Water and Development: The Importance of Irrigation in Developing Countries

By Karina Schoengold and David Zilberman

1. Overview

2. The Benefits and Cost of Irrigation

2.1. BENEFITS OF IRRIGATION

2.1.1. Contribution of Irrigation to Agricultural Productivity

2.1.2. Food Supply Expansion

Irrigation and agricultural land expansion

Irrigation and increased crop yields

Irrigation and double cropping of land

2.1.3. Welfare Improvements

Irrigation and employment opportunities

Irrigation and land values

2.1.4. Irrigation Supply Stabilization

2.1.5. Environmental Benefits

Irrigation and deforestation

2.1.6. Benefits of the Conjunctive Use of Groundwater and Surface Water

2.2. COSTS OF IRRIGATION

2.2.1. Capital Costs

2.2.2. Environmental Costs

Habitat destruction

Blocking migration of native species

Increased emissions of greenhouse gases.

2.2.3. Dynamic Cost on Water Resources

Increased salinity levels in freshwater supplies

Waterlogging and salinization of land

Decreased levels of sediment and nutrients in water

Contamination of water supplies

2.2.4. Social Concerns

Waterborne diseases

Displacement of native populations

International conflicts and water supply

2.2.5. Overuse of Groundwater Resources

2.2.6. Environmental Problems Associated with the Overdraft of Groundwater

3. Actions to Improve Efficiency of Irrigation

3.1. EFFICIENT INVESTMENT IN IRRIGATION PROJECTS

3.1.1. The Basic Economics of Oversized Water Projects

3.1.2. Dynamic Consideration and Uncertainty

3.1.3. Waterlogging and Drainage

3.1.4. Use of Non-Traditional Water Sources

3.1.5. Trade and the Concept of "Virtual Water"

3.2. IMPROVED CONVEYANCE AND THE ALLOCATION OF WATER.

3.2.1. Management of Conveyance System

3.2.2. Transition from Water Rights to Water Markets

Water rights systems

The transition to trading and markets

3.2.3. Improved Efficiency of Water Pricing Systems

Inaccurate volumetric measurement

Subsidization of water delivery costs

3.2.4. Improved Efficiency of Groundwater Management

Groundwater as an open-access resource

Subsidization of groundwater pumping costs

Introduction of efficient groundwater pricing

3.3. INEFFICIENCIES IN MICRO-LEVEL WATER MANAGEMENT

3.3.1. Land Allocation to Irrigation at the Farm Level

3.3.2. Irrigation Choice at the Farm Level

3.3.3. Existence of Low-Capital Efficient Irrigation Technologies

4. Conclusion

Appendix 1

Appendix 2

References

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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 management 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 cost in terms of loss of ecosystems, extinction of fish species, and contamination of water sources. This chapter provides an economic perspective on the contribution or irrigation and water resources to the post-WW II agricultural development and provides a perspective for agricultural water resource management and policies in the future.

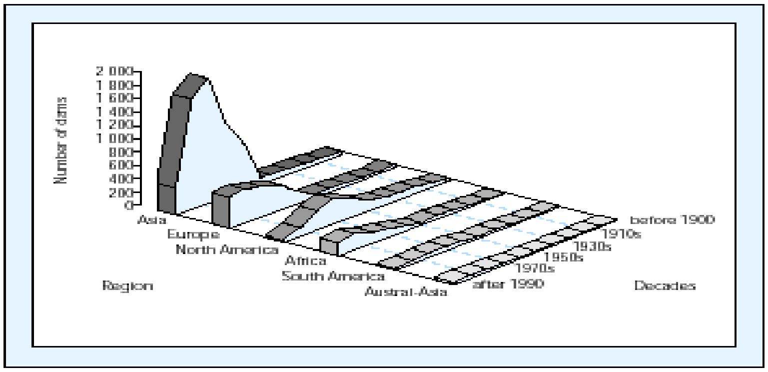
First, we will have an overview of the benefits and costs of agricultural water and irrigation projects in developing countries. There is a paucity of ex post integrated assessments of these projects, so we can put the pieces together, combing data with conceptual arguments. The second part of the chapter consists of three sections that present an economic framework for designing water institutions and policies in the future to improve water resource allocation and prevent some of the inefficiency in water resource systems at the present. The third part of the chapter ventures beyond irrigation and addresses impacts of agriculture on water quality and human and environmental health and presents mechanisms to address these impacts.

1. Overview

The last 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 (Gleick, 2000). Much of this increase has been in developing countries. Between 1962 and 1996, the irrigated area in developing countries increased at about 2 percent a year, leading to a near doubling in irrigated land. For example, in 1950 India had an irrigation potential of 22.6 mha. By 1993-94, this had grown to 86 mha (Saleth, 1996). Between 1949 and 1998, the amount of land in China under irrigation increased from 16 mha to 52.3 mha. This represented a change from 16% to 40% of China's total farmland (Guangzhi, Yuansheng, and Hansong, 1999). Currently 75 percent 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.

Despite all of these benefits, there have also been substantial costs as a result of the construction of water projects and the growth in cropland. These have been costs in the form of capital, environmental degradation, and diminished human health. In many areas there has been the destruction of native habitats, the displacement of indigenous people, soil erosion, a decrease in water quality, and an increase in waterborne diseases, just to name a few of the problems that result either directly or indirectly from the growth in irrigated lands. Globally there is a lot of heterogeneity among land qualities and populations. Not every location is well suited to water development, and the potential benefits of irrigation have not been spread evenly throughout the world. The following chart shows the distribution of irrigation dams built throughout the world.

There have been many irrigation projects developed in Asia, which have been mostly successful. South America and Africa have had relatively few irrigation projects developed, and the benefits have been minimal.



Source: ICOLD, 1998.

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 there are growing concerns about the quality of available water as well as the quantity. In addition, more is known about the potential 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. Water resources are not distributed evenly around the globe, and arid regions will continue to have conflicts over water supplies. In addition to the decreasing supply of water, larger 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, which require cereal crops as food for livestock. Estimates by IFPRI show that to meet demand for consumption and livestock feed in 2020; world production will have to increase 40% over 1995 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 the direction of reforming water systems as we prepare towards the future.

2. The Benefits and Cost of Irrigation

2.1 BENEFITS OF IRRIGATION

2.1.1. 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. With a rapidly growing world population and a limited food supply, fifty years ago it was common to hear concerns of food shortages and mass starvation. This was particularly true for the populations of developing countries. While malnutrition is still a concern in many countries, the reason is not a lack of a sufficient global food supply. In fact, in the early 1990s, nearly 80% of malnourished children lived in countries that produced food surpluses, evidence that the problem is not one of insufficient supply (FAO, 1999). The last 50 years has seen a larger increase in food production than expected, more than enough to match the growth in population. A report by IFPRI shows that between 1967 and 1997, global cereal production increased 84 percent at a time when population increased by 67 percent and that malnutrition among children under the age of five in developing countries declined from an aggregate rate of over 45 percent to 31 percent 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.

Water projects are generally composed of a system of reservoirs designed for storing water and canals designed for transporting water. Projects that provide water for irrigation have benefited developing countries in many ways. Benefits include the expansion of food supply, stabilization of water supply, the improved welfare of some native populations, and a relative decrease in deforestation of land for agriculture.

2.1.2. Food Supply Expansion

Irrigation and agricultural land expansion. One clear benefit of water projects is an expansion in the feasible land base for agricultural production. Worldwide, cropland under irrigation increased from 94 mha in 1950 to 271 mha in 1986 (Repetto, 1986). A region might have high quality soil for growing crops, but if it doesn't receive enough rainfall at the right times of the year, it can't be used for crop production. For areas that receive rainfall during the wrong season, 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. For those areas that don't receive enough water for growing crops, canals allow water to be transported from a water-rich area to an arid area.

