ALLOCATING WATER EFFICIENTLY IN THE PRESENCE OF RETURN FLOW EXTERNALITIES
A THEORETICAL ANALYSIS OF KEY ELEMENTS OF THE EGYPTIAN IRRIGATION SYSTEM

By
Birgitte Gersfelt[♣♠]
Institute of Food and Resource Economics, The Royal Veterinary and Agricultural University
and Department of Economics, The University of Copenhagen

WORK IN PROGRESS – PLEASE DO NOT QUOTE WITHOUT THE PERMISSION OF THE AUTHOR

Abstract

When water is scarce and agricultural production is dependent on irrigation, the question naturally arises how to allocate irrigation water most efficiently from society's point of view. In Egypt water scarcity is expected to be a growing problem due to population growth and reclamation of desert land for agricultural production. The Egyptian agricultural sector is the major water consumer in the Egyptian economy as crop production is virtually 100 per cent dependent on irrigation. Efficient allocation of the Egyptian irrigation water is thus becoming an important issue from an economic efficiency point of view. However, so far Egyptian farmers have not had to pay for their irrigation water, and the water allocation mechanism in place cannot ensure that the farmers always use irrigation water in a socially efficient manner.

The theoretical literature on externalities suggests that this kind of resource allocation problem could be solved through an appropriate set of tax policy instruments. The question is, though, which tax policy instruments should be used in order to ensure a socially efficient allocation of water? Standard volumetric water pricing targets the amount of water the farmer applies to his field. However, what matters from a social efficiency point of view is often not how much water is applied to the field, but rather how much water is consumed by the crops and evaporation, as a substantial amount of the water losses due to drainage and percolation tends to be recycled in a basin. This type of positive externality can be observed in many river basins around the world, including the Nile river basin in Egypt, as virtually all water losses from the Nile Valley are recovered by the basin system. This in turn has implications for the socially optimal choice of policy instrument to regulate the farmers' use of irrigation water.

The present paper presents a theoretical analysis of the efficiency properties of different water tax policy instruments in a setting characterized by recoverability of return flows from irri-gated agriculture and farmer-specific irrigation efficiency. The policy instruments, which are evaluated, include volumetric water taxes, return flow credits, and crop-specific land taxes. The results of the analysis show that a first-best allocation of irrigation water is achievable through a combination of volumetric water taxes and return flow credits, while it is not achievable in the case of a single volumetric water tax scheme or in the case of crop-specific land taxes. However, crop-specific land taxes are more likely to be practically

♣ Address: Institute of Food and Resource Economics, The Royal Veterinary and Agricultural University, Rolighedsvej 25, 1958 Frederiksberg C, Denmark. Phone: +45 35 28 68 16. Email: bg@foi.dk

♠ The author gratefully acknowledges the advice and collaboration of professor Philip Abbott on the modeling framework presented in this paper. The usual caveats apply.

implementable, as they do not depend on volumetric metering of irrigation water. When return flows are fully recoverable, the analysis shows that they may perform reasonably well although they cannot induce adaptation of water-saving production techniques for the production of a given crop.

While the analysis is conducted with reference to the features of the Egyptian irrigation system, the general results are not only relevant for Egypt, but also for other water scarce developing countries, where return flows are recycled in the river basins. Overall the analysis highlights the fact that field irrigation efficiency may actually not be that important from a water conservation point of view, and that a relatively efficient allocation need not require the ability to meter the water use of individual farmers, which may well not be possible in developing countries.

PAPER PRESENTED TO THE NORDIC CONFERENCE IN DEVELOPMENT ECONOMICS,

OSLO, JUNE 21-22, 2006

1. INTRODUCTION: EXTERNALITIES IN WATER ALLOCATION.

One of the central features in the economics of irrigation is the potential for significant externalities between different irrigators. The externalities arise due to the difficulties of assigning and enforcing property rights to irrigation water.

The perhaps most important type of externality is related to the allocation of water diversions between different irrigators. In the case of water scarcity, the supply of water is too small to meet all demands for water, and in the absence of water markets or regulatory intervention by the state, the scarce water resources are likely to be allocated inefficiently across competing irrigators. A classic example of this is the so-called head-end-tail-end problem, where irrigators at the head of an irrigation canal may have virtually unlimited access to irrigation water while irrigators at the tail end of the canal may only receive a small fraction of the water needed to cover their irrigation needs.

However, irrigators do not only take water out of the irrigation system through their water diversions, they typically also give water back to the irrigation system through return flows from their irrigation activities. Return flows arise from the fact that not all of the water applied to a field is consumed by the crops.[1] The ratio between water consumed and water applied is termed the field irrigation efficiency. If return flows from upstream irrigation activities are recovered by the river basin system, this creates another type of externality as these return flows affect the amount of water available for other irrigators downstream. Furthermore, the possibility of recycling the recovered return flows also implies that, although irrigation efficiency may be low at the individual farm level, irrigation efficiency at the river basin level may be high.

Both of these externality types clearly have implications for the degree to which scarce water resources are allocated efficiently between competing uses. However, while the policy implications of the former type are well-understood, the policy implications of the latter type of externality have not yet been fully recognized and explored. The purpose of the present analysis is therefore to analyze the efficiency properties of different policy instruments in a situation where both types of externalities are present simultaneously.

[1] In this paper the term "crop water consumption" is equated with crop evapotranspiration. Evapotranspiration is defined as the "the combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration" (FAO 1998 chapter 1 p 1). The concept is further examined in section 2.1.

The theoretical model presented in the following sections has been constructed to capture key properties of the Egyptian irrigation system. These features include a low degree of field irrigation efficiency and a high degree of return flow recoverability in some regions of the country. The low degree of field irrigation efficiency implies that farmers apply substantially more water to their fields than is consumed by their crops. The high degree of return flow recoverability implies that a high fraction of the apparent water losses are subsequently recovered by the river basin system thus making them available for additional diversion cycles. The combination of these two features, and the fact that the generation and allocation of return flows are not regulated efficiently, implies the presence of the return flow externality.[2]

As for the externality related to allocation of water diversions, this is also present in Egypt as there is no mechanism in place to regulate the individual farmer's appropriation of water. Apart from pumping costs farmers do not pay directly for their irrigation water. Furthermore, although the centralized water allocation system does imply some kind of quota scheme for allocating water between different regions, the traditional irrigation infrastructure in the Old Lands has not allowed for a quota scheme to be implemented at the individual farmer level. In other words, following the liberalizations of the Egyptian agricultural policies in the early 1990s, there has not been a policy scheme in place, which could ensure an efficient allocation of the country's fixed water resources.

The inefficiencies arising from externalities can be ameliorated through different types of policy interventions including taxes and quotas. The present analysis will focus on the tax policy instruments. The aim of the analysis is to ascertain to what extent the different policy instruments are able to ensure an efficient allocation of irrigation water. This is done by formulating the water allocation problem from the point of view of the social planner and an individual farmer and then comparing the first order conditions of these two problems. The following sections will first present the social planner's problem. Subsequently, the individual farmer's problem is presented under three different tax policy scenarios: Pricing of water

[2] Use of drainage water for irrigation is not allowed in Egypt without permission from the Ministry of Irrigation, which uses certain criteria for water salinity to determine whether or not drainage water is suitable for reuse (Bader 2004 p 26). However, Egyptian farmers' unofficial reuse of drainage water is substantial (Mohamed 2001 p 8 and Bader 2004 p 26). This aspect will not be included in the model analysis in section 2 and 3, but it will be addressed in the discussion in section 4.

diversions and crediting of return flows, only pricing of water diversions, and finally crop-specific land taxation.

2. SOCIETY'S POINT OF VIEW: THE SOCIAL PLANNER'S PROBLEM

The theoretical model, which has been constructed specially for this analysis of the efficiency of different water policy instruments, is formulated as a linear programming problem in line with the agricultural sector model tradition. The model is static and deterministic and thus disregards any dynamic aspects and issues arising due to uncertainty. As the model is tailored specifically to the aforementioned water policy issues, it is highly stylized in its specification of elements not directly related to water application, consumption, and recycling.

