RESPONSES AND THRESHOLDS OF THE EGYPTIAN ECONOMY TO CLIMATE CHANGE IMPACTS ON THE WATER RESOURCES OF THE NILE RIVER

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Abstract. Are there "thresholds" in greenhouse gas (GHG) concentrations above which associated climate change impacts become economically, socially or environmentally unacceptable? If thresholds exist, then emissions might be limited in such a way that GHG concentrations are not exceeded. Environmental, social, and economic systems should be examined in order to determine these threshold levels.

This paper addressed the potential impacts of climate change on the water resources of the Nile River and associated impacts on the Egyptian economy through the use of a recursively dynamic general equilibrium model. The model was used to examine both economy-wide and sectoral impacts, and impacts on social and national policy indicators under various economic growth and climate change scenarios. Macro-economic indicators such as Gross Domestic Product (GDP) showed that strict economic thresholds, characterized by discontinuities in the response function, did not occur. This was because autonomous economic adjustments generated a smooth socioeconomic transition over the 70-year simulation period. The economy underwent a gradual structural transformation, as capital and resources were moved from cropped agricultural to both the livestock and the non-agricultural sectors. Under "wet" climate scenarios, surplus water beyond 75 billion cubic meters (BCM) remained unused, as the marginal value of water dropped to zero and other resource constraints limited agricultural growth. For drier scenarios (below 75 BCM), water was a constraint to agricultural production into the 21^{st} century, as resources were diverted to less water demanding crops and the livestock and non-agricultural sectors. The reduced water scenarios showed agriculture declining in its total share of GDP, burdening the agricultural wage earner. Egypt increased its dependence on imports to meet food demand, dramatically decreasing grain self-sufficiency, while increasing protein self-sufficiency. If national policy requires a certain level of food self-sufficiency, then these metrics could be used in defining policy-based thresholds.

1. Introduction

The Nile River flowing north from Sudan enters Egypt directly into Lake Nasser, the reservoir behind the High Aswan Dam. The "Nile flood", predominantly from the Ethiopian Highlands of the Blue Nile, accounts for over 75% of the annual flow and arrives in the three month period from August to October. The storage reservoir provides a "firm" annual water yield of 55 billion cubic meters (BCM) and is released over the year as needed for agriculture, domestic use, navigation, and energy production. Currently, agriculture accounts for 89% of the water use;

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domestic uses represent 7%; and industrial and other economic activities account for the remaining 4%.

The Nile River water is the lifeblood of the Egyptian economy. Releases from the High Aswan Dam account for over 95% of the water resources of Egypt, making the Nile River the effective single source of freshwater for Egyptian agriculture, population, navigation and industry. Studies of climate change impacts on the Nile River show that the basin is extremely sensitive to temperature and precipitation changes (Gleick, 1991; Conway and Hulme, 1993; Riebsame et al., 1995; Strzepek et al., 1995; Yates and Strzepek, 1998a). For example, changes in runoff from a hydrological model using GCM based climate change scenarios for doubled global atmospheric CO_2 concentrations ($2 \times CO_2$) provide widely diverging pictures of possible future Nile flows (Strzepek et al., 1995): GISS– a 30 percent increase; UKMO– a 12% decrease; and GFDL– a 78% decrease. This translates into impacts on the annual yield from Lake Nasser of: GISS– a 14% increase; UKMO– a 13% decrease; and GFDL– a 78% decrease. The yields from Lake Nasser differ from total runoff due to evaporative losses from the lake surface.

Several studies have been conducted on the impacts of climate change on the economy of Egypt. Onyeji and Fischer (1993) examined climate change impacts on the Egyptian economy by examining impacts on crop yields due to changes in both CO_2 concentrations and climate. Strzepek et al. (1995) and Yates and Strzepek (1996) examined the impacts on the overall Egyptian economy to the integrated effects of climate change on water resources, crop water use and yields, and sea-level rise. Yates and Strzepek (1998b) also studied climate change impacts on water resources, crop water use and yields, and sea-level rise on the single agricultural sector. Both studies showed the ability of the Egyptian economy and the agricultural sector to undergo autonomous economic adjustments that reduced the impacts of climate change. These studies did show, however, significant impacts on other factors, such as changes in market structure, perilously low grain self-sufficiency, and impacts on social metrics such as wage earning ratios between the agriculture and non-agriculture sectors.

With the key role water plays in the current economy of Egypt, several questions are raised. 1) What is the future role of Nile River water in the economy and society of Egypt, especially if greenhouse gas (GHG) induced climate change should impact Nile River flow? 2) How will the future economy of Egypt respond if the Nile River flow changes? 3) How might an economic model, such as the one utilized in this study, help to develop adaptive economic strategies that would mitigate the potential negative effects of climate change, avoid threshold impact levels, but would not risk sustainable economic growth?

