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# Gains from Improved Irrigation Water Use Efficiency in Egypt

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**ABSTRACT** *Egypt's fortunes hinge on the Nile. However, little research to date has evaluated economic efficiency improvements that could be achieved by altering Egypt's agricultural water use patterns. This study develops an integrated catchment scale framework to identify potential economic benefits that can be supported by Egypt's irrigation water use. An optimization framework is developed to identify improvements in national farm income, which can be produced with current water supplies that are compatible with Egypt's hydrological, environmental, and institutional constraints. Results suggest that limited water trading across locations and seasons can increase national farm income by up to 28%. The methods used provide a framework for informing decisions on sustainable use of land and water for improved rural livelihoods in the developing world's irrigated areas.*

## Background

Egypt's long history of economic, political, and cultural achievement has been tied to the Nile's flows. Egypt's agriculture has had a long history of high productivity because of its moderate and uniform climate. Irrigated agriculture still occupies a central place in Egypt's economy, contributing about 17% to GDP, and employing about 31% of the labour force (Attia, 2004; CAPMS, 2008). Agriculture is characterized by scattered land holdings (Elarabawy *et al.*, 1998; Elarabawy & Toswell, 1998; Kandil, 2003), and contains a large drainage area, covering about two million hectares (Ali *et al.*, 2001; Wichelns, 2002a; Strzepek *et al.*, 2008; Abu-Zied & El-Shibini, 1997; Wahba *et al.*, 2005). Irrigated agriculture consumes about 85% of Egypt's freshwater. Additionally, the Nile's waters are an important source of electric power production, fishing, and navigation to support tourism and barge traffic.

Since the late 1800s, several agreements and protocols have established water-sharing arrangements among the various Nile basin countries. To date, the 10 Nile basin countries are still attempting to forge a mutually acceptable solution to sharing the Nile's water. One ongoing attempt, the Nile Basin Initiative (NBI), is a step towards basin-wide co-operation. One signature historic achievement was the 1959 Full Control and Utilization of the Nile Waters Agreement between Sudan and Egypt. The quantity of average annual

Nile flow was agreed at 84 billion cubic meters, measured at the High Aswan Dam (HAD). It assigned the average annual flow of the Nile to be shared between Sudan and Egypt at 18.5 and 55.5 billion cubic metres, respectively. Annual water losses due to evaporation have been estimated at about 10 billion cubic meters (Nasser & Allam, 2007; Wichelns, 2004; Allen, 1992; Hefny & Amer, 2005).

Despite the progress achieved by the NBI, ongoing debates remain between the basin's downstream users (Egypt and Sudan) and its upstream countries, especially Ethiopia. Many of these debates revolve around the distribution of the basin's water use and its associated economic benefits (Mekonnen, 2010; El-Fadel *et al.*, 2003; Drake, 1997; Kung, 2003; Cascão, 2009). A recent proposal is the Co-operative Framework Agreement (CFA). In May 2010, five upstream states signed this agreement in order to seek more water from the River Nile — a move strongly opposed by Egypt and Sudan. Much discussion among the Nile basin countries deals with water re-allocation (Laki, 1998; Mason, 2005). The basin's countries have not yet realized the potential benefits of joint co-operation and development of more efficient water management policies (Wu & Whittington, 2006; Laki, 1998; Hefny & Amer, 2005; Swain, 2008).

Upstream countries call for larger shares of the basin's water, with greater opportunities to develop and use hydropower. The downstream countries see this proposal as a threat to their historical use (Arsano & Tamrat, 2005; Hamad & El-Battahani, 2005). Increased conflict among Nile basin countries adds uncertainty to the reliability of water supplies for all basin countries. Ongoing conflict poses continued challenges to all the basin countries' policy makers, while highlighting the importance of more efficient and sustainable water management.

Growing population, food security issues, increased urban use, and potential impacts of climate change increase the attention given to more efficient and sustainable water management in Egypt. All these factors point to the continued challenges of guarding against Egypt's water demands outpacing its supplies (Allen, 1992; Wichelns, 2004; Elarabawy & Toswell, 2000). Policy alternatives to water pricing that could improve Egypt's irrigation water allocation efficiency are examined by He & Siam (2004). Simonovic *et al.* (1997) used an object-oriented framework to build a simulation model of Egypt's use of the Nile, with all major sources and uses of water considered. Malashkhia (2003) examined irrigation water-saving measures that could be applied in Egypt, with special attention given to water pricing and improved efficiency measures. Wichelns (2002b) conducted an economic analysis of investments in improved irrigation drainage to mitigate problems of waterlogging and salinization in Egypt.

Despite the achievements of these works, there seems to be no policy analysis to date that takes a national view of comprehensively analyzing outcomes for alternative policies that could be implemented for Egypt's use of the Nile. For this reason, the objective of this paper is to examine measures for improving the agricultural economic efficiency and sustainability of Egypt's Nile River water use, while respecting cultural, hydrological, environmental, and institutional constraints on urban and environmental uses. Its uniqueness lies in the formulation and application of an integrated catchment scale analysis of the sources and uses of water in Egypt, with a special emphasis on irrigated agriculture.

## Methods and Materials

### Overview

This study formulates and applies an integrated basin-scale framework to improve the economic productivity of the uses of Egypt's Nile River for irrigated agriculture while respecting numerous other constraints that limit the size and economic value of its water's re-allocations. Using data on national agricultural water supplies and demands, an optimization framework is developed to identify maximum total agricultural benefits, as long as that can be achieved while also respecting important hydrological, environmental, and institutional constraints unique to Egypt. The model is written in General Algebraic Modeling System (GAMS) (Brooke *et al.*, 1988). Sustainability was enforced by constraining terminal period reservoir storage to be at least as high as its starting values.

A major logistical challenge posed by this study was to unify data from different sources to consistently inform a range of water management decisions. Another challenge is that the land in Egypt is cultivated in three seasons each year, making it difficult to assemble consistent data on crop production, crop water use, and gauged flows on the Nile throughout the river's entire length in Egypt. The three cropping seasons in Egypt are: winter, November to May; summer, May to September; and *nili*, September to November (FAO, 1995). Farm budget data were obtained from the Ministry of Agricultural and Land Reclamation (MALR, 2008). These data included irrigated land, yield, cost of production, and prices by crop, season, and district. These data are available in different volumes, published yearly by the Department of Economic Affairs in MALR.

Additional important data were secured for gauged river flows, which came from the Ministry of Water Resources and Irrigation (MWRI). These data describe the varying crop water use requirements by season and by location in the country. MWRI has data on river flows at all the major Nile River gauges in Egypt. MWRI also collects data on storage volume for the main reservoirs in Egypt, including Lake Nasser, as well as the original Nile Lake created by the Low Aswan Dam. The two major data sources were merged, as well as could be done, while recognizing the difficulties of merging data from different ministries, a common challenge faced in developing countries.

Around three months were invested in merging data from these different sources to ensure reliability and compatibility of the data. For the purposes of this study, the data are classified by the main irrigation district, rather than by the administrative districts. The complete database for 2006 included three irrigation seasons, 14 crops, 13 major irrigated areas, and the total seasonal river flow at each of 10 river gauges. An important early task was the development of farm enterprise budgets for the base year.