2.1. THE SOCIAL PLANNER'S PROBLEM - MODEL SPECIFICATION

The general objective of the social planner is to maximize social welfare subject to the resource constraints facing the economy. In this analysis it is assumed that the social planner's objective can be achieved by maximization of social efficiency under due consideration of farmers' irrigation efficiency and the general recoverability of return flows.[3] The social planner's problem for a given region is consequently specified as follows:

$$\max_{X_{ijk}} \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}(y_{ijk}P_i - z_{ijk}C_Z)X_{ijk}$$

Subject to:

$$X_{ijk} \geq 0 \qquad \text{for all } i=1,...,I,\ j=1,...,J, \text{ and } k=1,...,K$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K} X_{ijk} = \overline{X}_j \qquad \text{for all } j=1,...,J$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}(e_{ik} + (1-\beta)(d_{ijk} - e_{ik}))X_{ijk} \leq \sum_{j=1}^{J}(\overline{E}_j + \overline{F}_j)$$

Where:[4]

[3] The assumption that maximization of social welfare can be achieved through maximization of efficiency presupposes that efficiency issues can be separated from equity considerations. This would be possible if the assumptions behind the second welfare theorem were fulfilled.

[4] Comment on notation:

- i : Index of crops, $i = 1,...,I$.
- j : Index of farmers, $j = 1,...,J$.
- k : Index of water-yield production techniques, $k = 1,...,K$.

- P_i : Price of crop i, measured in LE/ton.[5]
- C_Z : Cost of purchased inputs Z, measured in LE/ton.
- X_{ijk} : Size of area cultivated with crop i by farmer j using production technique k. X_{ijk} is measured in feddan.[6]
- $\overline{X}_j$: Farmer j's landholding in the base period, measured in feddan.
- $\overline{E}_j$: The amount of water evapotranspired by farmer j's production in the base period, measured in cubic meters. $\overline{E}_j = \sum_{i=1}^{I} \sum_{k=!}^{K} e_{ik} \overline{X}_{ijk}$.
- $\overline{F}_j$: The amount of water losses from farmer j's production, which do not return to the river basin system in the base period, measured in cubic meters. $\overline{F}_j = \sum_{i=1}^{I} \sum_{k=1}^{K} (1-\beta)(d_{ijk} - e_{ik}) \overline{X}_{ijk}$.

- y_{ijk} : Yield of crop i per area unit for farmer j when using production technique k. y_{ijk} is measured in ton/feddan.
- z_{ijk} : Amount of input Z per area unit used for production of crop i by farmer j using production technique k. z_{ijk} is measured in ton/feddan.
- e_{ik} : Amount of water evapotranspired (or "consumed") per area unit by crop i produced using production technique k. e_{ik} is measured in cubic meters/feddan.

- Upper case Latin letters generally denote variables, such as prices or quantities, save for the letters I , J , and K , which are used for indexes.
- Lower case Latin letters denote Leontief production coefficients, save for the letters i , j , and k , which are used for indexes.
- Lower case Greek letters denote special water coefficients, which are expressed as fractions.

[5] LE is the abbreviation of Egyptian pounds.

[6] Feddan is the Egyptian measure of area size, corresponding to 0.420 hectares or 1.037 acres (World Bank 1993).

- d_{ijk} : Amount of water diverted (or "applied") per area unit for production of crop i by farmer j using production technique k. d_{ijk} is measured in cubic meters/feddan. The amount of water applied is assumed to be partially determined by the amount of water consumed in accordance with the following equation: $d_{ijk} = \frac{1}{\gamma_{ijk}} e_{ik}$

- γ_{ijk} : Field irrigation efficiency for farmer j for crop i when using production technique k, measured as the share of water applied, which is consumed by the crops. $0 \leq \gamma_{ijk} \leq 1$.
- β : Fraction of water losses (i.e. the difference between water applied and water consumed), which are recovered by the river basin system. $0 \leq \beta \leq 1$.

According to the model specification, the social planner's objective is to maximize producer surplus gross of any water charges, subject to individual land constraints and a national water constraint.[7] In order for this maximization problem to be commensurate with maximization of social efficiency, the market prices of output P_i and purchased inputs C_Z would have to correspond to the socially optimal prices of these commodities. This is assumed to be the case here as the focus is merely on the efficient allocation of water.

In order to keep the model simple, reallocation of land between farmers is not allowed, and the land constraint in the social planner's problem is consequently specified at the individual farmer level. It outlines how the sum of the individual farmer's land areas allocated to the production of different crops has to equal the farmer's landholding in the base period. The fact that the land constraint is assumed to hold for each farmer implies that each farmer is assumed to be able to produce at least one type of crop at non-negative profits. Given the fact that yields and purchased input requirements are potentially farmer-specific in this model, this is not a trivial assumption. One way of getting around this assumption would be to add fallow to the set of crops I and assume that this particular crop does not require any input nor does it produce any output.

[7] The reason why the social planner's objective is to maximize producer surplus gross of any water charges is that these water charges would accrue to the social planner himself. They consequently net out of the social planner's maximization problem.

In order to adequately capture the return flow aspect, the national water constraint is specified in terms of water consumed and water irretrievably lost, rather than water applied. In order not to augment the resource base, the total amount of water available for consumption and losses is here set to equal the level of water consumption and losses in the base period. However, it could also be fixed at any other - higher or lower – level, which was deemed socially optimal and feasible. An important caveat is the fact that the present formulation does not capture any spatial or temporal aspects of the return flows, as it simply assumes that the return flows will be available immediately at any location desired. The implications of this simplification will be examined further in the discussion section.

The model specification contains three different indexes. Index i refers to the type of crop produced, but not the way in which this crop is produced. The choice of water-yield production technique is instead indexed by k ,which captures the farmer's option to produce crops by using less than optimal amounts of water. Such a sub-optimal input of water into crop production affects both the water consumption and yield of the crop, and it may also affect the amount of other inputs used in production of the crop. Index j captures the farmer specific features of production including those which are determining for the field irrigation efficiency. Examples of such features are soil type, land preparation, and irrigation technique (i.e. surface irrigation, sprinkler irrigation, or drip irrigation).

Field irrigation efficiency is captured by the parameter γ_{ijk} . It is assumed to be determined by irrigation technology and soil type, which, as mentioned above, are assumed to be farmer-specific characteristics. Although the farmer does in principle have a choice between different irrigation technologies, irrigation technology is not treated as a choice variable in this model, as technical aspects of the irrigation system in the Old Lands in Egypt may leave the farmer little choice in his use of irrigation technology. This aspect of the model will be further examined in the discussion section. Apart from the farmer specific characteristics, irrigation efficiency may also depend on the choice of crops, because "excess" water is part of the production of certain crops like rice, and it may also depend on the water-yield production technique with which the crop is produced.

The field irrigation efficiency coefficient is assumed to fully capture the relationship between water consumed and water applied, as it is defined as the fraction of water applied which is

actually consumed by the crops. Water consumption of a given crop produced using a given water-yield technique is captured by the coefficient e_{ik}. Water consumed is assumed to be independent of farmer-specific characteristics, while water applied on the other hand will depend on farmer-specific characteristics as the field irrigation efficiency coefficient also depends on these characteristics. As the following analysis will show, the assumption that water consumed is independent of farmer-specific characteristics is highly important for some of the model results, and it consequently deserves some elaboration.

The amount of water consumed by a crop is in this analysis equated with the crop's evapotranspiration.[8] Evapotranspiration is defined as the "the combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration" (FAO 1998 chapter 1 p 1). The reason for combining the two concepts evaporation and transpiration in the single concept evapotranspiration is that the two processes take place simultaneously and are not easy to distinguish from one another. When the crop is small water is primarily lost due to soil evaporation, whereas transpiration is the main source of water loss once the crop is well developed and covers most of the soil (FAO 1998 chapter 1 p 2).

According to FAO evapotranspiration for a given crop (ET_c) may be calculated by multiplying reference crop evapotranspiration (ET_o) by a crop-specific coefficient (K_c). The reference crop evapotranspiration ET_o refers to the evapotranspiration of a hypothetical grass reference crop with certain characteristics including abundant availability of water. Since water is abundantly available, ET_o only depends on climatic parameters and not soil factors. By multiplying ET_o by the crop specific coefficient K_c we then get the evapotranspiration ET_c for the crop in question under standard conditions. Standard conditions implies that the crop is disease-free, well-fertilized, and grown in large fields under optimum soil water conditions. If the crop is not grown under standard conditions - due to e.g. pests and diseases, soil salinity,

[8] FAO distinguishes between the notion of evapotranspiration and crop water requirement, where the former concept refers to the amount of water that is lost through evaporation, while the latter concept refers to the amount of water required to compensate the evapotranspiration loss from the cropped field. While evapotranspiration and crop water requirement are conceptually distinct, the values for these two concepts are nonetheless identical. There is also a third concept – irrigation water requirement – which basically corresponds to the difference between the crop water requirement and effective precipitation. However, the irrigation water requirement also includes additional water for leaching and compensation for non-uniform water application (FAO 1998 chapter 1 p 8).

low soil fertility, water shortage or waterlogging - this may adversely affect the crops growth and lower its evapotranspiration rate below ET_c (FAO 1998 chapter 1 p 6 and 8).