Response to climate change could occur along two different trajectories or response functions – smooth or discontinuous. For the smooth response, the response of the impact sector is continuous and could be characterized by either a simple linear (Figure 1a) or non-linear (Figure 1b) curve. The continuous, non-linear response curve could be made piecewise linear and would show inflection points

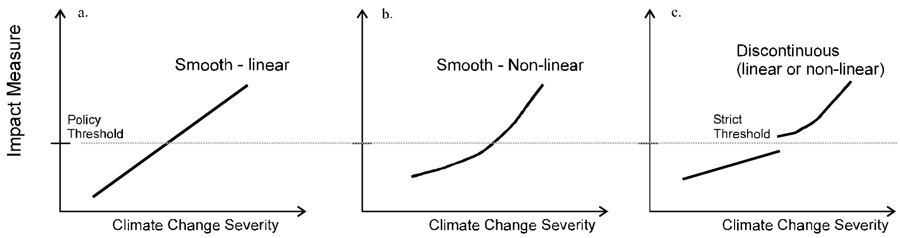

Figure 1. Classification of different threshold definitions under climate change.

along its trajectory. These inflection points are abrupt changes in the slope of the response curve, but are not what we are defining as a strict threshold. However, within the smooth response function, a policy threshold might be a point where the curve passes an unacceptable impact level (Figure 1a or 1b). Barring a catastrophic climate change scenario, agricultural systems will most likely undergo smooth transitions, as factors of production cannot be changed instantly, with labor, land and capital being obvious examples.

A discontinuous response function defines a more strict threshold definition, where the underlying sector undergoes an abrupt shift, a phase change, or acquires a new equilibrium state (Figure 1c.). Typically, natural systems exhibit these types of discontinuous thresholds. For example, Yates and Strzepek (1998a) showed the possible abrupt changes in runoff throughout the Nile River basin due to hydrological and geological characteristics. Either strict or policy-based thresholds can be useful in helping us understand acceptable levels of GHG concentrations.

The concept of "acceptable" climate change has risen in the discussion over limiting GHG emissions. Those against mitigating emissions hope to show that the consequences of GHG emissions are much less costly than the costs of forcing industry to reduce emissions. Those advocating a reduction in emissions are seeking to find the level of GHG where major impacts take place. The central question pertinent to both viewpoints is whether there is a "threshold" in GHG concentrations above which associated climate change impacts become economically, socially or environmentally unacceptable? If such a threshold exists, then we might devise plans that will limit emission so that this concentration threshold is not exceeded.

This paper uses a tool developed by Fischer et al. (1988) and the authors (Yates, 1996) and results from previous analysis (Yates and Strzepek, 1996) to analyze the impacts of changes in the Nile River on the Egyptian Economy to the year 2060. We examined whether thresholds (strict or policy-based) might exist in the economy of Egypt in regards to climate change impacts on water resource availability in Egypt, and the subsequent role of water both in the agriculture and non-agriculture economies.

2. Methodology

2.1. The Basic Linked System (BLS)

To perform the integrated assessment of climate change impacts, a dynamic computable general equilibrium (CGE) model of world food trade was used, the Basic Linked System (BLS) (Fischer et. al, 1988). The BLS consists of a set of national and regional models linked together through an international market, which globally balances commodities and adjusts international prices to generate a balanced state. Agriculture is broken into nine different sectors including wheat, rice, coarse grains, bovine and ovine meat, dairy products, other animal products, protein feed, other food, and non-food agriculture. There is a single non-agricultural sector.

The BLS is recursively dynamic: a set of initial conditions is specified for all countries and global trade conditions for the first year (including such things as domestic prices, production and consumption and international prices). An international exchange algorithm iterates over world market prices (maximizing net utility) by performing a commodity balance and determining final consumer demand (using a linear expenditure system), income formation at the given supply, market clearing conditions, net exports, etc. Processing of agricultural products and the purchase of intermediate inputs as well as the non-agricultural sector is considered in agricultural production. With the prices and incomes set at the current year, Engel curves are used to determine consumer demand, which are then used in the international exchange for the next year. Feed mix is estimated, but can adjust in the international exchange to allow for changes in imports or exports to meet target demands.

The majority of the national models are formulated as a Standard National Model (SNM). The SNM is a yearly growth model that is run in three modes: calibration, validation, and forecast. The model simulates from 1970 to 2060 in yearly time steps. The decade of the 70's is used to calibrate parameters, the decade of the 80's is used to validate the calibration, and the years 1990 to 2060 are forecast years with both calibrated and exogenous parameters used.

2.2. Water within the SNM

The Standard National Model was modified to incorporate water both as a resource constraint and as an input to production (Yates, 1996). Water availability constraints have been entered into the model based on annual aggregate values. Water is formulated as a constraint to agricultural production by limiting horizontal expansion and as a factor input used to determine commodity yield based on revenue maximization sub-model within the SNM. Agricultural production is determined by net revenue maximization based on a limited sector of factor input resources that include land, fertilizer, labor, and water.

2.3. Other water demands

Municipal and industrial water demand was given as a function of human population, income, and non-agricultural GDP. Per capita municipal water use grows with income (Raskin et al., 1997). This trend was modeled by scaling per capita water use by the natural log of GDP per capita. It was assumed that as non-agricultural GDP grows, the industrial sector will become a more efficient user of water, but overall demand will increase as the sector grows. Examining the Egyptian industry from 1970 to 1995 and global trends (Raskin et al., 1997) a non-linear growth model was used:

$$MI_w = w_p * ln(gdpcap) * pop + (gdpn^{0.85})$$

where:

MI_w	= municipal and industrial water use
$gdpcap$	= per capita gdp (1970 L.E.)
$gdpn$	= non-agricultural GDP (1970 L.E.)
w_p	= water use per capita 1970
pop	= population (1000's)

3. Analysis

To examine the potential effects of climate change on the Egyptian economy brought about by changes in Nile River flow, a number of scenarios were analyzed. Research discussed above, suggests significant increases and decreases in Nile flows as a result of GHG induced climate change. A set of scenarios that span the range of results was chosen.

