ANALYSIS

An economic model of waterlogging and salinization in arid regions

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Received 24 July 1998; received in revised form 24 February 1999; accepted 3 March 1999

Abstract

Waterlogging and salinization arise in arid areas largely because two essential resources, irrigation water and the assimilative capacity of unconfined aquifers, are not priced or allocated correctly to reflect scarcity values and opportunity costs. Farm-level and project-level models of crop production are examined to identify policies that will encourage farmers to consider opportunity costs and the effects of irrigation and leaching on depth to regional water tables. Appropriate policies include volumetric water pricing, water markets, tradable water allotments, adjustments in area-based cost recovery programs, and incentives for farmers to use irrigation methods that reduce deep percolation. Implementing appropriate versions of these policies may reduce the rate of increase in waterlogged and saline areas. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Drainage; Economics; Irrigation; Policy alternatives; Salinization; Waterlogging

1. Introduction

Waterlogging and salinization, known by some as the ‘twin menace’ of irrigated agriculture, have reduced productivity in arid regions since the rise and fall of Mesopotamia (Jacobsen and Adams, 1958). Currently, these problems affect many of the world’s large-scale irrigation systems, imposing farm-level and public costs in the form of lost production and efforts to reduce the rate of increase in affected areas (Kovda, 1983; Ghassemi et al., 1995; UNEP, 1997).

Waterlogged and saline soils are found naturally in many regions, but inappropriate irrigation also causes these problems, resulting in economic losses when crop yields are reduced by high water tables and soil salinity (Szabolcs, 1987; Rhoades, 1990; Smedema, 1990; Dregne, 1991; Scherr and Yadav, 1996; Abdel-Dayem, 1997). The areal extent of the problem is increasing worldwide, pri-
primarily as a result of the rapid expansion of irrigated area since 1950 (Kovda, 1980, pp. 179–188; Barrow, 1991; Szabolcs, 1992; World Bank, 1992; UNEP, 1997).

The primary irrigation-induced causes include leakage from poorly lined canals and reservoirs, excessive water application, and inadequate drainage of agricultural land (Barrow, 1991; Scott, 1993). Seepage from irrigation facilities and deep percolation from farm fields enter unconfined aquifers that often are saline. When a water table rises within 2 m of the soil surface, the root zone available to plants becomes restricted, salts rise to the surface by capillary action, and the resulting salinization can render land unsuitable for agriculture (Stone, 1984 p. 141; Arnon, 1987 p. 147; Abernethy and Kijne, 1993; Abrol and Sehgal, 1994; Hillel, 1994 p. 56; Kijne et al., 1998).

Some deep percolation is required in arid areas to remove salts from the root zone and sustain productivity over time (Oster, 1984; Hoffman, 1990; Rhoades and Loveday, 1990). However, actual leaching fractions often exceed leaching requirements because the farm-level costs of irrigation rise with efforts to achieve precise, uniform application of water (Letey et al., 1990; Dinar and Zilberman, 1991; Upton, 1996 p. 193) and many water allocation and pricing policies do not motivate efficient use (Abrol et al., 1988 p. 113; Prasad and Rao, 1991; Sampath, 1992; Meinzen-Dick and Mendoza, 1996; Rosegrant and Meinzen-Dick, 1996). Rotational water delivery systems, which are common in much of the world, lead to excessive deep percolation because farmers irrigate according to fixed schedules that do not match crop water requirements (Dhawan, 1989; Qureshi et al., 1994). In many systems, water prices are too low to encourage farm-level improvements in water management or to justify investments in irrigation methods that minimize deep percolation (Hillel, 1994 p. 217; Mageed, 1994).

This paper examines the economic causes of waterlogging and salinization in arid regions, to determine if economic incentives can be implemented to reduce the rate of increase in waterlogged and saline areas. Farm-level and project-level models of crop production are examined to identify policies that might encourage farmers to consider the effects of irrigation and leaching activities on depth to regional water tables.

1.1. Extent of the problem

The World Bank (1992, p. 57), states that salinization caused by inappropriate irrigation practices affects about 60 million ha, or 24% of all irrigated land. Severe declines in productivity are observed on about 24 million ha, or 10% of irrigated land. Umali (1993) reports that salinization affects 28% of irrigated lands in the US, 23% in China, 21% in Pakistan, 11% in India, and 10% in Mexico. Barghouti and Le Moigne (1991) suggest that the area affected by salinity, worldwide, is increasing at the rate of 1.0–1.5 million ha per year. Despite several decades of land reclamation efforts, new irrigated areas are being degraded faster than older soils are being reclaimed (World Bank, 1992, p. 57).

Estimates of problem areas in India range from 3.4 to 6.0 million ha (Dwivedi, 1994; Dhawan, 1995 p. 112). Large seepage losses, over-irrigation, and extensive production of crops with large water requirements have caused a steady rise of the water table in the command area of many Indian irrigation systems (Swaminathan, 1980; Reddy, 1991). The primary causes of the problem in India are the absence of economic incentives for farmers to conserve water, and over-irrigation (Joshi, 1987; Chopra, 1989; Joshi and Jha, 1991; Mitra, 1996; Saleth, 1996 p. 27). Singh and Singh (1995) report that rice, wheat, and cotton yields are reduced by 10–40% on waterlogged and saline soils in the Northwestern state of Haryana.