Irrigation and increased crop yields. There is indisputable evidence that irrigating land leads to increased productivity. Irrigation is a necessary input into the high yield varieties developed during the Green Revolution. One acre of irrigated cropland is worth multiple acres of rain-fed 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 ($95/ha/year for rain-fed cropland and $17.50/ha/year for rangelands).

Irrigation is generally used to produce high-value crops. 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 timing of rainfall. One recent study shows this result for crop production data from India. 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 tropical areas that are warm throughout the year, but have seasonal rains for a portion of the year while remaining dry and arid for the other part. The ability to store water during the rainy season for use in the dry season could allow a farmer to move from one annual crop to two or three. One area where 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. The region has 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).

2.1.3. Welfare Improvements

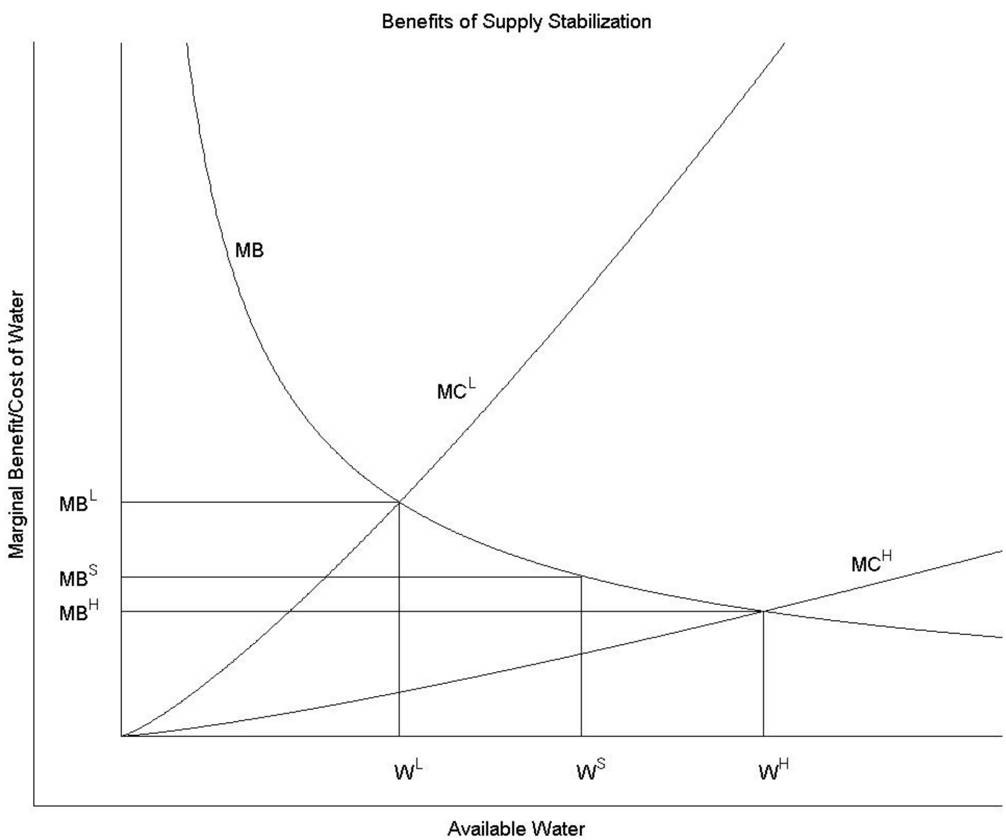
Irrigation and employment and income. There is evidence in many regions that employment opportunities have increased after the development of irrigation systems. This can occur either because labor is needed for new land brought into production, or for land that is being double cropped and therefore requires additional labor in planting and harvesting. 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).

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. 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). One question of importance in developing countries is that of land security. Areas where land rights are ill-defined will have lower benefits accruing to the local population than those areas with well-defined rights.

2.1.4. 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 when they can predict the supply of water available. The planting of certain crops, such as tree crops, requires the assurance of a sufficient water supply. 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 graph illustrates this point.

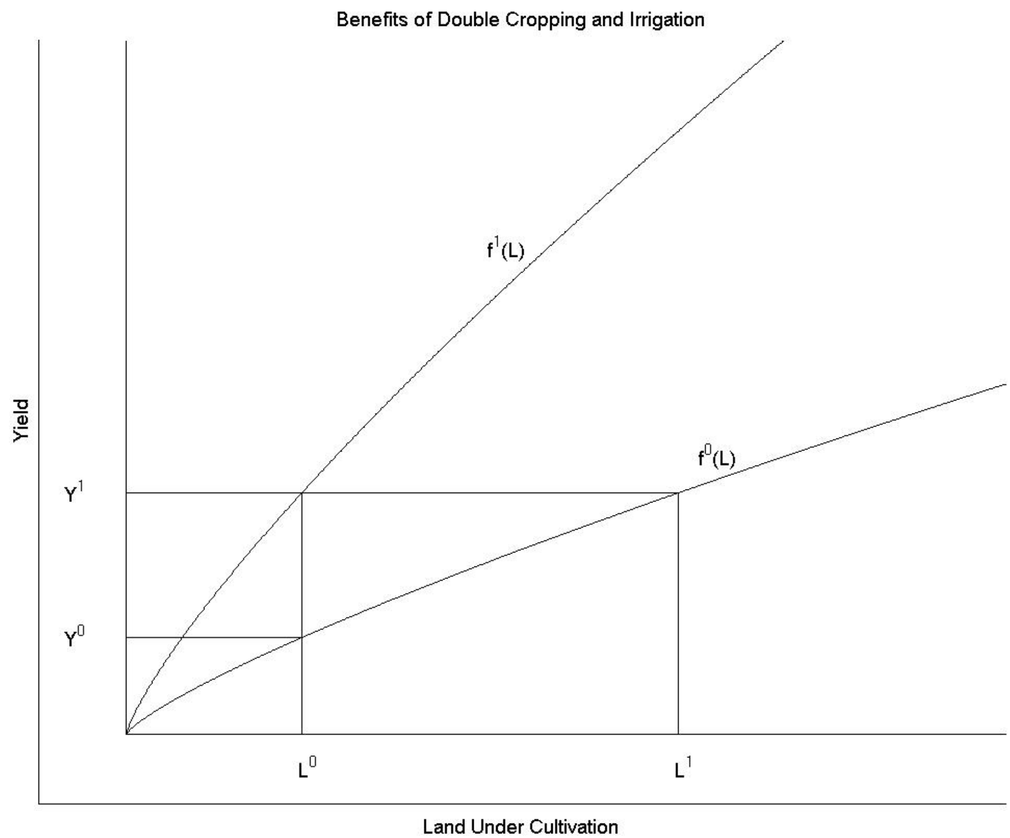
Let W denote the total amount of water available in a region. The weather acts as a supply shock, and in years with low rainfall, the marginal cost of obtaining water is MC^L, while in years with high rainfall, the marginal cost of obtaining water is MC^H. However, since the choice of crop and irrigation technology must be made before the weather is observed, the marginal benefit of water is the same in all years. Before an irrigation system is developed in a region, in equilibrium, water supply is W^H with probability α_H and W^L with probability α_L, giving the following as average water supply: $\overline{W} = \alpha_L \cdot W^L + \alpha_H \cdot W^H$. 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. Cropping decisions will be made on an annual basis, as it is too risky to plant permanent crops and risk losing the initial investment. If an irrigation system and reservoir is developed, then farmers can rely on receiving a water supply of W^S in every year. The removal of uncertainty from the water supply allows the farmers to make more informed decision on both crop choice and irrigation technology, as the supply shock from weather is removed.