3.1. Water resource scenarios

Guided by the results from Strzepek et al. (1995), four potential water resource scenarios were postulated for the year 2060. They include:

– 55 BCM: current annual Nile flow available to Egypt;
– 33 BCM: decrease from 55 to 33 BCM, declining linearly from 1970 to 2060;
– 76 BCM: increase from 55 to 76 BCM, increasing linearly from 1970 to 2060;
– 100 BCM: 90% increase from 55 to 100 BCM, increasing linearly from 1970 to 2060.

A fifth unlimited water supply scenario was examined, but the results were the same as for the 76 and 100 BCM analyses. By the year 2060, the agricultural sector can not reclaim and develop enough irrigated land to use more than 76 BCM. So the 100 BCM scenario is effectively 100 BCM and greater.

4. Optimistic and Pessimistic Baseline Scenarios

It is evident that not only Egypt, but any country involved in the global marketplace will face a host of uncertain possible futures. Any simulation that is generated by the BLS out fifty, sixty, seventy or more years in the future is really only a single realization of a myriad of possibilities. Therefore, a single simulation for a given set of assumptions within the BLS can be thought of as *only* a scenario and *not* a prediction. We developed both optimistic and pessimistic baseline scenarios, and then used these two baselines as reference cases for comparing a set of climate change scenarios. We first outline the optimistic development scenario.

For the optimistic scenario, the global community sees the advantage of Egypt's location and chooses to invest capital in the non-agricultural production sector (Mellor, 1990; Lofgren, 1995). Egypt becomes the "South Korea" of the 21st century. Egypt will invest in new, efficient technologies and will be able to use this to its advantage as compared to aging, less productive technologies.

Higher agricultural prices accelerate economic growth and generate employment for the poor in the non-agricultural sector in the long run. The short-term effect is higher prices, which reduces the purchasing power of the poor. Regardless, it is likely that the transformation from an agriculturally to a non-agriculturally dominated society would probably lead to heavy short-run costs reflected mostly onto the rural class poor. Egypt's economy might likely be experiencing some of these trends already (El-din, 1993). In order to achieve such dramatic, macro structural adjustment that the optimistic scenario predicts, domestic and foreign liberalization policies will have to occur. This is predicated on the idea that the Egyptian industrial sector can produce exportable goods that are competitive in the world market. Decreased government intervention will increase the flexibility of both agriculture and non-agriculture markets that will both benefit from liberalized policies. Specifically growth parameters and characteristics for the optimistic scenario included:

– high investment rate (12 % above depreciation rate for non-agricultural sector),
– high non-agricultural productivity rate increase (+2%/year),
– high labor transformation rate,
– high quality, competitively priced non-agricultural sector reflected through lower non-agricultural prices relative to world market,
– increasing labor rate relative to population growth,
– non-agricultural sector becomes highly dominant in the 21st century,
– non-agricultural sector has little dependency on the agricultural sector.

It is likely that capital investment decisions and capital constraints on agricultural development would have an effect on the magnitude of climate change impacts on the Egyptian economy. To examine these issues, a pessimistic development scenario was developed as an alternative to the optimistic scenario.

For the pessimistic scenario, Egypt continues to be a “major” consumer through inexpensive imports of food commodities (Omara, 1993; Hansen, 1991). Although Egypt has arguably some of the best agricultural land in the world, it is currently importing over two-thirds of its wheat and vegetable oils and one-third of its corn. Agricultural imports have increased by nearly 300% over the last twenty years and these imports are “costing” Egypt over $3 billion annually (Strzepek et al., 1995), yet the food production efficiency is quite low considering that almost 25% of the total cropped area is used for animal fodder which is grown on highly valuable land. Per unit output of animal products supported by fodder production is less cost effective when compared to the potential output from agricultural goods on the same land. Yet because of effectively low cost imports (Egypt’s food loans are often “forgiven” based on political decisions, and are considered to be “food aid”). The pessimist sees these trends as Egypt digging itself into a hole. Population will continue to outpace employment opportunities, foreign debt will increase, poor public policy will stymie growth, and investment within any sector will remain small. Structural change is often difficult because payoff is often delayed and there are immediate costs of undertaking structural reform. Policy makers are often unwilling to take such “painful” short-run risks without knowing the long-run benefits. Thus, the hole will only grow deeper. Specific growth and model parameters for the pessimistic scenario included:

– low investment rate, (4% above depreciation rate of non-agricultural sector),
– low non-agricultural productivity rate increase (1%/year),
– low labor transformation rate,
– no non-agricultural advantage to Egypt, reflected in higher relative price to world market,
– decreasing or constant labor rate relative to population growth, slow mobility from agricultural to non-agricultural sector,
– non-agricultural sector remains labor intensive: i.e., limited foreign capital investment,
– agricultural sector remains a dominant sector in the 21st century,
– non-agricultural sector is more dependent upon the agricultural sector.