Waterlogging and salinization may affect as much as 25% of irrigated land in Pakistan, reducing crop yields (Chambers, 1988 p. 21; Yudelman, 1989; Khan, 1991 p. 68). Khan (1991) reports that 48% of the soils in Sindh and Punjab are saline, while 18% of the soils are strongly saline. Secondary salinization in Pakistan is caused by excessive irrigation, rising groundwater tables, and extensive use of poor quality groundwater (Abernethy and Kijne, 1993; Kijne and Kuper, 1995;
Mustafa and Pingali, 1995; Faruqee, 1996; Smets et al., 1997). Inappropriate water allocation and pricing policies also contribute to the increase in affected areas (Ahmad and Kutcher, 1992; Lenton, 1994; Kemal et al., 1995a).

Irrigation in Central Asia has been sustained by large diversions of water from the Amu Dar’ya and Syr Dar’ya Rivers, reducing the volume of fresh water reaching the Aral Sea and causing extensive secondary salinization of agricultural lands (Micklin 1988; Kotlyakov, 1991; Micklin 1991; Levintanus, 1992; Micklin 1992; Glantz et al., 1993; Kharin et al., 1993; Saiko, 1995; Kharin, 1997; Spoor, 1998). In Egypt, construction of the Aswan High Dam in the 1960s enabled farmers in the Nile Valley and Delta to convert from basin to perennial irrigation, causing a rapid rise in shallow water tables and increasing soil salinity (Abul-Ata, 1977; Kinawy, 1977; Kishk, 1986; White, 1988; Scott, 1993). Within 20 years of the start of Aswan operations, waterlogging and salinization had affected 28% of farmland in Egypt and average yields in those areas had fallen by 30% (Speece and Wilkinson, 1982).

Ren (1992) and You (1992) describe the rapid increase in problem areas on the North China Plain during the late 1950s and early 1960s, when large volumes of irrigation water were diverted from the Yellow River. The area with saline soils increased from 1.5 to 2.0 million ha before 1958 to more than 4.1 million ha in 1961, or about 22% of the total cultivated area. Dregne et al. (1996) and Xiong et al. (1996) report that 40% of irrigated land on the Ningxia Plain in north China is affected by salinity, where high water tables are caused by excessive irrigation and canal seepage.

1.2. Potential role of economic incentives

Public programs to reduce the extent of problem areas include construction of regional drainage systems (Amer, 1996), operation of public tubewells (Chaudhry and Young, 1990; Afzal, 1996), and farm-level incentives to reduce deep percolation by improving irrigation methods (Wichelns, 1991; Wichelns et al., 1996). Subsurface and open-ditch drainage systems will remove saline drainage water from an irrigated area, but these systems are expensive (Kelleners and Chaudhry, 1998) and regional coordination is required in areas with many small farms (Datta and Joshi, 1993). In addition, environmental issues can arise regarding the discharge of drainage water into rivers or lakes (National Research Council, 1989; Abdel-Dayem, 1997; Madramootoo, 1997; Wolter and Kandiah, 1997).

Policies that motivate improvements in water management may reduce deep percolation and the volume of drainage water that must be disposed or re-used. Improved water management can also reduce the salt loads imported with irrigation water in arid areas. Rosegrant and Ringler (1997) recommend policy reforms including economic incentives for water conservation, water markets, privatization of management functions, and effluent charges. The World Bank (1992, p. 145) suggests that seepage losses, waterlogging, and salinization may be addressed more effectively by improving water management than by modifying physical structures. Faruqee (1996) suggests that fundamental changes in water pricing and institutions are required to improve the efficiency of allocating water and maintenance responsibility in Pakistan. Mellor (1996) includes water charges that recover operation and maintenance costs among his policy recommendations for Pakistan, while Pinstrup-Andersen and Pandya-Lorch (1994) suggest that appropriate allocation mechanisms are needed urgently to prevent excessive water use.

Saleth (1994) describes an ‘incentive gap’ between the scarcity value of water and the value generated by current water use and management efforts in India. He suggests that water policy reforms are required to close that gap, which currently encourages inefficient water use, resulting in aquifer depletion, waterlogging, and salinization in canal regions. Chopra (1990, p. 127) suggests that volumetric prices or quantitative controls are required to encourage efficient irrigation in Punjab, while Dev and Mungekar (1996) recommend volumetric water pricing and metered electricity sales to address waterlogging and salinization in Maharashtra. Chand and Haque (1997) recommend similar policies to sustain agricultural productivity in Punjab and Haryana.
2. Conceptual framework

Waterlogging and salinization arise in arid areas largely because two essential resources, irrigation water and the assimilative capacity of unconfined aquifers, are not priced or allocated correctly to reflect scarcity values and opportunity costs. Volumetric water prices are lower than optimal or non-existent in many irrigated regions, and allocation procedures are often based on rotational schedules that do not provide the flexibility or certainty required for farmers to optimize water use. In most irrigation systems, farmers may 'discharge' deep percolation to unconfined aquifers at no charge and with no restrictions, even though assimilative capacity is limited. As a result, the scarcity values of irrigation water and aquifer capacity are not communicated to farmers in resource prices or allocations, providing them with little incentive to consider the opportunity costs or the off-farm effects of irrigation and leaching activities.

The economic rationale for policy intervention is examined by reviewing farm-level and project-level crop production models to determine how the optimal strategies for individual farmers differ from those that maximize the sum of net benefits in an irrigated region. The dynamic models allow for changes in soil salinity and water table depth, and substitution among water and non-water inputs. Regional water supply constraints are included in the project-level model to describe the opportunity cost of water use.

