Chapter 58

THE ECONOMICS OF WATER, IRRIGATION, AND DEVELOPMENT

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Contents

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Abstract

The post-World War II era has witnessed a drastic increase in irrigation activities that have contributed substantially to the massive growth in agricultural production that enables humanity to feed its doubling population. However, a distinction has to be made between the overall positive contribution of irrigation and water to agricultural productivity and economic welfare and a significant amount of misallocation and mismanagement of resources that have accompanied the expansion of irrigation. In many cases, water resources have been overdeveloped; there has been overspending on capital; and significant costs in terms of loss of ecosystems, extinction of fish species, and contamination of water sources. This chapter provides an economic perspective on the contribution of irrigation and water resources to past agricultural development and future water resource management.

The efficiency of water use is affected by decisions made at many levels. In this chapter, we first analyze the inefficiencies that can occur at different levels of water management. We begin by discussing irrigation water use by an individual, and then move to the importance of regional water management. We then discuss the importance of dynamic considerations about the future, and the role of interregional management. Together, these sections present an economic framework for designing water institutions and policies to improve water resource allocation and prevent some of the current inefficiency in water resource systems. The second part of the chapter provides an overview of the benefits and costs that have been realized through agricultural water and irrigation projects in developing countries. There is a paucity of ex-post integrated assessments of these projects, so we put the pieces together, combining data with conceptual arguments.

Keywords

irrigation, water resources, developing countries, water project development

JEL classification: O13, Q1, Q25, Q5

1. Overview

The previous century has seen unprecedented growth in irrigation projects on a global level. The use of tube well irrigation has decreased the cost of using groundwater, and the subsidization of large reservoirs and canals has been used to achieve food security. Worldwide, irrigated land has increased from 50 mha (million hectares) in 1900 to 267 mha today, with much of this increase in developing countries [Gleick (2000)]. Currently 75% of all irrigated land is in developing countries. Irrigation has increased the amount of land under cultivation, and the yields on existing cropland. It has also allowed double cropping, and has decreased the uncertainty of water supplied by rainfall.

Table 1 shows the growth in irrigated areas worldwide in recent decades. Certain regions such as Asia have benefited greatly from irrigation. The countries with the largest areas in irrigation are China, India, and the United States, which consistently contain about half of the world's irrigated land. Other regions such as Africa have little land

Table 1
Total irrigated land (in thousands of hectares) and percentage of arable land under irrigation

	Year			
	1965	1975	1985	1995
Regional totals				
Africa	7,795	9,010	10,331	12,388
	4.9%	5.2%	5.6%	6.1%
Asia	97,093	121,565	141,922	180,507
	21.8%	26.7%	28.9%	32.4%
Australia	1,274	1,469	1,700	2,400
	3.4%	3.5%	3.6%	5.2%
North & Central America	19,526	22,833	27,471	30,478
	7.6%	8.5%	10.0%	11.2%
South America	5,070	6,403	8,296	10,086
	5.9%	6.2%	7.6%	8.4%
Europe	9,401	12,704	16,018	26,150
	6.3%	9.0%	11.4%	8.4%
Individual countries				
China	33,587	47,782	44,584	49,859
	32.1%	47.5%	35.4%	37.0%
India	26,510	33,730	41,779	53,001
	16.3%	20.1%	24.7%	31.2%
United States	15,200	16,690	19,831	21,800
	8.5%	8.9%	10.4%	11.8%
World totals	150,155	188,637	225,686	262,304
	10.9%	13.3%	15.2%	17.3%

Source: FAOSTAT.

Table 2
Total potential irrigation area (in thousands of hectares)

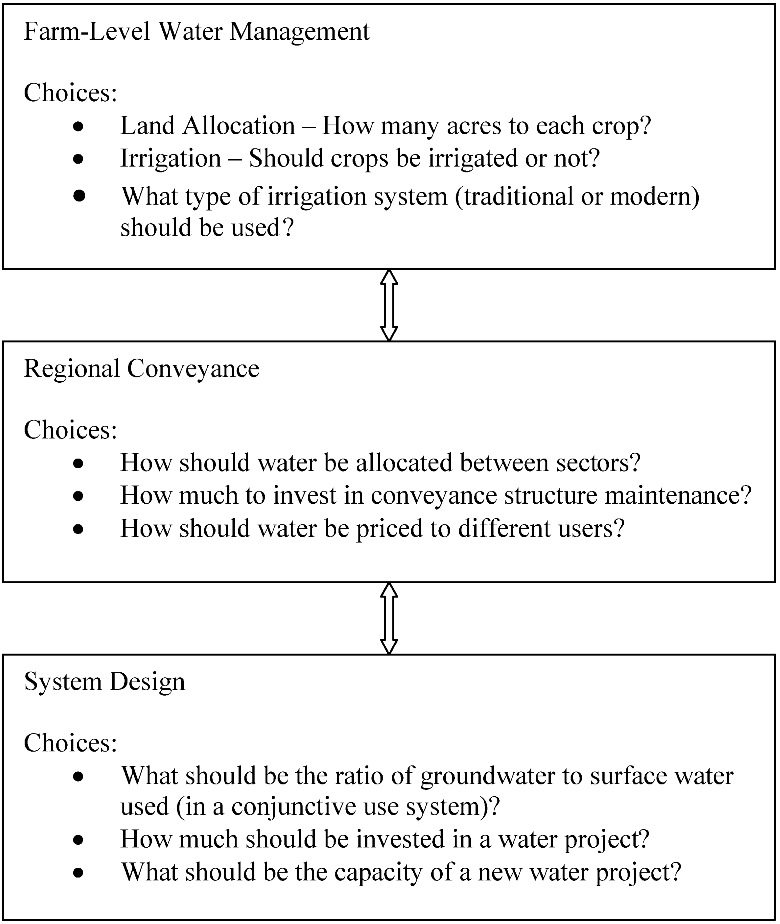
	Potential area	Actual to potential percent
Africa	48,155	25.7%
Asia	282,826	63.8%
South America	59,575	16.9%

under irrigation. The world total shows a large increase in irrigated land, with close to a doubling in a 30-year time frame. In addition, Table 1 shows the percentage of arable cropped land that is irrigated. This percentage varies significantly between regions. For example, in 1995 Asia has 32.4% of total cropland under irrigation, while in Africa it was only 6.1%. Also, some of the countries, such as the United States and China, have had their share of arable land in irrigation remain relatively constant between 1965 and 1995, while in India this percentage has almost doubled.

While there is little land in irrigation in certain regions of the world, such as Africa, in some cases there is a significant amount of potential irrigated land. Table 2 shows the potential for irrigated land in Africa, Asia, and South America. One interesting thing to observe is that the ratio of actual to potential irrigated land is much greater in Asia than in Africa and South America. One conclusion that we can make from this table is that the future expansion of irrigated acreage is limited in Asia, but that there is significant potential in other developing regions of the world. However, the distribution of the potential irrigated land has a considerable amount of variation. This variation in Africa, and its implications for development and food security, is discussed in more detail in Rosegrant and Perez (1997).

An important concern for the future is the limited supply of fresh water. Recent years have seen a decline in the number of water projects build worldwide, because of environmental and cost concerns. Most of the areas that are good locations for water projects have already been developed, and more is known about the negative environmental effects of the construction of large dams and poorly managed irrigation systems. Evidence of this change can be seen in the projects funded by the World Bank. There has been a shift from the development of new irrigation projects to the improvement of existing irrigation facilities. An example of this type of project is the water-saving competition in the Aral Sea region sponsored by the World Bank and IWMI [Murray-Rust et al. (2003)].

Water resources are not distributed evenly around the globe, and arid regions will continue to have conflicts over water supplies. In addition, growing populations in developing countries are expected to increase total demand for food in the coming century. Those in developing countries are eating more meat products, and increasing demand for cereal crops as livestock feed as a result. Estimates by IFPRI show that to meet demand in 2020, world production of cereal crops will have to increase 40% over 1995



Farm-Level Water Management

Choices:
- Land Allocation – How many acres to each crop?
- Irrigation – Should crops be irrigated or not?
- What type of irrigation system (traditional or modern) should be used?

Regional Conveyance

Choices:
- How should water be allocated between sectors?
- How much to invest in conveyance structure maintenance?
- How should water be priced to different users?

System Design

Choices:
- What should be the ratio of groundwater to surface water used (in a conjunctive use system)?
- How much should be invested in a water project?
- What should be the capacity of a new water project?

Diagram 1. The multiple levels of water system management.

levels. Better management of existing water systems, along with the use of more efficient irrigation technologies will be essential in upcoming decades. Thus, this chapter both assesses the performance of irrigation systems in the past and introduces a direction of water system reform for the future.

2. The multiple dimensions of water management

The efficiency of water use is affected by decisions at several levels of management. Diagram 1 illustrates what choices are made at each level of management, and how these different levels are interrelated. The listed questions are not meant to be an exhaustive list, but to illustrate some of the choices that are made at each level, choices that affect the efficiency of the entire water system. In choosing the optimal system design, it is important to use a backward induction approach, and to base the system design on the expected responses at the levels of the region and farm.

2.1. Micro-level water management choices

Ultimately, the efficiency of irrigation systems is determined by farm level choices. These include choices of land allocation among crops, the extent to which these crops are irrigated, the use of non-water inputs, and the type of irrigation technologies. These choices are interdependent, and complete modeling of these choices is likely to be cumbersome. Therefore, it is here we discuss land allocation among activities; we first address the choice between rainfed and irrigated agriculture, and then move to the choice of a particular irrigation system.

2.1.1. Land allocation to irrigation at the farm level

There is an extensive literature on adoption of technology which is useful in analyzing the selection of acreage under irrigation [Feder, Just and Zilberman (1985); Feder and Umali (1993)]. This literature, to a large part, assumes that farmers are risk averse and constrained by credit availability. Driven by anecdotal evidence, most existing work assumes that adoption of irrigation reduces risk and increases yield but requires extra investment. The following model of a farmer's choice to use rainfed agriculture or put land in irrigation is adapted from Feder, Just and Zilberman (1985). The inclusion of a credit constraint in the model is of particular relevance to farmers in developing countries.

Suppose a farmer has $\bar{L}$ acres of land and can allocate it among two activities, irrigated and rainfed agriculture. Profit per acre under both is distributed normally where mean profit per acre under irrigation is μ_1 and the variance of profit is zero. The mean and variance of profit per acre under rainfed farming is μ_0 and σ_0^2, respectively. We denote L_0 as acreage under rainfed farming and $L_1 = \bar{L} - L_0$ as irrigated acreage. Irrigation has fixed cost of K dollars and cost per acre of m dollars, and the farmer has a credit constraint of N dollars. Defining ϕ as a measure of risk aversion, we assume that the farmer has constant absolute risk aversion $\phi/2$ and thus his objective function is linear in the mean and variance of profit. If irrigation is selected but the credit constraints binds, acreage in irrigation is $L_1^* = (N - K)/m$. If credit is not constraining, and expected net profit per acre under irrigation is greater than rainfed farming, all the land will be irrigated ($L_1^r = \bar{L}$ if $\mu_1 - m - \mu_0 > 0$). Integrating this above condition, optimal acreage in irrigation is

$$L_1^* = \max\left\{0, \min\left(\bar{L}, \frac{N-K}{m}, \bar{L} + \frac{\mu_1 - m - \mu_0}{\phi\sigma_0^2}\right)\right\}.$$

Thus, irrigation will increase as the gain from irrigation is large, the risk reduction effect of irrigation is larger, costs of irrigation are smaller, and credit is less restrictive. From this result, we can conclude that the subsidization of financing irrigation investment is likely to increase acreage in irrigation, particularly as the yield gain and risk-reduction from irrigation increase.