4.1. Economic response for baseline conditions

The modified SNM model for Egypt was run for both the optimistic and pessimistic baseline cases with the historic average Nile flow of 55 BCM. Figure 2 shows the trajectories of non-agriculture and agricultural GDP over the simulation period. For the optimistic scenario, agriculture’s share of total GDP dropped from 19 to 7 percent of total GDP (from 1990 to 2060). While total agricultural output grew over this period, the cropped area increased until 2020 and then began declining through 2060 (Figure 3). The peaking of cropped land and its subsequent decline can be explained. After 2020, the Egyptian economy continued to grow, with an increase in per-capita GDP and accompanying demand for consumer goods. By 2020, water

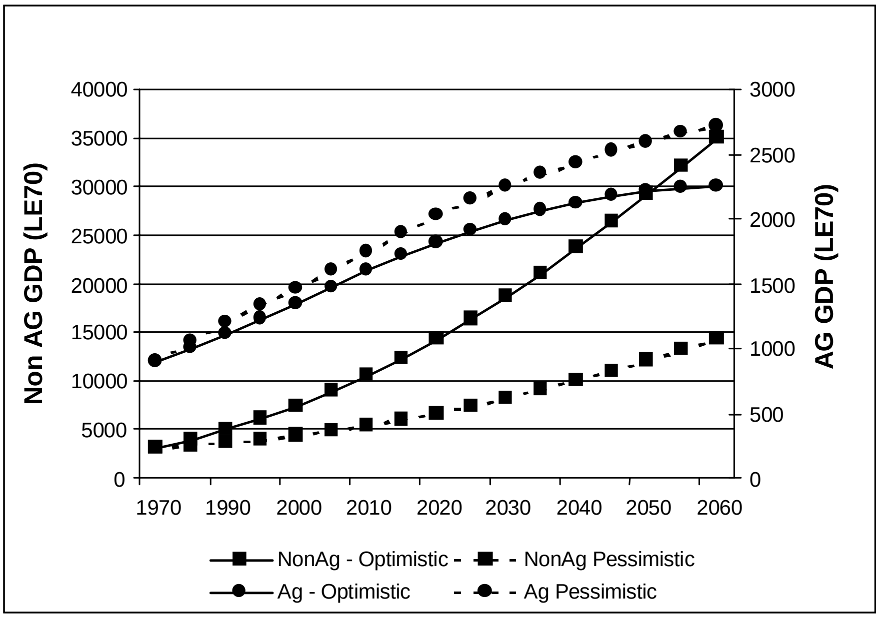

Figure 2. Agricultural and non-agricultural GDP for both the optimistic and pessimistic baseline scenarios from 1970-2060.

finally became a constraint to agricultural production, but after 2020 some available agricultural water actually went unused, as a larger share of domestic demand was met through imports purchased by a wealthier Egyptian consumer. Farmers shifted their cropping pattern, lowering their water requirements with an accompanying increase in crop yields. These new cropping configurations required less cultivated area and less water. The livestock sector increased relative to cropped agriculture, which demanded less water and land because feed requirements were also supported through imports. Capital resources shifted to the non-agricultural sector and municipal and industrial water demands continued to increase (Figure 3). Imports of grain increased dramatically, paid for by growth in the non-agricultural sector.

For the pessimistic scenario, the agricultural sector remained a larger portion of overall Egyptian economic output throughout the simulation period. By 2060, agriculture's share of GDP dropped only by 3 percentage points from 19 to 16%, and a larger number of workers remained in the agricultural sector. But by 2020, water became the limiting constraint to Egyptian agricultural growth (Figure 4). Shadow prices on land and water, obtained from an analysis using an Egyptian agricultural sector model, support this finding (Yates and Strzepek, 1998b). Horizontal expansion continued to increase cropped area, as farmers shifted their cropping patterns to yield higher marginal returns on water. The agricultural sector utilized all available water after 2020. Protein self-sufficiency was much higher in the pes-

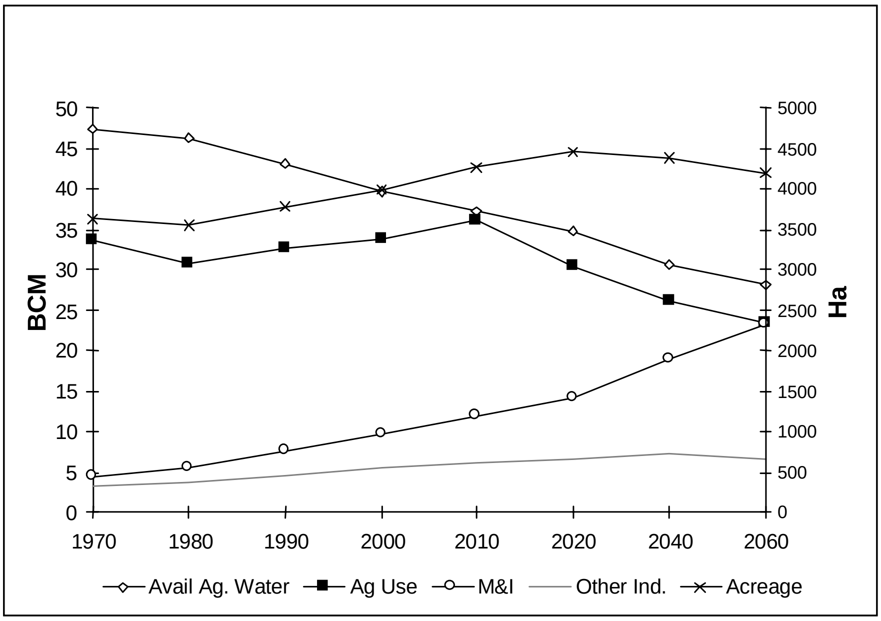

Figure 3. Water use by sector for the optimistic baseline scenario.

simistic baseline scenario when compared to the optimistic baseline, as Egyptian farmers supported a larger share of domestic livestock production and nutrient needs. Output from the livestock sector expanded considerably, as animal feed and crop residue was used to support a feed-lot style livestock sector (Table I, for the 55 BCM column).