2.1. Farm-level model

The farm-level irrigation objective can be described as maximizing the present value of net revenue, over time, while maintaining the quality of productive resources. Farmers in arid areas must apply supplemental water for irrigation and leaching to satisfy crop water requirements and prevent salt accumulation in the root zone. Both irrigation and leaching add salt to the soil profile. The net change in soil salinity is usually positive following irrigation events because plants use the water, while leaving salts in the soil (Rhoades and Loveday, 1990). Leaching events displace salts from the profile by flushing soils with relatively good quality water. In areas where downward movement of water is restricted by impervious clay layers, deep percolation can cause a rise in the height of shallow water tables. In the absence of policies that address irrigation and leaching, farmers will not have an economic incentive to consider the effects of their decisions on regional water tables.

A farmer’s objective function for production of a single crop on one unit of land can be described as follows:

\[
\text{Max PVNR} = \int_{t=0}^{\infty} \left[ P_Y (V_{\text{RM}}, V_{\text{LM}}, Q_R, Q_L, X_R, X_L, X_N, EC_S, DWT) - P_W (V_R + V_L) - P_R X_R - P_L X_L - P_N X_N \right] e^{-rt} \, dt
\]

subject to:

\[
\Delta EC_S = g(EC_S, EC_G, DWT, V_{\text{RM}}, V_{\text{RD}}, V_{\text{LM}}, V_{\text{LD}}, Q_R, Q_L)
\]

and:

\[
V_{\text{RM}} = V_{\text{RM}}(V_R, X_R); \quad V_{\text{RD}} = V_{\text{RD}}(V_R, X_R)
\]

\[
V_{\text{LM}} = V_{\text{LM}}(V_L, X_L); \quad V_{\text{LD}} = V_{\text{LD}}(V_L, X_L)
\]

where PVNR is the present value of net revenue, \(P_Y\) is the unit price of output, \(Y\) is output per unit area, \(V_R\) and \(V_L\) are the volumes of water used for irrigation and leaching, respectively, \(Q_R\) and \(Q_L\) are the salt concentrations in irrigation and leaching water, \(X_R\), \(X_L\), and \(X_N\) are indices of variable inputs used for irrigation, leaching, and non-irrigation tasks (with prices \(P_R\), \(P_L\), \(P_N\)), \(P_W\) is water price, \(EC_S\) is a measure of salinity in the crop root zone, \(EC_G\) is the salinity of shallow groundwater, \(DWT\) is depth to a shallow water table, \(V_{\text{RM}}\) and \(V_{\text{LM}}\) are the volumes of irrigation and leaching water, respectively, that remain in the crop root zone (available for transpiration), \(V_{\text{RD}}\) and \(V_{\text{LD}}\) are the volumes of irrigation and leaching water that move through the root zone, becoming deep percolation, \(\Delta EC_S\) is the time derivative of soil salinity, \(\Delta EC_S = g(\cdot)\) is the equation of motion, and \(r\) is the farmer’s financial discount rate. All variables include a time subscript, \(t\), which is omitted for clarity.
The model includes separate irrigation and leaching activities because farmers in arid areas often apply water specifically for leaching before crops are planted or while fields are fallow. They may also use different methods for irrigation and leaching events, and the impact of water deliveries on deep percolation may vary by technology and season. As a result, separate policy programs or parameter values may be appropriate for irrigation and leaching. The volume and quality of crop water requirements in late summer when root zone moisture is not maintained can affect plant growth. For example, many cotton farmers pre-irrigate fields to leach salts from the root zone and establish deep moisture to satisfy crop water requirements in late summer when they cannot irrigate large fields quickly enough to keep pace with evapotranspiration.

The farm-level objective can be viewed as an optimal control problem in which the control variables are the water used for irrigation and optimal control problem in which the control variables are the water used for irrigation and leaching events because some of the water and salt applied during leaching events remain in the soil and affect plant growth. For example, many cotton farmers pre-irrigate fields to leach salts from the root zone and establish deep moisture to satisfy crop water requirements in late summer when they cannot irrigate large fields quickly enough to keep pace with evapotranspiration.

The farm-level objective can be viewed as an optimal control problem in which the control variables are the water used for irrigation and leaching (\( V_R \) and \( V_L \)), and the other variable inputs (\( X_R \), \( X_L \), and \( X_N \)). The state variable is soil salinity (\( EC_S \)), which changes over time as a function of the salt load moving in and out of the soil profile. The regional water table depth (\( DWT \)) and salinity of shallow groundwater (\( EC_G \)) are treated as exogenous variables in the farm-level model because individual farmers have no incentive to consider the impacts of their activities on those variables.

A current value Hamiltonian (Pontryagin et al., 1962; Chiang, 1992) combines the farm-level objective function with the equation of motion, as in:

\[
\frac{dHF}{dV_A} = P_Y \frac{\partial Y}{\partial V_A} \frac{\partial V_{AM}}{\partial V_A} - P_w + \frac{m_i \frac{\partial g}{\partial V_{AM}} \frac{\partial V_{AM}}{\partial V_A} + m_i \frac{\partial g}{\partial V_{AD}} \frac{\partial V_{AD}}{\partial V_A}}{\partial V_A} = 0 \quad (3)
\]

(Eq. (3)) can be re-written as (Eq. (4)), which requires that farmers equate the marginal value product (MVP) of irrigation and leaching water plus the marginal value gained by removing salts from the soil with the price paid for water (\( P_w \)) and the marginal damage caused by adding salts.

\[
\text{MVP}_V + m_i \frac{\partial g}{\partial V_{AM}} \frac{\partial V_{AM}}{\partial V_A} = \quad \text{for } A = R, L. \quad (4)
\]

The costate variable, \( m_i \), describes the marginal cost, or damage, as a result of an increase in soil salinity. Hence, \( m_i \) will be negative when increasing soil salinity reduces crop yield. The partial derivatives describing the impact of deep percolation on the rate of change in soil salinity (\( \frac{\partial g}{\partial V_{RD}} \) and \( \frac{\partial g}{\partial V_{LD}} \)) will be negative, as a larger volume of deep percolation removes more salt from the crop root zone. The partial derivatives describing the change in deep percolation with changes in water deliveries (\( \frac{\partial V_{RD}}{\partial V_R} \) and \( \frac{\partial V_{LD}}{\partial V_L} \)) will be positive. Hence, the second term on the left side of (Eq. (4)) will be positive, adding incremental value to the marginal value product of water with respect to crop yield.