2.1.5. 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. Recently, such notable people as Norman Borlaug (Nobel Peace Prize winner and Father of the Green Revolution), Oscar Arias (Nobel Peace Prize winner and Former President of Costa Rica), and Per Pinstrup-Andersen (2001 World Food Prize winner and Director of IFPRI) (among others) signed a declaration that more intensive cropping practices, such as using high-yield varieties, are a necessary means of feeding the world's population without requiring large amounts of land to be deforested. Irrigation is a necessary input into many high-yield varieties of crops in production.

The following graph illustrates the tradeoffs between developing irrigation to intensify crop production and new land development. One major outcome is that irrigation can reduce the need for new agricultural land development. This could lead to a decrease in deforestation, and the resulting environmental problems such as soil erosion. This relies on the two benefits of irrigation mentioned earlier – higher yields and double cropping. In the following graph, $f^0(L)$ represents yields as a function of the amount of land under cultivation before irrigation development, and $f^1(L)$ represents yields after irrigation development. If an area lacks irrigation systems, then as increasing yields become necessary, they can be achieved either through the use of more land or the development of irrigation. Over time, yield increases are essential because of larger populations, higher standards of living, and increased meat consumption. The following graph shows the tradeoff between land and irrigation. If total yields must increase from Y^0 to Y^1, this can be done one of two ways. Either an irrigation system must be developed, or land under cultivation must increase from L^0 to L^1.



2.1.6. Benefits of the Conjunctive Use of Groundwater and Surface Water

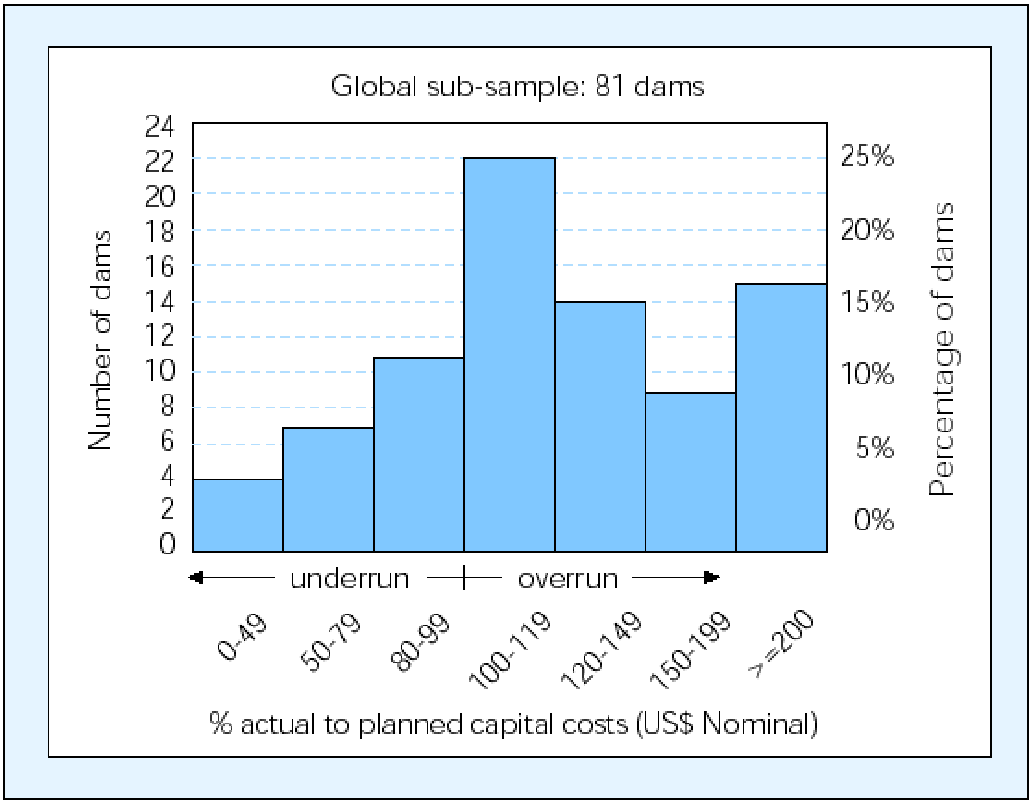
There is a large amount of literature on the benefits of conjunctive use of surface water and groundwater. These benefits accrue because of the different nature of the resources. Surface water usually has lower delivery and extraction costs, but is subject to variability in supply. Groundwater can be expensive to pump, but has a firm supply. In aquifers with recharge, the use of surface water during years with high levels of 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 groundwater supplies. In either case, the conjunctive use of the two sources can decrease the risk associated with a stochastic surface water supply.

2.2. 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. There have been environmental problems, such as habitat destruction and a decrease in water quality. There is also the human side of the costs of water projects. Construction of water projects has involved the displacement of native populations, and a growth in certain waterborne diseases that affect those populations.

2.2.1. 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%, with the distribution in the following chart. These cost overruns result in decreased net benefits of a water project, in comparison to the ex-ante predictions. The same study has found that the internal rate of return to most water projects at appraisal is well below the expected rate of return when the project was approved, although most of the return rates are still positive. As mentioned earlier, costs and benefits vary by location. 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).



Source: WCD Cross-Check Survey.

The costs of irrigation dams can be divided into two categories—the capital costs associated with dam construction and the operational and management costs associated with upkeep and delivery. Ideally, the benefits of water development in terms of increased production and employment opportunities should cover both of these costs if a project is to provide net social benefits. However, in practice revenues often fail to even cover the operational and management costs of water development, let alone the capital costs of construction. Postel reviews the result of a study by the World Bank that shows the cost of irrigation has increased substantially since the 1970s. The study of more than 190 Bank-funded projects found that irrigation costs now average $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 costs in Africa capital costs are $1,000,000-2,000,000 per square km. Mexico's irrigated area has actually declined since 1985 due to lack of capital (Postel).

2.2.2. 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. These changes can lead to permanent ecological changes, leaving native species without a viable habitat. Fish species that live in warmer waters might not survive the cold waters below a dam site, or species that thrive in flowing waters might have a difficult time surviving 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. Salmon species often are born in an upstream area, travel down a river during their lifetime, and 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, Ch. 3). Decreases like this not only affect the health of the species but also the social health of people who depend on the fish species for survival.

Increased emissions of greenhouse gases. One recent discovery by scientists is that the reservoirs created by large dams and water projects are a significant source of greenhouse gases (GHG). Rotting vegetation or carbon inflows cause the release of methane and carbon dioxide from a reservoir. Historically, the decrease in the use of fossil fuels has been touted as a benefit of building dams for hydroelectric power. The realization that all reservoirs emit GHG needs to be considered as an environmental cost of water project construction. One variable that hasn't been analyzed in these cases is the naturally occurring release of GHG before the construction of a large dam. Since the net change in emissions is most important for policy, further research is necessary to determine the net effect of the reservoir on emissions.

2.2.3. Dynamic Cost on 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 systems can increase the salinity levels of existing lakes and rivers. This happens when water that formerly ran into a freshwater lake is diverted, diminishing the freshwater replenishment of the lake, 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 severe changes in the ecological balance of the lake and the species that it supports.