Per-capita GDP for the pessimistic baseline scenario was substantially lower when compared with per-capita GDP from the optimistic scenario, implying a generally “poorer” society (Figure 5 for the 55 BCM data point). Over the 70-year simulation period, per-capita income grew at an average annual rate of 0.75 and 0.35%, for the optimistic and pessimistic scenarios, respectively. The larger growth in the optimistic scenario was largely due to a greater increase in the labor participation rate and a 1.63% annual growth in the non-agricultural sector over the 70 year simulation period. The non-agricultural growth rates were smaller for the pessimistic scenario, only 0.96%, while the agricultural growth rate was slightly higher in the pessimistic scenario (0.66%) when compared with the optimistic scenario (0.61%). With these base conditions as the backdrop, what will be the impact on Egypt of changes in Nile water resources from the current historic average of 55 BCM?

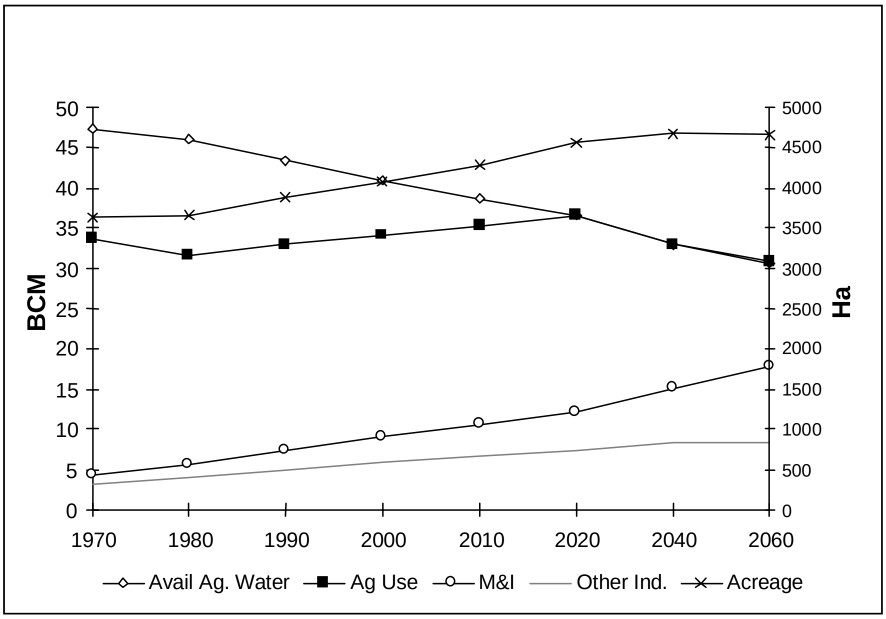

Figure 4. Water use by sector for the pessimistic baseline scenario.

5. Response under Climate Change Scenarios

Tables I and II present a summary of key socioeconomic indicators from the modified SNM model of Egypt run for four Nile flow scenarios of: 100, 76, 55 and 33 BCM for both the optimistic and pessimistic growth scenarios. These tables show that the amount of water supply had a small impact on the macro indicator of Egyptian GDP in 2060 for the optimistic scenario, while the impact of a changing water supply on GDP for the pessimistic growth scenario was more significant. Non-agricultural GDP accounted for 94 and 84 percent of total GDP by 2060 (optimistic and pessimistic scenarios, respectively) and was more sensitive to changes in water availability in the pessimistic scenario as compared to the optimistic scenario (+4.8% versus +0.8% for the 76 BCM scenario). Under the 33 BCM reduced water scenario, agricultural GDP dropped 35 and 29%, while non-agricultural GDP increased by 2 and 0.6%, producing little change in per-capita GDP for the optimistic scenario (-0.3%) and a greater decline in per-capita GDP for the pessimistic scenario (–4.0%). The 33 BCM reduced water supply scenario implied a larger impact on the overall economy for the pessimistic scenario as compared with the optimistic scenario. The impact on food consumption under the various water scenarios was shown to be of marginal significance for either the optimistic or pessimistic scenarios (Tables I and II).

