygon theme). The question here is how to link these themes to the simulation model. One of the potential methods to tightly couple them is object orientation programming. The VBA programming language embedded in ArcGIS enables us to create the necessary objects and feature classes, in order to link them to the simulation model.

Object-oriented programming became a standard in the software engineering industry during the 1990s, typified by the Microsoft Office suite of products. Objects from one application can be copied and used in another. This is possible because the Microsoft Office objects are built using a protocol called the Component Object Model (COM), which specifies how objects should interact with one another, thus enabling a Microsoft Excel table object to behave appropriately when inserted into an application environment different than the one in which it was created.

Visual Basic is the programming language used to build the interfaces to the Microsoft Office products, and a variant of Visual Basic, called Visual Basic for Applications, is used to construct macros and application programs that customize Microsoft Excel and Access to solve particular problems beyond their native capabilities. The remarkable feature of this environment is that it allows application programs in other languages, such as FORTRAN or C, to be attached as dynamic linked libraries (DLLs). Because of this, simulation models in languages such as C and C++ can be tightly linked into the system. The ArcGIS software also uses Visual Basic as its interface language, and its objects conform to the COM protocol. This means that ArcGIS objects can be copied/linked into a simulation software like Powersim and vice versa, so that an ArcGIS map and Powersim model can be inserted/linked into a Visual Basic Application. Moreover, data developed in ArcGIS and stored in a Microsoft Access personal geodatabase can easily be viewed in other applications such as Microsoft Excel.

This has created the opportunity to define a "spatial dynamic information system," which is a synthesis of geospatial and temporal data supporting (for example) hydrologic analysis, modeling, and decision-making. This is a very exciting new concept because rather than simply applying GIS to water resources management, what is being created is the foundation for a new way of thinking about how information technology can be used to support water resources policy design. On the other hand, unlike procedural programming languages, object-oriented programming language (i.e. Visual Basic) is considered as "event driven" which means that the chain of logic followed by the program can be initiated by user-generated events, such as clicking on the screen. That gives the potential to design a graphical user interface GUI for simulation models. The most critical aspect of this design is the design of the objects themselves.

Based on the potentials and capabilities mentioned above, our intention is to design a spatial dynamics data model SDGIS. The model may include an interactive map for the Nile with GIS tools and simulation control buttons appears below the map. During the simulation, the user should be able to observe the changes simultaneously on the map. This happens within a single spatial dynamic information system so that the movement of water throughout the river and canals network can readily be traced. Moreover, since any type of time series data can be linked to any geospatial feature in Arc Hydro, it is possible within ArcGIS to construct time-sequenced maps (with time stamped) for the water flow course through the landscape.

The SDGIS model should allow the user, at any time during the simulation, to emulate the modification of the hydrologic network or water allocations. These changes may be made in several ways. Changing water distributions or withdrawals redirects water flows in the network. Altering reservoir discharges changes storages. Setting the fractional flow in any water distributor canal to zero turns off that part of the network. Changing the fractional flow from zero turns on or introduces a new part of the network. Thus, experiments with new or planned additions to the irrigation system can be made by using the controls for distribution fractions to turn on or off new structures.

During the simulation, the user may create a control gate or barrage, increase a barrage height, and specify release discharges from any reservoir in the system. The effect of these changes is to raise the respective lake (reservoir) level upstream and reduce the variability of all flows throughout the irrigation system downstream.

Conclusion

The need for integration is driven by our need to make environmental choices. GIS and System Dynamics originated in and still represent substantially different domains of expertise, yet their complementarity will benefit environmental problem solving. Three primary reasons presumably indicate the need for integration are given here:

1. Spatial representation is critical to environmental problem solving, but GIS currently lack the predictive and related analytic capabilities necessary to examine complex problems.

Water scarcity problem solving, and presumably the goal of environmental modeling and environmental applications of GIS, requires that spatial aspects of problems be examined explicitly and that solutions incorporate such knowledge. GIS currently excels in such tasks so long as it relies on its ability to map what is manifest within a largely two-dimensional universe where all things seem certain, or equally uncertain, and where change with time is not a limiting consideration. Current GIS are typically limited to analytic compromises that include: static representations of dynamic space/time processes; use of simple logical operations to explore complex relationships; and non-stochastic treatments of uncertain events. Unfortunately GIS can become the implement of very simplistic thinking and the victim of everlasting data inadequacies insofar as they do not include or cannot easily facilitate the use of numerical models, highly time-variant relationships, and robust spatial statistical functions.

SD Models, in particular, could allow GIS to function beyond the limits of a static, planar domain where complex, often nonlinear relationships can be explicitly expressed and where change and uncertainty can be addressed in a direct way. Whether models are used to diagnose or predict, it is their ability to help us understand or anticipate change in complex dynamic systems that makes them so useful. G1S are currently very limited in their ability to examine any dynamic processes unless they are "wired up" in advance by analysts having singular objectives and very good understanding of both the technical aspects of GIS and the operation of a given model. This probably presumes more knowledge than many users possess.

2. SD Modeling tools typically lack sufficiently flexible GIS like spatial analytic components and are often inaccessible to potential users less expert than their makers.
Regardless the rich visualization, GIS could offer to SD modeling, in part, a flexible environment with a standardized array of spatial operators based on mathematical principles that describe, for example, the motion, dispersion, transformation, or other meaningful properties of spatially distributed entities. Sufficient intelligence could be built into such a tool to prevent some forms of misuse by the uninformed. Such an approach offers the benefits of a potentially common analytic medium in which more comparability would be possible and through which it might be possible to improve communications among modelers working in different disciplines.

3. SD Modeling and GIS technology can both be made more robust by their linkage and co-evolution.
Despite where the new SDGIS modeling co-functionality comes to reside, in or out of the GIS or the SD software environment, the effort to combine the strengths of the associated tools will be mutually beneficial. Naturally it is impossible to foresee all such benefits, but one can speculate (with confidence) that SD Modeling, at least, would benefit by the better engagement of the visual senses in evaluating the assumptions, operations, and results of models. Doubtless many readers could recount experiences wherein the better mapping/visualization of spatial properties brought new and sometimes startling understanding to those previously confident that they fully understood a target system and methods for its analysis

It is simple enough to imagine synergy by combining the spatial representations of GIS with the predictive capabilities of SD models and adding more adequate three-dimensional and temporal representation and the abilities to characterize uncertainty and error. It is more difficult and more challenging to ask how these tools should be made to become more interdependent and interactive. It is clear that to solve pressing environmental problems we will need different tools that work together in an intelligent way and are easy to use but that can be employed in a flexible manner to handle complicated problems. These seemingly conflicting objectives will need to be harmonized in order to make rapid progress. Without starting the first step, the allure of constantly improving technologies will continue to draw both GIS and System Dynamics along behind it. Without formalization of an effort to achieve integration, only the very able and the very fortunate will be able to incorporate the benefits of SD and GIS in their work because only they will have sufficient understanding and/or resources to overcome the difficulty of coupling tools that, despite certain affinities, remain quite dissimilar.

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