2.1.2. Irrigation technology choice at the farm level

The previous section assumed that a farmer had the option to grow crops on rainfed land. In many places, rainfall is insufficient to grow any crop. In these cases a farmer cannot choose to irrigate or not, he/she must choose the type of irrigation technology to employ. Traditional irrigation methods, such as flood or furrow, use gravity to disperse water over a field. These methods have low costs of adoption, but are also relatively inefficient with water use. Modern technologies such as micro-sprinkler or drip irrigation have higher adoption costs, but deliver the water directly to the crop, applying water in a more precise fashion than traditional technologies.

To discuss the efficiency of different types of irrigation technology, we will use the notions of "effective water" and "applied water". Applied water is the total amount of water that is used by the farmer on the field, while effective water is the amount of water actually used by the crop. The difference between the two is due to evaporation and runoff, and irrigation efficiency is the ratio of effective water to applied water. In addition to the irrigation technology, land quality characteristics such as the slope of the land and the water-holding capacity of the soil affect irrigation efficiency. Theoretical and empirical studies have shown that an increase in water price is positively correlated with adoption of precision irrigation technology [Caswell and Zilberman (1985, 1986); Dinar and Yaron (1992)].

According to Caswell and Zilberman (1986), under plausible conditions, modern irrigation technologies increase yields as well as saves water in most cases, but the gains from this technology are reduced as land quality improves. This counterintuitive result is because differences in water holding capacity lead to differences in the effective price of water, where the effective price under traditional irrigation decreases as land quality improves. Therefore, the relative gains of a switch to precision irrigation are lower with high quality land. Except for cases where the initial land quality is very low, a gain in productivity will also be associated with water saving. Adoption occurs when the yield and price saving effect of precision irrigation are greater than the fixed cost of the technology, thus we expect that modern technology will first be adopted in locations with low quality land such as steep hills and sandy soil. The details of this model are presented in Appendix A.

Another counterintuitive result of the analysis is that the availability of efficient irrigation technology can actually lead to a net increase in water use in a particular region. This is because there are two types of effects from efficient irrigation availability; those at the intensive margin and those at the extensive margin. At the intensive margin, farmers that adopt efficient irrigation technology are likely to decrease total water use. However, there can also be a change at the extensive margin. Those with low quality land often find that it is not profitable to farm using traditional irrigation methods, since the effective price of water is high when irrigation efficiency is low. However, modern irrigation technology increases water use efficiency, decreasing the price of effective water. This can make it profitable to farm land that was left fallow under flood irrigation. Both the intensive and extensive changes in water use need to be evaluated with a change in water price or technology availability.

The increase in water use efficiency reduces unutilized water and thus with drip irrigation the problems of water buildup and waterlogging are diminished. Caswell, Lichtenberg and Zilberman (1990) show that when a penalty on drainage is introduced, adoption of sprinkler and drip irrigation are likely to accelerate. These technologies provide both an increase in productivity as well as a reduction in negative externalities, and their adoption will be enhanced by improved pricing of water and the introduction of drainage fees.

Providing the correct incentives for farmers to adopt efficient irrigation can have dramatic effects on water use. Switching from furrow or sprinkler irrigation to drip systems decreases water applications by up to 35% [Schoengold, Sunding and Moreno (2005)]. Global use of drip irrigation is twenty-eight times the level of the mid-1970s, but still accounts for less than 1% of world irrigated area, while sprinkler irrigation is used on 6% of irrigated land [Postel (1996)]. Improvement in water use efficiency is not limited to agriculture, and industrial and residential water users can also do a lot to improve the efficiency of their water use. With techniques available today, farmers could cut their water demands by 10–50%, industries by 40–90%, and cities by a third with no sacrifice of economic output or quality of life [Postel (1996)].[1]

2.1.3. *Productivity of water*

An important factor in determining the response of farmers to a change in water price is the shape of the function relating production output with water inputs. Following Caswell and Zilberman (1985) we define output per acre (Y) as a function of effective water (e), where effective water is the quantity used by the plant. This is equivalent to the product of the water-use efficiency parameter and applied water.

Some of the early work on water productivity was done by Hexem and Heady (1978), who use field experiments in the United States to estimate yield as a function of inputs including water and fertilizer. One commonly used production function in the economic literature is a Cobb–Douglas production function of the form $Y = Ae^{\delta}$, with a requirement that $\delta < 1$. While some work has shown that this representation is reasonably accurate at an aggregate level, econometric evidence has shown that this is a poor representation of the yield response of water at a more micro-level. There is evidence that a quadratic function, such as $Y = a + be - ce^2$ where $a, b, c > 0$, is a better representation of water productivity. This functional form has the property that above some level of input use, yields begin to decline. With an extreme weather shock, such as a flood, one

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[1] While these values may be feasible from an engineering perspective, designing appropriate policies which provide the right incentives for individuals to change their behavior is difficult. As such, these levels of reductions are difficult to achieve in practice.

can easily see how a field of crops is washed away, and the benefits of that additional water are negative. Another commonly used function is the Von Liebig, which assumes water exhibits constant returns below some threshold level, and a zero return above that threshold. This takes a form such as $Y = Ae$ if $e \leqslant e^*$ and $Y = Ae^*$ if $e > e^*$. Berck and Helfand (1990) have shown that different choices of functional forms for production can be reconciled with certain assumptions about the heterogeneity of land quality. Existing work finds it is unclear which of these functional forms is the most accurate, and further work needs to be done on the subject.

In addition to the theoretical work done on the functional form of water productivity, empirical work has been done to estimate the returns to water in several locations. One study of the Syr-Darya River basin finds the average return to water in the region is $\$0.11/\mathrm{m}^3$. However, this value varies significantly throughout the area, and water use in non-saline areas is as much as five times higher than saline areas [Murray-Rust et al. (2003)]. There has also been work done on the relationship between high yielding varieties (HYV) and the productivity of water. Since HYV increase the marginal product of water, they have been found to also stimulate investment in irrigation [McKinsey and Evenson (xxxx)].

2.1.4. *Existence of low-capital efficient irrigation technologies*

Efficient irrigation technologies do not necessarily entail a high capital cost of adoption. There are examples from water-scarce areas that show the ingenuity of farmers in their ability to adapt to limited water supplies. One example is the leveling of farmland. Terracing of farmland has been used for thousands of years as a way of increasing the efficiency of applied water. A flat surface leads to less water runoff, and increased water use efficiency of the plant. Another method that has been used is the placement of clay pots below the ground level near the roots of tree crops. The porous clay permits the water to slowly drip from the pot, and provides a constant supply of water to the tree. One other example of a low-cost irrigation technology is the use of village tanks in India. Traditionally, villages in India have gathered rainwater in tanks, with each village having a system that designates how water is to be divided among users, and who is responsible for the upkeep of the system [Whitaker, Kerr and Shenoi (1997)]. There has also been a low-capital system of drip irrigation developed that is being used in parts of India. This system uses simple holes instead of emitters, and a cloth filter. Despite requiring a much lower investment in capital than most drip irrigation systems, it is remarkably efficient in water use [FAO (1999)]. The use of bucket drip irrigation, a method where water is delivered through drip tubes from an overhanging bucket, can reduce water use by as much as 50%.

2.2. *Regional allocation of water*

At a regional level, there are many aspects of water management that need to be addressed to improve the overall efficiency of a water system. In this section, we first discuss the initial choices made about a system, including the location and size of a water project, as well as the importance of financing the project. We then move to the discussion of important management choices of existing systems, such as conveyance, water trading, and water pricing.

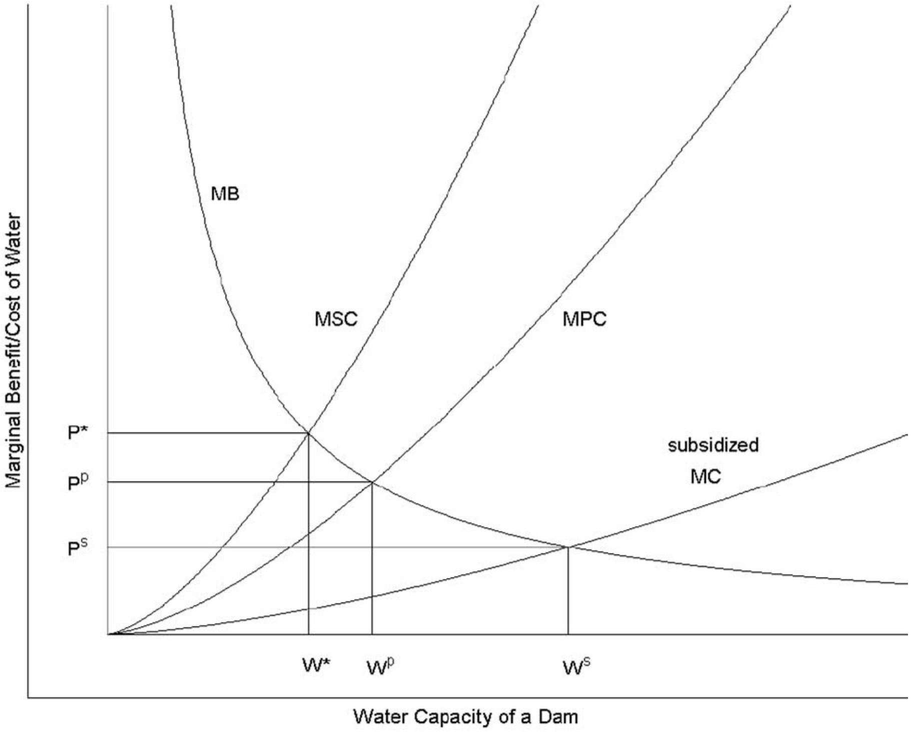
2.2.1. The basic economics of oversized water projects

In the decision to construct a new water project, the benefits of the project must be compared with the costs. The large water projects in the Western United States were some of the first government-funded projects that required a benefit–cost analysis to be completed before the project was approved. Water projects funded by international agencies such as the World Bank also require such studies before approval. In addition to the decision on the location, the choice of the size of a dam and conveyance system also must be made. Economic theory has some insight into the choice of the optimal size of a dam. While dams provide many benefits through the supply of irrigation water, hydropower, and flood protection; the full costs of construction have often been ignored, both in the decision to build a dam and in the choice of the size of the water project. The externalities associated with construction are often ignored entirely, decreasing the perceived marginal cost of development. Also, it is often the case that development costs are subsidized, either by governments or international agencies. In these cases, the perceived costs of water development are below the true private costs.

A simple static model depicts the forces that lead to overinvestment in projects such as dams. Let W denote the capacity of a dam. The marginal market benefit to the surrounding region of building the dam and increasing the water supply are shown in the MB curve. The costs of building a dam can be broken down into two categories – direct capital and construction costs and externality costs. The marginal direct cost of building the dam is shown by the MPC curve, and the marginal social cost is shown by the MSC curve. The difference between these two curves accounts for the externalities associated with dam construction. These externalities include environmental costs such as the destruction of natural habitat and degradation of the soil, and other costs such as the welfare loss of displaced populations. Now suppose that construction is subsidized. Because of subsidies, the cost facing developers is often well below the full private costs, leaving the perceived cost of water development as shown by the subsidized MC curve.

The most important result of Graph 1 is that in cases where costs are subsidized and externalities are ignored, the dam capacity will be too large, and the marginal benefit of water supplied will be too low. If the full social cost of dam construction is taken into account, the optimal capacity of the dam will be W^*, and the marginal benefit will be at P^*.

It is also important to consider the relationship between storage capacity and other components of water delivery. The benefits of water development are a function of three activities – conveyance, management, and storage capacity. To some extent, these three activities can be considered substitutes for each other. When subsidies lead to a low relative cost of storage capacity, there is overinvestment in storage capacity and un-



Graph 1. Effects of externalities and subsidies on water project capacity.

derinvestment in conveyance and management of irrigation systems. While it is clear that irrigation and water development have provided tremendous benefits, the omission of the true costs has led to the construction of large dams, often in locations that are inappropriate for water project development because of fragile landscapes and ecosystems.