TABLE I
Economic Response - Pessimistic Scenario in 2060

	Water Supply (BCM)			
	100	76	55*	33
Macro Indicators				
GDP	17930	17930	16915	16236
Ag.GDP	2976	2976	2640	1871
Non-Ag GDP	14954	14954	14275	14366
Ag Wage	0.24	0.24	0.21	0.15
Labor Ag	12535	12535	12803	12859
Labor Non-Ag	21462	21462	21167	21087
Food KCAL/Cap/day	2943	2943	2889	2851
Grain self-sufficiency	56	56	36	11
Protein self-sufficiency	70	70	93	94
Agriculture				
Cultivated Land	6657	6657	4993	3034
GDP/Hectare	0.44709	0.44709	0.52871	0.61658
Water Use				
Agriculture (BCM)	59.4	59.4	37.7	15.8
Ag-GDP/(AG-BCM)	50	50	70	119
NonAg (BCM)	17.6	17.6	17.3	17.2
NonAg-GDP/(NonAg-BCM)	4229	4229	4199	4203

Note: * 55 BCM is also the baseline scenario.

Figures 3 and 4 show how water was allocated among the different sectors (agricultural, municipal, and industrial) in the SNM of Egypt. The modified SNM provides for water policy to be specified. In Egypt, water is not priced. It is first provided to municipal users and then industry and agriculture “compete” for the resource. In the model, the competition for water between industry and agriculture is based on the marginal value of water to GDP production. Tables I and II indicate that the average value of water by 2060 in the non-agricultural sector was substantially higher than that of the agricultural sector, while capital was primarily directed to the highly productive non-agricultural sector. Agricultural shortfalls were met through imported agricultural goods that were used to meet domestic food demand.

The impact in 2060 on GDP for the pessimistic scenarios under both increases and decreases in water supply were more significant than those given for the optimistic water scenarios, although still modest. GDP increased by 6% and decreased by 4% in 2060 relative to the pessimistic baseline, for the 76 and 33 BCM water

TABLE II
Economic Response - Optimistic Scenario in 2060

	Water Supply (BCM)			
	100	76	55*	33
Macro Indicators				
GDP	37612	37612	37117	37004
Ag.GDP	2497	2497	2283	1481
Non-Ag GDP	35116	35116	34834	35524
Ag Wage	0.26	0.26	0.24	0.16
Labor Ag	9425	9425	9622	9237
Labor Non-Ag	25082	25082	24875	25254
Food KCAL/Cap/day	3337	3337	3326	3317
Grain self-sufficiency	55	55	35	8
Protein self-sufficiency	54	54	59	73
Agriculture				
Cultivated Land	5832	5832	4534	2493
GDP/Hectare	0.42810	0.42810	0.50346	0.59374
Water Use				
Agriculture (BCM)	53.8	53.8	31.9	9.8
Ag-GDP/(AG-BCM)	46.4	46.4	71.5	150.8
NonAg (BCM)	23.1	23.1	23.1	23.2
NonAg-GDP/(NonAg-BCM)	4806	4806	4801	4815

Note: * 55 BCM is also the baseline scenario.

supply scenarios, respectively. Two important insights can be gained from these results. First, the development path to 2060 was generally more important to Egypt than the role of water resources in the Economy. Second, the Egyptian economy was more sensitive to changes in water resources when agriculture was a larger percentage of the total GDP.

The reasons for these two results are as follows. As the Egyptian economy grew, it experienced a structural change away from agriculture, particularly for the optimistic scenario. Even though agricultural GDP in 2060 was greater than that of 1990, it represented only 6% of total GDP (optimistic scenario). Thus, when the water supply was reduced, its impact was primarily on a less economically significant sector of the economy. In contrast, the agricultural sector in the pessimistic scenarios remained a larger share of total GDP, staying near 1990 levels. The pessimistic scenarios gave rise to a domestic agricultural sector that had roughly 25% more output when compared to the output from the optimistic scenarios in

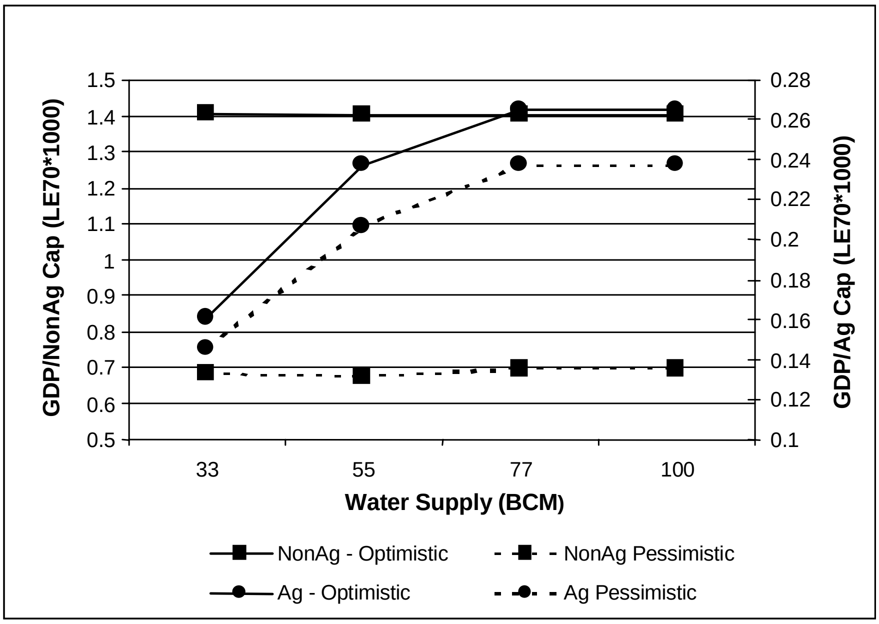

Figure 5. Per-capita GDP for both the agricultural (AG) and the non-agricultural (NonAg) sectors and for both the optimistic and pessimistic economic scenarios under varying levels of annual water availability. Note: 55 BCM is also the baseline condition.