### Basin Scale Framework

The analysis at the basin scale treats the entire Nile catchment within Egypt as a single unit. While complex, it offers many advantages over analyzing separate political, hydrological, and administrative boundaries. It accounts for upstream and downstream interactions throughout the country and in different time periods. Accounting for these interactions comprehensively ensures consistent treatment of alternative water allocation and management plans (Wegerrich, 2004; Allen, 1992; Prairie, 2006). The basin framework integrates hydrology, land use, agronomy, economics, and institutions to support improved policy design, implementation, and evaluation (Ward & Velazquez, 2008; Gohar & Ward,

2010; Rosegrant *et al.*, 2000; Ringler, 2001; Mainuddin *et al.*, 2007). Where possible, a basin framework should include stakeholders, in order to improve the perceived sustainability of water resources management (Mouratiadou & Moran, 2007).

### *Approach to Modelling*

This study formulated an integrated framework of Egypt's Nile basin that accounted for recent historical water uses for the nation's three major irrigated regions: Upper, Middle, and Lower Egypt. We constructed a catchment scale integrated mathematical optimization model, accounting for hydrological, economic, agronomical, institutional, and environmental dimensions of Egypt's use of the Nile. We also calibrated the model so that its predicted gauged flows were close to actual data at all major river gauges. Calibration presents numerous challenges for hydrological and watershed analysis, many of which continue to be debated. A short list of celebrated papers published since the 1990s, dealing with watershed calibration, include the works of Janssen & Heuberger (1995), Yapo *et al.* (1998), Karvonen *et al.* (1999), Sophocleous *et al.* (1999), Madsen *et al.* (2002), and Singh & Woolhiser (2002). Other, more recent, papers include those of Doherty & Johnston (2003), Legesse *et al.* (2003), Butts *et al.* (2004), Merz & Blöschl (2004), and Muleta & Nicklow (2005).

The idea behind the calibration was to have the model's predicted base year streamflows close to observed flows at all major gauges from Lake Nasser to the Mediterranean. To achieve this, the model was constrained to irrigate the observed amount of land in production by crop, season, and irrigated area. This required a fair amount of experimentation. The calibration was started at the HAD. Beginning from that point, crop water use patterns were adjusted at an irrigated region for each of the three seasons, so that the predicted gauged river flow matched actual gauged measurements. When predicted flows were too high, the crop water use coefficients were increased so that more would be taken from the river for irrigation.

As the experiment proceeded downstream, observed gauged flows were progressively less than flows predicted by the model. When the deviation became large, it was concluded that there were unmeasured quantities being taken from the river. These unmeasured quantities were caused by several sources, including unmeasured groundwater pumping, unmeasured river evaporation, and unmeasured diversions for urban use, an amount that became larger as the Nile approached the Giza and Cairo urban areas. Differences between observed and model-predicted river flow were resolved by defining the concept of 'unmeasured river diversion' associated with each major agricultural use region. The final piece of our calibration exercise was to calculate this unmeasured use. This use was calculated by defining unmeasured river diversions so that predicted river flows matched actual gauged flows, even at the lower end of the basin. The program was calibrated in this way so that under the base policy characterizing actual crop production and water use patterns, observed and predicted streamflows were close. The complete program code, written in GAMS as well as data used and program output, are available from the authors on request, as well as being posted at <http://agecon.nmsu.edu/fward/water/>.

*Economics.* Hydrological data were assembled on water diverted, cropping patterns, and crop water use by region, crop, and season. These data were combined with farm

production details that accounted for crop prices, cost of production, and crop yields. Net income per unit of land and total land in production by irrigated region, crop, and season were identified. Net income from any single crop was defined as price multiplied by yield minus the sum of all input costs, including both variables and fixed costs. Variable costs contain all costs that change with the level of output. These include the various costs of cultivation, such as expenses associated with land preparation, harvesting, fertilizers, labour, and irrigation. Fixed costs typically do not vary with the level of output. Examples include depreciation, taxes, interest, and land rent.

Net farm income per unit of land was calculated by region, crop, and season. The constrained optimization framework was designed to examine ways to allocate the Nile's waters throughout Egypt to maximize net discounted farm income summed over crops, seasons, time periods, and locations, subject to a number of constraints. This discounted net present value was maximized over a five-year planning period, with a time step consisting of three seasons per year, as described above. It was designed to account for various hydrological, cultural, or institutional constraints that could limit potential water reallocations compared to existing water use patterns.

*Hydrology.* The long history of Egyptian irrigation has produced a complex, intricate, and time-tested irrigation system. The schematic shown in Figure 1 shows a highly simplified view of the current sources and uses of water for agriculture in Egypt. Additional details on the pattern of Egypt's canals are in Hvidt (1998). The entire irrigation system shown in the schematic includes three major regions in Egypt. Starting from Lake Nasser, Upper Egypt contains five main canals: Asfon, Kelabia, East Naghammadi, and West Naghammadi divert the water from the Nile, while the Toshka canal takes water directly from Lake Nasser. Middle Egypt includes two main canals, including the Ibrahimia canal, which divides its water between many sub canals to serve numerous areas in the Assiut Region. These sub canals include El-Minia, Beni Suef, Fayoum, and Giza. The second main canal in Middle Egypt is the Ismailia canal, which provides irrigation water to the Suez Canal region and part of Elshrkia. Finally, at Lower Egypt, downstream of the Delta gauge, the Nile River splits into two branches called Rosetta and Damietta, creating the Nile Delta. The Rosetta branch includes the Menufia, Beheira, Nasser, and Mahmodia canals, while the Damietta branch includes the Tawfikia and Alsalam canals, which also include numerous sub canals.

### *Policy Analysis*

*Without water trading.* Despite the fact that surface water is free in Egypt (Malashkhia, 2003; He & Siam, 2004), there can be considerable costs for pumping when surface water is conveyed to fields lying above irrigation canals. Moreover, until 1999, Egypt's water management policy attempted to meet all irrigation water demands, regardless of water's opportunity cost or the cost of other resources consumed in the process of using water (Simonovic *et al.*, 1997; Elarabawy & Toswell, 2000). The opportunity cost of water is the economic benefits displaced by taking water from another use, location, or time period. More recently, Egypt has formulated The National Water Resources Plan (NWRP, 2005). A partial list of measures for implementing this strategy includes:

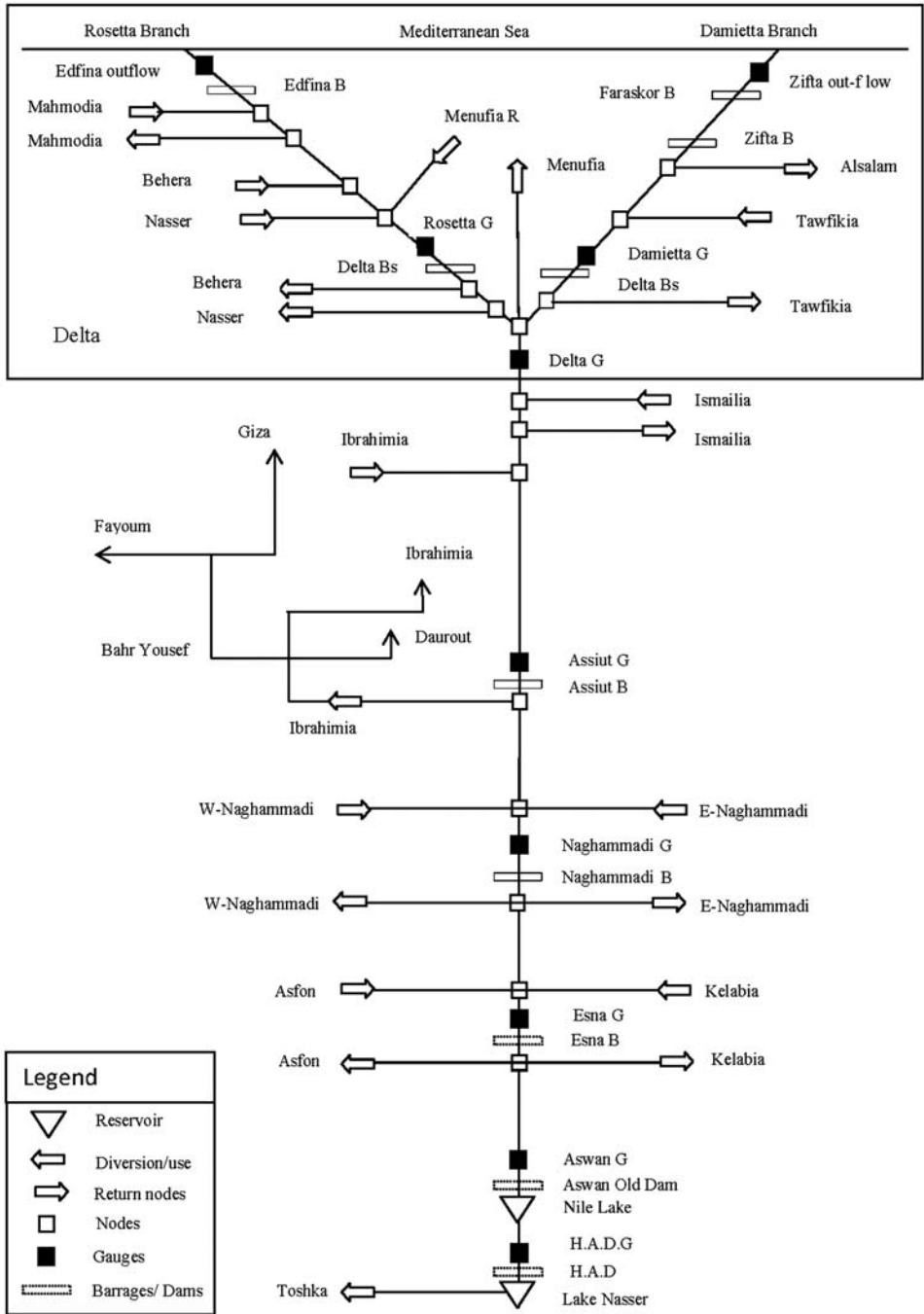


Figure 1. Schematic of Nile basin, Egypt.

- co-operating with other Nile basin countries to increase effective supplies;
- monitoring, developing, and increasing water from various sources, including shallow, deep, and brackish groundwater, in addition to harvesting floodwaters and desalination in coastal areas;
- making better use of existing water resources, including the improvement of irrigation efficiencies by maintaining canals and using modern irrigation technology, and improving the drainage efficiency by expanding drainage water reuse; and
- water allocation with the co-operation of water user associations at the *mesqa* level and water boards at the irrigation district level. Water would be allocated based on equal opportunities, with upper bounds on use per unit land, which would limit certain high water-using crops.

For the purposes of this paper, an analysis of ‘without water trading’ and ‘with water trading’ was conducted. Without water trading was simulated by constraining the basin model to reproduce historical water use, streamflow, land in production, and cropping patterns to match observed values for 2006, the only year for which we were able to assemble consistent and reliable data.

*With water trading.* A parallel analysis was conducted to reflect the results of a policy that would permit more widespread water trading within irrigated agriculture than is currently practiced in Egypt. The potential for greater total national agricultural income was examined by testing whether it was possible to increase the total economic value of Egypt’s farm income compared to income achieved under baseline historical conditions. The ‘with trading’ policy scenario reflected a search for potential income gains that could be achieved by re-allocating water through limited trading to produce greater total economic benefits over irrigated areas, crops, and seasons.

The ‘with trading’ proposal falls under the National Water Resources Plan’s principle of making better use of existing water (NWRP, 2005). The implementation of that principle increases land available for production to the maximum expected arable land in Egypt, currently estimated at 4.62 million hectares, which is 1.05 million hectares more than current land in production in the base year. Although more land could be brought into production, no additional water supplies overall would be made available for irrigated agriculture under the ‘with trading’ proposal. That is, the total water available for irrigation was constrained to be no greater than the total actual historical base year use in Egypt of Nile River water in farming.

Under the ‘with trading’ scenario, small reductions of water use for any irrigated area were permitted. However, water use reductions through reductions in irrigated land could be no more than 10% of the base year’s historical land in production. Even if Egyptian agriculture would benefit nationally from large water supply trades from a water exporting area to a water importing area, high volumes of water exports may be politically and culturally unacceptable. Several changes were considered in the analysis of water use under the ‘with trading’ policy. Under ‘with trading,’ all constraints on the Nile’s gauged flows throughout Egypt were removed. That is, gauged flows could depart from observed flows in any way needed to increase national farm income, consistent with the upper bound on irrigated land reductions described above.

Reservoir storage volume was also considered as part of the package defined by ‘with trading.’ Storage volumes at both major Nile basin reservoirs, Lake Nasser and Lake Nile,



were constrained. That constraint was established so that, in the terminal period of the five year planning horizon, both reservoirs had at least as much water in storage as actually occurred at the beginning of the base year. By imposing this constraint on terminal period reservoir storage, a sustainable water use pattern was assured, under both the 'without trading' and 'with trading' policy. In addition, environmental flows at the two Nile Delta gauges into the Mediterranean Sea (Edfina and Zifta) were constrained to be at least as high as their base year outflows. This constraint was imposed to assure adequate flow levels in the Nile to support tourism demands and to protect the irrigation environment by guarding against saltwater intrusion.

*Cap and trade.* Cap and trade systems are becoming increasingly common in water resources management as a water trading mechanism to encourage water to move to a higher valued use when it exists. A recent paper by Speed (2009) described efforts by Chinese water planners who are starting to take steps down this path with the development of a new water rights transfer system.

A market institution that promotes water re-allocation such as cap and trade should meet three criteria to be acceptable. It should reduce water consumption in low valued water uses, be perceived as equitable, and signal water's real scarcity. Any water trading institution requires a water rights system to be in place before the full power of the market can be harnessed in moving water to higher valued uses in ways that benefit both water buyers and water sellers (Gohar & Ward, 2010). Egypt currently has no legal foundation supporting well-defined, secure, and transferable water rights assigned to individual farmers. Water rights, and the rules governing their use and transfer, need to be clearly defined for a cap and trade system to work.

A cap and trade water transfer programme in Egypt, if established, could provide elements of all three criteria. It could be a culturally acceptable way to reduce water use by sending the right water price signals to Egypt's irrigators. Under the programme, all farmers could be assigned a water entitlement per unit land irrigated, namely the cap. The cap could be established with the idea of an equitable base right in mind. For example, something like 1.3 meters depth per hectare per year could be assigned as a base irrigation water right. That base right could be assigned to every farmer that demonstrated historical irrigation for a set amount of recent years. While the details obviously need to be worked out carefully, the amount chosen could be based on the full yield flood irrigation requirements of all but the most water-intensive crops, like sugar cane or rice. A higher cap could be possibly assigned to farmers in irrigated areas where higher temperatures produced higher evaporation and greater crop evapotranspiration.