In the present analysis, all standard conditions are assumed to be met except for the requirement of sufficient water availability. Inadequate water supply and its effect on yields are captured by the choice of water-yield technique as outlined above. It should be noted, that since this is a static one period model, the differences in crop response to water stress in different parts of the growth period are disregarded. As the effects of water stress are assumed to be captured by the k index and all other standard conditions are assumed to be met, it seems reasonable to assume that the water consumed coefficient will only depend on the type of crop and the choice of water-yield technique.[9]

In order for the return flows generated by low field irrigation efficiency to constitute an externality, they must be at least partially recoverable. In the model, the degree to which return flows are recoverable is captured by the parameter β. This fraction will typically depend upon the location of production, as the degree of recoverability may change from one region to the other depending in part on the drainage and percolation characteristics of the regions. In order to keep the model simple the present model is specified for a given region, within which drainage and percolation characteristics are assumed to be uniform across farms. It is consequently possible to capture the recoverability of return flows by the single coefficient β.

Location may also affect crop production and water use, as crop water requirements differ across agro-climatic zones. In this case location would directly affect the water consumption coefficient e_{ik} and through this also the water applied coefficient d_{ijk}. Furthermore it may also affect the set of crops I, which the farmer can chose to produce, as well as the yield coefficients y_{ijk}, and the purchased input coefficients z_{ijk}. However, as mentioned above the model is specified for a given region, which is assumed to be contained within one agro-climatic zone.

[9] Individual farmer fields in the Old Lands in Egypt are normally very small. The question is whether they are too small for the standard conditions to be valid?

The specification of water applied, water consumed, and return flows in the model focuses on the quantities of water diverted, evapotranspired, and recycled. The quality of the water, on the other hand, and the changes it undergoes in the production process are not taken into account in the policy analysis, and leaching requirements are not considered either. Possibilities for introducing water quality considerations into the model will be examined in the discussion section.

2.2. FIRST ORDER CONDITIONS FOR THE SOCIAL PLANNER'S PROBLEM.

The approach used to determine the socially optimal policy design for allocating irrigation water in the presence of return flow externalities centers on the first order conditions for the social planner's problem and the individual farmers' problems. The first order conditions are derived using the Lagrange optimization method. The Lagrange function for the social planner's problem may be written as:

$$L = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}(y_{ijk}P_i - z_{ijk}C_Z)X_{ijk} - \sum_{j=1}^{J}\lambda_{1j}[\sum_{i=1}^{I}\sum_{k=1}^{K}X_{ijk} - \overline{X}_j]$$
$$- \lambda_2[\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}(e_{ik} + (1-\beta)(d_{ijk} - e_{ik}))X_{ijk} - \sum_{j=1}^{J}(\overline{E}_j + \overline{F}_j)]$$

As some of the constraints of the optimization problem are inequalities rather than equalities the first order conditions for this optimization problem are given by the following Kuhn-Tucker conditions:[10]

$$X_{ijk} \geq 0$$

$$\frac{\partial L}{\partial X_{ijk}} = y_{ijk}P_i - z_{ijk}C_Z - \lambda_{1j} - \lambda_2(e_{ik} + (1-\beta)(d_{ijk} - e_{ik})) \leq 0$$

$$X_{ijk}\frac{\partial L}{\partial X_{ijk}} = X_{ijk}(y_{ijk}P_i - z_{ijk}C_Z - \lambda_{1j} - \lambda_2(e_{ik} + (1-\beta)(d_{ijk} - e_{ik}))) = 0$$

for all $i = 1,...,I$, $j = 1,...,J$, and $k = 1,...,K$

[10] The other conditions, which need to be fulfilled in order for the first order conditions to be sufficient conditions for optimization, is that the objective function and the constraint functions be C^1 functions, that the Lagrange function be a concave function of X_{ijk}, and that a solution $(X^*_{ijk}, \lambda^*_{1j}, \lambda^*_2)$ for all $i = 1,...,I$, $j = 1,...,J$, $k = 1,...,K$ exist (cf. Berck and Sydsæter 1992, p 75). As both the objective function and the constraints are linear in X_{ijk}, the first condition is met. The second condition is also met as the Lagrange function is also linear in X_{ijk}.

$$\frac{\partial L}{\partial \lambda_{1j}} = -[\sum_{i=1}^{I}\sum_{k=1}^{K} X_{ijk} - \overline{X}_j] = 0 \qquad \text{for all } \; j = 1,...,J$$

$$\lambda_2 \geq 0$$

$$\frac{\partial L}{\partial \lambda_2} = -[\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}(e_{ik} + (1-\beta)(d_{ijk} - e_{ik}))X_{ijk} - \sum_{j=1}^{J}(\overline{E}_j + \overline{F}_j)] \geq 0$$

$$\lambda_2 \frac{\partial L}{\partial \lambda_2} = -\lambda_2[\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}(e_{ik} + (1-\beta)(d_{ijk} - e_{ik}))X_{ijk} - \sum_{j=1}^{J}(\overline{E}_j + \overline{F}_j)] = 0$$

The first of these first order conditions is the non-negativity constraint on the activity level, which simply states that a farmer cannot allocate a negative amount of land to the production of a crop. The second condition states that the profits per area unit (defined as revenue minus costs of purchased inputs and opportunity costs of non-traded endowments) for all activities must be either zero or negative in the optimum. The third condition is a complementary slackness condition, stating that in the optimum it is not possible to have a non-zero activity level without profits per area unit being zero for this activity. Taken together these three conditions assert that a positive activity level implies that profits per area unit for the activity in question must be zero, while a zero activity level implies that profits per area unit for the activity in question are negative.

The fourth condition is simply the individual farmers' land constraint, stating that for each farmer the sum of land areas used for production activities must equal his initial land holdings.

The three last conditions relate to the water constraint. The first of these conditions states that the social planner's shadow price of water must be non-negative. As the social planner's water constraint is formulated in terms of water consumed or irretrievably lost, the social planner's shadow price of water relates to water consumed or lost. The second of these three conditions is simply the national water constraint, which states that the sum of water consumed or irretrievably lost must not be greater than the sum of water consumed or lost in the base period. The final of the three conditions is a complementary slackness condition stating that it is not possible to have a non-zero shadow price of water unless the national water constraint binds. Taken together the three conditions assert that the social planner's

shadow price of water consumed or lost will be positive if the national water constraint binds and will equal zero if the constraint does not bind.[11]

These first order conditions sum up the conditions, which have to be met, in order for the irrigation water to be allocated in a socially efficient manner. Provided the social planner cannot actually dictate the actions of the farmers, his only options for implementing the socially efficient allocation of water is to design the water allocation policy instruments in such a way as to align the individual farmer's water allocation incentives with his own water allocation incentives. The following section will present the individual farmer's production and water allocation incentives under different tax policy schemes designed to regulate the allocation of irrigation water.

3. Farmer's Point of View: The Farmer's Problem Under Different Policies

Unlike the social planner, the individual farmer is not concerned about the national water constraint. The only thing that matters to him is his own access to irrigation water and how it affects the profitability of his production.

3.1. Pricing of Water Diversions and Crediting of Return Flows - The Farmer's Problem and Associated First Order Conditions

Since the farmer's unregulated use of irrigation water gives rise to two types of externalities, it should be possible to achieve a socially optimal allocation of irrigation water by using two policy instruments which each targets one of the externalities.