One example of an irrigation project that has been an environmental disaster is that of the Aral Sea, located between Uzbekistan and Kazakhstan. There has been the destruction of a water habitat and an industry that employed many citizens. 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 U.S.S.R. In 1956, construction of the Kara Kum Canal was completed, a project that diverted water to Turkmenistan to be used to increase cotton supplies. Between 1962 and 1994, the volume of water in the sea was reduced by seventy-five percent. The salinity of the sea has increased from 10 grams per liter 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 (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 costs the world's farmers $11 billion per year in lost income (Postel, 1999). Salinization of the soil occurs when the salt content of the soil increases, which affects the productivity of the land. This can also limit the potential crop choice to those that are salt tolerant. 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. Also, high rates of evaporation increase the concentrations of salt remaining in the soil. When too much 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." When applied water is not used by a crop, it can percolate into the ground below and accumulate over time. 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.

One location in which waterlogging and soil salinization is a serious problem is the Indus Basin in Pakistan. In Pakistan, about 38 percent 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 percent 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.

One 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. First, the naturally eroding soil is not being replaced by sediment, leading to erosion on the banks of the river. The lack of sufficient sediment is causing erosion in the coastline of the Nile Delta by 5-8 meters per year. Also, the sediment was a source of nutrients. The lack of sediment has required farmers to increase their use of fertilizers on the soil, which has led to problems with the run-off of chemicals into the river and a decreasing level of water quality.

Contamination of water supplies. Water supply contamination from agricultural water use can occur from a number of sources. These include animal waste, or fertilizer and pesticide runoff. With rain, pesticides and fertilizers used in agriculture are washed into fresh water supplies. Water that has been contaminated with animal waste 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.

2.2.4. Social Concerns

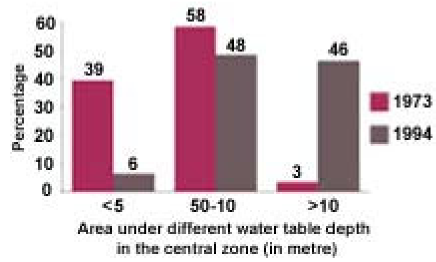
Waterborne diseases. There have been a number of large dams whose construction was the cause of local public health problems. Increases have occurred in diseases such as malaria, diarrhea, cholera, typhoid, schistosomiasis, and onchocerciasis (river blindness). However, there is evidence that these cases 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. Incorporating public health concerns into the planning of a new water project can reduce the impact of the project (von Braun, 1997). 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. This has been because of the development of breeding grounds for mosquitoes in the reservoirs and canals used for irrigation water. An increased level of the snail host in irrigation canals has led to the increased levels of schistosomiasis in the Senegal River Valley and the Niger River Basin (Matlon and Adesina, 1997).

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. People who live next to a river often depend on crop production for their livelihood, since water is available and soils are generally well-suited for agriculture. 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 changes has usually been minimal, if it occurs at all. Resettlement plans have often failed to take into account the loss of a viable livelihood in addition to the loss of physical land. Because of this, resettled populations are often worse off after being resettled than before the dam was constructed. 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, Ch.4). 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, Ch.4).

International conflicts and water supply. There are 261 rivers that cross international boundaries. The division of water resources between countries can either be a source of conflict or a reason for necessary cooperation. As discussed by Wolf (1998), despite discussions of ‘water wars’, historical evidence has shown many international water agreements as a result of negotiations, and few conflicts. Wolf’s analysis of treaty and conflict records shows that in the last century, while there were only seven minor skirmishes over water, there were 145 international treaties discussing allocation or management of shared water resources. A recent agreement between Israel and Jordan to increase freshwater flows into the shrinking Dead Sea is an example of such cooperation.

2.2.5. Overuse of Groundwater Resources

Irrigated agriculture relies both on ground and surface water. Most of the large-scale irrigation projects are diverting surface water (rivers, lakes, etc.). However, a significant increase in irrigation in the last century is the result of adoption of tubewells and increased pumping of groundwater. Tubewell use in India increased by more than 100-fold between 1960 and 1985 (Postel, 1999). In many situations groundwater resources is being replenished by rainstorm, and in this case it is a renewable resource. 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 km3/year from a desert aquifer will probably dry up the aquifer in 40-60 years (Postel, 1999). Severe water scarcity presents the single biggest threat to future production. As much as 8 percent of food crops grow on farms that use groundwater faster than the aquifers are replenished (Postel). In any case whenever the stock of water and the aquiver at each period is the difference between replenishment and pumping, and when pumping is greater than replenishment, groundwater is depleted. There is growing evidence of reduction of stock of water as well as depletion of aquifer. For example, the Punjab region of India is rapidly depleting its groundwater reserves. The following graph shows the change in groundwater levels that has occurred in the Punjab region. 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. As shown in the following graph, the percentage of land where the water table is below 10 meters has increased from 3 percent to 46 percent between 1973 and 1994. This overuse of groundwater threatens the future of the area and the national goal of food security.



Source: Water Resources Directorate, Chandigarh, Punjab (see http://www.punjabilok.com/misc/environment/parched_pun.htm).

2.2.6. Environmental Problems Associated with the Overdraft of Groundwater

In some areas, the overdraft of aquifers is leading to a sinking of the ground level above the aquifer. This is occurring in major cities such as Jakarta and Bangkok. 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 costs of flood protection (Barker and Molle, 2002). Another problem that can occur with overdraft of coastal aquifers is the intrusion of seawater 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. This is a particularly serious problem, because it increases 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 ocean. 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. As a result, there has been a decrease in both the yields and the quality of the crop. High salinity levels have forced a change from citrus crops to other more salt-tolerant fruits and vegetables.

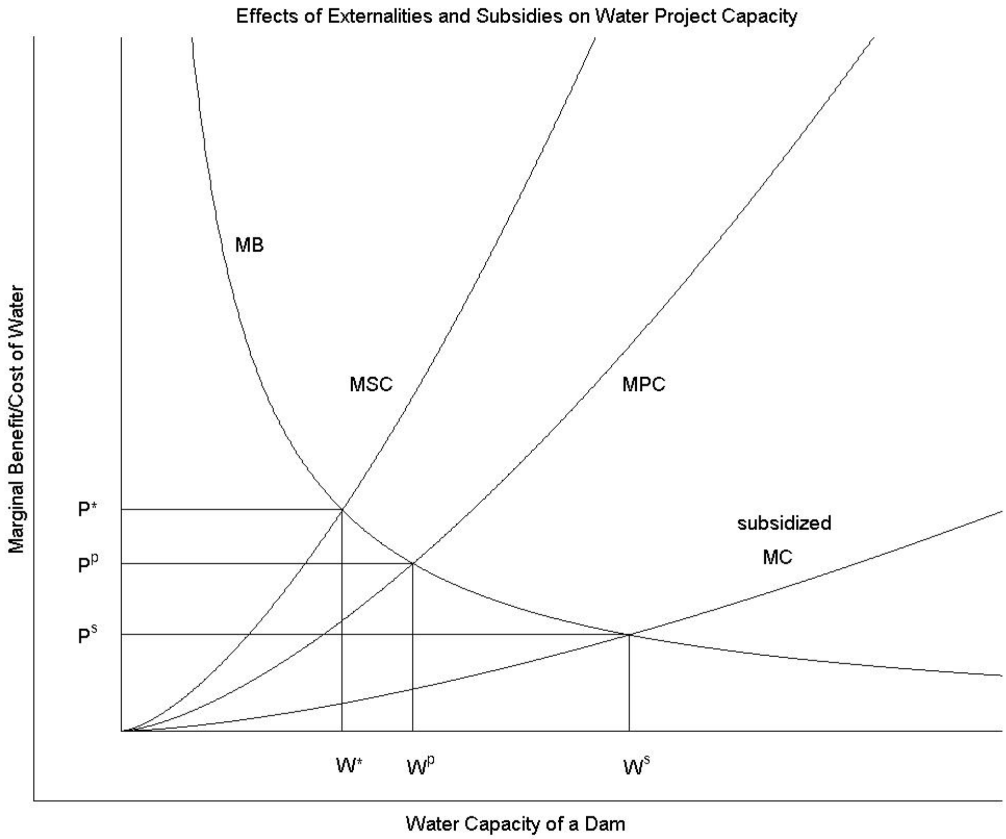
3. Actions to Improve Efficiency of Irrigation

3.1. EFFICIENT INVESTMENT IN IRRIGATION 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. The decision to build a water project in a certain location is only the first step. Economic theory has some insight into the choice of the optimal size of a dam in a given location. While dams provide many benefits through the supply of irrigation water, 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.