2.2.2. *Management of conveyance systems*

The construction of water conveyance systems is an important element of the overall efficiency of the system, as better management of conveyance systems reduces the need for new water projects. Many canal systems were built at a time when the costs of constructing an efficient distribution system were greater than the additional benefits. Various methods exist to improve the distribution of water. For example, lining the canals is one method that can limit the amount of water lost during conveyance. Another problem is poor maintenance of existing canal systems – over time there is deterioration, which leads to increased amounts of lost water. Poor management of irrigation systems leads to conveyance losses of up to 50% [Repetto (1986)].

Inefficiency also stems from the water lost to evaporation in canals and reservoirs. These problems have a disproportionate effect on the downstream users in a water system, creating equity problems among different water users. The maintenance of a canal system at one location has benefits to the local users; however it also has benefits to all of the downstream users of the water system. Because of this, canal maintenance provides a positive externality, as the social benefit of canal maintenance is greater than the private benefit to each water user. If these positive externalities are ignored, there will be too little investment in canal maintenance, leading to an inefficient water conveyance system. Chakravorty, Hochman and Zilberman (1995) show that without collective action (which leads to optimal investment and conveyance), canal systems will be shorter than optimal, with over-application of water close to the source and under-application far away. Transition to optimal conveyance will expand canals and production and will actually reduce the rental rate of lands that are upstream, even though the overall rent is likely to increase.

As discussed by Easter (1986), there has been a shift in recent years from the development of new water projects to better management of existing projects. This has led to an increased reliance on water user associations (WUAs). A WUA is a group of farmers who collectively manage and distribute their combined available water supply. A shift to management of water resources by the water users is being promoted as a means to improve conveyance systems, cost recovery, and the efficiency of water use.

In various places WUAs have existed side by side with publicly run irrigation systems for many years. Evidence suggests that higher yields, better conveyance structures, improved maintenance, greater efficiency, and a more reliable supply are associated with WUAs. One important question for economists concerns the effectiveness of different management strategies for a common resource; the irrigation system. In a study of Mexican farmer-managed irrigation systems, Dayton-Johnson (2000) investigates the incentives for an individual to provide collective maintenance labor under different WUA distributive rules. He finds that because of higher system wide costs, a system where labor requirements and water allocation are proportionally distributed may not be optimal. A better system is one of equal labor requirements and water allocation, with trading possible between members. He also finds that economic inequality among water users is positively correlated with a proportional distribution rule, evidence that wealthier landholders are able to push for a higher share of total water supply.

One country that now primarily uses WUAs to manage irrigation systems is Madagascar. An ordinance passed in 1990 requires water users to pay the costs of irrigation infrastructure, and the result has been an average cost recovery of 80–90%, well above most developing countries [Rabemanambola (1997)]. Another country with growing use of WUAs is India. Since seeing a decline in irrigation performance, the state of Andra Pradesh in India has created over 10,000 WUAs covering 3.7 mha of land. As Dayton-Johnson's results indicate, it does seem like some level of equality in land-holdings is necessary for the success of a WUA. Pakistan, where many areas have a few large landholders, has been less successful in the formation of WUAs. In Hubei, China, one goal of the shift to WUAs is financial autonomy. WUAs are required to purchase the water they use, giving them an incentive to conserve and use water efficiently [Easter (2000)].

2.2.3. Political economy of water system management

An understanding of the politics underlying water resource development and management is crucial for improvement in the future. Work by Rausser and Zusman (1991) shows that when those with political decision making authority place unequal weights (termed 'political power' by Rausser and Zusman) on different interest groups, the resulting water pricing and allocation methods are economically inefficient. Rausser (2000) extends this model into a multilateral bargaining model based on a Nash–Harsanyi bargaining framework. This model illustrates the tradeoffs between different interest groups who are concerned about water distribution and allocation.

One reason that has been offered to explain the poor management of conveyance structures in many public irrigation systems is termed the 'political economy of neglect'. This theory says that if agencies who fail to provide the necessary upkeep to their irrigation system are bailed out by a donor agency, there will be a lower incentive for them to provide efficient levels of maintenance. This describes the situation in many public irrigation systems. The funding for the initial costs of constructing the project usually comes from agencies such as the World Bank or the Asian Development Bank. This funding is often contingent on the recipient country managing the irrigation system so that revenues cover the operating costs of the system. However, the countries also know that if they fail to adequately maintain the irrigation systems, international agencies will provide additional funding. This provides an incentive for the public agency to neglect to provide adequate maintenance, creating a cycle of dependence on outside funding.

Another explanation for poor management and low quality service is discussed in Spiller and Savedoff (1999). Their paper looks at how government opportunism affects the efficient provision of water. Their paper focuses on countries in Latin America, but many of the conclusions have general implications. They discuss the emergence of low-level and high-level equilibriums in water service provision. A low-level equilibrium refers to the case when government wants low water prices to keep their citizens happy. When water is provided either by public agencies, or private agencies that can be partially controlled by the government, water prices are kept artificially low. Unless subsidized by other sources, this leads to limited service and poor infrastructure, and a public who is unwilling to pay higher prices for water service that they perceive as inefficient and low-quality. While it does not maximize social welfare, a low-level equilibrium is stable. A high-level equilibrium, one with higher water price, but also high-quality water service that is well-maintained improves social welfare. However, in cases where the government is short-sighted and had control over water service, it might not be stable. In their analysis of Latin America, Spiller and Savedoff identify several countries in each category. Honduras and Peru are examples of countries with low-level equilibriums, while Mexico, Chile, and Argentina have high-level equilibriums.

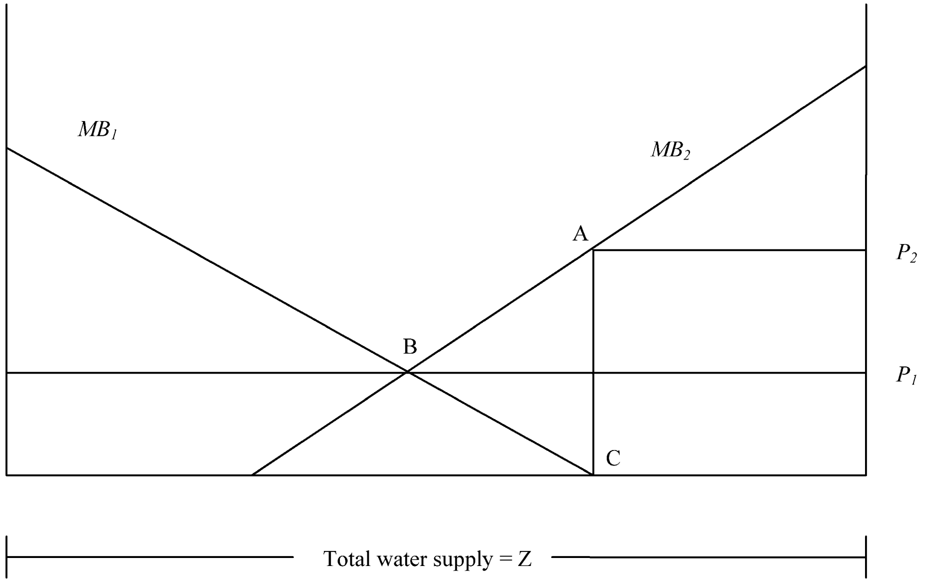
2.2.4. Transition from water rights to water markets

Water rights systems In most parts of the world, the price paid by water users is well below the marginal value product of the water as an input. Existing estimates of the ratio of water charges to farmer benefits range from 26–33% in Korea to 5% in Nepal [Repetto (1986)]. Given the low price paid by users, demand would greatly exceed supply of water if it was allowed. Since water resources are scarce, and the price paid by users is below the input value, water must be allocated using a non-market mechanism. In many parts of the world, water is allocated using a "queuing" system [see Easter (1986) for an overview; Chambers (1988) for the Indian subpeninsula; and Lee (1990) for South America]. Queuing systems use either a historical or spatial basis to assign an order to the users of a water system. Two of the most common types of queuing systems are a prior appropriation system and a riparian rights system. The prior appropriation system is based on the principle of "first in time, first in right". Seniority in water rights is given to the first person to divert water for beneficial use. The riparian rights system gives any landowner with land adjacent to a water source the right to use that water.

It is also common to have restrictions on trade within a watershed system (quite frequently of the form "use it or lose it"). In these systems, senior rights holders or upstream water users have little incentive to invest in water-saving irrigation technology, because they are assured of a stable water supply. These types of systems were established at a time when water was plentiful, and governments wanted to provide an incentive for private development and innovation. However, water in many systems is now over appropriated, and better management is essential to make the best use of a limited resource.

The transition to trading and markets Both riparian and prior appropriation rights systems involve limitations on trade in water, leading to inefficiencies in water distribution. Neither type of system is economically efficient, as the water is not used in the activity where it earns the highest marginal value. Economic efficiency dictates that if transaction costs are low, either water markets or tradable permits are the best way to allocate water supplies [Burness and Quirk (1979); Coase (1960)]. These systems ensure that scarce water will flow to the user who earns the highest marginal value from the water. Graph 2 shows two farmers who earn a benefit from water of MB_1 and MB_2, respectively; however, farmer 1 has senior rights to water while the other (farmer 2) has junior rights. Total water available for a season is Z. A shift to a system of tradable water rights can increase the welfare of all parties involved, as shown in Graph 2.

With a prior appropriation system, senior rights holders have their demand fully satiated before junior rights holders receive any water. In Graph 2 the marginal benefit to farmer 1 of an additional unit of water is zero, while the marginal benefit to farmer 2 is P_2. If trading in water rights is allowed in the preceding model, there will be positive gains to society from trading. Farmer 1 will sell water to farmer 2 until the marginal benefit to both is P_1, and the increase in social welfare is the area of triangle ABC.



Graph 2. Gains from tradable water rights.

When transaction costs are introduced to the above model, the welfare gains of tradable permits will be reduced. If water is not very scarce, the transaction costs of trading water may be greater than the benefits. However, as demand for water expands over time and the shadow value of water increases, the benefits of trade will outweigh any transaction costs. Evidence for this is suggested by observations that in developed countries that allow water trading, trading activities increase significantly during drought years. Also, as discussed by Johansson (2000) [citing work by Renfro and Sparling (1986), Shah (1993), and Anderson and Snyder (1997)], informal water markets have repeatedly been developed under conditions of water scarcity.

There are alternative mechanisms of water trading that have to be considered when reforms are introduced. The first choice is whether to use a system of transferable permits or transfer ownership of water to the government agencies that will sell it in the market. Water users with senior rights will prefer transferable rights systems as they are able to earn the associated rents. A water agency might prefer water markets, as they earn the proceeds of water sales, and can use the revenue to improve service and management of water supplies. Brill, Hochman and Zilberman (1997) distinguish between passive and active water markets. In the case of passive water markets, water users buy and sell water to a regional water authority that controls water supply and conveyance. In the case of active markets, agents trade among themselves. Passive markets are more appropriate within regions and especially among water users that are served by the same utility, while active markets are appropriate between districts. Some form of passive trading within districts exists within many parts of the world.

Another choice is whether to only allow individuals to rent the right to use water on an annual basis or to allow complete transfer of ownership rights. In cases of infrequent droughts, renting the water rights to those with a high willingness to pay might be a better option than a permanent sale. In places with chronic water shortages, a rights holder might be better off with a sale of those rights. In addition, the permanent sale of water rights secures a future water supply for users. This can promote capital investment in the land that would not occur with an uncertain water supply.

A third decision is if out-of-basin trading among water users should be allowed. When water users in a single water basin are allowed to trade, the transaction costs, and especially the third party and environmental costs, will be lower. If water users are allowed to trade their rights outside of their water basin, concerns about third party effects must be addressed. These third parties may be individuals who use runoff or deep percolating water from the land, or the environmental benefits that accrue through the supply of residual fresh water. Addressing these issues may require limiting the quantity traded to the effective water, and not the applied water used by an individual. A discussion of the essential component in a water market is in Easter, Becker and Tsur (1997).