As the first type of externality from irrigation water allocation is associated with the diversions of irrigation water, a tax is placed on the amount of irrigation water diverted by each farmer. The second type of externality is associated with return flows. As only quantity – not quality – of water is considered in this model, recoverable return flows constitute a positive externality. A credit is consequently introduced for the amount of return flows from

[11] However, there is also the possibility of degenerate solutions, where both elements of the complementary slackness condition equal zero in the optimum.

each farmer.[12] With these two policy instruments in place farmer j's problem can be expressed in the following way:

$$\max_{X_{ijk}} \sum_{i=1}^{I}\sum_{k=1}^{K}(y_{ijk}P_i - z_{ijk}C_Z)X_{ijk} - T_D\sum_{i=1}^{I}\sum_{k=1}^{K}d_{ijk}X_{ijk} + T_R\sum_{i=1}^{I}\sum_{k=1}^{K}(d_{ijk} - e_{ik})X_{ijk}$$

Subject to:

$$X_{ijk} \geq 0 \qquad \text{for all } i = 1,...,I \text{ and } k = 1,...,K,$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K}X_{ijk} = \overline{X}_j$$

Where:

- T_D : Price of water diversions (i.e. water applied), measured in LE/cubic meter.
- T_R : Credit for return flows, measured in LE/cubic meter.

According to this model specification, the individual farmer's objective is to maximize producer surplus including water taxes and credits, subject to his individual land constraint. The policy scheme presupposes that the social planner is able to meter or deduce not only the farmer's water diversions but also his return flows. While this would generally not be a realistic assumption, the policy scheme does serve as a useful benchmark for the other policy scheme analysed.

The Lagrange function for farmer j's problem can be written as:

$$L = \sum_{i=1}^{I}\sum_{k=1}^{K}(y_{ijk}P_i - z_{ijk}C_Z - d_{ijk}T_D + (d_{ijk} - e_{ik})T_R)X_{ijk} - \lambda_{1j}[\sum_{i=1}^{I}\sum_{k=1}^{K}X_{ijk} - \overline{X}_j]$$

The first order conditions for this maximization problem are given by the following Kuhn-Tucker conditions:

$$X_{ijk} \geq 0$$

[12] As specified here, the credit is applied to all return flows, be they recoverable or not. However, as the analysis will show, the degree of recoverability does enter into the solution. Alternatively the credit could be specified as only applying to those return flows, which are recoverable. The solution would then be adjusted accordingly (cf. the following footnote).

$$\frac{\partial L}{\partial X_{ijk}} = y_{ijk}P_i - z_{ijk}C_Z - d_{ijk}T_D + (d_{ijk} - e_{ik})T_R - \lambda_{1j} \leq 0$$

$$X_{ijk}\frac{\partial L}{\partial X_{ijk}} = X_{ijk}(y_{ijk}P_i - z_{ijk}C_Z - d_{ijk}T_D + (d_{ijk} - e_{ik})T_R - \lambda_{1j}) = 0$$

for all $i = 1,...,I$ and $k = 1,...,K$,

$$\frac{\partial L}{\partial \lambda_{1j}} = -[\sum_{i=1}^{I}\sum_{k=1}^{K} X_{ijk} - \overline{X}_j] = 0$$

Comparing these first order conditions for farmer j's problem to the first order conditions of the social planner's problem derived in section 2.2, there are obviously strong similarities. The non-negativity constraints on activity levels are trivially identical. As the model does not allow for reallocation of land between farmers, the individual farmer's land constraints are also identical. The main difference between the two sets of first order conditions is the fact that while water is treated as an endowment in the social planner's problem, it is in fact treated as a purchased input in the farmer's problem, although the price of water is a tax rate rather than a market price. The second of the first order conditions outlined above consequently states that it is the farmer's profit per area unit for a given crop and water-yield technique after deduction of the tax on water diversions and addition of the credit on return flows, which must be either zero or negative in the optimum. The third condition is again the corresponding complementary slackness condition stating that in the optimum it is not possible to have a non-zero activity level without profits per area unit being zero for this activity.

The social planner's problem basically consists of optimization problems for each of the J farmer's, which are tied together through the national water constraint. However, as water is treated as a purchased input from the farmer's point of view, the national water constraint does not appear in farmer j's problem. Instead equilibrium between national water supply and demand is assumed to be achieved through adjustment of the tax rate on water diversions and the credit rate for return flows.

In order for a socially optimal allocation of water to be implemented through taxation of water diversions and crediting of return flows, the individual farmer has to be given the same water allocation incentives as the social planner has. As the farmer's water allocation decisions are inferred from his choice of crops to produce and water-yield techniques to use in the production of these crops, this implies giving him the incentives to choose the same crops

and water-yield techniques that the social planner would choose. These choices are governed by the profits per area unit for each combination of crop and water-yield technique, and the socially optimal levels for the tax and credit rates are consequently those, which ensure that the farmer's profits per area unit correspond to the social planner's profits per area unit. In order for the corresponding first order conditions from the farmer and the social planner's problems to be identical, the following condition must hold:

$$y_{ijk}P_i - z_{ijk}C_Z - d_{ijk}T_D + (d_{ijk} - e_{ik})T_R - \lambda_{1j} = y_{ijk}P_i - z_{ijk}C_Z - \lambda_{1j} - \lambda_2(e_{ik} + (1-\beta)(d_{ijk} - e_{ik}))$$

$$\Leftrightarrow d_{ijk}T_D + (d_{ijk} - e_{ik})T_R = \lambda_2(e_{ik} + (1-\beta)(d_{ijk} - e_{ik}))$$

$$\Leftrightarrow d_{ijk}T_D + (d_{ijk} - e_{ik})T_R = \lambda_2(d_{ijk} - \beta(d_{ijk} - e_{ik}))$$

$$\Leftrightarrow T_D + (1-\gamma_{ijk})T_R = \lambda_2(1-\beta(1-\gamma_{ijk}))$$

$$\Leftrightarrow T_D = \lambda_2 \text{ and } T_R = \beta\lambda_2$$

This result says that the tax on water applied should be set equal to the social planner's shadow price of water consumed or irretrievably lost, while the credit on return flows should be set equal to the social planner's shadow price of water consumed or lost times the fraction of the return flows, which are recoverable. The latter part of the result reflects the fact that from society's point of view return flows only constitute a positive externality to the extent that they are recoverable. If no fraction of the return flows were recoverable (i.e. if $\beta = 0$), the return flow credit rate should consequently be set to zero.[13] Furthermore, as both the tax rate on water diversions and the credit rate for return flows are determined unambiguously in this solution, in the sense that neither of these rates depends on either farmer-specific characteristics or choice of crop or water-yield technique, it also follows that the introduction of such a policy scheme would achieve a socially optimal allocation of water.

In order to better understand the implications of this result, the condition $T_R = \beta T_D$ is substituted into the farmer's objective function:

$$\max_{X_{ijk}} \sum_{i=1}^{I}\sum_{k=1}^{K}(y_{ijk}P_i - z_{ijk}C_Z)X_{ijk} - T_D\sum_{i=1}^{I}\sum_{k=1}^{K}d_{ijk}X_{ijk} + T_R\sum_{i=1}^{I}\sum_{k=1}^{K}(d_{ijk} - e_{ik})X_{ijk}$$

[13] As noted in the previous footnote, the credit could alternatively be specified as only applying to those return flows, which are recoverable, in which case the socially optimal solution would be to set the credit rate on return flows equal to the tax rate on water diversions. This should in turn equal the social planner's shadow price of water consumed or irretrievably lost. This is not a surprising result given the model specification. Since the model does not incorporate spatial, temporal, or quality aspects of the return flows, there are no inherent differences between initial water diversions and recycled recoverable return flows, and they should consequently be valued at the same rate.

$$\Leftrightarrow \max_{X_{ijk}} \sum_{i=1}^{I}\sum_{k=1}^{K}(y_{ijk}P_i - z_{ijk}C_Z)X_{ijk} - T_D\sum_{i=1}^{I}\sum_{k=1}^{K} d_{ijk}X_{ijk} + \beta T_D\sum_{i=1}^{I}\sum_{k=1}^{K}(d_{ijk} - e_{ik})X_{ijk}$$

$$\Leftrightarrow \max_{X_{ijk}} \sum_{i=1}^{I}\sum_{k=1}^{K}(y_{ijk}P_i - z_{ijk}C_Z)X_{ijk} - T_D\sum_{i=1}^{I}\sum_{k=1}^{K}(d_{ijk} - \beta(d_{ijk} - e_{ik}))X_{ijk}$$

$$\Leftrightarrow \max_{X_{ijk}} \sum_{i=1}^{I}\sum_{k=1}^{K}(y_{ijk}P_i - z_{ijk}C_Z)X_{ijk} - T_D\sum_{i=1}^{I}\sum_{k=1}^{K}(e_{ik} + (1-\beta)(d_{ijk} - e_{ik}))X_{ijk}$$

As these calculations show, taxing water diverted by T_D and crediting return flows by βT_D amounts to taxing water consumed or irretrievably lost by T_D. As these are exactly the aspects of irrigation water use, which are assumed to matter from society's point of view, it is not surprising that T_D should be set equal to society's shadow price of water consumed or irretrievably lost.