3.1.1. The Basic Economics of Oversized Water Projects

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 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 this graph is that in cases where costs are subsidized and externalities are ignored, the dam capacity will be too large, and the price of the water supplied by the dam 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 water will be priced at P^*. However, when costs are subsidized, so that perceived costs are below actual costs, and externalities are ignored, the chosen capacity of the dam will be W^S, with water priced at P^S. The benefits of water development are a function of three activities—conveyance, management, and storage capacity. When the relative cost of higher storage capacity is low, because of subsidies, there is often overinvestment in storage capacity and underinvestment 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.

3.1.2. Dynamic Consideration and Uncertainty

The previous section presents the water project design as a static problem, but in reality it is an investment decision under uncertainty. 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 $f\left(\overline{W}\right)$. At period *t*, the amount of water utilized is $W_t \leq \overline{W}$. The water provides benefits of $b\left(W_t,\varepsilon_t\right)$ where $\varepsilon_t$is a random variable.

The annual cost of the water is $c\left(W_t\right)$ (it includes both direct and externality costs). Assuming a project design for (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.,

$$(1) \qquad \max_{\overline{W},W_t} \int_0^T e^{-rt}\ E\left\{B\left(W_t,\varepsilon_t\right)-c\left(W_t\right)\right\}\,dt - f\left(\overline{W}\right)$$

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

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

$$\max_{\overline{W}} \frac{EB(\overline{W},\varepsilon) - C(\overline{W})}{r} - f(\overline{W}).$$

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

(2) $$MN(\overline{W}) = rMF(\overline{W}).$$

There is a vast literature on the appropriate discount rate for development project, and we will not address this point here. In cases where the interest rate is subsidized (for example, when a donor agency expects repayment of the principle with no interest), using equation (2) will lead to overinvestment in projects and diversion capacity. It is not necessarily optimal for the project to operate at a full capacity, for example, if 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. 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 there 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 $t \le t^*, W_t < \overline{W}$, and $W_t = \overline{W}$

for $t \geq t^*$. Higher increase in the variance over time will increase the diversion capacity at the size of the unutilized capacity at the early periods.

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 $\bar{\varepsilon} + \eta_t$ 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.

Arrow and Fisher (19974) and more recently Dixit and Pindyck (1994) develop models that suggest that in these cases the decision maker may consider making the decision about optimal project design to allow delay of decisions so more information can be made. Delaying building a project by one or two periods may lead to losses of benefits in these periods but will lead to extra gain as more information is taken into account. 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 as a result of 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.

In Arrow and Fisher's (1974) paper, they show that in cases where irreversible harm can occur with the construction of a water project, and there is uncertainty about available technology in the future, there can be a gain by waiting to construct a project until further information is known about future technologies and preferences. They emphasize the importance of assessing the option value of delaying irreversible decisions. For example, the construction of a reservoir involves the permanent flooding of natural habitats and recreational areas. This results in a loss of biodiversity in an area, and can lead to the extinction of native animal species. Arrow and Fisher show that if uncertainty and irreversibility are taken into account, many water projects that would pass a standard cost-benefit analysis will not be constructed. In other cases, the optimal size of a water project would decrease, limiting the environmental impact of the project.

The size of a water project could be suboptimal for other reasons as well. 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 too large. This is because crop yields in irrigated areas are higher than in rain fed areas. 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 is also a possibility that the construction of a water project will increase total water demand, as arid areas that otherwise were unproductive are able to grow crops. In these cases, the demand for water will expand after the project development. When constant future water demand is often presumed, the resulting dam size is usually suboptimal.

3.1.3. Waterlogging and Drainage

There are two solutions to the problem of waterlogging, which are not mutually exclusive. These are the construction of a drainage system and the use of more efficient irrigation technology, which would decrease the levels of excess water applied to the land. 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).

The following model illustrates the impact of drainage consideration on project evaluation. Suppose per period benefits of water is given by $b(W_t)$. 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, the stock at time *t* is S_t, and the equation of motion is $\dot{S}_t = \alpha W_t$. 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

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

subject to

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

and

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

Using the technique in Hochman and Zilberman (1985), 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 (fraction of water that contributes to a water project) will reduce the water project capacity and water deliveries.

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, say, year t_0 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

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

and thus the optimization problem is

$$\max_{\overline{W}, W_t, D} \int_0^{\bar{t}} e^{-rt} B(W_t, S_t) dt - \varepsilon(\overline{W}) - e^{-rt_D}\ C_D(D)$$

subject to

$$\dot{S}_t = \alpha W_t \qquad \text{for} \quad t < t_D$$

$$\dot{S}_t = \alpha W_t - D \quad \text{for} \quad t < t_D$$

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

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.

3.1.4. Use of Non-Traditional Water Sources

As traditional water supply sources have become scarcer, there is growing use of nontraditional sources of water. These include the reuse of wastewater, desalination of ocean water, and water reclamation and reuse. 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). The world's 7500 desalting plants can produce 0.1% of the world's water use (Weber). 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.

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 taking advantage of drainage water and other low-quality water, but they require maintaining inventories of water of various quality. Desalination of ocean water, while still very expensive, has begun to be used in water-scarce regions such as North Africa and the Middle East.

3.1.5. Trade and the Concept of "Virtual Water"

Water scientists traditionally assumed that self-sufficiency of water was desirable and commonly assumed that annual per-capita requirements for water was 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 5,000 m^3 in Canada and Northern Europe to 100 m^3 in Jordan. Trade in food products can alleviate some of the water constraints. Countries with limited water resources may produce high value crops that enable them to purchase grains that are water intensive but are rather 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 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 isn't 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 towards 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).