The partial derivatives describing the impact of water entering the crop root zone on the rate of change in soil salinity (\( \frac{\partial g}{\partial V_{RM}} \) and \( \frac{\partial g}{\partial V_{LM}} \)) and the partial derivatives describing the change in root zone moisture with changes in water deliveries (\( \frac{\partial V_{RM}}{\partial V_R} \) and \( \frac{\partial V_{LM}}{\partial V_L} \)) will be positive. Hence, the second term on the right side of (Eq. (4)) will be negative, resulting in the addition of incremental costs to the price farmers pay for water.

(Eq. (4)) extends the static equi-marginal criterion regarding the marginal value product and price of water to include the long-term effects of irrigation and leaching on soil salinity. Farmers will consider both the salt that is added to soils by irrigation and leaching events, and the salt that is removed by deep percolation, when determining the optimal amount of water to apply.
The first-order necessary conditions with respect to the non-water inputs used for irrigation and leaching ($X_R$ and $X_L$) are the following (where $A = R, L$):

$$\frac{\partial H_F}{\partial X_A} = P_Y \frac{\partial Y}{\partial V_{AM}} \frac{\partial V_{AM}}{\partial X_A} + P_A + m \frac{\partial g}{\partial V_{AM}} \frac{\partial V_{AM}}{\partial X_A} = 0$$

(Eq. (5)) can be re-written as (Eq. (6)), which requires that farmers equate the marginal value product of non-water inputs and the marginal value gained by reducing the rate of salt accumulation in the soil with the price of those inputs ($P_R$ and $P_L$) and the marginal cost of reducing the rate of salt removal.

$$MVP_{X_A} + m \frac{\partial g}{\partial V_{AD}} \frac{\partial V_{AD}}{\partial X_A} = P_A - m \frac{\partial g}{\partial V_{AD}} \frac{\partial V_{AD}}{\partial X_A} ; \text{ for } A = R, L. \quad (6)$$

The first term on the left side of (Eq. (7)) describes the economic impact of an increase in soil salinity on crop yields in the current year, while the second term describes the economic cost of salt accumulation in the root zone. The third term is the time derivative of the costate, which may rise or fall, over time, in response to changes in crop prices or production costs. For example, when crop prices rise, relative to costs, the economic cost of salinity-induced yield reductions increases. In sum, the terms on the left side of (Eq. (7)) describe the current-year and long-term farm-level marginal damages from an increase in soil salinity. A farmer would be willing to pay this amount to prevent salt accumulation in any year.

The term on the right side of (Eq. (7)), $rm$, can be interpreted as the annual payment a farmer would need to make, to ‘discharge’ his or her salts on the land of another identical farmer, with that farmer’s agreement. Given that the costate, $m$, represents the marginal damage generated by an additional unit of salt, a farmer accepting such damage would require that payment as compensation. The annual opportunity cost of the payment is $rm$. Therefore, (Eq. (7)) suggests that the optimal rate of salt accumulation occurs when the marginal damage caused by salts is just equal to the annual opportunity cost of the payment that would be required to prevent the damage.

### 2.2. Project-level model

The public’s goal regarding a publicly funded irrigation project may be described as maximizing the present value of net benefits generated over time. The model describing that objective includes the farm-level components, described above, and accounts for the effects of farm-level activities on regional water tables and soil salinity. A project-level model is constructed by enhancing the farm-level model as follows: 1) many farmers are considered; 2) an equation of motion for regional depth to a shallow water table is added; and 3) a constraint is added regarding the total supply of surface water available to farmers in the project.

The current value Hamiltonian for the project-level model is the following:

$$P_Y \frac{\partial Y}{\partial EC_S} + m \frac{\partial g}{\partial EC_S} \frac{\partial m}{\partial t} = rm_t \quad (7)$$
\[ HP_i = \sum_{l=1}^L P_Y Y_i^l - P_R X_R^l - P_L X_L^l - P_N X_N^l + n_i^l g_i^l - TC_W \left( \sum V_R^l + V_L^l \right) \]

\[ + z_i h \left( \sum V_{RD}^l, \sum V_{LD}^l, DWT_i \right) + \lambda_i \left( TV_i - \sum V_R^l - \sum V_L^l \right) \]

where \( HP \) represents the project-level Hamiltonian and individual farmers are described by the superscript \( i = 1, \ldots, I \). There is a current value costate pertaining to soil salinity, \( n_i^l \), for each farmer, while there is a single costate, \( z_i^l \), pertaining to depth of the shallow water table, \( DWT_i \). The rate of change in depth to water table, over time, is a function, \( h(\cdot) \), of the sum of deep percolation from irrigation and leaching on all farms in the region. There is a current value Lagrange multiplier, \( \lambda_i \), pertaining to the annual water supply constraint. The variables \( TV_i \) and \( TC_W \) denote the total volume of surface water available and the total costs of water delivery in the project area during year \( i \). All of the water and non-water inputs in the yield function are superscripted with \( i \), denoting farm-level choices of those inputs.

