AN ABSTRACT OF THE THESIS OF

Harold E. Seely for the degree of Master of Science in Agricultural and Resource Economics presented on August 6, 1997.

Title: Impact of Artificial Flooding on Farm Profits and Streamflow in Echo Meadows, Oregon

Abstract Approved: Redacted for Privacy

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Competition for water both from within the irrigation community and from outside interests has been a major source of conflict in the West. In the Umatilla Basin of central Oregon, Umatilla River water is diverted to irrigate a variety of crops, while instream flows have value in salmonid production. Historically, the Umatilla Basin supported runs of fall and spring Chinook as well as steelhead and resident trout but native fish populations have largely disappeared from the river system. The decline in salmonid production has been blamed, in part, on a combination of low streamflow and high water temperatures in the summer months resulting from diversions by agricultural users.

This thesis examines a proposed project designed to increase streamflow in the lower Umatilla River during the summer months by artificially flooding selected agricultural land in the Echo Meadows area of the basin during the late winter. The thesis also examines alternative options to increase streamflow. Estimates of the economic and hydrologic impacts of winter water spreading and other options provides information to policy-makers and irrigators on the costs and benefits associated with various project management alternatives.

Using information on agricultural production and water supply in the lower Umatilla Basin, this thesis constructs a mathematical optimization model of representative farms in the area. In addition, because return flows represent an important component of streamflow in summer months, water applications determined by the representative farm models are used to assess the impacts of the artificial flooding project on streamflow in the Umatilla River below the study area.

The results of the representative farm models indicate that the artificial flooding project increases farm profits by $37,620 and streamflow by 18.58 cubic feet per second. Alternative techniques to obtain similar increases in streamflow are more costly and would have negative effects on the agricultural community.

Impact of Artificial Flooding on Farm Profits and Streamflow in Echo Meadows, Oregon

by

Harold E. Seely

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented August 6, 1997
Commencement June, 1998

Master of Science thesis of Harold E. Seely presented on August 6, 1997

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Redacted for Privacy

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Harold E. Seely, Author

ACKNOWLEDGMENT

I would like to thank Dr. Richard Adams for the support and guidance he offered during my work on this thesis and other projects throughout my master's degree program. His knowledge and patience added greatly to my experience at Oregon State University. In addition, I would like to thank Dr. Greg Perry who spent a considerable amount of time with me during the model building and programming stage of this analysis. Without his assistance I would undoubtedly still be battling with the mainframe. Other committee members, Dr. Marshall English and Dr. William Boggess were extremely helpful and generous with their time. I thank them both.

Lastly, I would like to thank my family for unending support during my graduate work and life in general.

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CHAPTER 1. INTRODUCTION

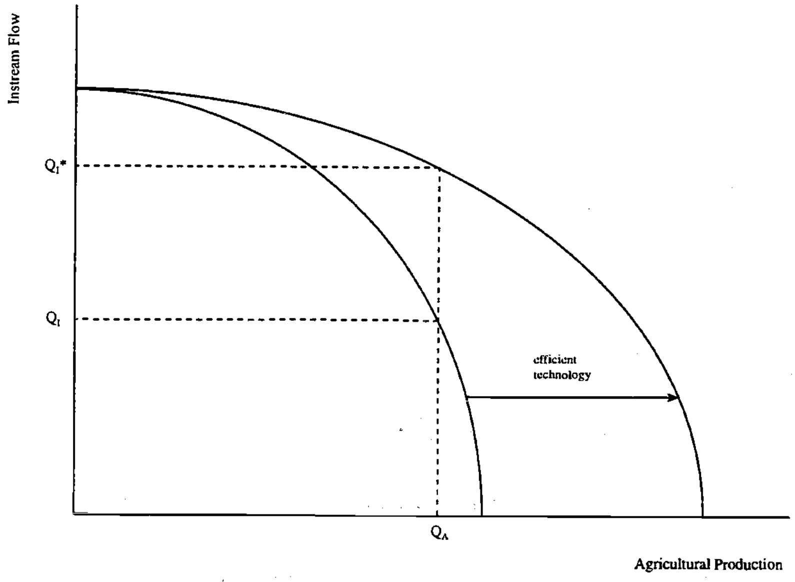
Conflicts among competing water users have intensified in the western United States as demand for water for irrigation and other uses has increased while opportunities for developing new water sources have declined. In the Pacific Northwest, a conflict exists between groups who rely upon adequate streamflows to supply anadromous fish for economic and cultural purposes and agricultural groups who divert water from rivers and streams to produce agricultural outputs. To complicate the issue, most water supplies are fully appropriated, so there is little opportunity to allocate water to nonconsumptive uses such as instream flow for salmonids without diminishing the quantity available to irrigators. Consequently, it is becoming increasingly important to develop innovative methods of meeting the demands of all water users.