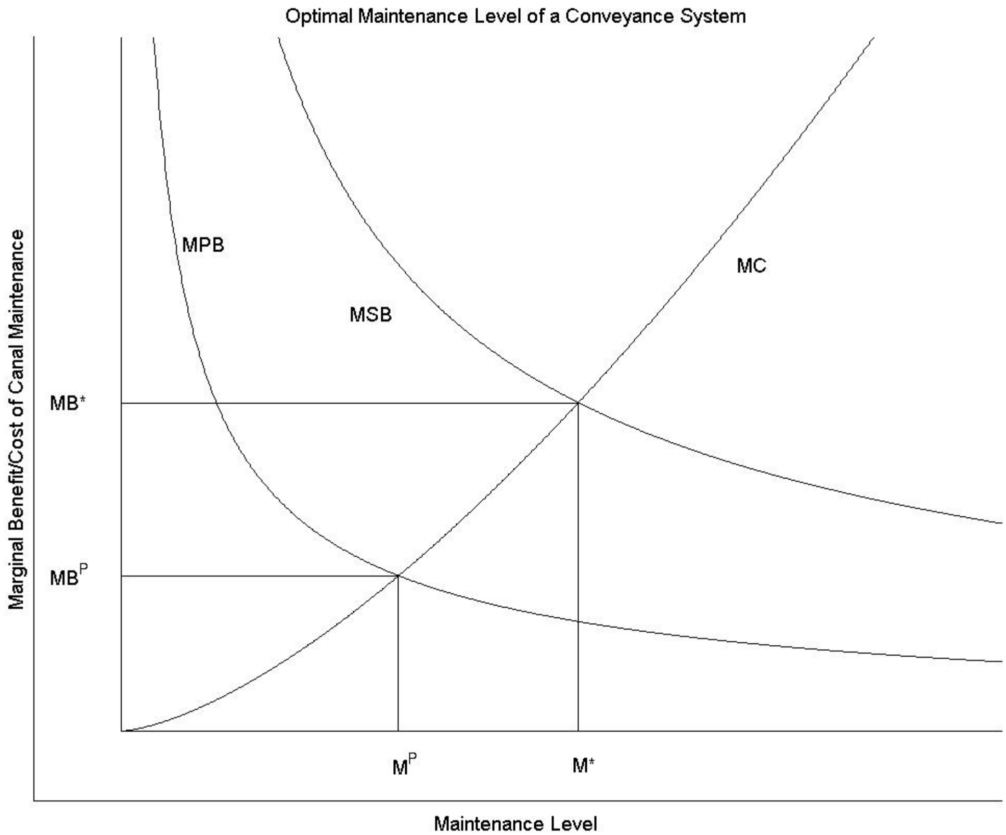
3.2. IMPROVED CONVEYANCE AND THE ALLOCATION OF WATER.

Inefficiency in water allocation can either occur in the decisions made by an individual using the water provided by the system, or in decisions made about the system as a whole. At a system wide level, water can be lost through the conveyance system, either through evaporation or seepage.

3.2.1. Management of Conveyance Systems

The construction of water conveyance systems is an important element of the overall efficiency of the system. Better management of conveyance systems reduces the need for new water projects. Many canal systems were built at a time when the benefits of constructing an efficient distribution system were not worth the extra costs. With a canal system, lining the canals is one method that can limit the amount of water lost during conveyance. Another problem is the maintenance of the canal system—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 percent (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, 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. The following graph clearly shows this. If only private benefits are considered in the maintenance decisions, the users will choose maintenance level M^P, with marginal benefit MB^P. When the total social benefits are considered, including those positive externalities that accrue to downstream users, the optimal maintenance level is M^*, with marginal benefit MB^*. Taking into account social benefits of the maintenance of conveyance systems leads to higher investments in maintenance, with greater social benefits.

Chakravorty, Hochman, and Zilberman (1995) show conceptually and with simulation that without collective action that leads to optimal investment and conveyance, canal systems will be shorter with overapplication of water close to the source and underapplication far away. Transition to optimal conveyance will expand canals and production and will actually reduce the rate of land that are upstream, even though the overall rent is likely to increase.

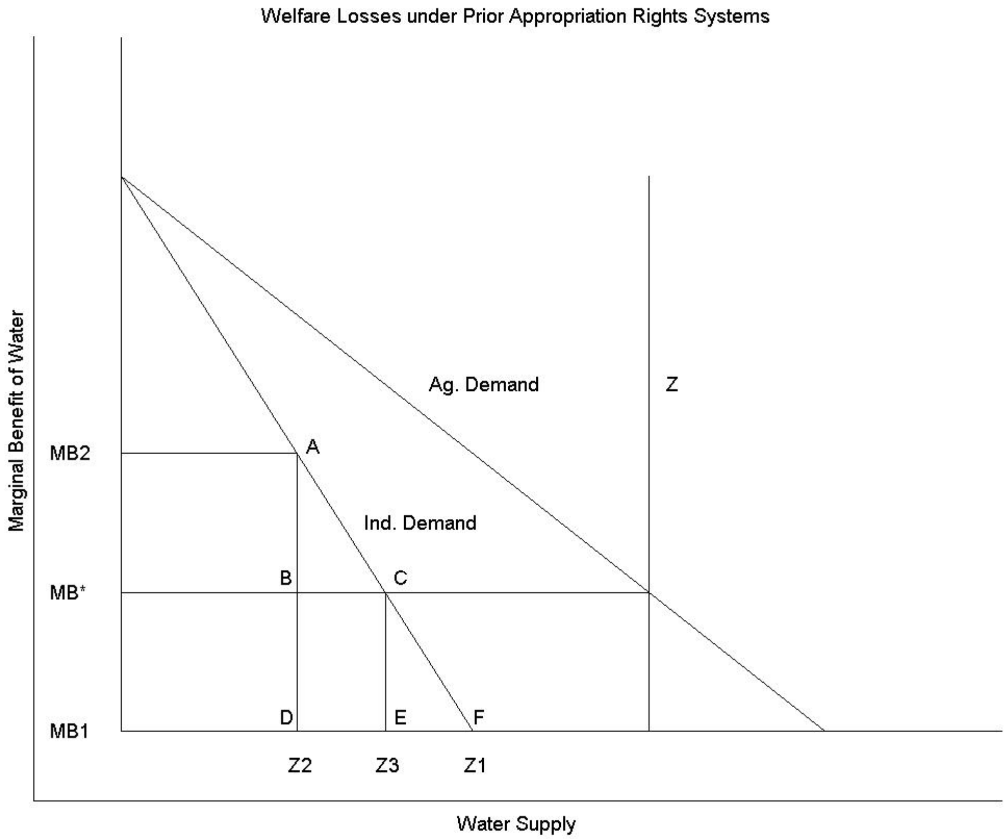


As discussed by Easter(1986), there has been a shift in recent years from the development of new water projects to better management of existing projects. This has also led to an increased reliance on water user associations (WUAs). Evidence shows that water systems run by a WUA are more efficient and better maintained than managed systems. One country that now primarily uses WUAs to manage irrigation infrastructure 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 percent, 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. 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. The shift to WUAs often improves the pricing and allocation inefficiencies in water. In Hubei, China, one goal of the shift is financial autonomy. WUAs are required to purchase the water they use, giving them an incentive to conserve and use water efficiently (Easter, 2000).

3.2.2. 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. 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 a historical 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. It is also common to have restrictions on trade in water with systems (quite frequently of the form "use it or lose it"). In this type of system, senior rights holders have little incentive to invest in water-saving irrigation technology, because they are assured of their right to a certain quantity of water annually. The riparian rights system gives any landowner with land adjacent to a water source the right to use that water. Again, those users who are upstream have little incentive to limit the amount of water they use, despite the externality imposed on users downstream who have a less reliable 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, now the water in many systems is 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 isn't 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. These systems ensure that scarce water will flow to the user who earns the highest marginal value from the water. This following graph shows two farmers who have identical technology available; however farmer 1 has senior rights to water while the other (farmer 2) has junior rights. Since the two farmers are identical except for the rights they hold, each has identical benefit from water; therefore aggregate demand is just twice each farmer's individual demand. 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 the following graph:



With a prior appropriation system, senior rights holders have their demand fully satiated before junior rights holders receive any water. The following shows this graphically: farmer 1 receives Z_1 units of water, while farmer 2 only receives Z_2 units of water. The marginal benefit of additional water to farmer 1 (*MB1*) is zero, while the marginal benefit of additional water to farmer 2 is *MB2*. If trading in water rights is allowed in the preceding model, there will be positive gains to society from trading. Farmer 1 will trade quantity (*Z*1 - *Z*3) for a price greater than the area of triangle CEF. Farmer 2 is willing to buy quantity (*Z*3 – *Z*2) for a price less than area ADEC. Since area ADEC is less than area CEF, the two farmers can agree on a price between these two quantities, and both will have improved their own welfare after the trade. The marginal benefit to both farmers will be *MB**, and each will use quantity *Z*3.