Under a cap and trade arrangement, any water use in excess of the cap would be legal, but would require a trade of cash for water from a willing seller. Gohar & Ward (2010) describe in detail some of the challenges surrounding trades of water for cash in Egypt. A cap and trade programme avoids the most undesirable effects of government-administered prices, namely that administered prices can be unjust as well as rarely signaling the real scarcity of water (Stavins, 2008). Who would be willing water suppliers under a cap and trade programme in Egypt? Those supplies would come from irrigators who used less than their assigned cap. Some supplies would also come from irrigators who exceeded their capped use at the time of the assigned cap, but who later invested in conservation measures to reduce water use to lower than capped levels. Conservation could come from on-farm water conserving measures like deficit irrigation, land leveling, shifting crops,

and spreading water more uniformly over time or space. Sellers could also be farmers who fallowed part of their land, permitting them to irrigate with full supplies to meet crop requirements associated with maximum yields applied to remaining lands.

Under such a cap and trade arrangement, market forces and not government edict establish the price of water. The market price of tradable water would vary from time to time, as the scarcity of water or its economic value changed. These changes could be brought about from any adjustments that affected any crop's price, yield, or production costs. It could also fall with advances in plant genetics or irrigation engineering that reduced any crop's water use or application requirements. Variability in water's price from time to time would signal changes in water scarcity, providing immediate economic incentives that reward farmers who quickly adjust their behaviour to changes in water scarcity. Changes in water scarcity could be brought about by outside forces like climate change, or new agreements for sharing the Nile's supplies throughout the entire basin. Higher prices for tradable water would reward conservation, while lower prices would reward farmers who take advantage of its reduced scarcity.

## Results and Discussion

### *Overview*

Results are described for each of two policy scenarios: water use without trading and water use with trading, subject to the cultural, institutional, and hydrological constraints described above. Results for each policy scenario are shown for their impacts on water stocks, water flows, irrigated land, cropping patterns, and farm income.

### *Water Stocks and Flows*

Streamflows are shown for 10 mainstem Nile gauges located in Egypt, from the HAD to the Mediterranean. Reductions in river flow between any two gauges indicate how much water is depleted in the irrigated area between the gauges, including depletions based on the calibration exercise described previously. Table 1 shows the results of streamflows by stream gauge, season, and policy. This table reveals several messages. It shows reduced winter flows in Upper and Middle Egypt as well as increased summer flows in the Upper and Middle part of the country, which would occur under a 'with trading' policy. It also shows reduced flows throughout Egypt in the *nili* season, which would occur under the 'with trading' policy. The table shows a general re-allocation of river flows from Lower to Middle and Upper Egypt, in order to support higher valued patterns of irrigation water use in Middle and Lower Egypt under the water trading policy. In all cases, the column indicating change in flow shows the difference in flows between the without water trading and with water trading policy. A positive/negative entry indicates that greater/less gauged flow would occur under a with water trading policy at a given stream gauge, compared to the without trading policy.

Table 1 also shows that the 'with trading' policy results in small increases in gauged flow from the Upper and Middle Egypt to Lower Egypt and from winter and *nili* to summer. In comparing the without trading and with trading policy, a positive change in gauged flow can only occur with reduced agricultural use or increased reservoir releases or a combination of the two. For a given level of total supply of water into Lake Nasser, higher reservoir releases reduce reservoir storage volume. Outflows at the Zifta and Edfina

**Table 1.** Nile River flow by gauge, season, and policy, Egypt, in million cubic meters per season, 5 year average.

Gauge	Region in Egypt	Winter			Summer			Nili		
		Without trading	With trading <sup>1</sup>	% Change	Without trading	Without trading	% Change	Without trading	With trading	% Change
		Aswan High Dam	15,900	15,488	-3	36,650	37,147	1	4,700	4,593
City of Aswan	15,900	15,522	-2	36,600	37,097	1	4,286	4,179	-2	
Esna	15,100	14,751	-2	35,500	36,103	2	3,200	3,098	-3	
Naghammadi	13,500	13,277	-2	32,700	33,588	3	3,100	3,003	-3	
Assiut	10,800	10,741	-1	25,500	26,742	5	2,300	2,254	-2	
Delta	10,800	10,754	0	23,400	24,651	5	600	554	-8	
Rosetta	1,468	1,584	8	3,177	4,479	41	90	83	-8	
Demitta	3,800	3,881	2	7,400	7,362	-1	1,100	1,097	0	
Edfina outflow	500	500	0	0	0	0	0	0	0	
Zifta outflow	0	0	0	0	0	0	0	0	0	

Notes: <sup>1</sup> With trading refers to limited trades of water for cash or other assets. Results of 'with trading' are produced in the model by a constrained optimization model of agricultural water use throughout Egypt. The model searches for the crop water use patterns in irrigated agriculture throughout Egypt's part of the Nile basin that maximize discounted net present value of farm income, while respecting existing constraints described in the text. Constraints are written to also sustain water use patterns for urban and environmental demands.

gauges match flows that occurred during the base period, both with and without water trading, ensuring that, with 'with trading' policy, protected environmental values are associated with outflows to the Mediterranean.

Table 2 presents water use (ET) in irrigation by district, season, and policy for a five year average. Overall, the table shows that higher flows associated with a water trading policy are incurred to support higher crop water use from that policy, especially for the Behera and Mahmodia Districts. Moreover, that increased crop water use is especially pronounced during summer. The table shows a decrease in agricultural water use of around 10%, averaged over the seasons, for Upper and Middle Egypt, occurring under a water trading policy. This reduction in water use occurs because of a typically lower economic value of water use in Upper and Middle Egypt farming compared to the value of water used for irrigation in Lower Egypt.

For Lower Egypt, water use under a water trading policy decreases by about 10% in the *nili* season for most areas, compared to historical water use patterns. However, during winter, water use increased for Nasser, Mahmodia, and Alsalam areas, while it decreased for the rest of the areas under the water trading policy, when compared to without trading base condition. The largest increase in water use under water trading occurred at the Alsalam and Mahmodia areas, increasing by 122% and 49% in winter and summer respectively. Mahmodia and Alsalam Districts are major supply sources for fresh produce exported to European markets, as well as supplying fresh food for mega cities like Cairo and Alexandria. These regions produce much higher farm income per unit of land and water than income produced in other regions or seasons. Water use increases are shown for Nasser, Behera, and Mahmodia Districts, all major fresh produce irrigating areas, under a with trading policy during summer. Water use decreased for the remainder of irrigated areas at this region during summer.

Table 3 shows patterns of water storage volumes for Lake Nasser, Egypt's largest reservoir, for the same two policy comparisons. It shows water storage volume as well as evaporation by season, year, and policy. Overall, higher reservoir storage volumes are required to support with water trading policy in the *nili* and winter seasons. These higher storage volumes are carried over to support higher summer crop water use throughout the country. Under with trading policy, water is allocated to crop production and away from evaporation that would have otherwise been brought about by high summer reservoir storage.