The necessary conditions of the project-level model with respect to water applied for irrigation and leaching (\( V_R^l \) and \( V_L^l \)) are:

\[ \frac{\partial HP_i}{\partial V_A^l} = P_Y \frac{\partial Y_i^l}{\partial V_A^l} \frac{\partial V_{AM}^l}{\partial V_A^l} - MC_W + \]

\[ n_i^l \frac{\partial g}{\partial V_{AM}^l} \frac{\partial V_{AM}^l}{\partial V_A^l} + n_i^l \frac{\partial g}{\partial V_{AD}^l} \frac{\partial V_{AD}^l}{\partial V_A^l} \]

\[ + z_i \frac{\partial h}{\partial V_{AD}^l} \frac{\partial V_{AD}^l}{\partial V_A^l} - \lambda_i = 0 \quad \text{for} \quad i = 1, \ldots, I; \]

\[ \text{and A = R, L.} \]

Three terms in (Eq. (9)) do not appear in necessary conditions for the farm-level problem: \( MC_W \), \( \lambda_i \), and the chain-rule derivative describing the economic effect of irrigation and leaching water on depth to water table. The first term is the marginal cost of water delivery to farmers, while \( \lambda_i \) represents the opportunity cost of water to other farmers in the region. The value of \( \lambda_i \) will be zero if the regional water supply constraint is not binding, and positive when the volume of water demanded by all farmers exceeds the available supply.

The third term includes the current value costate, \( z_i^l \), which is positive in cases where an increase in water table depth improves productivity. The partial derivative of water table depth with respect to deep percolation, \( \partial h / \partial V_{LD}^l \), will be negative, while the partial derivative of deep percolation with respect to the volume of water diverted for leaching, \( \partial V_{LD}^l / \partial V_{L}^l \), is positive. Hence, the third term will be negative in cases where deep percolation causes a rise in the shallow water table, reducing productivity. This term describes an external cost that farmers do not consider when choosing the volume of water to divert for irrigation and leaching events (Young and Horner, 1986; Izac, 1994; Strojan, 1995). These are the external costs that generate regional waterlogging and salinization problems in irrigated areas.

Another potential difference in the models involves the discount rates that are embedded in the current value costates, \( m_i \) in the farm-level model and \( n_i^l \) in the project-level model. If individual discount rates are higher than the social rate, farmers will place greater relative emphasis on the near-term benefits of irrigation and leaching than would the public, resulting in faster rates of waterlogging and salinization than may be socially optimal. This effect, in combination with inappropriate prices and poorly defined property rights, may explain why many large-scale irrigation projects encounter problems of waterlogging and salinization sooner than expected by project planners (Abul-Ata, 1977; Kapoor and Kavdia, 1994; Ramathan and Rathore, 1994).

The necessary conditions for the project-level model with respect to the non-water inputs used for irrigation and leaching (\( X_R^l \) and \( X_L^l \)) are:

\[ \frac{\partial HP_i}{\partial X_A^l} = P_Y \frac{\partial Y_i^l}{\partial V_{AM}^l} \frac{\partial V_{AM}^l}{\partial X_A^l} - P_A + \]
\[
\frac{n_i^t \partial g}{\partial V_{AM}^t} \partial V_{AM}^t \partial X_A^t + n_i^t \frac{\partial g}{\partial V_{AD}^t} \partial V_{AD}^t \partial X_A^t + z_i^t \frac{\partial h}{\partial V_{AD}^t} \partial V_{AD}^t \partial X_A^t + 0; \text{ for } i = 1, \ldots, I; \text{ and } A = R, L. \tag{10}
\]

(Eq. (10)) contains one term that does not appear in the necessary conditions for individual farmers. That term describes the economic value of the marginal effect of irrigation or leaching inputs on depth to water table. As noted above, the value of the costate, \(z_i\), will be positive, while improvements in irrigation methods will reduce deep percolation and increase the depth to water table. Therefore, the sign of this new term is positive in (Eq. (10)), describing an external benefit of improvements in irrigation methods. An economic incentive program would be needed to motivate farmers to consider this external benefit when choosing irrigation inputs.

The necessary conditions pertaining to soil salinity on farm fields are:

\[
P_Y \frac{\partial Y_i^t}{\partial EC_{z_i}^t} + n_i^t \frac{\partial g_i^t}{\partial EC_{z_i}^t} + \frac{\partial h_i^t}{\partial t} = s n_i^t, \tag{11}
\]

for \(i = 1, \ldots, I\).

These conditions are similar to those for individual farmers maximizing the present value of net revenue, as shown in (Eq. (7)). However, as noted above, the social discount rate, \(s\), likely differs from farm-level discount rates, causing the costate values, \(n_i^t\), to differ from farm-level costates. The necessary condition pertaining to water table depth is:

\[
\sum_{i=1}^{I} \left[ P_Y \frac{\partial Y_i^t}{\partial DWT_i^t} + n_i^t \frac{\partial g_i^t}{\partial DWT_i^t} \right] + z_i^t \frac{\partial h_i^t}{\partial DWT_i^t} + \frac{\partial z_i}{\partial t} = s z_i. \tag{12}
\]

The first term on the left side of (Eq. (12)) includes the sum of the economic impact of higher water tables on crop yields in the region and the long-term impact of rising water tables on soil salinity. The partial derivatives of crop yield with respect to water table depth, \(\partial Y_i^t / \partial DWT_i^t\), are positive, as greater depths improve productivity. The partial derivatives of soil salinity with respect to water table depth, \(\partial g_i^t / \partial DWT_i^t\), are negative, as rising water tables cause upward movement of salts into the root zone. Given that output price, \(P_Y\), is positive and the costates, \(n_i^t\), are negative, the first term describes the near-term and long-term regional benefits from an increase in water table depth.