When transaction costs are introduced to the above model, the welfare gains of tradable permits will be reduced. It could be the case that when water is not very scarce, the transaction costs of trading water are greater than the benefits. However, as demand for water expands over time and water becomes scarcer, 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.

There are alternative mechanisms of water trading that have to be considered once reform is 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. Senior rights owners 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. Another choice is whether to allow individuals to sell the right on an annual basis (which is equivalent to rent) or whether 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. A third decision is whether to allow out-of-basin trading among water users. When water users in a single water basin are allowed to trade, the transaction, 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 effect must be addressed. These third parties may be individuals who use runoff or deep percolating water from the land that was irrigated with the water that is being traded. To address the rights of these individuals may require limiting the quantity being traded to the effective water, and not the applied water used by an individual. An essential element in all of these decisions is the transaction costs involved. If transaction costs are large, and water supplies are not very scarce, it is likely that the costs of any type of trading system will exceed the benefits. However, as demand expands over time, and water supplies remain constant, the benefits of trading will increase, and will come to overshadow the transaction costs.

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. Active markets are appropriate between districts.

Some form of passive trading within districts exists within many parts of the world. In 1981, Chile reformed its Water Code, changing the nature of water rights. After the change, water rights became completely separated from land ownership, and can be freely bought, sold, or temporarily 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 is that few transactions are actually observed in practice. Also, 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 (Bauer, 1998). In some cases though, initial allocation of water is not far from optimal. Immediately after the reform, the number of transactions are rather small. But even if only 5% or 10% of the water is changing hands every years and these are final sales, the impact may be significant if the gain in productivity for this water is substantial. Eventually, as conditions changes, and new actors enter the system, transactions may increase.

3.2.3. Improved Efficiency of Water Pricing Systems

The costs of providing irrigation water include a variable cost, which depends on the quantity of water supplied, and a fixed cost of operation and maintenance (O&M). 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 don't even attempt to recover the initial capital costs. Recovery of operation and maintenance costs ranges from a low of 20-30 percent in India and Pakistan to a high of close to 75 percent 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 also work as an incentive for water users to adopt water-conserving technologies, or to alter the amount of land under cultivation. A volumetric 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 first charge is assessed per hectare, and is designed to repay the capital costs of the project. These are calculated using a 50-year repayment period and a subsidized interest rate. The other charge is a volumetric fee, and 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 Azeveda, 1997).

Overwhelmingly, developing countries use a per-hectare water fee, if they charge at all. Part of the reason for this is the difficulty in accurately assessing volumetric use of individuals. 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 variation across crops is not related to either the water requirements or the profitability of the crop. Other countries, such as Egypt and Indonesia, don't charge farmers anything for the water they use but require farmers to maintain and operate the irrigation canal system.

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, water districts lack the technology to accurately measure the amount of water used by a farmer. Other pricing systems have been developed as an alternative to volumetric pricing. 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 highly efficient irrigation technology is available, its use 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 doesn't 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 1983-86, 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 by Repetto of six Asian countries showed that the irrigation charge as a percentage of total cost ranged from 1.0% to 22.5%. A transition to modern, water-saving irrigation technologies can decrease water use, increase yields, and reduce problems with water logging and salinization.

3.2.4. Improved Efficiency of 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 start pumping the water for his or her personal use. However, since the same groundwater table is available to many users, each user inflicts an externality on others, since the water extracted is not available to other users or in the future.

Appendix 1 presents a formal model that suggests that optimal use of groundwater requires equating marginal benefit of water with the cost of pumping plus the user cost that represents the future loss of benefits because of depletion of losses as well as the increase in pumping cost associated with depleted stock. User costs are rarely paid, and in most cases as discussed below, in most cases, even the full pumping cost is not fully paid by the user. This exacerbates the problem of over pumping.

Subsidization of groundwater pumping costs. Another obstacle to efficient management 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 groundwater. A lower pumping cost leads to a higher than optimal extraction rate of groundwater. This is a serious problem in India and Pakistan, and is part of the reason for the overdraft of groundwater that is occurring in these countries. This subsidization has led to the increased use of groundwater resources in India. From 1951 to 1986, the use of tank irrigation has fallen slightly, while the use of canal irrigation and well irrigation has increased dramatically. The amount of land under canal irrigation has increased from approximately 8 thousand ha to 15 thousand ha, while the land under well irrigation has increased from 6.5 thousand ha to 20 thousand ha, 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. A first-best solution would be to impose a tax equal to the user cost on every acre foot of groundwater extracted. However, the monitoring and enforcement of a tax like this would be logistically impossible. 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.

3.3. INEFFICIENCIES IN MICRO-LEVEL WATER MANAGEMENT

Ultimately, the efficiency of irrigation systems is determined by micro-level irrigation choices. These include choices of land allocation among crops, the extent to which these crops are irrigated, the relation of other inputs, and the choices of irrigation technologies. These choices are interdependent, and complete modeling of irrigation choices in likely to be cumbersome. Therefore, it is here we first discuss land allocation among activities and, in particular, irrigation of rain-fed farming and the relation of irrigation technologies. .

3.3.1. Land Allocation to Irrigation at the Farm Level

There is an extensive literature on adoption of technology (Feder. Just, and Zilberman, 1985, and Feder and Umali, 1993) that is useful in analyzing the selection of acreage or irrigation. This literature, to a large part, assumes that farmers are risk averse and constrained by credit availability. To a large extent, adoption of irrigation reduces risk and increases yield but requires extra investment.

Suppose a farmer has *L* acres of land can allocate it among two activities, irrigated and nonirrigated land Profit per acre under both is distributed normally where mean profit under irrigation is U_1, assuming that the variance of profit is zero. The mean and variance of profit per acre under rain-fed farming is U_0 and σ_0^2, respectively. A farmer with $\overline{L}$ acres of land has to allocate it among the two technologies when L_0 is acreage under dry farming and $L_1 = \overline{L} - L_0$ is 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. For simplicity, we will 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. The analysis in Just and Zilberman (1988) suggests that if the irrigation is selected but the credit constraints binds, acreage in irrigation is $L_1^c = \dfrac{N-K}{m}$. If the constraint is not binding and the irrigation is selected, the irrigation acreage is

$$L_1^r = \min\left(\overline{L}_1 \frac{\mu_1 - m - \mu_0}{\phi\sigma^2} + \overline{L}\right).$$

If credit is not constraining, and expected net profit per acre under irrigation is greater than rain-fed farming, all the land will be irrigated $\left(L_1^r = \overline{L} \text{ if } \mu_1 - m - \mu_0 > 0\right)$. Integrating this above condition, optimal acreage in irrigation is

$$L_1^* = \left(\bar{L}, \frac{M-K}{m}, \frac{\mu, M-\mu_0}{D\sigma^2} + \bar{L} \right).$$

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. Thus, subsidization and finance irrigation investment are likely to increase acreage in irrigation. It is especially the case when the yield gain and risk-reduction gain from irrigation increase.