2060. Thus the Egyptian economy was more "dependent" on water, albeit smaller than in 1990, for the pessimistic scenarios.

These results have shown that water supply had a relatively minor impact on the macro economic and social welfare indicators such as GDP and per capita food consumption by 2060. However, a more detailed look at the agricultural sector in Tables I and II and associated figures reveals that social impacts, particularly on the agricultural sector, might be more significant. These potential impacts are discussed below.

5.1. SOCIAL IMPACTS

The previous discussion focused on water supply impacts on key economic metrics. However, highly aggregated indices such as GDP may not reflect broader social impacts. The SNM is an aggregated macro-economic model but reports some indices that reflect societal welfare. The impact of water supply on five indices: agricultural labor, agricultural wage, daily food consumption, national grain and protein self-sufficiency are reported in Tables I and II, and Figures 5 and 6.

Tables I and II show there was little impact on daily per-capita food consumption under changing water supplies. This modeling outcome poses an interesting

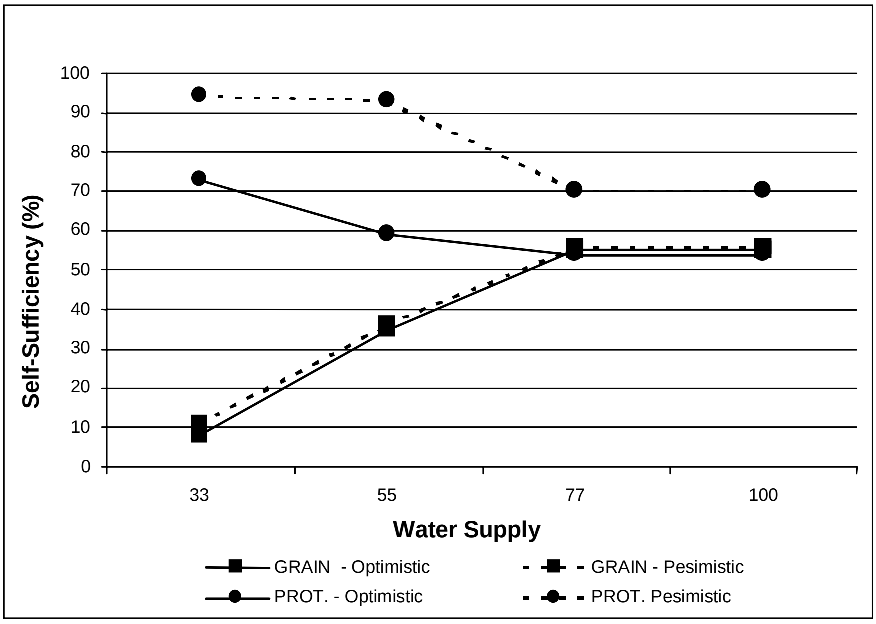

Figure 6. Protein and grain self-sufficiency for both the optimistic and pessimistic economic scenarios under varying levels of annual water availability. Note: 55 BCM is also the baseline condition.

question regarding the future role of small scale farming in Egypt. Will small-scale farmers, the landless poor and rural laborers be able to purchase imported food if there is a reduction in irrigated lands and a shift of cultivated agricultural to cash crops and livestock? Model results suggested that the labor structure between agriculture and non-agriculture would not be significantly impacted by a decrease in water supply, but per-capita Ag-GDP was impacted in both the optimistic and pessimistic scenarios (Tables I and II; Figure 5). The agricultural wage-rate dropped dramatically as water supply declined, whereas the non-agriculture wage remained more stable for both economic scenarios. This result suggested that the rural and urban poor may not have the economic means to purchase this level of food consumption. Model results also suggested that when water was plentiful, agricultural wages were higher. Fringe agriculture would be more readily available to landless farmers and would more easily support small-scale farming, the prevalent practice currently observed in Egypt.

Figure 6 shows that as the water supply declined by 2060, grain self-sufficiency dropped from a maximum of 55% to approximately 10%. Water was shifted to higher valued crops and inexpensive grains were imported, which was true for both the optimistic and pessimistic scenarios. Protein self-sufficiency increased as the water supply declined, although this self-sufficiency index was significantly higher for the pessimistic scenario as compared with the optimistic scenarios. This opposite self-sufficiency trend between grain and protein reflected a shift of marginal agricultural lands from fodder cultivation to feed-lot livestock production. The livestock sector grew considerably under decreased water availability and was supported through inexpensive grain imports. This was true for both the optimistic and pessimistic scenarios, where only the magnitude of change differed (Tables I and II). This result would imply a major structural transformation of the Egyptian agricultural sector and would imply impacts on a large portion of the population.