Table 3 shows that a with water trading policy has no major effect on the storage volume level of water in Lake Nasser for any season or year. Storage volumes for the much smaller Lake Nile are not shown. Each of the two reservoirs was constrained to have a terminal period storage volume at least as high in each year and season under trading water policy as actually occurred for the same year and season for the base policy. In general, results showed reduced overall evaporation by very small increases in water storage in winter compared to summer and *nili*. Table 3 also shows estimated evaporation for Lake Nasser by year, season, and policy. These results illustrate small changes in evaporation losses at Lake Nasser over time from without water trading to with water trading management for all seasons. Total evaporation per year is about 8.388 billion cubic meters under both policy alternatives, slightly less than existing estimates.

### *Land in Production*

Table 4 presents the results of cropland by irrigation region, season, crop class, and policy. In general, it emphasizes the importance of water reallocated to increase fresh produce supply

**Table 2.** Nile River water use in agriculture by irrigation district, season, and policy, Egypt, in million cubic meters, 5 year average.

Irrigation District	Region in Egypt	Winter			Summer			Nili		
		Without trading	With trading	% Change	Without trading	With trading	% Change	Without trading	With trading	% Change
Toshka	Upper	110	99	-10	0	0	0	9	8	-11
Asfon	Upper	165	148	-10	775	698	-10	31	28	-10
Kelabia	Upper	123	111	-10	286	257	-10	19	17	-11
W_Naghammadi	Upper	789	710	-10	2,054	1,849	-10	30	27	-10
E_Naghammadi	Upper	468	421	-10	795	716	-10	18	16	-11
Ibrahimia	Middle	2,303	2,138	-7	3,845	3,491	-9	507	456	-10
Ismailia	Middle	132	119	-10	90	82	-9	7	6	-14
Nasser	Lower	629	653	4	1,168	1,326	14	84	76	-10
Behera	Lower	1,094	1,074	-2	1,345	1,592	18	83	75	-10
Menufia	Lower	1,405	1,331	-5	3,182	2,908	-9	97	87	-10
Mahmodia	Lower	1,065	1,181	11	2,640	3,942	49	68	62	-9
Tawfikia	Lower	2,750	2,577	-6	5,187	5,044	-3	99	89	-10
Alsalam	Lower	67	149	122	379	342	-10	25	23	-8

**Table 3.** Water storage volume and evaporation for Lake Nasser by season, year, and policy, Nile River basin, Egypt, in million cubic meters per season.

	Years	Winter			Summer			Nili		
		Without trading	With trading	% Change	Without trading	With trading	% Change	Without trading	With trading	% Change
Lake Nasser volume	1	140,000	140,000	0.0	140,842	140,891	0.0	138,777	138,933	0.1
	2	141,502	142,173	0.5	142,297	142,333	0.0	140,217	140,359	0.1
	3	142,920	143,577	0.5	143,671	143,694	0.0	141,576	141,706	0.1
	4	144,257	144,903	0.4	144,967	144,978	0.0	142,859	142,977	0.1
	5	145,520	146,153	0.4	146,190	146,190	0.0	144,070	144,176	0.1
Lake Nasser evaporation	1	2,241	2,241	0.0	4,508	4,510	0.0	1,466	1,468	0.1
	2	2,265	2,275	0.4	4,555	4,556	0.0	1,481	1,483	0.1
	3	2,287	2,298	0.5	4,599	4,600	0.0	1,496	1,497	0.1
	4	2,309	2,319	0.4	4,640	4,641	0.0	1,509	1,510	0.1
	5	2,329	2,339	0.4	4,680	4,680	0.0	1,522	1,523	0.1

**Table 4.** Land in production by irrigation district, crop class, season, and policy, Nile River basin, Egypt, 1000 ha/year, 5 years average.

Irrigation district	Region in Egypt	Seasons						Crop categories					
		Winter		Summer		Nili		Vegetables		Fruits		Grains and fiber and other crops	
		Without trading	Change with trading %	Without trading	% Change with trading	Without trading	% Change with trading	Without trading	% Change with trading	Without trading	% Change with trading	Without trading	% Change with trading
Toshka	Upper	20	-10	0	0	2	-10	1	-10	0	-10	21	-10
Asfon	Upper	32	-10	55	-10	5	-10	16	-10	3	-10	73	-10
Kelabia	Upper	24	-10	30	-10	3	-10	13	-10	2	-10	42	-10
W. Naghammadi	Upper	137	-10	271	-10	4	-10	113	-10	14	-10	286	-10
E. Naghammadi	Upper	84	-10	110	-10	3	-10	41	-10	0	-10	156	-10
Ibrahimia	Middle	495	-6	479	-9	96	-10	174	4	57	-10	839	-10
Ismailia	Middle	28	-10	10	-10	1	-10	4	-9	4	-10	31	-10
Nasser	Lower	165	-1	158	19	18	-10	98	41	87	2	156	-10
Behera	Lower	275	-4	210	20	19	-10	78	76	39	20	387	-10
Menufia	Lower	340	-7	320	-8	21	-10	42	12	17	45	622	-10
Mahmodia	Lower	260	4	323	71	16	-10	137	184	53	50	409	-10
Tawfikia	Lower	673	-7	651	0	22	-10	139	45	75	-2	1,132	-10
Alsalam	Lower	16	81	45	-10	5	-10	9	-7	47	20	9	-10

with water trading policy. Under that policy, greater amounts of water pass through Upper and Middle Egypt to make way for additional water delivered to Lower Egypt. Grains, fiber, and other crops show a general decline throughout Egypt under the water trading policy. This pattern again reflects the reduced economic value of water when used for staples, compared to a considerably higher value of water used to grow fruits and vegetables.

Results illustrate that irrigated land cultivated for grains and fibre decrease for all regions under water trading policy. This decrease occurred for all districts across Egypt and did not exceed 10%. For fruit crops, the change in irrigated cropland under the water trading policy was much different. While some regions would see a significant increase in irrigated cropland under with water trading arrangement, others show a reduction in irrigated cropland. The greatest increase in irrigated cropland occurred in Mahmodia and Meunfia, by about 50% and 45% respectively. Moreover, the Lower Egypt districts showed large gains in irrigated land in production under water trading management, with the exception of the Tawfikia region, which showed a small reduction in irrigated land mentioned policy. In contrast, all Middle and Upper Egypt districts experienced 10% reductions in irrigated cropland under the water trading policy.

For vegetables, irrigated land decreased for all Upper Egypt districts with the water trading policy. The decrease occurred by 10% at all regions. In the Middle Egypt districts, while vegetable land increased slightly in Ibrahimia, it decreased by 9% at Ismailia under the water trading policy. Some districts gained considerably for irrigated vegetable production in Lower Egypt. The highest increase occurred at Mahmodia District, followed by smaller amounts at Behera, Tawfikia, Nasser, and Meunfia Districts, while a 7% reduction occurred at Alsalam District.

Cropland in production by season and policy are shown also in Table 5. It shows a general pattern of reduced cropland in production in winter under water trading, making way for much larger summer cropland under production for Lower Egypt, with special emphasis on the importance of the heavy produce suppliers of Behera and Mahmodia Districts. The table's results illustrate that the change in irrigated land in production varies widely by season and region. Irrigated land decreased for all regions during the *nili* season under water trading arrangement. Those reductions occurred by similar percentages, about 10%, for all seasons in Upper and Middle Egypt. The irrigated land decreased for all seasons under the improved policy compared to the base year, where the farmers mostly irrigate low valued crops such as grain and fibre, and clover crops. The reduction in irrigated land ranged from 6–10% for most areas under water trading policy.