Examples of countries that have transitioned to water markets are Chile, South Africa, and Australia. Chile is probably the most well-known example of such a transition on a national scale. In 1981, Chile reformed its Water Code, and by doing so, changed the nature of water rights. After the change, water rights became completely separated from land ownership, and can be freely bought, sold, or rented. The government now has little control over water use, and most of the managerial decisions about conveyance systems and maintenance are made by private water users associations.

An interesting result of the shift to water markets in Chile is that few transactions have been observed in practice, while most of the transactions have been in combination with a sale of land, with water right rarely being sold separately than land rights. Part of the reason for this is the low value of land without water rights. There are also institutional reasons – at the time of the reform, there was a lot of uncertainty about the ownership of much of the water used. Much of the energy since the reform has gone into defining water rights, and some areas have seen 10 times as many water rights approvals as water sales [Bauer (1998)]. Clearly, well-defined water rights are a necessary condition for welfare-improving water sales. In some cases though, initial allocation of water is not far from optimal. However, even if only a small proportion of the total water used is being sold and these are final sales, the impact may be significant if the gain in productivity for this water is substantial. Eventually, as water rights are better defined, new actors enter the system, and conditions change, transactions will increase.

Another example of a country with a major change in its water law is South Africa. In 1998, the New South African Water Act changed the ownership of water from private to public; however, farmers still have private rights to use certain quantities of water. Transfers of water between users are allowed, although certain administrative policies must be followed. Nieuwoudt, Armitage and Backeberg (2001) discuss case studies of two agricultural regions to highlight the factors that can either lead to or impede an active water trading market. They find that despite costly administrative requirements, the

Lower Orange River area has an active water trading market. Reasons for this include water scarcity and a heterogeneous group of water users. Some of the farmers in the area grow table grapes, which are a high value crop, while others grow wine or raisin grapes, which earn a lower price. Since the marginal value of water is greater to growers of table grapes, the benefits of trading outweigh the transaction costs. In the second region (the Nkwaleni Valley), an active trading market has failed to emerge. Despite water scarcity, none of the water users have been willing to part with their water rights. The farmers in this region are fairly homogeneous, and all grow a combination of sugar cane and citrus. While some are willing to buy more water, if it was available, none are willing to sell. One clear implication of these results is that for water trading to be successful, there needs to be heterogeneity among potential water users.

Australia has also moved to a water-trading regime, and has decoupled ownership of land from the right to use water, in a similar manner as Chile. The shift from traditional water rights stemmed from a growing realization that greater flexibility was needed in water rights, and in particular, water resources are necessary in the natural habitat. A 1994 bill separated water rights from land ownership, and established a water allocation for environmental services and the development of water markets. The results of the change in Australia have been positive, and estimates are that the annual gains from the shift to tradable water rights are \$12 million in Victoria, and \$60–\$100 million in New South Wales [ACIL (2003)]. Despite these gains, there are still some barriers that have been identified as an impediment to the highest possible returns to tradable water rights. One of these impediments is a limitation on the lease of water-use rights. Water rights can be permanently sold in all States of the country, but some States still have a restriction on short-term (i.e., one year) leases of those rights. Another aspect that has been identified as a limitation on the benefits of trading is the lack of an options market in water resources. The elimination of these barriers of a fully functioning water market will only increase the benefits already realized in Australia.

2.2.5. *Water pricing systems*

The costs of providing irrigation water include a fixed cost of operation and maintenance (O&M) and a variable cost, which depends on the quantity of water supplied. In addition, there is a capital cost of constructing a water project. There are many pricing systems used for recovering some or all of these costs. In most countries, the revenues received fall far short of the costs of supplying irrigation water to users, and often do not even attempt to recover the initial capital costs. Recovery of operation and maintenance costs ranges from a low of 20–30% in India and Pakistan to a high of close to 75% in Madagascar [Dinar and Subramanian (1997)]. In some areas of India, receipts even fail to cover the administrative costs of collection [Saleth (1996)].

Water pricing systems can be designed to provide an incentive for water users to adopt water-conserving technologies, or to alter the amount of land under cultivation.[2] A vol-

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[2] For a more detailed discussion of irrigation water pricing systems, see Johansson (2000).

umetric fee provides an incentive to limit water use, while a per-hectare fee provides an incentive to cultivate agricultural land more intensively. Some of the most common pricing systems are per-hectare fees, increasing or decreasing block rates, and volumetric fees. These rates can either be fixed or depend on the area and time of year. Many systems combine these; for example, charging a per-hectare fee for access to water, and then a reduced volumetric fee for water delivered. This is the type of pricing system used in Brazil for irrigation water. Irrigation water is mostly metered in Brazil, and the irrigation law requires that the price of irrigation water be the sum of two charges. The per-hectare charge is designed to repay the capital costs of the project, which are calculated using a 50-year repayment period and a subsidized interest rate. The volumetric fee is designed to repay the operation and maintenance costs of the water project. However, the revenues from this are unpredictable, and in practice have failed to cover the costs of water projects [Todt de Azevado (1997)].

Inaccurate volumetric measurement One source of inefficiency in water pricing stems from the inability to measure the quantity of water an individual uses. In many areas of both the developed and the developing world, the cost of installing metering devices to accurately measure water use by individuals is prohibitive. Various pricing systems have been developed as an alternative to volumetric pricing. Overwhelmingly, developing countries use a per-hectare water fee, if they charge at all. One country that used per area pricing is Pakistan. In Pakistan, water charges are levied on a per unit area basis, and vary across region, crop, and season. However, the price variation across crops is not related to either the water requirements or the profitability of the crop. Other countries, such as Egypt and Indonesia, do not charge farmers anything for the water they use but require farmers to maintain and operate the irrigation canal system. One commonly used pricing scheme is based on the duration of water delivery. This system can approximate a volumetric measure using an expected quantity per minute or hour.

Subsidization of water delivery costs While precision irrigation technology can dramatically reduce water use, its adoption is minimal. One reason for this is that the price of irrigation water generally does not reflect the scarcity value of the water. Irrigation water is subsidized in many regions, and the price often does not even reflect the cost of delivery, let alone the shadow value of a scarce resource. An example of inefficient pricing can be seen in India, where from 1983 to 1986, the estimated working expenses of major water projects was 2.2 times the gross revenue collected from the water users [Saleth (1996)]. Using 1987 data, a study of six Asian countries showed that the irrigation charge as a percentage of total cost ranged from 1.0% to 22.5% [Repetto (1986)]. The elimination of subsidies on water delivery will promote the adoption of precision irrigation, which will decrease water use, increase yields, and reduce environmental externalities such as water logging and salinization.

Improved pricing and water theft Another benefit of improved water pricing policies is discussed by Ray and Williams (1999). Their paper explains the prevalence of water theft on shared canals in India. Upstream water users are able to steal water meant for downstream users, and the penalties, if they exist, are usually some type of bribe to the inspector. Their analysis uses a linear programming model to show the effects of various pricing policies on farms along the canal. Eliminating price supports and water subsidies increases social welfare, but the gains are not uniform along the canal. Without water theft, farmers at all points along the canal have higher revenues with subsidized prices. However, when water theft is taken into account, farmers at the head of the canal lose, while those in the middle gain from a shift to non-subsidized water and output prices. Those at the tail end of the canal are slightly better off with subsidies, but the loss to them of improved pricing is minimal.

2.2.6. Groundwater management

Groundwater as an open-access resource When property rights to a natural resource are ill-defined, there is often a problem of open access to many individuals. In cases where the resource is limited in supply, users of the resource will not take into account the effects of their use on the future availability and cost of the resource to other users. One of the biggest obstacles to the optimal management of groundwater systems is the open access problem. Since groundwater is rarely regulated, anyone has the ability to dig a well and pump water for personal use. However, since the same groundwater table is available to many users, each user inflicts an externality on others, as a greater level of water extracted reduces availability to other users in the future.

Subsidization of groundwater pumping costs One obstacle to the efficient management of groundwater is the subsidization of pumping costs. The main cost of pumping groundwater is the power required to lift the water to the surface. In many countries electricity is subsidized, which decreases the marginal cost of pumping, and leads to increased extraction of groundwater. Two countries with subsidization of electricity costs are India and Pakistan, and this subsidization is part of the reason for the overdraft of groundwater that is occurring in these countries. From 1951 to 1986, the use of tank irrigation in India fell slightly, while the use of canal irrigation and well irrigation increased dramatically. Tank and canal irrigation depend on surface water while well irrigation relies on groundwater supplies. The amount of land under canal irrigation has increased from approximately eight thousand to fifteen thousand hectares, while the land under well irrigation has increased from six and a half thousand twenty thousand hectares, an increase of over 300%. This is partly due to technological improvements that make digging wells and pumping water easier, but it is also due to the low costs paid for pumping of water. Electricity users pay a low flat rate, almost eliminating the marginal cost of groundwater pumping [Whitaker, Kerr and Shenoi (1997)].

Introduction of efficient groundwater pricing Because of the externality imposed on other water users, the elimination of electricity subsidies still leads to a sub-optimal groundwater price. The theory of exhaustible resources dictates that the price of groundwater should equal the sum of the cost of extraction and the user cost, with the user cost equal to the opportunity cost [Hotelling (1931); Devarajan and Fisher (1981)]. Appendix B presents a formal model that shows that optimal use of groundwater requires equating the marginal benefit of water with the sum of the pumping cost and the user cost. The user cost measure the loss of future benefits because of depletion and the increase in future pumping costs associated with depleted stock. A first-best solution would be to impose a tax equal to the user cost on every acre foot of groundwater extracted [Shah, Zilberman and Chakravorty (1993); Howe (2002)]. However, the monitoring and enforcement of a tax like this would be impossible with the cost and availability of currently available technology. As discussed in Shah, Zilberman and Chakravorty (1993), a second-best solution would be to base the tax on the irrigation technology and crop choice.

2.2.7. Between sector allocations of water

One area we have neglected to mention earlier is the interaction between agricultural water users and other sectors, such as urban and industrial groups. Many times there not only are misallocations of water among farmers, but also between sectors. With limited water supplies, competing interests between user groups become important. Among these three sectors, agriculture uses the lions share of the water supply, despite the fact that it often earns the lowest marginal value of water. As populations increase, pressures to supply an adequate amount of water for domestic and industrial purposes also increase, causing conflicts between sectors. This has been true for over 100 years in places such as California. In Chile, growing cities such as Santiago have bought water rights from agricultural users to supply urban residents. However, an adequate solution to the question of between sector allocations is more complicated than a simple transfer of water from agriculture to the urban sector. For example, a study of Hyderabad City, the capital of Andhra Pradesh in India finds that improvements in the pricing structure of urban water could lead to more efficient urban water allocations, removing the need for costly transfers from the agricultural sector [Saleth and Dinar (1997)]. Also, differences in water quality requirements exist between sectors. Much of the water used in agriculture would require further treatment for use in other sectors.

2.2.8. Use of non-traditional water sources

As traditional water supply sources have become scarcer, there is growing use of non-traditional sources of water. These include the reuse and recycling of wastewater, and desalination of ocean water. In the Western United States and parts of Africa and the Middle East, there has been a growth in the use of reclaimed wastewater for industrial, agricultural, and commercial uses [Gleick (2000)]. Reclaimed water may be produced at a cost of 30 to 40 cents per cubic meter and will be competitive with other sources of water in Israel and Jordan. In Israel, partially reclaimed water is used extensively in production of industrial crops such as cotton. Crops that can tolerate saline water are able to reuse the water that was initially applied on salt-intolerant crops. Another option is desalination of ocean water. While still expensive, desalination has begun to be used in water-scarce regions such as North Africa and the Middle East, and the world's 7500 desalting plants can produce 0.1% of the world's water use [Weber (1991)].