The second term describes the long-term economic impact of rising water tables, where both the costate, \(z_i\), and the partial derivative of the equation of motion with respect to water table depth, \(\partial h_i^t / \partial DWT_i^t\), are non-negative. The third term is the time derivative of the costate, which may rise or fall, over time, in response to changes in crop prices or production costs. In sum, the terms on the left side of (Eq. (12)) describe the current-year and long-term regional marginal benefits of an increase in water table depth.

The term on the right side of (Eq. (12)), \(s z_i\), can be interpreted as the annual opportunity cost of obtaining the payment a region would have to make to obtain an incremental increase in depth, if such a market existed, where the value of that increment is described by \(z_i\) and the social discount rate is \(s\). As noted above, the left side of (Eq. (12)) describes the regional marginal benefits of an increase in water table depth. Hence, optimization of the project-level model requires that marginal benefits are equal to the opportunity cost of obtaining an increase in water table depth in all years.

3. Policy implications

Differences in the first-order necessary conditions for the farm-level and project-level optimization models explain why farm-level choices of irrigation and leaching inputs are not socially optimal. Farmers are not motivated to consider the external effects of deep percolation on a regional water table and farm-level discount rates may exceed the social rate. In addition, farm-level water use will exceed the social optimum when the price of water is less than the marginal cost of delivery or when farmers are not presented with opportunity costs. Farm-level choices of non-water inputs will also differ from the optimum when prices do not reflect off-farm effects. Policies that
modify the farm-level price or availability of inputs may be useful in closing the gap between farm-level and socially optimal input choices.

3.1. Water prices

The necessary conditions in (Eq. (4)) and (Eq. (9)) suggest that the optimal prices for irrigation water are the following:

\[ P_{WA}^{*} = MC_{W} - z_{i} \frac{\partial h}{\partial V_{AD}} \frac{\partial V_{AD}'}{\partial V_{A}} + \lambda_{i} = 0 \]

for \( i = 1, \ldots, I; \quad A = R, L. \) (13)

where \( P_{WA}^{*} \) represents the optimal irrigation and leaching water prices. In theory, if such prices are substituted for \( P_{W} \) in (Eq. (4)), farmers will be motivated to select the socially optimal volumes of irrigation and leaching water, as prices will reflect opportunity costs and the long-term impacts of deep percolation. However, several practical issues arise regarding the estimation and use of these optimal water prices.

(Eq. (13)) depicts prices that vary among farmers according to the impacts of farm-level water deliveries on deep percolation. In most irrigated areas those effects cannot be estimated accurately, and farm-specific water prices are not feasible. However, an estimate of the average value of the impacts described by the second term on the right side of (Eq. (13)) can be obtained using hydrologic data or assumptions regarding the impact of water deliveries on water table depths. Technical coefficients that describe proportions of surface runoff, deep percolation, and crop water use for alternative irrigation methods can be used to estimate the deep percolation derivatives, \( \partial V_{RD}/\partial V_{R} \) and \( \partial V_{LD}/\partial L \), while soil characteristics and hydrologic relationships can be used to estimate the water table depth derivatives, \( \partial h/\partial V_{RD} \) and \( \partial h/\partial V_{LD} \). The costate, \( z_{i} \), which is the marginal value of an increase in water table depth, can be estimated by examining data describing the impact of regional water table depth on agricultural production values (e.g. Kemal et al., 1995b, p. 24).

The value of \( \lambda_{i} \) can be estimated by considering the increase in regional net revenue that could be generated with additional water supply. In regions with an active water market, \( \lambda_{i} \) may be estimated using market prices, as these reflect the opportunity cost of water. The marginal cost of water supply, \( MC_{W} \), includes operation and maintenance costs for the delivery system and a capital replacement charge. The portion of those costs included in water prices may vary with public goals and the distribution of benefits from irrigation projects (Sampath, 1992).

Implementing water prices can also provide an economic incentive for public agencies to reduce seepage along main and secondary canals, particularly if agency budgets are made dependent upon the collection of revenue from water sales (Moore, 1989; Small and Carruthers, 1991, pp. 52–53; Ellis, 1992 p. 271). Water agency personnel in regions where water is delivered at no charge to farmers and water rights are not assigned have little incentive to spend limited funds on canal improvement projects (Repetto, 1986). Placing a value on water at the agency-level may reduce the extent of waterlogging and salinization caused by seepage from main and secondary canals.

Volumetric water pricing is common in the Western US and other industrialized regions where the scarcity value of water justifies the cost of accurate measurement, and where automated metering technology is available. Water is also priced by volume, or an appropriate proxy, in many developing countries. For example, many farmers in India and Pakistan purchase groundwater in local markets, paying hourly rates for the use of pumps and fuel (Pant, 1991). Rates vary according to water quality, pump size, and energy source (diesel or electricity), and are substantially higher than the equivalent price of canal water (Shah and Raju, 1988; Janakarajan, 1993; Mitra, 1998).