3.2. Pricing only Water Diversions - The Farmer's Problem and Associated First Order Conditions

While the combination of taxing water diversions and crediting return flows will ensure a socially optimal allocation of irrigation water in a theoretical model, it is not likely that this approach can be implemented in reality. The reason is that this policy scheme presupposes that the social planner is able to meter or deduce not only the farmer's water diversions but also his return flows. While it is technically feasible to meter the farmer's water diversion given the right type of irrigation infrastructure, it will generally not be possible to meter his return flows as only a part of these will end up in the drainage system, while the rest may percolate into the ground. Furthermore, even if the social planner is able to meter the farmer's water diversions, he is still not likely to be able to estimate the size of the farmer's return flows, as this would require not only knowledge of the farmer's choice of crops but also his choice of water-yield techniques for producing these crops as well as the farmer-specific field irrigation efficiency coefficient. Neither the choice of water-yield technique nor the farmer-specific irrigation efficiency may be fully observable, and in the present analysis these features are assumed to be unobservable to the social planner.

The question is then to what extent pricing only water diversions will result in a socially optimal allocation of irrigation water. If only water diversions are taxed farmer j's problem becomes:

$$\max_{X_{ijk}} \sum_{i=1}^{I}\sum_{k=1}^{K}(y_{ijk}P_i - z_{ijk}C_Z)X_{ijk} - T_D\sum_{i=1}^{I}\sum_{k=1}^{K}d_{ijk}X_{ijk}$$

Subject to:

$$X_{ijk} \geq 0 \qquad \text{for all } i = 1,...,I \text{ and } k = 1,...,K,$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K}X_{ijk} = \overline{X}_j$$

Once again the farmer's objective is to maximize producer surplus subject to his individual land constraint but this time his producer surplus only includes water diverted taxes. The Lagrange function for farmer j's problem can subsequently be written as:

$$L = \sum_{i=1}^{I}\sum_{k=1}^{K}(y_{ijk}P_i - z_{ijk}C_Z - d_{ijk}T_D)X_{ijk} - \lambda_{1j}[\sum_{i=1}^{I}\sum_{k=1}^{K}X_{ijk} - \overline{X}_j]$$

The first order conditions are given by the Kuhn-Tucker conditions:

$$X_{ijk} \geq 0$$

$$\frac{\partial L}{\partial X_{ijk}} = y_{ijk}P_i - z_{ijk}C_Z - d_{ijk}T_D - \lambda_{1j} \leq 0$$

$$X_{ijk}\frac{\partial L}{\partial X_{ijk}} = X_{ijk}(y_{ijk}P_i - z_{ijk}C_Z - d_{ijk}T_D - \lambda_{1j}) = 0$$

$$\text{for all } i = 1,...,I \text{ and } k = 1,...,K,$$

$$\frac{\partial L}{\partial \lambda_{1j}} = -[\sum_{i=1}^{I}\sum_{k=1}^{K}X_{ijk} - \overline{X}_j] = 0$$

The interpretation of these first order conditions are basically identical to the interpretation of the first order conditions for farmer j's problem in section 3.1 except that in the present case the farmer does not receive a credit for his return flows.

Comparing this set of farmer's first order conditions with the first order conditions for the social planner's problem, it follows that in order for profits per area unit for a given crop and water-yield technique to be identical in these two optimization problems the following condition must hold:

$$y_{ijk}P_i - z_{ijk}C_Z - d_{ijk}T_D - \lambda_{1j} = y_{ijk}P_i - z_{ijk}C_Z - \lambda_{1j} - \lambda_2(e_{ik} + (1-\beta)(d_{ijk} - e_{ik}))$$

$$\Leftrightarrow d_{ijk}T_D = \lambda_2(e_{ik} + (1-\beta)(d_{ijk} - e_{ik}))$$

$$\Leftrightarrow d_{ijk}T_D = \lambda_2(d_{ijk} - \beta(d_{ijk} - e_{ik}))$$

$$\Leftrightarrow T_D = \lambda_2(1 - \beta(1 - \gamma_{ijk}))$$

This result shows that in order to ensure an optimal allocation of irrigation water the tax on water applied should be set equal to the social shadow price of water consumed times the fraction of water applied, which is not recycled (i.e. the fraction of water applied, which is either consumed or irretrievably lost). This in turn implies that the tax rate on water applied should be lower than the social shadow price of water consumed in order to compensate for the fact that a fraction of water applied is recycled. However, as the result also shows, the fraction of water diverted, which is not recycled, depends on irrigation efficiency, which is assumed to depend on farmer-specific features as well as choice of crop and water-yield production technology. Provided that irrigation efficiency does indeed differ across either farmers or crops or water-yield production technologies, it will consequently not be possible to achieve a socially efficient allocation of irrigation water using a single tax rate on water diversions.

It is worth noting the role of return flow recoverability in this result. If $\beta = 0$, meaning that no water losses are recovered, then a socially optimal allocation of water can be achieved by setting $T_D = \lambda_2$. This is not surprising, because if no water losses are recovered then the externality related to the recoverability of the return flows disappears. The only remaining externality then relates to the allocation of water diversions, and it can be alleviated through the introduction of a tax on water diverted. It should also be noted that the importance of field irrigation efficiency from a society's point of view is inversely related to the fraction of water losses, which are recovered. In the case of $\beta = 0$ the degree of field irrigation efficiency is thus highly important from the social planner's point of view. However, if socially optimal pricing of water diversions is introduced, then farmers bear the full costs of the water losses, and they will therefore have the proper incentives to reduce these losses through their choices of irrigation technology, crops, and water-yield techniques (although switching irrigation technology is not allowed for in the present model).

In the case of $\beta = 1$, meaning that all water losses are recovered, the model result shows that a socially optimal allocation of water requires the uniform tax rate T_D to always equal $\lambda_2\gamma_{ijk}$, which is not possible if irrigation efficiency differs across farmers, crops, or water-yield

production technology. All in all it may be concluded that a single tax on water diversions is only able to produce a socially efficient allocation of irrigation water if water losses are non-recoverable and hence the externality of recoverable return flows non-existent.

Before turning to another water allocation policy instrument, it is worth considering how a single tax on water diversions will affect the choices of crops and water-yield techniques in the general setting, where return flows are at least partially recoverable. Looking at the expression for the farmer's profits per area unit, the farmer obviously bases his profit maximization on water applied, whereas the social planner bases his maximization of profits per area unit on water consumed or irretrievably lost. To the extent that water applied were to be uniformly proportional to water consumed or lost across all crops and water-yield techniques, the farmer would choose the same crops and water-yield techniques as the social planner. However, at least in the case of choosing between rice and other crops, this would typically not be the case, as traditional rice production requires application of excess amounts of water. When return flows are at least partially recoverable, a single tax on water diversions may thus induce farmers to choose a different mix of crops and perhaps also water-yield techniques than would have been chosen by the social planner and this is clearly not optimal from society's point of view.

3.3. Crop-specific Land Taxation - The Farmer's Problem and Associated First Order Conditions

As shown in the previous section, taxation of water diversions only targets water applied. However, when return flows are recoverable, it is water consumed or irretrievably lost, which matters from society's point of view, and a single tax on water diversions can consequently not bring about a socially efficient allocation of irrigation water. Furthermore, although it is in principal feasible to meter the amount of water applied by the farmers, the actual irrigation infrastructure in many developing countries is not equipped for volumetric metering at the individual farmer level. The introduction of a tax on water diversions would consequently require substantial investments in the irrigation infrastructure in these countries. In Egypt metering at the individual farmer level is not possible in the traditional irrigation system in Old Lands. The new irrigation system, which is being introduced under the Irrigation Improvement Project, does in principle allow for volumetric measurement, but the system has

not been working properly (Hellegers and Perry 2004 p 68). In the New Lands metering water at the point of delivery is possible (Abu-Zeid and Rady 1992 p 98).