Rhodes and Dinar (1991) present results that suggest that for crops such as cotton and certain vegetables, yield levels can be maintained if high quality water is used early in the life of a plant and more saline water is applied toward the end of the season. Their approach will enable water planners to take advantage of drainage water and other low-quality water, but will still require maintaining inventories of water of various qualities. Amir and Fisher (2000) explain that farmers in the Jezreel Valley of Israel use both high quality freshwater and brackish reclaimed water in crop production. An arbitrary policy to limit production of low-value crops such as cotton does increase the average return of water, but it also limits the ability of producers to optimize their use of both types of water sources. This evidence shows there is a benefit to having multiple qualities of water available for different end uses. However, this option requires evaluating the economic tradeoff between the cost of separate storage and the cost of bring all water quality to the highest standard.

2.3. Intertemporal aspects of water

2.3.1. Dynamic consideration and uncertainty

The previous section presented a model of the optimal size of a water project using a static framework. This is useful, but neglects some of the dynamic considerations that are important. A water project is planned not just for a single period, but for many years. Dynamic considerations include calculations of future benefits and costs, the choice of an appropriate discount rate, and population growth. Because of the high rate of population growth in many developing countries, it might be optimal to choose a larger water capacity than current demand indicates.

One source of uncertainty comes from expectations about future demand for water. It is often difficult to accurately predict future demand for water from a newly developed irrigation system. If developers assume that demand for water inputs will stay constant after the construction of a water project, the chosen supply level could be either too high or too low. Water demand could decrease for several reasons after the construction of a water project. One reason is that crop yields in irrigated areas are higher than in rainfed areas, and higher benefits per unit of water might reduce total demand for water. Another factor is the choice of irrigation technology. If farmers adopt precision irrigation technology that is more water efficient, this could also decrease the total demand for water after a water system is built. There are also several reasons for a potential increase in water demand. Many water projects are built in countries with high rates of population growth, which can increase demand for water. Water projects and the resulting employment opportunities can also increase migration into the developed area. In addition, arid areas that otherwise are unproductive are able to grow crops after water development, leading to an increase in water demand for agricultural uses. While the direction of the shift in water demand is unclear, if constant future water demand is presumed, the resulting dam size is usually suboptimal.

In a simplest form, the decision in designing a water project is related to construction of capacity to convey a certain amount of water, from a source to a destination [see Chakravorty, Hochman and Zilberman (1995)]. Let $\overline{W}$ be the upper bound of water that can be diverted during a period and the fixed cost of the project is $f(\overline{W})$. At period t, the amount of water utilized is $W_t \leqslant \overline{W}$. The water provides benefits of $B(W_t, \varepsilon_t)$ where ε_t is a random variable.

The annual cost of the water is $c(W_t)$ (it includes both direct and externality costs). Assuming a project design for T years and discount rate of r, the optimal size of the project is determined by maximizing discounted expected net benefits, i.e.,

$$\max_{\overline{W}, W_t} \int_0^T e^{-rt} E\big\{B(W_t, \varepsilon_t) - c(W_t)\big\}\, \mathrm{d}t - f(\overline{W}) \tag{1}$$

s.t. $W_t \leqslant \overline{W}$.

For an infinite planning horizon and identical random element, $\varepsilon_t = \varepsilon$, the water use at each period is $W_t = \overline{W}$ and the optimal design problem is reduced to

$$\max_{\overline{W}} \frac{E[B(\overline{W}, \varepsilon)] - C(\overline{W})}{r} - f(\overline{W}),$$

where $E[B(\overline{W}, \varepsilon)]$ is the expected benefit per period and $N(\overline{W}) = E[B(\overline{W}, \varepsilon)] - C(\overline{W})$ is the net expected benefit per period. Optimal capacity is at the level when the marginal net expected benefit $MB(\overline{W}) = \partial N / \partial \overline{W}$ is equal to the marginal cost of capacity $MC(\overline{W}) = \partial f / \partial \overline{W}$ times the interest rate, i.e., when

$$MB(\overline{W}) = MC(\overline{W}). \tag{2}$$

There is a vast literature on the appropriate discount rate for project development, and we will not address this point here [see Arrow (1997) for an overview]. Low discount rates place a greater weight on future costs and benefits (compared to current costs and benefits) than a high discount rate. In cases where the interest rate is subsidized, such as when a donor agency expects repayment of the principle with no interest, using Equation (2) will lead to overinvestment in projects and diversion capacity. Failure to account for all costs, including externalities, leads to the same result. It is not necessarily optimal for the project to operate at a full capacity in every period. Suppose that the random factor ε_t does not have identical independent distribution at all periods and instead has the same mean but its variability increases over time. This could occur if uncertainty about benefits is greater for periods further in the future. For simplicity, assume that ε_t is normal and is with mean μ and variance σ_t^2 and expected benefit is of the form $B(\overline{W}, \varepsilon_t) = a\mu\overline{W}_t + b\overline{W}^2\sigma_t^2$.

The marginal benefit of increased capacity increases with the random effect in cases when it represents temperature and the gain from increased water delivery capacity is higher when the probability of increased climate variability increases.

If the variance increases substantially over time, optimal water use will be below capacity at an early period and will reach full capacity at time t^*. Thus for $t \leqslant t^*$, $W_t < \overline{W}$, and $W_t = \overline{W}$ for $t \geqslant t^*$.

The stochastic element ε_t may represent random natural phenomena, but in some cases it represents uncertainty about the key parameters of the system at the time when the design of the dam or other projects is made. Suppose that $\varepsilon_t = \bar{\varepsilon} + \eta_t$ where $\bar{\varepsilon}$ represents true randomness and η_t represents a random effect of lack of knowledge. Extra time that allows for learning can reduce both mean and variance of η_t.

Traditional cost–benefit analysis asks if a project should be built or not. If the net present value of the project is positive, then it should be built, and if it is negative, it should not. This type of analysis ignores a third possibility – the option of waiting. If the value people place on the benefits of this ecosystem is uncertain, then waiting to build the project can allow further information to be learned about these benefits as increased knowledge becomes available.

Arrow and Fisher (1974) and more recently Dixit and Pindyck (1994) develop models that suggest that in these cases the decision maker may consider delaying the decision about optimal project design so that more information can be learned. They not only look at the question ‘to build or not to build’, but they also consider the importance of when to build. Delaying building a project by one or two periods may lead to a loss of benefits in these periods but will lead to a future gain as more information is taken into account. This work shows that if the gains from acquiring new information are greater than the foregone benefits of current construction, it is better to delay construction of a new project. The gain from the option not to make an immediate decision is referred to as “option value”. In particular, in cases when there is uncertainty about productivity of water as a result of availability of a new technology or uncertainty about environmental impacts of water diversion activities, the option value of waiting may be quite high and there may be significant gain from delay. Because of this, a positive net present value of a benefit–cost analysis is a necessary, but not a sufficient condition for construction.

Zhao and Zilberman (**?**) extend this analysis to consider projects where restoration is costly but feasible. This is more realistic for water development. Dams are being removed from many sites worldwide, and natural habitats are being restored. They find that in some cases, it might be better to construct a new project even if there is a chance it will lead to costly restoration in the future. This could happen if the expected benefits of a project are larger than the expected future restoration costs.

2.3.2. Waterlogging and drainage

A solution to the problem of waterlogging should combine two elements – a functioning drainage system and the use of more efficient irrigation technology. Various details regarding the development of a plan to manage drainage are discussed in Dinar and Zilberman (1991). The construction of a drainage system can decrease levels of waterlogging in the soil. A well-functioning drainage system can allow an otherwise exhaustible soil resource to become sustainable over time. While effective, this has problems of its own. The construction of a drainage system can be very expensive, and the drained water has to be deposited in an area where the saline water will not have negative environmental effects. It may be best to combine a limited drainage system with the use of efficient irrigation technology, limiting the need for drainage and deposit of stored water [see Chakravorty, Hochman and Zilberman (1995)]. While drainage and waterlogging are problems in many areas of the world, quantitative data on the prevalence of these problems are not widely available for all regions. However, areas such as Asia and South America have very good data available. In China, 24.6 million hectares are susceptible to waterlogging, with drainage equipment on 20.3 million of those hectares. In the former USSR, 12% of the cropped land has been drained, although this varies from 6% in the Russian Federation to over 100% in the Baltic States.[3] In Mexico, over 5.2 million hectares have been drained for agriculture, along with 1.3 million hectares in Brazil, figures which represent 19.1 and 2.0% of the arable land, respectively.[4]

The following model illustrates the impact of drainage consideration on project evaluation. Suppose the per period net benefit of water is given by $B(W_t, S_t)$, where S_t is the stock of water trapped underground at time t, while $f(\overline{W})$ is the cost of constructing a water project of capacity $\overline{W}$. Let a fraction of the water be percolating and generate a stock of rising water level that eventually hampers production. The initial stock is S_0, and the equation of motion is $\dot{S} = \alpha W_t$. The productivity of water declines as S_t, the stock of water trapped underground, rises. In this case the optimal water project design problem is

$$\max \int_0^\infty e^{-rt} B(W_t, S_t)\,\mathrm{d}t - f(\overline{W})$$

subject to

$$\dot{S} = \alpha W_t$$

and

$$W_t \leqslant \overline{W}.$$

Using the technique in Hochman and Zilberman (1985), the optimal solution to this problem is such that an optimal capacity $\overline{W}^*$ is established, for an initial period water diversion is constrained by the capacity, but beyond a critical point water deliveries declines over time as the user cost (associated with the extra waterlogging cost) reduces the net benefit of water use. A lower capacity to accumulate waterlogging and higher α

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[3] In this area the drained area is greater than the total cropped area due to a need to use drainage for construction sites.

[4] All of this data is available from AQUASTAT, 2003, from the Land and Water Division of the FAO.

(fraction of water that contributes to waterlogging) will reduce the water project capacity and water deliveries. Further details on the dynamics of drainage management are presented in Tsur (1991).

As suggested by Van Schilfgaarde (1991), water project designers have ignored the drainage consideration and, as a result, the benefits of water projects have been overstated, and their capacity exceeded the socially optimal level. If the cost of waterlogging is low at an early period of a water project, the buildup of a drainage canal can be delayed to year t_D and, once drainage facilities are introduced, the dynamics of water use may change. Specifically, both t_D and D, the drainage capacity, may be policy variables. Let the cost of the drainage capacity be $C_D(D)$. When drainage is introduced, equation of motion becomes

$$\dot{S} = \alpha W_t - D_t$$

and the optimization problem is

$$\max_{\overline{W}, W_t, t_D, D_t} \int_0^{\infty} e^{-rt} B(W_t, S_t)\, \mathrm{d}t - f(\overline{W}) - e^{-rt_D} C_D(D)$$

subject to

$$\begin{aligned} &\dot{S} = \alpha W_t \quad \text{for } t < t_D, \\ &\dot{S} = \alpha W_t - D_t \quad \text{for } t > t_D, \\ &W_t \leqslant \overline{W}. \end{aligned}$$

Lower cost of drainage will tend to increase $\overline{W}$ and water use at every period. When the cost of drainage is sufficiently low, the system may reach a steady state when $W_t = \overline{W}$ with all the infiltrating water is being drained to prevent any buildup of underground water stock.

2.4. Interregional choices

2.4.1. Conflicts and cooperation over water

In many places, water sources cross political boundaries, and agreements are necessary to determine not only the division of water between user groups, but also the allowable activities and levels of pollutants in that water. International dialog and agreements are necessary in many areas to protect both the allocation and the water quality levels of freshwater resources. While it has often been argued that conflicts over water supplies are increasingly likely to occur as populations increase, and existing freshwater supplies are over appropriated, work by Wolf (1998) suggests otherwise. Wolf finds that the number of agreements to cooperate on water management is many times greater than the number of conflicts. In addition, Wolf outlines the necessary conditions for an armed conflict over water to emerge, and finds that there are few possible sites that meet the criteria. Work by Franklin Fisher and the Middle East Water Project has developed the WAS (Water Allocation System), a model of the potential gains from the trade of water between Israel, Jordan, and the Palestinians [Fisher (**?**)]. Their model finds that there are potentially significant gains from the trade of water between the Israeli and the Palestinian governments, regardless of the initial allocation, however, the paper also discusses some of the political and security reasons that such trade might not occur.