6. Is there a Water Supply Threshold?

In order to address this question, we must briefly return to our definition of a threshold. In the strictest sense, a threshold is a point along a response function that possesses a discontinuity. This discontinuity leads to an abrupt shift in the system, as the underlying sector undergoes a phase change or acquires a new equilibrium state. The recursively dynamic nature of the BLS precludes an assessment of discontinuous thresholds, as feedbacks are specified that relate model outcomes to model parameters that generally yield smooth economic transitions from year-to-year. Model dynamics require an updating and recalculating of many model parameters, such as those related to domestic demand and foreign trade deficits. Agricultural production has specific characteristics – factors of production cannot be changed within a short time period, land and capital being the most obvious examples. Agricultural labor tends to adjust in a sluggish way, and the BLS characterizes labor as following demographic trends and trends in labor participation rates based on three-year moving averages.

Thresholds in economic sectors are not well defined, as is often the case in natural systems. However, thresholds could be defined as policy goals such as an acceptable level of food self-sufficiency. This specified level could then be defined as a policy-threshold. Obviously, policy-thresholds defined in this manner would need to be pre-determined in order to decide if they were exceeded in the analysis process. We did not attempt to define specific policy-threshold levels, but used the fact that many countries set food self-sufficiency as a high priority for their agricultural policy goals to highlight potential policy-based thresholds.

If one looks solely at Egyptian GDP or per-capita food consumption to identify thresholds, then changes in annual water supply had little impact on these two measures. The insensitivity of GDP to water supply was an artifact of the economic structure of Egypt in 2060, particularly for the optimistic scenario (the pessimistic economic growth scenario did show more significant impacts on GDP compared to the optimistic growth scenario).

Two important social indicators showed significant shifts under the various climate change scenarios – agricultural wage and food self-sufficiency. Examining Figures 5 and 6, there was an inflection point at approximately 76 BCM. Above 76

BCM the agricultural sector could not use the additional water. Below 76 BCM there was a strong response to water supply of agricultural wage earnings and both grain and protein self-sufficiency, with impacts more pronounced between 33 and 55 BCM than 55 and 77 BCM. The sharp change in these indices under the reduced water supply scenarios suggested that policy-thresholds, such as food self-sufficiency or equity between agricultural and non-agricultural wage earners, would be violated.

There was most likely a lower bound on the water supply for both the optimistic and pessimistic scenarios. If water supply continued to decrease, especially below the requirements of both the municipal and industrial sectors (23 BCM and 17 BCM for the optimistic and pessimistic scenarios, respectively), there would certainly be a greater impact on society and/or the non-agricultural sector. Climate variables such as precipitation and temperature, taken from GCMs, have not suggested this kind of significant decrease in water supplies to Egypt. Should Nile flows drop by this much, strict-thresholds would certainly exist, as water levels in Lake Nasser would drop below the outlet level at the dam and the gravity fed irrigation system would not be able to supply water to agricultural fields. These kind of drastic reductions in water resources would represent a catastrophic scenario. At the other end of the spectrum, sustained annual Nile flows, such as those suggested by the 76 BCM values and higher, would also be of concern to Egypt. Water resource manager would be worried about flooding, the security of Lake Nasser, and other problems associated with these types of high flows.

7. Summary and Conclusions

This modeling exercise examined the impacts of water supply changes on the performance of the Egyptian economy and revealed several important insights:

- While economy-wide indicators may not show strict-thresholds, sectoral and social indicators may reveal policy-thresholds (such as food self-sufficiency, earnings ratios, etc.) in their response to changes in water resource availability.
- The economic structure and the dependence of its major sectors on water resources is a key to finding policy threshold levels. Understanding the role of water resources in each sector of the economy will help to determine the response of the economy to changes in water supply.
- The rate of capital investment and the associated economic development path, together with development of non-agricultural sectors of the economy, will have a major effect on the significance of climate change impacts on the Egyptian economy.
- Along smooth response functions, policy thresholds likely exist that relate water resource availability to economic performance. These thresholds are dynamic and are a function of the sectoral structure of the economy, the level

of technology employed in each sector of the economy, and governmental policies on food security and self-sufficiency.

– Social indicators such as food self-sufficiency and agricultural wage earnings pointed to the concern that the landless poor, and/or small rural farmers could be most vulnerable to reduced water supplies of the Nile. These people will be hard pressed to meet their food needs from purchased imports.

Given the adaptive nature of economic systems and, perhaps more importantly, the characteristics of the modeling tool used in this study, the economic and resource variables used to assess climate change impacts (e.g., GDP, self-sufficiency, land use, water use, earnings, etc.) were not characterized by abrupt discontinuities in their response. Strict thresholds were not observed. Autonomous economic adjustments generated smooth socioeconomic changes over the 70-year simulation period. The economy underwent a gradual structural transformation, as capital and resources were generally shifted among cropped agricultural and both the livestock and the non-agricultural sectors. Beyond 75 BCM of water, water's marginal value dropped to zero and other resource constraints, such as land, limited agricultural growth. For scenarios below 75 BCM, water was a constraint to agricultural production in the 21^{st} century. Resources were diverted to less water demanding crops, and the livestock and non-agricultural sectors. The reduced water scenarios showed agriculture declining in its total share of GDP, burdening the agricultural wage earner. Egypt increased its dependence on imports to meet food demand, substantially decreasing grain self-sufficiency, and increasing protein self-sufficiency when water was a greater constraint to agricultural production. This outcome implied a major structural change in the Egyptian agricultural sector. When water was more readily available, grain self-sufficiency increased, while protein self-sufficiency decreased. If national policy requires a certain level of food self-sufficiency, then these metrics could be used to define policy-based thresholds.

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