The state government of Gujarat (India) has decided that water delivered from the Sardar Sarovar Dam on the Narmada River will be supplied only volumetrically (Maloney and Raju, 1996 p. 171). Irrigation water will be delivered to outlets that serve many farmers who will need to form water user groups to manage the water and to collect and transmit water fees. Volumetric supply to command areas of 30–40 ha may be feasible and affordable (Mitra, 1990).
Farmers in Bulgaria have been required to pay both a fixed and variable charge to the national government for irrigation water service since 1994. The initial prices of US$ 7.30 per ha and US$ 0.025 per m³ ($30.85 per acre-foot) discouraged irrigation and the government collected less than 25% of the fixed charges (Koubratova, 1997). Prices have been reduced in recent years, reaching $1.60 per ha and $0.009 per m³ in 1996. Farm-level questions regarding the procedures used to determine water prices and to estimate water volumes where meters have not been installed are being addressed by the central government.

Economic reforms in China have encouraged irrigation districts to implement water pricing programs to support operation and maintenance. Irrigation charges are $13.08 per ha and $0.0017 per m³ in the Nanyiao Irrigation District, and $1.74 per ha and $0.0084 per m³ in the Bayi Irrigation District, both of which are in the Shijiazhuang Prefecture (Johnson et al., 1998). Farmers irrigating with groundwater in Bayi are charged an additional $17.44 per hectare. Water rates have increased substantially since the middle 1980s, motivating farmers to reduce water deliveries by improving irrigation practices.

3.2. Water markets and water rights

Formal and informal water markets enable farmers to lease or sell a portion of their water supply for a specific time interval or in perpetuity (Dudley, 1992; Rosegrant andBinswanger, 1994; Rosegrant et al., 1995; Rosegrant and Meinzen-Dick, 1996; Dinar et al., 1997). Markets encourage farmers to consider opportunity costs explicitly when they choose crops and irrigation methods (Dinar and Letey, 1991; Weinberg et al., 1993). Farmers with water market opportunities may choose to improve management practices to make water available for sale or lease. Farm-level efforts to ‘convert’ surface runoff or deep percolation into marketable water volume will reduce pressure on regional water tables.

Water markets relieve public agencies of the task of estimating the opportunity cost or scarcity value of water, as market prices reflect current perceptions and expectations regarding those values. However, markets do require that property rights to water are defined and enforced (Wypenny, 1994 p. 57; Hearne and Easter, 1995; Anderson and Snyder, 1997, pp. 22–25; Perry et al. 1997). Transaction costs may prevent market formation in some areas (Rosegrant and Binswanger, 1994), and improvements in measurement and control capability may be needed. However, those improvements may also support volumetric water pricing and may enable water agencies to provide farmers with greater flexibility in scheduling water deliveries.

Informal water markets have existed for many years in Pakistan and northern India, where farmers trade their time allotments on surface water canals or buy and sell groundwater pumped from private tubewells (Easter and Hearne, 1995). Groundwater markets have expanded in recent years, enabling many small and marginal farmers to increase agricultural production by supplementing their limited surface water supplies (Chaudhry, 1990; Shah, 1993; Meinzen-Dick, 1994; Repetto, 1994, pp. 41–43; Shah and Ballabh, 1997). Groundwater and canal water transactions account for 30% of the irrigation water used by farmers in some regions (Rinaudo et al., 1997). Extensive pumping of shallow groundwater relieves pressure from high water tables in some areas, while in other regions excessive pumping causes concern regarding groundwater depletion (Rao, 1993).

The establishment of secure, transferable water rights in Chile, in conjunction with other market-oriented reforms, has contributed to large gains in agricultural output during the past 20 years, with little investment in new hydraulic infrastructure (Gazmuri, 1994; Hearne and Easter, 1995; Gazmuri and Rosegrant, 1996). Many farmers rent or sell a portion of their water rights to other farmers or nearby cities, using the proceeds to pay for improvements in water management practices or to plant perennial crops (Bauer, 1997). Transaction costs have not prevented water market activity, as most trades have occurred within a canal command area or within the region around a large city.
Tradable water entitlements were introduced in South Australia in 1983, where subsequent marketing of water rights has enabled farmers to expand the production of higher valued crops using more efficient irrigation methods, while the volume of water applied to lower valued crops using less efficient methods has declined (Bjornlund and McKay, 1998). State officials require water buyers to develop an irrigation and drainage management plan to limit the impact of return flows from upstream areas on the salinity of water available to farmers in downstream areas.

3.3. Water allotments

Much of the world’s irrigation water is delivered in large-scale systems that are managed by central or regional governments, with limited ability to measure farm-level deliveries accurately. Public officials determine how much water will be delivered to tertiary canals by controlling the release and delivery of water along main and secondary canals (Upton, 1996, pp. 200–201). Water allotments to farmers are often defined by public agencies, or by water user associations that are formed to allocate water among farmers and collect funds for operation and maintenance. In many areas, water allotments are not clearly defined or enforced, resulting in the uneven distribution of water among farmers (Bromley et al., 1980; Easter and Welsch, 1986; Chambers, 1988; Wade, 1988; Bhatta and Vander Velde, 1992). Excessive use of water by head-end farmers causes waterlogging and degrades the quality of water received by tail-end farmers.

Negative externalities can be reduced by implementing or enforcing water allotments and allowing farmers to trade their allotments individually, or as members of water user associations. Many farmers in India and Pakistan trade their delivery turns to enhance irrigation flexibility within the otherwise rigid warabandi rotation system that has been used to allocate limited water supplies for more than 125 years. Improvements in operation and maintenance, and institutional enhancements may reduce seepage losses and improve the equity and efficiency achieved within the warabandi system (Bandaragoda, 1998; Perry and Narayananmurthy, 1998).