Joint cooperation is necessary to maintain or improve quality of water, in addition to agreements over quantity allocation. Several examples exist of joint cooperation between regions to improve water quality. For example, in 1972, Canada and the United States signed the Great Lakes Water Quality Agreement. This agreement made both countries responsible for activities that affect the water quality in the Great Lakes. This agreement, and the ongoing dialog it began between countries, has been at least partially responsible for the dramatic increase in water quality of the Great Lakes [Botts and Muldoon (1996)]. Another example of such an agreement between different states is the Chesapeake Bay Agreement, designed to improve water quality in the Chesapeake Bay. This agreement was signed by Maryland, Virginia, Pennsylvania, and the District of Colombia; and was designed to reduce nutrient levels in the water 40% below a 1985 benchmark [Bockstael and Bell (1998); McConnell and Strand (1998)].

2.4.2. Trade and the concept of "virtual water"

Water scientists have traditionally assumed that annual per-capita requirements for water are 1000 m^3 [Gleick (2000)]. Looking just at the numbers, this requirement leaves many developing countries with a severe water shortage. For example, the annual per-capita water supply in Jordan is only 100 m^3. However, the 1000 m^3 requirement is an average amount, and assumes self-sufficiency in food production and, in particular, in grains needed to feed humans and livestock. There is significant heterogeneity and availability of water ranges from 5000 m^3 in Canada and Northern Europe to 100 m^3 in Jordan.

Trade can alleviate some of the water constraints. Countries with limited water resources may produce high value goods for export that enable them to purchase grains that are water intensive but cheap. Thus, water scientists introduce the notion of virtual water. For example, if every acre-foot of water put into tomatoes earns $500, while every acre-foot of water put into wheat earns $20, then an acre-foot used to grow tomatoes is worth 25 acre-feet in wheat. The idea of "virtual water" is that if a society can generate enough value (through the use of their available water) to get 1000 m^3 worth of food, then that society has enough virtual water. This could be accomplished if water-scarce countries concentrate on exporting non-agricultural commercial products or growing high value crops for export (like flowers or produce) and then use the revenues to import staple crops like grains. Even though water itself is not tradable across nations, this allows countries to substitute trade in goods produced with the water available to them for direct trade in water. An example of a water scarce country with a shift toward high value crops is Yemen. Yemen has actively pursued a policy of subsidizing imported cereal products instead of supporting its own production, and consequently imports three-quarters of its cereal crops. Between 1970 and 1996, agricultural land used for cereal crops decreased from 85% to 61% of cultivated land, while the share of cash crops increased from 3% to 14% [Ward (2000)].

3. The benefits and costs of irrigation

3.1. Benefits of irrigation

3.1.1. Contribution of irrigation to agricultural productivity

Increased supplies of irrigation water have been instrumental in feeding the populations of developing countries in the last 50 years. Irrigation water has increased food security and improved living standards in many parts of the world. Fifty years ago it was common to hear concerns of food shortages and mass starvation, and while malnutrition is still a concern in many countries, the reason is not an insufficient global food supply. In fact, in the early 1990s, nearly 80% of malnourished children lived in countries that produced food surpluses, evidence that the cause of malnutrition is a lack of sufficient income by households to purchase food, not a lack of supply [FAO (1999)]. A report by IFPRI shows that between 1967 and 1997, global cereal production increased 84% at a time when population increased by 67% and that malnutrition among children under the age of five in developing countries declined from an aggregate rate of over 45% to 31% during this period. India, a historically impoverished country, has not had a major famine since the 1960s.

There are a number of reasons for this increase in food production, including high yield varieties of seed and increased use of fertilizers. However, the role of water development in providing irrigation water to cropland has also been significant. Benefits include the expansion of food supply, stabilization of water supply, flood protection, and the improved welfare of some native populations.

3.1.2. Food supply expansion

Irrigation and agricultural land expansion One benefit of water projects is an expansion in the feasible land base for agricultural production. Many regions with high quality soils have a Mediterranean climate and receive rainfall during the winter months when it cannot be used for crop production. For these areas, the development of reservoirs allows water to be stored during the rainy time of the year, and then used for farming during a dry part of the year. Canals allow water to be transported from water-rich to arid areas, where it can be used for crop production.

Irrigation and increased crop yields There is indisputable evidence that irrigating land leads to increased productivity. One acre of irrigated cropland is worth multiple acres of rainfed cropland. Globally, 40% of food is produced on irrigated land, which makes up only 17% of the land being cultivated. Dregne and Chou (**?**) estimate the value of production of irrigated cropland at $625/ha/year, compared to $95/ha/year for rainfed cropland and $17.50/ha/year for rangelands. In Asia, yields from most crops have increased 100–400% after irrigation [FAO (1996)]. Irrigation allows farmers to apply water at the most beneficial times for the crop, instead of being subject to the erratic timing of rainfall. One recent study using Indian production data from 1956 through 1987 shows that irrigation affects total factor productivity (TFP) beyond the input value of the water [Evenson, Pray and Rosegrant (1999)].

Irrigation and double cropping of land Another benefit of reservoirs is that stored water can be used for double cropping of fields. There are many tropic and sub-tropic areas that are warm throughout the year and have seasonal rains for a portion of the year, but remain dry for the other portion of the year. The ability to store water during the rainy season for use in the dry season could allow a farmer to move from a single harvest per year to two or three. An example of this occurs is in the central plain of the main island of the Philippines. This area has a rainy season from mid-June into November, and more than 70% of the total rainfall falls in a 4-month period. Water storage systems have allowed the region to have two cropping seasons in a year – the first is mainly dependent on rainwater, with irrigation water used to supplement times of drought, while the second, from December to May, is almost entirely dependent on irrigation water [Ferguson (1992)]. Although statistics are generally not available, there is anecdotal evidence that the expansion of double cropping has allowed land to be saved for nature, instead of developed for agricultural production.

3.1.3. Welfare improvements

Irrigation, employment opportunities, and income Employment opportunities in many regions have increased after the development of irrigation systems. This can occur because additional labor in planting and harvesting is needed for new land brought into production, for land that is being double cropped, or for industries that support agricultural production. One example of this occurred in Borletar, Nepal. The construction of a large public works project during the 1980s has doubled total labor demand in the region, improving productivity and welfare. Production potential has increased by 300% and income by 600%, leading to increased food security for the native population [FAO (1999)]. A 1997 study in Kenya and Zimbabwe showed that the average net increase in income from irrigation was $150–$1000 per family farm [FAO (1999)]. Growth in agricultural productivity also has a multiplier effect, providing benefits for non-agricultural sectors as well. Using data from India, Hazell and Haggblade (1990) show the value of non-agricultural output increases by 2.19 times the value of increases in irrigated production output.

Irrigation and land values Land values in a region are a function of the productive potential of the land. The development of irrigation systems allows farmers to grow higher yields of existing crops, or more profitable cash crops. Because of this, the benefits to landholders of irrigation development can be large. An example of this can be observed in the land supported by the Loskop Irrigation Scheme in South Africa. Non-irrigated grazing land in the area is worth between R1000/ha and R1500/ha while land with irrigation pivots is worth R10,000/ha [Tsur et al. (2004)].

3.1.4. *Irrigation supply stabilization*

The construction of a water storage and conveyance system decreases the risk associated with stochastic rainfall. Farmers are better able to plan their cropping patterns with a reliable water supply. The planting of certain crops, such as tree crops, requires the assurance of a sufficient water supply and may not be an economically rational choice for farmers before water development. Irrigation also allows farmers to apply water at the times that are most beneficial for the crop, instead of being subject to the variation in rainfall. The following example illustrates this point.

Due to weather shocks, the water supply is stochastic. During dry years, which occur $\alpha\%$ of the time, the available water supply is W_L, while during wet years, which occur $(1-\alpha)\%$ of the time, water supply is W_H. Since the choice of crop and irrigation technology must be made before the weather is observed, farmers must make these choices under uncertainty. If farmers are only assured of receiving a water supply of W_L ex-ante, then they might be unwilling to invest in high-value crops such as fruit and nut trees, or vine crops; as these crops require a minimum level of water each year. If an irrigation system and reservoir is developed, then farmers can rely on receiving a water supply of $\overline{W}$ in every year, where $\overline{W} = \alpha W_L + (1-\alpha)W_H$. The removal of uncertainty from the water supply allows the farmers to improve their welfare through their decisions on both crop choice and irrigation technology.

3.1.5. *Environmental benefits*

Irrigation and deforestation The expansion of agriculture is a primary cause of deforestation in developing countries. For example, between 1975 and 1988 the forested area in Northeast Thailand decreased by almost 50% because of growth in cassava production [Siamwalla (1997)]. Increasing food production in a region requires either more intensive use of existing cropland or an expansion of agriculture onto new cropland. Over time, production increases are essential because of larger populations, higher standards of living, and increased meat consumption. Using high-yield varieties of crops increases output on existing cropland, and irrigation is a necessary input into many high-yield varieties of crops in production. While deforestation is still an important problem worldwide, one would expect that without the benefit of irrigation, the remaining forest cover today would be less than we observe.

3.1.6. *Benefits of the conjunctive use of groundwater and surface water*

There is a large amount of literature on the benefits of conjunctive use of surface water and groundwater [Burt (1964); O'Mara (1988); Fisher et al. (1995)]. These benefits accrue because of the different nature of the resources. Surface water usually has lower delivery and extraction costs, but is subject to variability in supply. Groundwater can be expensive to pump, but has a reliable supply. In aquifers with recharge, the use of surface water during years of high precipitation can recharge an existing aquifer and decrease future overdraft of groundwater supplies. In aquifers without recharge, the availability of surface water for irrigation can be a substitute for nonrenewable groundwater supplies. In either case, the conjunctive use of the two sources can decrease the risk associated with a stochastic surface water supply. Arvin Edison Water and Storage District (AEWSD), located in California's Central Valley, provides a model of beneficial conjunctive use. AEWSD utilizes underground water banking in their water management plan. In wet years when they receive large quantities of surface water, they store some of it underground, and then pump this stored water during dry years, when the surface water supply is insufficient to meet district demand. Tsur (1997) estimates the value of this supply stabilization by the district to be $488,523 per year, a value equal to 47% of the total value of groundwater.

3.1.7. *Benefits of flood control*

A major purpose cited for the construction of many dams is flood control. While floods are rare occurrences in many areas, they have high costs when they do happen. Floods can cause tremendous damage – destroying property, killing people, and ruining environmental habitats. Dams have been instrumental in reducing these costs. The World Register on Dams shows that 17.3% of large dams report flood control as a main purpose. The majority of these dams are in developed countries (United States, Europe, and Japan make up a large proportion of the total); however developing countries have shared in some of these benefits as well.

One of the difficulties in measuring the value of the flood control benefits of a dam is that the benefits are probabilistic. When a dam is constructed, it is impossible to predict in which years there will be floods, and how damaging those floods will be. Because of this, a cost–benefit analysis of a proposed dam must use an expected value for the benefits of flood control. As discussed by Krutilla (1966), a dam that reduces the probability of flood damage to zero will not be feasible in a traditional cost–benefit analysis or economically optimal, due to the necessarily high costs.

3.2. *Costs of irrigation*

Despite the benefits discussed in the preceding section, there have also been many negative impacts of water projects. There have been financial, environmental, and social costs of developing water systems. Environmental problems include habitat destruction and a decrease in water quality while social costs include the displacement of native populations, and increased occurrences of waterborne diseases that affect those populations.

3.2.1. Capital costs

The costs of constructing a dam and conveyance system for irrigation are often many millions of dollars. In deciding whether a project is worth undertaking, it is important to weigh the anticipated benefits against the expected costs. Historically, the capital costs of constructing water projects have been consistently underestimated. A recent study of 81 large dams by the World Commission on Dams found that the average cost overrun was 56%. In addition, ex-ante predictions of the benefits of water projects have often been overly optimistic. This combination of factors has resulted in observations that the internal rate of return to most water projects is well below the expected rate of return, although most of the return rates are still positive. This result varies by region; investment costs for irrigation projects in West Africa have averaged over three times more per hectare irrigated than projects in Asia. The West African region has not used double cropping methods and has had poor management of water supplies. Because of this, returns to most of the West African projects have been negative [Matlon and Adesina (1997)].