3.3.2. Irrigation Choice at the Farm Level

When irrigation water is available to a grower, that grower must not only decide how much water to use, but also what type of irrigation technology to employ. It isn't much of a simplification to divide irrigation technologies into two categories—"traditional" and "modern." 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 sprinklers or drip irrigation use systems of equipment to deliver the water directly to the crop. Because of this, the water can be applied in a more precise fashion than with traditional technologies. Modern irrigation technologies have higher adoption costs, but are more efficient.

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. Irrigation efficiency is the ratio of effective water to applied water. With traditional technologies, this is around 0.6, while with modern irrigation methods it is about 0.9. The slope of the land and the water-holding capacity of the soil, as well as the irrigation technology affect irrigation efficiency.

According to Caswell and Zilberman, under plausible conditions, modern irrigation technologies increase yields as well as save water in most cases, but the gains from this technology are larger as land quality is declining. The reason is the differences in water holding capacity lead to differences in effective price of water, and the effective price of water under the modern technology is lower, thus it will increase effective water per acre and productivity under most circumstances. Except for cases where the initial land quality is very low, the gain in productivity will also be associated with water saving. Overall the gains in adoption are increasing as land quality declines. Thus, adoption occurs when the yield and price saving effect are greater than the fixed cost of the technology, thus we expect that modern technology will be adopted in locations with low quality land, for example, on steep hills and sandy soil. Since the cost of drip and sprinkler irrigation is substantial, they are more likely to be adopted with high value crops.

The increase in water use efficiency actually reduces residue of unutilized water and thus with drip irrigation buildup and waterlogging is much slower. Caswell, Lichtenberg, and Zilberman (1990) showed that when a penalty on drainage is introduced, adoption of sprinkler as well as drip irrigation is likely to accelerate. Thus these technologies provide both an increase in productivity as well as a reduction in negative side effects, and their adoption will be enhanced by introduction of real pricing of water as well as a drainage fee.

Switching from furrow or sprinkler irrigation to drip systems cuts water use by 30-60%. 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. Global use of drip irrigation has grown 28-fold since the mid-1970s, but still accounts for less than 1% of world irrigated area. The inclusion of sprinkler irrigation only increases this to 6% of irrigated land (Postel, 1996). Drip-irrigated sugar cane yields 12-30% more per unit-area, while cutting water use by 30-65% (Postel, 1999).

3.3.3. Existence of Low-Capital Efficient Irrigation Technologies

It should be noted that 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 who are able 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 flatter land surface leads to less water runoff, and more water used by 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 low level 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%.[1]

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[1] For additional information, see http://www.sowerproject.org/drip_irrigation.html.

4. Conclusion

According to Gardner, irrigation was the source of more than 50% of the increase in global food production during 1965-85 and more than 60% of the value of Asian food crops comes from irrigated land (Hinrichsen). 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. In addition to the concern with the environmental side effect of projects, and sustainable ecosystems, there is a big challenge of increasing food supplies by at lest 40% in the next 50 years. Increased productivity shouldn't come by expansion of water but by increased productivity of existing sources. That can be achieved through complete reform of water design and management systems. In particular, 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 cost of water to represent both 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. The growing use of water user associations (WUAs) is a positive step towards the improvement of water management systems. Experience that we have with trading in water suggests that it can improve efficiency given that 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

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

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 approach the new millennia.

Appendix 1

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 $C' < 0$. 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 $B(u_t) - u_t \cdot C(S_t)$.

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:

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

Solving this yields the following condition:

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

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.

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:

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

Solving this yields the following condition:

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

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.

Appendix 2

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:

$$\Pi_i = \underset{i}{Max}\{Pf(h_i(\alpha) \cdot a_i) - wa_i - k_i\}$$

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.

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 the graph below, the quasi-rent difference can either be positive or negative. In the following graph, $f^0(L)$ represents the profit earned by the traditional irrigation technology, as a function of land quality, while $f^1(L)$ 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:

$$g_i(\alpha) \le 1 - h_i(\alpha)$$

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

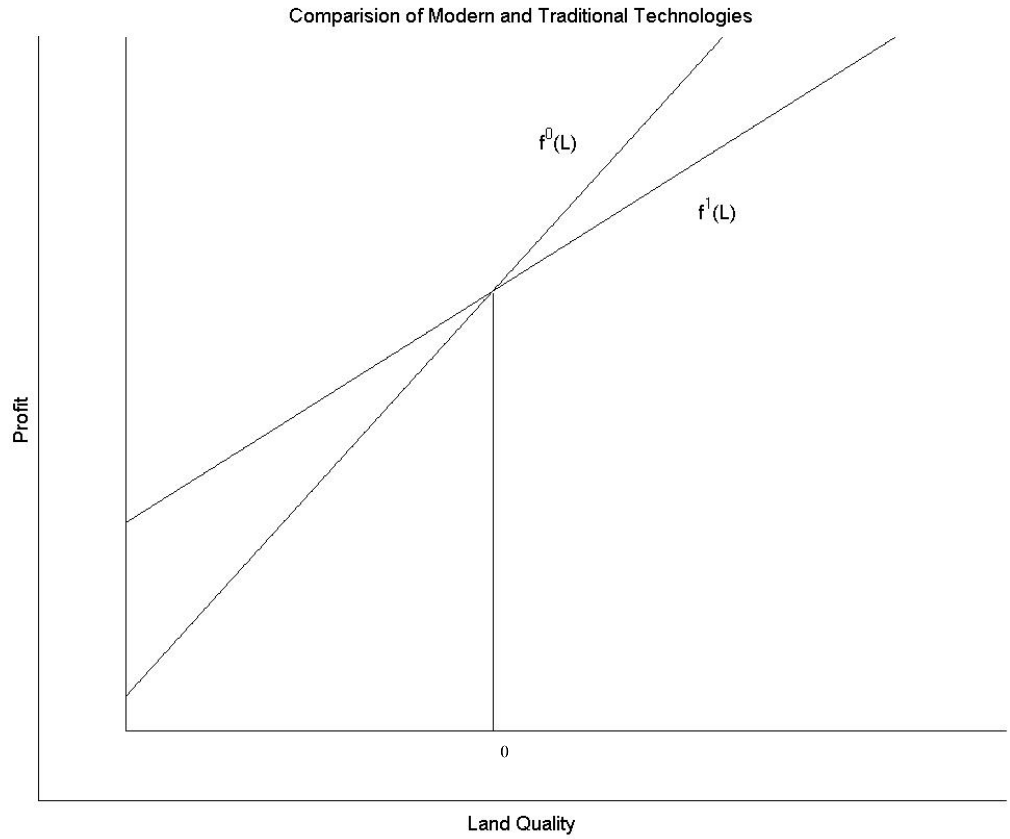
If the producer bears the costs associated with the pollution arising from water residual accumulation, the individual's profit maximization problem becomes:

$$\Pi_i(\alpha) = \underset{a_i}{Max}\{Pf(h_i(\alpha)\cdot\alpha) - wa_i - k_i - (x \cdot g_i(\alpha))\}$$

where *x* denotes the cost per unit of pollution. Usually this cost is a production externality that isn't 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 the above graph, as land quality increases, the benefit of modern technology adoption decreases and the quasi-rent differential between the two technologies declines.

Frequently, the imposition of a pollution tax on agricultural drainage is not feasible due to the difficulty in identifying and monitoring the polluters. An alternative policy may be to subsidize irrigation technologies, which results in reduced agricultural drainage flows. Subsidization of the modern technology will increase the quasi-rent associated with its adoption, leading to higher adoption rates and lower amounts of agricultural drainage.



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)[3], which measures how responsive the crop is to further irrigation. Under most conditions, adoption results in both a decrease in overall water use and an increase in crop yields.

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

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