In Lower Egypt, some irrigated regions showed increases in irrigated land under water trading policy, while others showed a reduction in irrigated land for both winter and summer seasons. Growth in irrigated land during winter ranged from 81% for Alsalam District and 4% for Mahmodia District. This increase in cropped land could be explained by the domination of high valued crops like fruits and vegetables at these areas.

### *Farm Income*

Table 5 presents the results of farm income by irrigation district, crop class, season, and policy. Overall, the table reveals similar results to those shown in Tables 1–4. This reaffirms the significance of with water trading policy that would encourage growth in Lower Egypt for fresh produce, with an attendant reduction in water allocated to staples throughout the country. The table shows Lower Egypt to be very productive for fruits and



**Table 5.** Farm income by irrigation district, crop class, season, and policy, Nile River basin, Egypt, US\$ million/year 5 year average.

Irrigation district	Region in Egypt	Seasons categories						Crops categories					
		Winter		Summer		Nili		Vegetables		Fruits		Grains & fibre and other crops	
		Without trading	Change with trading %	Without trading	Change with trading %	Without trading	Change with trading %	Without trading	Change with trading %	Without trading	Change with trading %	Without trading	Change with trading %
Toshka	Upper	20	-10.62	0	0.00	3	-12.50	1	-0.17	0	0.00	21	-2.10
Asfon	Upper	37	-9.81	117	-10.04	5	-9.68	60	-9.83	8	-11.36	91	-9.96
Kelabia	Upper	30	-10.08	62	-9.83	3	-10.15	50	-10.14	5	-10.34	41	-10.30
W. Naghammadi	Upper	150	-9.92	593	-10.01	7	-9.76	454	-9.97	35	-9.95	261	-9.97
E. Naghammadi	Upper	94	-9.98	219	-9.98	2	-7.69	178	-10.03	2	-10.20	136	-9.90
Ibrahimia	Middle	558	0.78	741	-7.10	108	-10.20	475	7.21	155	-10.01	777	-10.00
Ismaïlia	Middle	30	-9.83	18	-8.82	2	-16.67	10	-7.14	11	-9.23	29	-10.30
Nasser	Lower	147	37.84	375	49.93	29	-9.64	194	114.08	223	14.58	134	-10.22
Behera	Lower	252	19.17	340	81.47	29	-9.70	180	169.42	106	48.76	335	-10.41
Menufia	Lower	350	5.85	327	0.96	12	-9.86	53	68.42	49	90.71	587	-10.01
Mahmodia	Lower	292	53.20	645	188.35	20	-10.43	404	310.67	155	97.74	398	-10.11
Tawfikia	Lower	679	1.52	780	29.29	22	-9.52	218	152.01	191	6.77	1,073	-10.09
Alsalam	Lower	29	246.99	111	-9.94	7	-9.52	15	-4.76	127	48.01	6	-12.50
Total/Average		2,669	12.38	4,326	40.35	251	-9.94	2,290	92.06	1,067	31.12	3,868	-10.00

vegetables and, with water trading policy in this region, has considerable potential to produce large increases in Egypt's farm income.

Table 5 also shows farm income split out by season rather than by crop class. The results show that farm income under water trading policy would decrease by almost 10% for most of Upper Egypt's areas, in all seasons. For Middle Egypt, farm income would decrease for all seasons, except for a slight increase for Ibrahimia District in winter. For Lower Egypt, farm income would decrease by 10% in the *nili* season for all districts under water trading arrangement. However, farm income increases for both winter and summer seasons for all nodes except Alsalam District in summer, which decreased by almost 10% under trading policy implication.

### Policy Implications

Flexible management of water resources is essential to sustain the culture and economic activity in the world's dry regions. The economic and cultural future of the Nile basin's residents, both inside and outside Egypt, will rely on the development of resilient institutions for adapting to unexpected changes in future water supplies or demands. These institutions will need to smooth the adaptation to future climate change, growing population, and emerging agreements on the sharing of the Nile basin's waters.

Irrigators who are armed with better information on price of tradable water can make more informed decisions on crop selection, water application rates on cropped areas, and irrigation technology, as well as the type and use of non-water inputs like fertilizers, new crop varieties, capital and labour. For climate and political reasons, Egypt is likely to receive no more than its current 55.5 billion cubic meters per year of the Nile's waters for the foreseeable future. So, despite its growing population, movement to democracy, and growing industrial base, Egypt faces the challenge of making better use of its existing water supplies.

The methods used for our analysis of Egyptian water policy provide promising tools to inform future water policy debates. The integrated basin framework presents a comprehensive approach for tracking water use among locations, time periods, and crops. Moreover, it has the potential to be a versatile framework for addressing water use and water policy where there are multiple competing uses, such as hydropower, urban use, irrigation, and environmental uses. Our catchment scale framework considers all irrigation water users and seasons in Egypt. The framework accounts for the storage volume for the main reservoirs as well. Moreover, our framework accounts for some of Egypt's most important hydrological, institutional, urban, and environmental constraints.

The results illustrate the importance of water trading as a low cost measure to increase the national farm income produced by existing irrigation water used in Egypt. Findings from the analysis indicate that limited adjustments to existing irrigation water use patterns, motivated by mutually beneficial trades among buyers and sellers, could raise the efficiency by which water is used in irrigated agriculture. Requiring that 90% or more of current land in production stays in production in the face of water trading protects all regions' agriculturally-related industry, while increasing national income from farm production by 28% per year. Both sellers and buyers of traded water stand to benefit: water buyers increase their farm income by moving water from lower to higher valued crops; and those who trade water for cash gain from the value of the traded water exceeding the current value in irrigated agriculture. Some of those receipts could be invested in water-conserving irrigation technologies.

The results showed that, under limited water trading, water use that currently occurs at some locations and crops in Upper and Middle Egypt moves toward more economically-productive crops and regions in Upper Egypt. In addition, a water trading programme will move water from low-valued grains and fibre crops to more commercially-valued crops, such as vegetables and fruits. The findings highlight the urgent need for more innovative measures to reduce the planting of highly water-using crops like the rice and sugar cane crops that dominate Upper Egypt and parts of Lower Egypt. Nevertheless, despite the potential gains from water trading, Egypt's current water distribution system is not well-suited to implement water trading. Volumetric pricing of water, supported by a more efficient physical distribution system, could reduce important current constraints to water trading in Egypt (NWRP, 2005).

Integrated river basin management (IRBM) tools, such as the one developed for this paper, are a powerful way to analyze proposals for re-allocating the Nile's flows among the Nile basin countries. Put into the right hands at the right time, IRBM could support the discovery of mutually beneficial water development, allocation, or trading proposals of the kind currently under debate among basin's countries. The IRMB framework, currently limited to Egypt, could be expanded to include other countries as a step for national basin co-operation, helping to mitigate conflicts in the basin.

The analysis described in this paper has several limits, all pointing to the need for continued work. Economic benefits from water uses outside agriculture are not directly measured. These uses include hydropower, urban and domestic use, recreation, ground-water recharge, and environmental uses, all of which are important. This study also performed no analysis of the technical, financial, or institutional requirements needed to establish or sustain water trading. It also did not directly address the methods to communicate to stakeholders the gains from water trading. Egyptians are demanding a growing voice in the nation's future, and therefore Egyptian water stakeholders will need to be consulted before water trading can be initiated on a large scale.