In light of the model results and these practical considerations of metering farmers' water diversions, the question arises whether another policy instrument exists, which would better target the relevant aspects of water use while not relying on volumetric metering. As water consumption is closely tied to the choice of crop and the size of the area used for cultivation of this crop, a possible candidate for such a policy instrument would be crop-specific taxes on cultivated land, which reflect the relative water consumption of the crops. With crop-specific land taxes farmer j's problem becomes:

$$\max_{X_{ijk}} \sum_{i=1}^{I}\sum_{k=1}^{K}(y_{ijk}P_i - z_{ijk}C_Z)X_{ijk} - T_{Li}X_{ijk}$$

Subject to:

$$X_{ijk} \geq 0 \qquad \text{for all } i = 1,...,I \text{ and } k = 1,...,K,$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K} X_{ijk} = \overline{X}_j$$

Where:

- T_{Li} : Crop specific land tax, measured in LE/feddan.

According to this specification the farmer's objective is to maximize profits net of crop-specific land taxes, subject to his individual land constraint. The Lagrange function for farmer j's problem can subsequently be written as:

$$L = \sum_{i=1}^{I}\sum_{k=1}^{K}(y_{ijk}P_i - z_{ijk}C_Z - T_{Li})X_{ijk} - \lambda_{1j}[\sum_{i=1}^{I}\sum_{k=1}^{K} X_{ijk} - \overline{X}_j]$$

The first order conditions are given by the Kuhn-Tucker conditions:

$$X_{ijk}\frac{\partial L}{\partial X_{ijk}} = X_{ijk}(y_{ijk}P_i - z_{ijk}C_Z - T_{Li} - \lambda_{1j}) = 0$$

$$X_{ijk} \geq 0$$

$$\frac{\partial L}{\partial X_{ijk}} = y_{ijk}P_i - z_{ijk}C_Z - T_{Li} - \lambda_{1j} \leq 0$$

$$\text{for all } i = 1,...,I \text{ and } k = 1,...,K,$$

$$\frac{\partial L}{\partial \lambda_{1j}} = -[\sum_{i=1}^{I}\sum_{k=1}^{K} X_{ijk} - \overline{X}_j] = 0$$

Again the interpretation of these first order conditions are very similar to the interpretation of the first order conditions for farmer j's problem in section 3.1 except that in the present case crop-specific land taxes have replaced the taxes and credits on water diversions and return flows.

Comparing this set of farmer's first order conditions with the first order conditions for the social planner's problem, it follows that in order for profits per area unit for a given crop and water-yield technique to be identical in these two optimization problems the following condition must hold:

$$y_{ijk}P_i - z_{ijk}C_Z - T_{Li} - \lambda_{1j} = y_{ijk}P_i - z_{ijk}C_Z - \lambda_{1j} - \lambda_2(e_{ik} + (1-\beta)(d_{ijk} - e_{ik}))$$

$$\Leftrightarrow\ T_{Li} = \lambda_2(e_{ik} + (1-\beta)(d_{ijk} - e_{ik}))$$

$$\Leftrightarrow T_{Li} = \lambda_2(d_{ijk} - \beta(d_{ijk} - e_{ik}))$$

$$\Leftrightarrow T_{Li} = \lambda_2(1 - \beta(1-\gamma_{ijk})d_{ijk}$$

This result says that in order to ensure a socially optimal allocation of irrigation water the crop-specific land taxes must equal the social shadow price of water consumed times the amount of water consumed or irretrievably lost per area unit for the crop in question.[14] While this result may initially appear similar to the result in case of a single tax on water diversions, further examination of the role of return flow recoverability shows that there is an important difference. The reason is that in the case of $\beta = 1$, the socially optimal rate for a given crop-specific land tax becomes:

$$T_{Li} = \lambda_2(1 - (1-\gamma_{ijk})d_{ik} = \lambda_2\gamma_{ijk}d_{ik} = \lambda_2 e_{ik}$$

If all return flows are recovered by the river basin system, the crop-specific land taxes should be set equal to the social shadow price of water times the amount of water consumed by the crop per area unit. The amount of water consumed by a given crop under a given choice of water-yield technique is assumed to be independent of farmer-specific characteristics and may in principle be estimated. In the case of all return flows being recovered, the optimal design of

[14] Note that $(1-\beta(1-\gamma_{ijk}))$ is the fraction of water applied, which is not recycled. As previously mentioned, this corresponds to the fraction of water applied, which is either consumed or irretrievably lost. When this fraction is multiplied by the coefficient of water applied per area unit for a given crop, the result becomes the amount (rather than the fraction) of water consumed or irretrievably lost per area unit for the crop in question.

a crop-specific land tax scheme consequently depends on crop water consumption coefficients, which are known to the social planner.

However, unless the social planner is able to observe or deduce the individual farmer's choice of water-yield technique, it will not be possible to achieve a socially efficient allocation of irrigation water using only crop-specific land taxes, as such taxes cannot address the choice of water-yield technique for a given crop. In this model the social planner is not assumed to be able to verify the farmer's choice of water-yield technique, and he is consequently not able to make the land tax depend on it. Once the land tax has been set for all the crops, the farmer will consequently choose a mix of crops and water-yield techniques, which maximize his profits. The reason, why the social planner is not assumed to be able to deduce the individual farmer's choice of water-yield technique based on the prices the farmer is facing, is that yield and other input requirement for production of a given crop is specified as being potentially farmer-specific, and the choice of crops and water-yield techniques may consequently differ across farmers. Hence, although crop-specific land taxes avoid the problem of unobservable irrigation efficiency in the case where all water losses are recovered, they are not able to ensure the socially optimal choices of water-yield techniques for the different crops.

In the case where $\beta = 0$, meaning that no water losses are recovered and the only externality arises from the allocation of water diversions, the socially optimal rate for a given crop-specific land tax becomes:

$$T_{Li} = \lambda_2 d_{ijk} = \lambda_2 \frac{e_{ik}}{\gamma_{ijk}}$$

In this case the problem of non-observability of not only water-yield technique choice but also farmer-specific irrigation efficiency is present, and crop-specific land taxes will consequently not be able to produce a socially efficient allocation of irrigation water. The problem is that crop-specific land taxes generally target crop water consumption (save for the water-yield technique dimension), but what matters from a social point of view is not only water consumption but also the irretrievable water losses, which the crop-specific land taxes do not capture. When the fraction of water losses recovered is strictly less than 1, both farmer-specific irrigation efficiency and the degree of return flow recoverability matters for the optimal rate of crop-specific land taxes, and the social planner is only assumed to know the degree of return flow recoverability.

4. DISCUSSION OF MODEL ASSUMPTIONS AND THEIR IMPLICATIONS.

The model, which has been used for analyzing the efficiency properties of the different water policy instruments, rests on several assumptions, which deserve further scrutiny in order to determine their appropriateness and their impact on model results. The present section is consequently dedicated to discussing these assumptions and their implications.

Overall the model is characterized by being a static, deterministic model with Leontief production technology. Starting with the implications of the Leontief production technology, this in combination with the few binding constraint on the farmer's and the social planner's problems will result in over-specialized solutions. A given farmer will thus generally only engage in one non-zero production activity when water allocation is regulated by taxes and this does not seem realistic. This feature of over-specialized solutions is a direct result of the simplified linear production technology and the inability to adequately specify all the constraints, which the farmer actually faces in his production decisions. However, as the objective here is merely to capture the implications of recoverable return flows and analyze how the ensuing externality may be alleviated through different policy instruments, the use of Leontief production technology is only a problem if it significantly affects the policy conclusions of the analysis.

One way in which the choice of Leontief technology might affect the conclusions of the analysis is if the inherent lack of substitutability between different production factors would mask any distortionary impact of the policy instruments, be this impact beneficial or detrimental. However, the problem of lacking substitutability has been addressed in the model through the introduction of different water-yield techniques for producing the same crop. As the choice of water-yield technique is assumed to potentially affect the use of other inputs, this specification captures the substitution between water, land, and other inputs.[15] However, it does not capture the substitution between different types of other inputs in the case where the water-land ratio is held constant. While this latter case may clearly be relevant for agricultural production in general, it is not expected to play an important role in the present

[15] One important example of substitution of water with other inputs is the substitution of water for labor in rice production, as "pounding water in greater depth" is a means to reduce weed growth and hence save on labor costs (Tiwari and Dinar ?? p 10).

policy analysis, as the analyzed policy instruments target land or water and hence must be expected to also influence the water-land ratio rather than only the ratios of other inputs.