The national groundwater agency in the Cape Verde Islands has implemented a fixed-access rotation system, replacing one in which farmers could withdraw as much water as desired during each rotation. The new system reduces uncertainty regarding water allotments and the time interval between rotations. Farmers trade access times to gain the flexibility required for producing higher valued crops (Langworthy and Finan, 1996).

In Mexico, the National Water Commission has transferred responsibility for operation and maintenance of secondary and tertiary canals to water user associations that allocate water according to each farmer’s proportion of the total irrigable area (Kloezen and Garces-Restrepo, 1998; Levine et al., 1998). Some associations use farm-level crop intentions to determine water allocations, effectively restricting the area planted in crops with large water requirements during dry years. Others allocate each year’s water supply among farmers, allowing them to choose crops accordingly. Associations adjust time allocations to compensate for water losses in delivery channels, improving the distribution of water among head and tail sections of tertiary canals.

3.4. Land assessments

Public water agencies in India, Pakistan, and other countries with major irrigation projects charge farmers for water delivery services using area-based assessments intended to recover the costs of operation and maintenance (Sangal, 1991; Puttaswamaiah, 1994 p. 187; Kemal et al., 1995b; Sinha, 1996; Tsur and Dinar, 1997). The charges are usually higher for crops with larger water requirements and in regions with higher costs of service. These programs are less costly to implement than volumetric water pricing (Small and Carruthers, 1991 p. 141) and they offer some incentive to choose crops with smaller water requirements, but the farm-level marginal cost of water within a season is zero.

An incentive to reduce deep percolation can be incorporated in area-based assessment programs
by modifying the crop-specific price structure to reflect the deep percolation objective. In particular, an area-based surcharge can be imposed on fields that receive larger water deliveries than crop-specific targets determined by a water agency, in consultation with farmers and water user associations. The targets could be established at levels that enable farmers to satisfy crop water and leaching requirements without generating excessive deep percolation. Surcharge parameters could be determined by estimating the external costs of deep percolation which include the capitalized value of yield reductions in future and the amortized cost of installing a regional drainage system to manage the high water table.

3.5. Non-water inputs

Improvements in water management practices can generate farm-level benefits by reducing the volume of water applied to soils and, thus, reducing the rate of salt accumulation (Eq. (5)). This provides an incentive to implement such practices, which include sprinkler and drip irrigation, laser leveling, and the hiring of additional labor to improve the management of surface irrigations. Irrigating with greater precision enables farmers to reduce drain water volume, while maintaining or improving crop yields (Khanna and Zilberman, 1997). However, the near-term cost of irrigation increases with higher technology systems and a long-term cost may arise if the reduction in deep percolation reduces the rate at which salts are removed from soils. Farmers selecting irrigation methods will evaluate both of these effects, but will not consider the off-farm benefits of increasing regional water table depth (Eq. (10)).

The public benefits of improvements in irrigation methods may be sufficient to justify policies that motivate farm-level adoption, such as subsidies for hiring additional labor or for purchasing selected irrigation systems. Providing small farmers with access to credit and offering low-interest loans may encourage them to purchase new irrigation systems or to install private tubewells to pump water from shallow aquifers (Shankar 1992, pp. 160–168; Wichelns et al., 1996). However, credit subsidies and flat-rate energy pricing can exacerbate problems of excessive withdrawals and salinization in regions where the off-farm impacts of groundwater pumping are negative (Bhatia, 1992; Rao, 1993).

4. Conclusions

Waterlogging and salinization continue to cause economic losses in many areas of the world, though farmers and scientists have been aware of these problems and potential technical solutions for thousands of years. The farm-level and project-level models presented here suggest that improvements in the definition of property rights to scarce resources and more appropriate pricing of irrigation and drainage inputs may reduce the rate of increase in waterlogged and saline areas. Many of these improvements can be implemented while installing or renovating water delivery and subsurface drainage systems, and when transferring responsibility for operation and maintenance from central government agencies to local irrigation districts.

Public policies that acknowledge farm-level economic incentives have been implemented in many regions during the 1980s and 1990s. Tradable water rights have been implemented in Chile and Australia, for example, while farmers in India and Pakistan have expanded their use of formal and informal water markets for surface water and groundwater. Responsibility for irrigation systems has been transferred to water user groups in Indonesia, Mexico, the Philippines, and Turkey. Water pricing programs have been enhanced in Bulgaria, China, Mexico, the US, and many other countries.

Support for these programs has not always been immediate among farmers and agency personnel, and results have not matched expectations in all cases. For example, while many local irrigation districts have improved the quality of services provided to farmers following the transfer of system responsibility from central governments, some have failed to operate and maintain system facilities adequately and have not been successful in recovering costs from farmers. Water pricing programs and changes in water allocation proce-
dures have encouraged farm-level improvements in water management in many irrigated areas, while in others, public officials have not implemented such programs due to concerns regarding the inability to control and measure farm-level water deliveries accurately.

Efforts to improve water delivery systems and to recover the costs of those improvements from farmers will likely continue in many countries, as the scarcity value of water and the economic losses caused by poor water management increase in the future. Public officials and water agency staff can enhance those efforts by developing pertinent incentive programs, selecting appropriate parameter values, and seeking support for implementation among farmers and water user associations. Experience suggests that such efforts may be very helpful in motivating farmers to improve irrigation practices, reduce deep percolation, and apply leaching fractions that maintain soil quality, while reducing the rate of increase in waterlogged and saline areas.

Acknowledgements

This paper is Rhode Island Agricultural Experiment Station Publication Number 3685. The helpful comments of three reviewers are appreciated.

References