In addition, the rates of return have been declining over time. Postel (1999) reviews the result of a World Bank study that shows the cost of irrigation has increased substantially since the 1970s. The study of more than 190 bank-funded projects found that irrigation development now averages $480,000 per square km. This cost varies by location – the capital cost for new irrigation capacity in China is $150,000 per square km, while the capital costs in Africa are $1,000,000–2,000,000 per square km. There are a few reasons for this increase in the cost of irrigation development. The best sites for water projects have already been developed, and those that remain are increasingly expensive. Also, improved knowledge about the environmental impacts of dam construction has led to requirement of detailed environmental impact reports before the approval of many projects.

3.2.2. Environmental costs

Habitat destruction The construction of a large dam causes changes in a river ecosystem. There are changes in stream flow, water temperature, and water quality. These changes affect the flora and fauna living in a river basin area. Fish species that live in warmer waters might not survive the cold waters below a dam site, or species that thrive in flowing waters may not survive in the still water of a reservoir.

Blocking migration of native species Many river systems are used by species of migratory fish, such as salmon. In the course of their lifetime, salmon species are born upstream, swim down a river, and eventually return upstream to mate and reproduce.

The construction of large dams can block the routes used by these fish, and affect their reproductive behavior. This affects both the sustainability of the fish species and those whose livelihood depends on the fishery. One example of this occurred on the Porto Primavera Dam in Brazil. Construction of this dam obstructed the migration of native fish species, and led to an 80% decrease in upstream fish catch [WCD (2000)]. Decreases like this not only affect the health of the species but also the welfare of people who depend on the fish species for their consumption or livelihood.

3.2.3. Dynamic costs of water resources

The development of irrigation projects had allowed crop production on otherwise arid lands. This has had many benefits, including expanding output and increasing land values. However, there are environmental problems that have occurred over time as the amount of land being irrigated has expanded. These costs include increased salinity levels in fresh water sources, and waterlogging and salinization of soil.

Increased salinity levels in freshwater supplies The development of irrigation can increase the salinity levels of existing lakes and rivers. This happens when water that formerly ran into a freshwater lake is diverted, or when water withdrawals from a river are too great. With less freshwater available, the level of a lake will decrease, and as water evaporates, the salt content of the lake will increase. With a river basin that flows into a sea, if water withdrawals are too great, the salt water from the sea can recede into the river basin. Over time this can lead to changes in the ecological balance of a river or lake and the species that it supports.

One area where irrigation has led to environmental disaster is in the Aral Sea, located between Uzbekistan and Kazakhstan. The ecological balance of the habitat has been destroyed and an industry that employed many citizens has been wiped out. The two rivers that feed into the Aral Sea are the Amu Darya and the Syr Darya. The area has been a site of irrigated agriculture for centuries, but until the last century this has been at a sustainable level. In the last century, the region became a large producer of cotton, an export crop for the USSR. In 1956, construction of the Kara Kum Canal was completed, a project that diverted water to be used to increase cotton supplies. Between 1962 and 1994, the volume of water in the sea was reduced by 75% and the salinity level of the sea has increased from 10 to over 100 grams per liter. This has taken a toll on the wildlife that lives in the area. The Aral Sea used to be a thriving site for the fishing industry, employing 60,000 individuals. This industry has been entirely wiped out, with many of the fish species disappearing [Murray-Rust et al. (2003); Calder and Lee (1995)]. Another example occurs in the Periyar River Basin in Kerala, India. On this river basin, a system of dams has increased freshwater withdrawals from the river. Because of this, seawater intrudes nearly 20 miles up the river system during the dry season, which has forced seasonal closures of factories that are dependent on river water [Repetto (1986)].

Waterlogging and salinization of land Waterlogging and salinization are two problems related to the productivity of land that often occur together. Salinization occurs when the salt content of the soil increases, affecting the productivity of the land and limiting the crop choice of a grower. This is particularly a problem in lands that are arid or semi-arid. In arid regions, there is little rainfall to dissolve the salts in the soil. When water is applied without proper drainage, the evaporation in arid climates can quickly lead to high levels of salt in the soil, reducing the yield potential of the land. Another type of problem that can occur on irrigated lands is known as "waterlogging". This can happen if there is a layer of rock that forms a barrier, through which the water cannot escape. Over time, the water can accumulate and reach the root zone of the plants, making agricultural production impossible. Waterlogging eventually leads to the salinization of the soil, as water evaporates and the salt content of the soil increases. Estimates are that 20% of the irrigated land worldwide is affected by salinity levels in the soil, and that 1.5 million hectares are taken out of production each year as a result of high salinity levels in the soil. The costs of this are significant. One estimate is that salinization costs the world's farmers $11 billion per year in lost income [Postel (1999)]. However, this estimate does not include the general equilibrium effects of an increase in output price due to lower output, so it should be considered an upper bound.

One location in which waterlogging and soil salinization is a serious problem is the Indus Basin in Pakistan. In Pakistan, about 38% of the irrigated area is waterlogged. The problems are worst in the Sindh Province of the Indus Basin, which contains more than half of the area affected by waterlogging and soil salinization. This area has seen a decline of 40–60% in crop production as a result of these problems [Wambia (2000)].

Decreased levels of sediment and nutrients in water One benefit of river systems is the movement of sediment and nutrients. Sediment that is moved downstream by the river can replace eroding soil, and provide beneficial nutrients to downstream cropland. The construction of a dam in a river system can trap sediment and nutrients behind the dam, degrading the quality of the downstream river system.

An example of this is on the Nile River in Egypt. Traditionally, the Nile River would flood each year, irrigating the banks of the river, and replacing eroding soil with new sediment. The new sediment not only kept the land from eroding, it also added nutrients to the soil. Since the construction of the Aswan Dam in southern Egypt, most of the sediment in the river is caught behind the dam and is not released downstream. There have been a few problems because of this. The lack of sufficient sediment is causing erosion in the coastline of the Nile Delta by 5–8 meters per year, and the removal of a natural source of nutrients has required farmers to increase their use of fertilizers.

Contamination of water supplies Water supply contamination from agriculture can occur from several sources, including animal waste, or fertilizer and pesticide runoff. Using water that has been contaminated with animal waste for domestic uses can cause diseases such as diarrhea, hepatitis, or typhoid fever. More than one-third of the world's population lacks access to basic sanitation, and most of these people live in developing countries. Over half of China's population consumes water that exceeds the maximum permissible limits on human and animal waste, and an estimated 80% of the diseases and one-third of deaths in developing countries are caused by consumption of contaminated water.

As agricultural runoff is a nonpoint source of water pollution, its regulation poses difficulties. In comparison to point source pollutants, the control of nonpoint source pollutants is more difficult, as individual emission levels cannot be directly measured, limiting the choice of policy instruments [Shortle and Horan (2001)]. Nonpoint source pollution control must be achieved through an indirect measure, necessitating a second-best outcome in efficiency. One possible policy may be to subsidize irrigation technologies, which results in reduced agricultural drainage flows. Subsidization of the modern technology will lead to higher adoption rates and lower amounts of agricultural drainage.

3.2.4. Social concerns

Waterborne diseases In many places, large dams and irrigation projects have been blamed for public heath problems, including increased incidences of diseases such as malaria, diarrhea, cholera, typhoid, schistosomiasis, and river blindness. For example, higher levels of the snail host in irrigation canals have led to the increased occurrences of schistosomiasis in the Senegal River Valley and the Niger River Basin [Matlon and Adesina (1997)]. However, there is evidence that many of these cases have been the result of poor planning, and not a necessary effect of dam construction. Often, increased vector breeding occurs in fields and not in the dams and canals [Von Braun (1997)]. Incorporating public health concerns into the planning of a new water project can reduce the impact of the project. For example, a new reservoir can be an attractive breeding ground for mosquitoes, which can lead to the spread of malaria. Using sprays for pest control can decrease this risk. In areas where this risk has been ignored, such as the Senegal River Valley and the Kou Valley in Burkina Faso, there have been increased outbreaks of malaria in the regions. In addition, there have been areas where the incidence of malaria and other waterborne diseases actually decreases after the development of irrigation projects.

Further evidence that the effect of irrigation on public health is ambiguous has been show by the work of public health researchers, who have found a range of outcomes when studying the impact of irrigation development on disease incidence. One study from the Tigray region of Ethiopia compared the incidence of malaria in villages located near dam sites (less than 3 km) to villages at similar altitudes located far from dam sites (more than 8 km) [Ghebreyesus et al. (1999)]. In their study, they compared the incidence of disease at various times of the year in children under the age of 10. In all cases, the incidence of malaria was greater in the at risk villages than in the control villages, and this difference was statistically significant. However, Ijumba and Lindsay (2001) review many studies from Africa and find that irrigation development does not always lead to a higher incidence of malaria, and can actually decrease incidence under certain situations. They find that this result varies by location, and while irrigation development increases the incidence of malaria in highland regions where populations lack any immunity, in many parts of Sub-Saharan Africa irrigation development can actually decrease malaria incidence. Ijumba and Lindsay (2001) also discuss other factors that affect the incidence of malaria and are also closely related to the development of irrigation systems. One factor is population migration. The development of irrigation systems and the resulting employment opportunities can lead to an inflow of people, many of whom may lack any resistance to malaria. This factor can partially explain the estimated incidence of malaria resulting from irrigation development in certain locations. Another factor is increased wealth, which can be a result of irrigation development. Increased wealth allows access to anti-malarial drugs and prevention techniques such as bed nets. This factor is one of the explanations for the decreases in the incidence of malaria observed in some locations after irrigation development.

Displacement of native populations The development of water projects in the last century has led to the displacement of 40–80 million people. In addition to their physical displacement, it has also often resulted in forced lifestyle changes. Between 1950 and 1990, 26 to 58 million people were displaced in China and India (two of the major dam building nations). Compensation for these forced resettlements has been minimal, if it occurs at all. Resettlement plans regularly fail to take into account the loss of a viable livelihood in addition to the loss of physical land, often leaving resettled populations worse off than before dam construction. For example, one study found that 72% of the 32,000 people displaced by the Kedung Ombo Dam in Indonesia were worse off after resettlement [WCD (2000)]. The construction of the Liu-Yan-Ba Dam on the Yellow River in China forced the resettlement of 40,000 people from fertile valleys to unproductive wind-blown highlands. This has led to extreme poverty for many of the resettled people [WCD (2000)].

3.2.5. *Overuse of groundwater resources*

Irrigated agriculture relies both on ground and surface water. Most of the large-scale irrigation projects divert surface water, but a significant proportion of the new land under irrigation in the last century is from the pumping of groundwater. In many situations groundwater resources are renewable and are replenished by rainstorms. Sometimes, as in the case of Libyan Desert, aquifers where fossil water is being mined are not replenished. Libya's plan to extract 2.2 km^3 per year from a desert aquifer is estimated to deplete the aquifer in 40–60 years [Postel (1999)]. Worldwide, as much as 8% of food crops grow on farms that use groundwater faster than the aquifers are replenished [Postel (1999)]. For example, the Punjab region of India is rapidly depleting its groundwater reserves. Punjab is a major production region of India, and most of the crops produced are cereal grains, such as rice and wheat. The past two decades have seen groundwater levels dropping at 25–30 cm per year. At groundwater depths below 15 meters, the commonly used tubewells will not function, and a well must be abandoned.

The percentage of land where the water table is below 10 meters has increased from 3% to 46% between 1973 and 1994.[5] This overuse of groundwater threatens the future of the area and the national goal of food security.

In some areas such as Jakarta and Bangkok, the overdraft of aquifers is leading to a sinking of the ground level above the aquifer. In Bangkok, one-third of the city is below sea level. The fall in the ground level has led to increased damage from floods and higher costs of flood protection [Barker and Molle (2002)].