The fact that the model is deterministic precludes the incorporation of uncertainty in the analysis. Uncertainty is an important element in irrigation economics in part because uncertainty regarding the timing and amount of future irrigation water deliveries may lead to water hoarding behavior on the part of the individual farmers.[16] While this aspect can not be addressed directly in the present deterministic model it could indirectly be captured in the field irrigation efficiency coefficient if this coefficient were assumed to also capture intangible farmer characteristics such as managerial skills. Likewise the yield coefficient and the input coefficient for other inputs are assumed to be farmer-specific partly in recognition of the fact farmer-specific characteristics in water management may also affect yield and the use of other inputs in production.[17]

The static property of the model precludes explicit analysis of multi-period aspects like investment decisions. Although analysis of investment decisions on irrigation technology would be relevant for the policy analysis, such matters are consequently not included in the present model, and the farmer is therefore assumed not to have a choice regarding his irrigation technology. However, as mentioned in section 2.1, the typical Egyptian farmer may also not have much choice regarding what irrigation technology to use. Farmers in the Old Lands in Egypt generally use surface irrigation techniques, which do not require continuous supply of irrigation water. Sprinkler and drip irrigation, on the other hand, normally require a continuous supply of water (Abu-Zeid and Rady 1992 p 96), but this is not available in the Old Lands under the traditional irrigation system, and it may not even become available in these lands following the implementation of the National Irrigation Improvement Project. Bader also lists several restrictions on farmer's adoption of sprinkler and drip irrigation including high capital costs for these techniques (while capital costs of surface irrigation is zero), fragmented land holdings, farmer's low knowledge and skill levels, as well as the notion that most crops like cotton, rice, maize, wheat, and clover should be irrigated using

[16] In Egypt there are examples of farmers applying substantially more water to their fields than needed in part due to lack of water control (Hvidt 1998 p 5).
[17] The other reason for allowing these coefficients to be farmer-specific is that yield and the use of other inputs may depend on soil type, which is assumed to be a farmer-specific attribute.

surface irrigation (Bader 2004, p 30).[18] In the New Lands in Egypt the use of sprinkler or drip irrigation is mandated by law, and the farmer's choice of irrigation technology is consequently also somewhat restricted in these areas.[19]

While farmers may have limited choice of irrigation technology, they do, however, have a choice regarding the degree of land preparation they undertake, and this will also affect their field irrigation efficiency. The degree of land preparation may possibly be improved by use of existing capital and more labor, but another way of improving land preparation would be to switch from manual to mechanized land preparation (Mohamed 2001 p 121). In this latter case, improvement of land preparation might then also entail some form of investment decisions, which the present model is not well suited for addressing. [20]

The lack of a time dimension in the model may also be considered problematic in relation to the recycling of return flows. While return flows from drainage canals may return to the system fairly quickly, this obviously need not be the case with return flows from percolation. In order to fully capture this latter type of return flow, the static model would have to be converted to a dynamic model. However, if the solution to the static model is thought of as a kind of steady state solution to a dynamic model in which technology, endowments, prices, and policies are constant from one period to the next, then the current return flows, which may not yet be accessible, will be equal to last periods return flows, which would by now have become accessible. The analysis in section 3.1, 3.2, and 3.3 of the introduction of various policy instruments should then be interpreted as referring to a point in time when the irrigation system have again attained a steady state after the policy instruments have been introduced.

Another important aspect of return flows, which the model does not address, is the issue of spatiality. If the farmers were to be located around a lake, which the return flows would return

[18] Note also that rotational irrigation is suitable for cultivation of long-rooted crops (i.e. sugar cane, maize, wheat, and berseem), while it is ill-suited for cultivation of short-rooted crops (i.e. vegetables), as these require more frequent irrigation (Hvidt 1998 p 15).

[19] Some of the issue relating to farmer's choice of irrigation technology in a situation where return flows are recoverable have been addressed in models by Chakravorty and Umetsu (cf. Chakravorty and Umetsu (2003), and Umetsu and Chakravorty (1998)).

[20] One way in which multi-period investment decisions on irrigation technology could be indirectly introduced into the static model would be to annualize the capital cost and include it as an extra cost term in the farmer's objective function. The input coefficient of water applied would then have to be indexed across types of irrigation technology and so would the yield coefficient and the other inputs coefficient to the extent that yield and the use of other inputs would be affected by the choice of irrigation technology.

to, then the spatial dimension would not be important. If, on the other hand, the farmers are located along a river, then the location of the farmer would affect the value of the recoverable return flows he generates, as recoverable return flows are only valuable if they can be used by other agents.[21] However, while the spatial dimension is clearly important and also seemingly simple to address in the case where return flows are returned to a river, it is less obvious how to handle the spatial dimension in the case where return flows recharge aquifers, which stretch over large areas, as this would require detailed knowledge of the water flow in the aquifer. Furthermore, the fact that a river can also recharge an aquifer only highlights the complexity of this spatial issue.

The perhaps most critical aspect, which the analysis has not addressed, is the fact that reuse of return flows is not merely a question of quantities of water. It is very much also a question of the quality of the return flows. The reason is that every time water is diverted and used for irrigation, the quality of the resulting return flows will be lower than the quality of the water, which was applied, as the crops consumptive use of water reduces the volume of water in which the initial natural salts are dissolved (Williardson et al 1997 p 218).[22]

Quantity and quality of water are closely connected. If the quality of the return flows deteriorates sufficiently, they will no longer be usable even if they are recoverable. This in turn suggests how the quality aspect may be introduced in the present model framework, as the coefficient capturing the recoverability of the return flows, β, could be adjusted to measure the fraction of return flows, which are not only recoverable but also reusable. Alternatively the quality aspects could be captured by having β measure the fraction of return flows expressed as "clean-water-equivalents".

Whether or not such an adjustment would make sense depends to some extent on how the drainage system is constructed. While drainage water of reasonably good quality may be reused directly for irrigation purposes, drainage water of poorer quality will require mixing with higher quality water before it may be reused (Williardson et al 1997 p 220). However, if it is not possible to dilute the poor quality return flows sufficiently or if the return flows have

[21] The issue of the environmental value of return flows is disregarded here.
[22] Since the issue of water quality is not addressed in this model, the necessity and benefits of leaching are also not incorporated in the model. If the leaching requirement where to be introduced in the model this could be done by altering the specification of the field irrigation efficiency coefficient γ_{ijk} to also include the need for additional water for leaching purposes.

become polluted with toxins making them unsuitable for reuse, mixing return flows and fresh water may ultimately ruin the fresh water resources rather than making the return flows reusable. In order to avoid such a situation the social planner would need to be able to keep drainage water and fresh water resources separate in the cases where there is a risk of the former damaging the latter. This would in turn imply that the social planner could control which fraction of the recoverable return flows it would be safe to recycle. In Egypt drainage water from the Nile Valley is collected in drainage canals and returned to the Nile, resulting in an increase in Nile water salinity (Williardson et al 1997 p 233). However, water quality is still adequate for most uses in the Nile Valley (Mohamed 2001 p 5). In the Nile Delta drainage water is collected in drainage canals and some of the water is diverted to coastal lakes and the sea. However, government pumping stations also lift some of the water from the Delta drainage canals into the irrigation canals for mixing with fresh water before reusing it for irrigation (Williardson et al 1997 p 233). In the Nile Delta there is severe water pollution downstream of large communities and industrial cities, but the water in the irrigation canals remains relatively clean (Mohamed 2001 p 5).