Looking to the future, a more detailed analysis of the potential benefits of reclaimed land currently not being used for agriculture would address a number of questions currently being posed in Egypt (NWRP, 2005). Additional constraints addressing Egypt's food security and employment should be examined. Water reallocations resulting from the implementation of water trading will likely reduce domestic production of food staples that will otherwise need to be imported into Egypt. For farmers who reduce their water use by trading it for cash, income earned from agricultural production will decline, even though their total income will increase because of water sold, rented, leased, or lent. Especially for high water-using crops in Upper Egypt, regional income and employment generated from food production can be negatively affected by water exports. A more comprehensive analysis than the one conducted for this paper would support a more powerful policy analytic capacity.

It is hoped that the methods of analysis will be improved. While not known for certain, it appears that Egypt's irrigation policymakers can be better informed by the use of a new method of analysis known as 'positive mathematical programming' (PMP). PMP outperforms conventional optimization methods in predicting current crop production, crop yields, farm income, and water use. It also avoids unexpected large changes in predicted crop production and crop water uses in the face of the kinds of changes in policies or water supplies that are likely to occur in future years.

Integrating hydropower, recreation, urban, and environment uses into a single framework makes for a more comprehensive analysis of policy proposals. There is great promise from the use of integrated basin framework as a tool to communicate among all the basin's countries as they debate their future economic and development process (DCBTANBC, 2007). Financial, trade, and infrastructure policy could be included in the future models to evaluate the potential benefits and consequences of wider co-operation among the Nile basin countries.

## **Conclusions**

Worldwide, the potential amount of water that could be conserved in agriculture and the best measures to achieve that conservation are matters of long standing debate. Water conservation strategies in Egypt typically avoid promotion of water-conserving irrigation technologies like sprinkler or drip irrigation, because widespread implementation of these measures will reduce return flows to the river and may even increase the overall water consumed in irrigation, as a result of their higher crop yields. Rather, most irrigation conservation measures in Egypt address the problem of farmers lacking control of the timing, duration, and amount of water supply, irrigating too early and over-applying water. In fact, over-irrigation can be an economically rational measure to reduce the risk of future supplies coming at the wrong time or in the wrong quantity. A bank of water stored in the soil profile is an on-farm measure to guard against the risk of unreliable future surface supplies.

The aim of this study was to identify the economic and hydrological impacts of potential adjustments in Egypt's water and land use patterns in irrigated agriculture that could occur under a policy of limited water trading. Like other analyses of ways to improve the performance of irrigation water management conducted in recent years, the findings of this study indicate that water re-allocation over time, space, and crops could increase overall economic performance of Egyptian irrigated agriculture. The goals were achieved by examining the economic potential that could arise from a special form of water conservation in Egyptian irrigated agriculture. It identified potential gains in national farm income that could result from a better use of existing Nile River water supplies in Egypt for crop irrigation. It reached several conclusions:

- better allocation of water among crops, seasons, and locations in Egypt has the potential to increase national farm income by about 28% per year with existing water supplies and with no change in existing irrigation technologies;
- the increased potential economic growth earned in irrigated agriculture could be achieved with no irrigated region exporting any more than 10% of its current water use for cash in any time period;
- it was not possible to identify which policies or institutions provide the best road map to improve the economic performance of Egypt's crop irrigation. However, water trading is one institution that could establish the right incentives to move water from current- to higher-valued uses in irrigation; and
- a system of water rights must be in place for water trading to be successful in moving water to higher-valued uses. Because of the lack of a formal system of adjudicated water rights consistently administered throughout Egypt, a cap-and-trade like arrangement such as the one described by Speed (2009) has the potential to perform important functions. It could serve the dual roles of the

beginnings of a workable water right system as well as a mechanism to move water from lower-valued to higher-valued times, locations, and crops.

By accounting for all major sources and uses of water for Egypt's share of the Nile River, this study has taken a modest first step at a comprehensive hydrologic and economic framework that can be used by water managers and policy makers. The methods and results described in this analysis can assist water policy makers in Egypt, and elsewhere, in the search for policies consistent with economic goals that are compatible with hydrological, cultural, and environmental constraints.

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### References

- Abu-Zied, M. A. & El-Shibini, F. Z. (1997) Egypt's High Aswan Dam, *Water Resources Development*, 13(2), pp. 209–217.
- Ali, A. M., Van Leeuwen, H. M. & Koopmans, R. K. (2001) Benefits of drainage agricultural land in Egypt: results of five years' monitoring of drainage effects and impacts, *International Journal of Water Resources Development*, 17(4), pp. 633–664.
- Allen, J. A. (1992) Substitutes for water are being found in the Middle East and North Africa, *GeoJournal*, 28(3), pp. 375–385.
- Arsano, A. & Tamarat, I. (2005) Ethiopia and the eastern Nile Basin, *Aquatic Sciences*, 67, pp. 15–27.
- Attia, B. B. (2004) Water as a basic human right in Egypt, *Global Issue Papers*, 11(1), pp. 36–59.
- Brooke, A., Kendrick, D. & Meeraus, A. (1988) *GAMS — A User Guide* (Beaconsfield: Scientific Press).
- Butts, M. B., Payne, J. T., Kristensen, M. & Madsen, H. (2004) An Evaluation of the Impact of Model Structure on Hydrological Modelling Uncertainty for Streamflow Simulation, *Journal of Hydrology*, 298, pp. 242–266.
- CAPMS (2008) Central Agency for Public Mobilisation and Statistics, Egypt. Available at <http://www.msrinta.net.capmas.gov.eg/pls/fdl/ab2?lang=1&lname=free> (accessed 11 August 2011).
- Cascão, A. E. (2009) Changing power Relations in the Nile River basin: Unilateralism vs. Cooperation, *Water Alternatives*, 2(2), pp. 245–268.
- Doherty, J. & Johnston, J. M. (2003) Methodologies for Calibration and Predictive Analysis of a Watershed Model, *Journal of the American Water Resources Association*, 39, pp. 251–265.
- Drake, C. (1997) Water resource conflicts in the Middle East, *Journal of Geography*, 96, pp. 4–12.
- DCBTANBC (2007) Development of Cross Border Trade Among Nile Basin Countries: A Scoping Study, Nile Basin Initiative, Socio-Economic Development and Benefit Sharing Project.
- Elarabawy, A. & Toswell, P. (2000) Integrated water resources management for Egypt, *Water Supply Research and Technology*, 49(3), pp. 111–125.
- Elarabawy, M., Attia, B. & Toswell, P. (1998) Water resources in Egypt: strategies for the next century, *Journal of Water Resources Planning and Management*, 124(6), pp. 310–319.
- Elarabawy, M. & Toswell, P. (1998) An appraisal of the Southern Valley development project in Egypt, *Aqua*, 47(4), pp. 167–175.
- El-Fadel, M., El-Sayegh, Y., El-Fadl, K. & Khorbotly, D. (2003) The Nile River basin: a case study in surface water conflict resolution, *Journal of Natural Resources and Life Sciences Education*, 32, pp. 107–117.
- FAO (1995) Food and Agricultural Organization. Irrigation in Africa Figures. Available at <http://www.fao.org/docrep/v8260b/v8260b0p.htm> (accessed 1 July 2011).
- Gohar, A. A. & Ward, F. A. (2010) Gains from expanded irrigation water trading in Egypt: an integrated basin approach, *Ecological Economics*, 69, pp. 2535–2548.
- Hamad, O. E. & El-Battahani, A. (2005) Sudan and the Nile Basin, *Aquatic Sciences*, 67, pp. 28–41.
- He, L. W. T. & Siam, G. (2004) *Improving Irrigation Water Allocation Efficiency Using Alternative Policy Options in Egypt* (Denver, CA: American Agricultural Economic Association).