Another problem that can occur with overdraft of coastal aquifers is seawater intrusion into the aquifer. If the water table of the aquifer is drawn down to a low enough level, seawater from the adjacent ocean can enter the system; increasing the salinity level of the fresh water remaining in the aquifer. For irrigators relying on the available groundwater, this can limit the crop choice to those that can withstand high salinity levels of applied water. One area where this is a problem is in the Gaza Strip, which lies between Israel and the Mediterranean Sea. Gaza relies entirely on groundwater for its freshwater supply. Increased pumping has lowered the levels of the aquifers located in Gaza, and has allowed the intrusion of seawater. Citrus crops, which have traditionally been a source of revenue for the area, are intolerant of high salt levels in water, and there has been a decrease in both the yields and the quality of the crop. In some parts, high salinity levels have forced a change from citrus crops to other more salt-tolerant fruits and vegetables.

4. Conclusion

Irrigation was the source of more than 50% of the increase in global food production during 1965–1985 [Gardner (1996)] and more than 60% of the value of Asian food crops comes from irrigated land [Hinrichsen (1998)]. Irrigation in the last half of the twentieth century took advantage of most opportunities for diversion of water and in some situations, exploited non-renewable water resources. The environmental benefits of a sufficient fresh water supply for ecosystems are much better understood now than 50 years ago. Despite a growing concern about the third-party effects of water projects, there is a challenge to increase food supplies by at least 40% in the next 50 years, due to growing populations and changing preferences. Increased productivity should not come by expansion of water but by increased productivity of existing sources. That can be achieved through reform of water design and management systems. In particular, reform should include increased reliance on cost–benefit analysis for water projects, emphasis on appropriate design and management of conveyance facilities, and use of mechanisms that establish the price of water to represent the marginal cost of extraction, user costs, and environmental costs. Correcting these institutional problems is a necessary step to improve water quality and increase the supply of effective water.

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[5] *Source*: Water Resources Directorate, Chandigarh, Punjab.

The growing use of water user associations (WUAs) is a positive step toward the improvement of water management systems. Experience with trading in water suggests that it can improve efficiency as long as attention is paid to issues of third-party effects. Water quality issues should be addressed more by incentives to limit pollution. Current technologies allow the maintenance of yields with significant reduction of water use, but technology may be costly and many are in their infancy. New wireless technologies and improved power of computers that can reach even the most remote areas may suggest that the challenge of research is to develop water use management technology that is affordable by the poor, as well as mechanisms to enhance adoption of these technologies. Effective policies, pricing and management of water is one of the major challenges that society is facing as we enter the new millennium.

Appendix A

Below we present a simple model of irrigation technology choice, as developed by Caswell and Zilberman (1986). Consider an area with a fixed amount of heterogeneous quality land that grows a single crop. Let y denote the yield per acre, and e the effective water per acre. Output is given by a constant-returns-to-scale production function, $y = f(e)$. The applied water per acre under technology i is a_i and α is the land quality index, which assumes values from 0 to 1. Assume that there are two technologies: a traditional technology ($i = 0$) and a modern technology ($i = 1$). Irrigation effectiveness is defined as $h_i(\alpha) = e_i(\alpha)/a_i(\alpha)$ and for each α, $1 > h_1 > h_0 > 0$. The cost per acre associated with each technology is k_i. This cost includes annualized repayment of investment costs and annual operating costs. The modern technology is assumed to be more capital-intensive, so that $k_1 > k_0$.

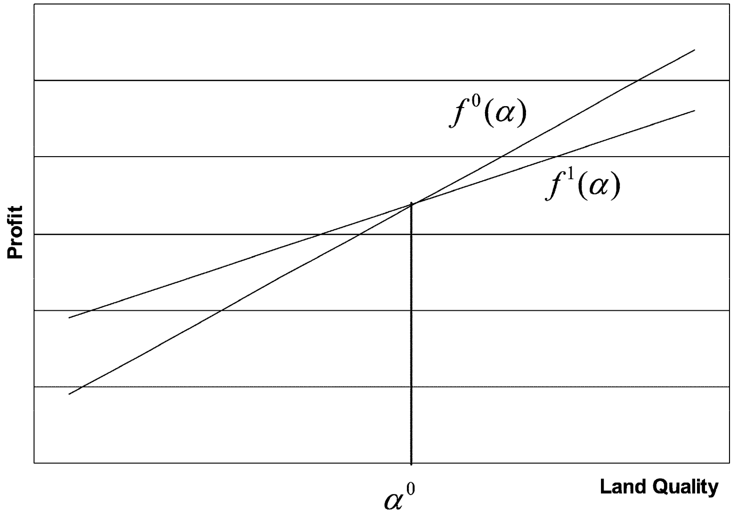
The profit-maximizing choice of water application rate and irrigation technology is solved via a two-stage procedure. First the optimal amount of water for each technology is chosen and then the more profitable irrigation technology. Let $\Pi_i(a)$ denote the quasi-rent (exclusive of land rent) per acre of technology i, determined according to the following choice problem:

$$\Pi_i = \max_i \bigl\{ Pf\bigl(h_i(\alpha) \cdot a_i\bigr) - wa_i - k_i \bigr\},$$

where P is the output price and w the price of applied water. The first-order condition is

$$Pf'h_i - w = 0.$$

The price of effective water is the price of applied water divided by the irrigation efficiency (w/h_i), so optimal production occurs where the marginal product of applied water is equal to the price of effective water: $Pf' = w/h_i$. The price of effective water is lower under the modern technology due to the higher irrigation efficiency; therefore higher levels of effective water will be used and higher yields may be obtained.



Graph 3. Comparison of modern and traditional technologies.

The optimal water application under each technology determines the quasi-rent associated with the technology (Π_i), and the technology with the highest quasi-rent is selected, assuming it is non-negative. The quasi-rent difference between the two technologies can be written as

$$\Delta\Pi = P\Delta y - w\Delta a - \Delta k.$$

As shown by Graph 3, the quasi-rent difference can either be positive or negative. In the graph, $f^0(\alpha)$ represents the profit earned by the traditional irrigation technology, as a function of land quality, while $f^1(\alpha)$ represents the profit earned by the modern irrigation technology. The parameter indicates the quality of the land. There is a single value of the parameter that separates optimal irrigation technology by quality of land. For $\alpha < \alpha^0$, it is more profitable to use the modern, efficient irrigation technology. For $\alpha > \alpha^0$, a high land quality already results in a high level of water efficiency, resulting in higher profits from the traditional technology.

Inclusion of environmental costs of water runoff

This model can be extended [Caswell, Lichtenberg and Zilberman (1990)] to illustrate how irrigation technology choice affects the generation of negative environmental externalities in the form of agricultural drainage water. Irrigation water that is not used by crops is a major source of pollution, as it may result in waterlogging, salinization of soil, and pesticide runoff. By extending our simple model of technology choice and water use, we gain insight into the incentives for farmers to reduce agricultural drainage flows.

Let the pollution coefficient associated with water residuals be $g_i(\alpha)$, which is the fraction of water applied by technology i, on land of quality α, that is not utilized by the crop and which is environmentally damaging. The pollution coefficient is defined as

$$g_i(\alpha) \leqslant 1 - h_i(\alpha).$$

Since the modern technology is more water efficient, it is reasonable to assume that it has a lower pollution coefficient, i.e., $g_1(\alpha) < g_0(\alpha)$.

If the producer bears the costs associated with the pollution arising from water residual accumulation, the individual's profit maximization problem becomes

$$\Pi_i(\alpha) = \max_{a_i}\bigl\{Pf\bigl(h_i(\alpha)\cdot\alpha\bigr) - wa_i - k_i - \bigl(x\cdot g_i(\alpha)\bigr)\bigr\},$$

where x denotes the cost per unit of pollution. Usually this cost is a production externality that is not incorporated by farmers in their water use decisions. However, one could imagine the imposition of a pollution tax associated with water residuals.

The imposition of a pollution tax increases the profitability of adopting the water conserving technology, especially in situations where the initial costs of pollution per unit of water are large relative to water price. As shown in Graph 3, as land quality increases, the benefit of modern technology adoption decreases and the quasi-rent differential between the two technologies declines.

The modern technology will be selected in cases where the increased profits from higher yields or lower water costs offset the higher costs associated with adoption of the technology. These results indicate that modern technology adoption will increase with increasing water or output prices. In addition, modern technology adoption is more likely to occur with poor land quality, due to the high price of effective water under the traditional technology, and the land-augmenting qualities of the modern technology. The impact of modern technology adoption on aggregate applied water use levels depends on the elasticity of the marginal productivity of water (EMP), which measures how responsive the crop is to further irrigation.[6] Under most conditions, adoption results in both a decrease in overall water use and an increase in crop yields.

Appendix B

The following model is adapted from Provencher and Burt (1993). It shows the difference between the decisions made by a social planner and the decisions made by individuals in their use of a nonrenewable common property resource.

A region overlying a nonrenewable aquifer has N identical water users. In each period, each user withdraws u_t units of groundwater for use. The total available stock of water at time t is S_t, and the per-unit cost of pumping groundwater is $C(S_t)$, with

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[6] EMP is defined as $\varepsilon_i(e) = -f''(e_i)\cdot e_i/f'(e_i)$.

$C' < 0$. The benefit that each user receives from the use of u_t units of groundwater is $B(u_t)$. We assume that $B' > 0$, and that $B'' < 0$. Since the aquifer has no recharge, the equation of motion for the available stock of groundwater is $S_{t+1} = S_t - N \cdot u_t$. The current value of the net benefit to each user in period t of using u_t units of water is $B(u_t) - u_t \cdot C(S_t)$.

B.1. Social planner's decision

Let $V(S_t)$ be the value at time t of the future net benefits to a single water user. Using the dynamic programming methodology, a social planner will want to solve the following:

$$N \cdot V(S_t) = \max_{u_t} N\big[B(u_t) - u_t \cdot C(S_t) + \beta \cdot V(S_{t+1})\big]$$
$$\text{s.t.} \quad S_{t+1} = S_t - N \cdot u_t.$$

Solving this yields the following condition:

$$\frac{\partial B}{\partial u_t} - C(S_t) = \beta \left\{ \frac{\partial B}{\partial u_{t+1}} - C(S_{t+1}) - N \cdot u_{t+1} \cdot \frac{\partial C}{\partial S_{t+1}} \right\}.$$

The left side of this equation is the net benefit of extraction of one more unit of groundwater in period t, while the right side is the discounted future benefit, taking into account the increased costs in the future that result from pumping groundwater today. This condition takes into account the additional future costs faced by all users of the aquifer, not just one individual.

B.2. Individual user's decision

For an individual decision maker, $\widetilde{V}(S_t)$ is the value at time t of future net benefits to a single water user. However, when an individual makes their decision about water use, they consider the decisions of other users as given. From an individual's perspective, the equation of motion governing available stock is $S_{t+1} = S_t - (N-1) \cdot u_t^* - u_t$, where u_t^* is the quantity of water used by each of the other growers. Using the dynamic programming framework, an individual will want to solve the following:

$$\widetilde{V}(S_t) = \max_{u_t}\big[B(u_t) - u_t \cdot C(S_t) + \beta \cdot \widetilde{V}(S_{t+1})\big]$$
$$\text{s.t.} \quad S_{t+1} = S_t - (N-1) \cdot u_t^* - u_t.$$

Solving this yields the following condition:

$$\frac{\partial B}{\partial u_t} - C(S_t) = \beta \left\{ \frac{\partial B}{\partial u_{t+1}} - C(S_{t+1}) - u_{t+1} \cdot \frac{\partial C}{\partial S_{t+1}} \right\}.$$

Comparing the result from the social planner and the individual, we see that the social planner takes full account of the impact of withdrawing water today on future costs. The individual assumes that the actions of other are given both in the present and in the future. Therefore the individual ignores the impact of others, and only considers the impact of his/her own water use on his/her own future water costs. This results in each individual extracting too much groundwater per period.

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