If the β coefficient is to capture the quality of the return flows it must be rendered farmer-specific, as the degree of recoverability of the return flows would no longer just depend on the drainage and percolation characteristics of the area but also on farmer behavior. The farmer may thus affect the quality of his return flows through his use of fertilizers and pesticides. Another important aspect of farmer behavior, which would affect the quality of his return flows, is unofficial reuse of drainage water. While the social planner may be able to estimate the quality of the water resources given the natural and official reuse of water,[23] farmers' unofficial reuse of drainage water for irrigation makes it more difficult for the social planner to manage the water quality. In Egypt farmers' unofficial reuse of drainage water is substantial (Mohamed 2001 p 8). Unofficial reuse of irrigation water is not included in the present policy analysis, but it would obviously pose a challenge in the scenarios where pricing of water diversions are introduced, as the farmer would have an incentive to substitute parts of his costly fresh irrigation water with free, lower quality drainage water. The crop-specific land tax scheme, on the other hand, would not be as vulnerable to unofficial reuse of drainage, as the tax is based on inferred water consumption rather than metered water application.

[23] Natural reuse of drainage water takes place, when rivers or canals serve as drains for hydrologic basin aquifer systems (Williardson et al 1997 p 216).

The final issue, which will be considered here, relates to the distribution of water. In the model delivery of water to the farmers' fields is implicitly assumed to be costless. This is clearly not a realistic assumption, and its implications consequently need to be considered. The costs associated with delivery of irrigation water may be divided into those costs, which are borne directly by the farmer, and those costs, which are borne by society. The farmers' costs may be divided into the variable costs associated with the acquisition of water and the (semi) fixed costs related to maintaining irrigation and drainage infrastructure and equipment. In the traditional irrigation system in the Old Lands in Egypt, water is generally delivered below field level, and farmers therefore have to lift their irrigation water up to field level. Having to lift the irrigation water implies that farmers incur pumping costs, which in principle should give them incentives to conserve water. However, over time low cost pumps have become available, which have lowered the cost of pumping and reduced the time it takes to pump a given amount of water (Hvidt 1998 p 17-18 and Hellegers and Perry 2004 p 67). The variable costs of pumping water consequently do not appear to have a large impact on the farmer's water application decisions. On the other hand, it would not be difficult to introduce farmer pumping costs into the present framework, as this would simply amount to specifying an additional cost on the farmer's water diversions.

With respect to the (semi) fixed costs related to maintaining irrigation and drainage infrastructure, Egyptian farmers are only responsible for the tertiary irrigation canals and field drains, while the Egyptian state is responsible for the entire irrigation and drainage system above this level. The operations and maintenance costs for these parts of the irrigation and drainage system are not fully covered by farmers' tax payments, and cost recovery in the irrigation system is consequently an important issue in Egypt. Having to deliver larger amounts of irrigation water due to low field irrigation efficiency as well as potentially having to pump return flows from aquifers in order to reuse them may clearly raise the costs of utilizing return flows. As such, this issue is relevant for the analysis of the socially efficient allocation of irrigation water, as it would tend to increase the profitability of heightening field irrigation efficiency and hence lowering the need for recycling water. [24]

Other important aspects of the conveyance system, which are also not included in the model, relate to the physical efficiency of water conveyance and the ability of the social planner to

[24] Chakravorty and Umetsu (2003) also include aspects of water provision costs in their model with recoverable return flows.

ensure water deliveries to various sections of the irrigation system. Substantial amounts of water are lost in the conveyance system due to either percolation or evaporation. Water losses due to percolation may not be a major problem if these water losses are recoverable. Water losses due to evaporation, on the other hand, constitute an unbeneficial consumption of water to the extent that they are not converted into precipitation in areas relevant to the social planner. However, with respect to the present policy analysis, evaporation losses may not be that important if they remain virtually unchanged after the introduction of new water allocation policies. Finally it should be mentioned, that while the ability of the social planner to ensure that the socially optimal amount of water is delivered to the relevant sections of the irrigation system is a major challenge in the real world, this issue can not be included in the present type of policy analysis, as it would require modeling of the actual layout of the irrigation system in question.

5. CONCLUSION.

The purpose of the present analysis has been to analyze the efficiency properties of different policy instruments in a situation characterized by the presence of two types of externalities – the externality related to the allocation of water diversions between different irrigators and the externality related to recoverability of return flows from irrigation. The policy analysis has focused on the use of tax policy instruments to alleviate these externalities.

As the set-up is characterized by the simultaneous presence of two externalities, it is hardly surprising that a theoretical first-best solution can be achieved by introducing a Pigovian tax on water diversions and a Pigovian credit on return flows. However, as this approach would require that the social planner be able to meter or deduce the individual farmer's return flows, it is not likely that it can be implemented in reality. The analysis consequently proceeded to investigate the efficiency properties of placing a tax only on water diversions or alternatively introducing crop-specific land taxes.

As the analysis showed neither a uniform tax on water diversions nor crop-specific land taxes would be able to ensure a fully socially efficient allocation in the presence of recoverable return flows. While the former targets water applied and hence cannot handle recoverability of return flows, the latter targets water consumed and cannot handle irretrievable water losses. While the introduction of either of these policy instruments might well entail a more efficient

allocation of irrigation water than in the situation without any regulation of the water allocation, the resulting allocation would in both cases still only be second-best.

This conclusion naturally leads to the question of which of these two second-best policy instruments that would produce the more optimal allocation of irrigation water. However, as the answer to this question depends on the values of the key parameters this question should be addressed by empirical investigation of a given case. Future work will consequently entail an empirical investigation of the Egyptian irrigation system in order to determine which of the two second-best instruments would achieve the most efficient allocation of irrigation water in Egypt. However, apart from the efficiency aspects of the different policy instruments, their practical feasibility should also be considered. As already mentioned metering of individual farmer's water diversion is often not possible in many developing countries, and in this case crop-specific land taxes may be the best option for improving the allocation of irrigation water.

As discussed in the last section, the model rests on a number of simplifying assumptions, which suggests a need for future research. Two important aspects of reusing return flows, which have not been explicitly included in the model, are thus the issues of the decreasing water quality and the increasing pumping and conveyance costs associated with additional water diversion cycles. Future extensions of the model to account for these issues would clearly be desirable, and as the discussion suggested this may well be doable within the current type of modeling framework.

LITERATURE REFERENCES.

Abu-Zeid, M.A. and M.A. Rady (1992). Water Resources Management and Policies in Egypt. Chapter in Guy Le Moigne et al (eds): Country Experiences with Water Resources Management – Economic, Institutional, Technological and Environmental Issues. World Bank Technical Paper number 175. Washington D.C.: The World Bank.

Bader, Esam (2004). Mathematical Programming Models for Optimising Irrigation Water Management in Egypt. Kiel.
(PhD dissertation – Institut für Agrarökonomie, Christian Albrechts Universität zu Kiel)
http://e-diss.uni-kiel.de/diss_1289/d1289.pdf

Berck, Peter and Knut Sydsæter (1992). Matematisk formelsamling for økonomer. Oslo: Universitetsforlaget.

Chakravorty, Ujjayant, and Chieko Umetsu (2003). Basinwide water management: a spatial model. Journal of Environmental Economics and Management 45, p 1-23.

FAO (1998). Crop evapotranspiration – Guidelines for computing crop water requirements. FAO Irrigation and Drainage paper 56.
http://www.fao.org/docrep/X0490E/X0490E00.htm#Contents

Hellegers, P.J.G.J. and C.J. Perry (2004). Water as an Economic Good in Irrigated Agriculture – Theory and Practice. Report 3.04.12. The Hague: Agricultural Economics Research Institute (LEI).

Hvidt, Martin (1998). Water, Technology, and Development – Upgrading Egypt's Irrigation System. London: Tauris Academic Studies.

Mohamed, Ahmed Shawky (2001). Water Demand Management: Approach, Experience and Application to Egypt. Delft: DUP Science.
(PhD dissertation – Delft University of Technology and the International Institute for Infrastructural Hydraulics and Environmental Engineering)
http://www.library.tudelft.nl/delftdiss/pdf/2001/ceg_mohamed_20010606.pdf

Tiwari, Dirgha and Ariel Dinar (??). Role and Use of Economic Incentives in Irrigated Agriculture.
http://siteresources.worldbank.org/INTWRD/Resources/RoleandUseofEconomicIncentivesPaper.pdf

Umetsu, Chieko and Ujjayant Chakravorty (1998). Water conveyance, return flows and technology choice. Agricultural Economics 19, p 181-191.

Williardson, L. S., D. Boels, and L. K. Smedema (1997): Reuse of drainage water from irrigated areas. Irrigation and Drainage Systems, 11: 215-239.

World Bank (1993). Arab Republic of Egypt – An Agricultural Strategy for the 1990s. Washington D.C.: The World Bank.