- Hefny, M. & Amer, S. (2005) Egypt and Nile basin, *Aquatic Sciences*, 67, pp. 42–50.
- Hvidt, M. (1998) *Water, Technology, and Development: Upgrading Egypt's Irrigation System* (London: Tauris Academic Studies).
- Janssen, P. H. M. & Heuberger, P. S. C. (1995) Calibration of process-oriented models, *Ecological Modelling*, 83, pp. 55–66.
- Kandil, H. M. (2003) Institutional reform vision for the irrigation sector in Egypt, *Water Resources Development*, 19(2), pp. 221–231.
- Karvonen, T., Koivusalo, H., Jauhiainen, M., Palko, J. & Weppling, K. (1999) A hydrological model for predicting runoff from different land use areas, *Journal of Hydrology*, 217, pp. 253–265.
- Kung, R. (2003) Addressing the dimensions of transboundary water use - The Nile basin initiative, *Mountain Research and Development*, 23, pp. 4–6.
- Laki, S. L. (1998) Management of water resources of the Nile Basin, *International Journal of Sustainable Development and World Ecology*, 5, pp. 288–296.
- Legesse, D., Vallet-Coulomb, C. & Gasse, F. (2003) Hydrological response of a catchment to climate and land use changes in tropical Africa: case study south Central Ethiopia, *Journal of Hydrology*, 275, pp. 67–85.
- Madsen, H., Wilson, G. & Ammentrop, H. C. (2002) Comparison of different automated strategies for calibration of rainfall-runoff models, *Journal of Hydrology*, 261, pp. 48–59.
- Mainuddin, M., Kirby, M. & Qureshi, E. (2007) Integrated hydrologic-economic modelling for analyzing water acquisition strategies in the Murray River basin, *Agricultural Water Management*, 93(3), pp. 123–135.
- Malashkhia, N. (2003) Social and environmental constraints to the irrigation water conservation measures in Egypt, Master thesis (unpublished), Lunds University, Lund, 2003.
- Mason, S. A. (2005) Are we scorpions? The role of upstream-downstream dialogue in fostering cooperation in the Nile Basin, *Mountain Research and Development*, 25, pp. 115–120.
- Mekonnen, D. Z. (2010) The Nile Basin Cooperative Framework Agreement negotiations and the adoption of a 'water security' paradigm: flight into obscurity or a logical cul-de-sac? *European Journal of International Law*, 21, pp. 421–440.
- Merz, R. & Blöschl, G. (2004) Regionalisation of catchment model parameters, *Journal of Hydrology*, 287, pp. 95–123.
- Ministry of Agriculture and Land Reclamation (MALR) (2008) *Agricultural Statistics*. Sector of Economic Affairs. Arab Republic of Egypt, Cairo.
- Mouratiadou, I. & Moran, D. (2007) Mapping public participation in the water framework directive: a case study of the Piniös River basin, Greece, *Ecological Economics*, 62(1), pp. 66–76.
- Muleta, M. K. & Nicklow, J. W. (2005) Sensitivity and uncertainty analysis coupled with automatic calibration for a distributed watershed model, *Journal of Hydrology*, 306, pp. 127–145.
- Nasser, M. A. & Allam, G. I. (2007) Water resources in Egypt: Future challenges and opportunities, *Water International*, 32(2), pp. 205–218.
- NWRP (2005) *Water For the Future*. (Cairo: MWRI Planning Sector, Ministry of Water Resources and Irrigation).
- Prairie, J. R. (2006) Stochastic nonparametric framework for basin wide streamflow and salinity modeling: Application for the Colorado River basin, Ph.D. thesis (unpublished), University of Colorado, 2006.
- Ringler, C. (2001) Optimal water allocation in the Mekong River basin, *Zef Discussion Papers on Development Policy No. 38* (Bonn, Germany: Centre for Development Research).
- Rosegrant, M. W., Ringler, C., McKinney, D. C., Cai, X., Keller, A. & Donoso, G. (2000) Integrated economic-hydrologic water modelling at the basin scale: the Maipo River basin, *Agricultural Economics*, 24, pp. 33–46.
- Simonovic, S. P., Fahmy, H. & El-Shorbagy, A. (1997) The use of object-oriented modeling for water resources planning in Egypt, *Water Resources Management*, 11, pp. 243–261.
- Singh, V. P. & Woolhiser, D. A. (2002) Mathematical modeling of watershed hydrology, *Journal of Hydrologic Engineering*, 7, pp. 270–292.
- Sophocleous, M. A., Koelliker, J. K., Govindaraju, R. S., Birdie, T., Ramireddygar, S. R. & Perkins, S. P. (1999) Integrated numerical modeling for basin-wide water management: the case of the Rattlesnake Creek basin in South-Central Kansas, *Journal of Hydrology*, 214, pp. 179–196.
- Speed, R. (2009) Transferring and trading water rights in the People's Republic of China, *International Journal of Water Resources Development*, 25, pp. 269–281.
- Stavins, R. N. (2008) A meaningful US cap-and-trade system to address climate change, *Harvard Environmental Law Review*, 32, pp. 293–371.

- Strzepek, K. M., Yohe, G. W., Tol, R. S. J. & Rosegrant, M. W. (2008) The value of the High Aswan Dam to the Egyptian economy, *Ecological Economics*, 66, pp. 117–126.
- Swain, A. (2008) Mission Not yet accomplished: managing water resources in the Nile River basin, *Journal of International Affairs*, 61(2), pp. 201–214.
- Wahba, M. A. S., Christen, E. W. & Amer, M. H. (2005) Irrigation water saving by management of existing subsurface drainage in Egypt, *Irrigation and Drainage*, 54, pp. 205–215.
- Ward, F. A. & Pulido-Velazquez, M. (2008) Efficiency, equity, and sustainability in a water quantity-quality optimization model in Rio Grande basin, *Ecological Economics*, 66(1), pp. 23–37.
- Wegerrich, K. (2004) Coping with disintegration of a river-basin management System: multi-dimensional issues in central Asia, *Water Policy*, 6, pp. 335–344.
- Wichelns, D. (2002a) An economic perspective on subsurface drainage programmes in developing countries, with an example from Egypt, *Water Resources Development*, 18(3), pp. 473–485.
- Wichelns, D. (2002b) Economic analysis of water allocation policies regarding Nile River water in Egypt, *Agricultural Water Management*, 52, pp. 155–175.
- Wichelns, D. (2004) The role of virtual water in efforts to achieve food security and other national goals, with an example from Egypt, *Agricultural Water Management*, 49(2), pp. 20–50.
- Wu, X. & Whittington, D. (2006) Incentive compatibility and conflict resolution in international river basins: A case study of the Nile Basin, *Water Resources Research*, 42, W02417, doi:10.1029/2005WR004238.
- Yapo, P. O., Gupta, H. V. & Sorooshian, S. (1998) Multi-objective global optimization for hydrologic models, *Journal of Hydrology*, 204, pp. 83–97.