1.1 Oregon's Streamflow Programs

In recent years, the state of Oregon has implemented programs designed to recognize and allow for nonconsumptive uses of water. One of these programs is the Allocation of Conserved Water Program (ACWP, ORS 537.455 to 537.500). Under this program, an irrigator who conserves water may sell the amount conserved, use it on other land not initially included in the water right, sell it to others, or donate it for instream flow purposes. The program also stipulates that 25 percent of the conserved water be forfeited to the state for instream flow augmentation (Parrow, 1995). In addition, if the irrigator wishes to apply the savings to another field, a water right with the same seniority date of the existing right is issued.

Figure 1 provides a theoretical illustration of the effects of an improvement in irrigation technology on the trade-off between instream flow and crop production (assuming a fixed supply of surface water).

Figure 1.1 Tradeoff Between Instream Flow and Agricultural Production



The production possibilities frontier shows that an improvement in efficiency will allow more land to be cultivated with a given amount of water and therefore increase crop production. Alternatively, holding agricultural production fixed at Q_A demonstrates that improvements in irrigation technology can increase instream flows from Q_I to Q_I^* as the economy moves from the lower to the higher production possibilities frontier.

Since its implementation in 1987, very few irrigators have participated in the program. One explanation is that there are psychological and physical constraints that have prevented the program's success in appropriating water to instream flow (Parrow, 1995). Specifically, irrigators may be suspicious of any program that reduces a water right endowment, despite the fact that it may be economically efficient, because they believe that any reduction in a water right reduces land value. In addition, it is possible that revenue from the amount of land that could be serviced by conserved water are too small to justify the expense of a new irrigation system. Other critics argue that the time and expense associated with the application process, which requires a water rights review and water use monitoring, has deterred program participation.

Interestingly, some economists have argued that the conservation program may actually work to decrease instream flows due to increased evapotranspiration in specific cases (Whittlesey and Huffaker, 1995). Evapotranspiration (ET) is a measure of water loss from the soil to the atmosphere. It includes both water which evaporates from the plant itself, referred to as transpiration, and water lost from the soil through direct surface evaporation. As irrigation efficiency improves, ET increases due to increased yield which means that return flows will be reduced. To complicate matters, if a farmer chooses to irrigate new land, total crop consumption of water will increase as well. Therefore, decreased return flows due to increased evapotranspiration may actually outweigh the 25 percent of savings that are reserved for instream flow.

In addition to the ACWP, Oregon has also established a water rights market whereby water rights can be purchased by potential users to meet irrigation demands or to establish instream flow rights. Currently, however, few market transactions are taking place due to high transactions costs. Transactions costs in the Oregon water market include: costs of identifying a trading partner; costs associated with verifying the ownership and physical description of the water right; administrative costs associated with the transfer application procedure; and costs that might arise from a protest hearing or litigation associated with the proposed transfer (Landry, 1995). As Brajer et al. (1989) note, fees for water rights transfers typically range between $3,000 and $4,000 but can be as high as $6,000.

Oregon passed the minimum streamflow law (ORS 536.235, 536.310(7), and 536.325) in 1955. This law allowed the state to set minimum flow levels to support recreation, wildlife, or reduce pollution on the state's waterways. Minimum streamflows are only operational on streams which are not fully appropriated. To deal with this limitation, the state created instream water rights in 1987. Instream water rights establish flow levels on a month-by-month basis and are usually set for particular reaches of a stream. They are given a priority date and regulated in the same manner as other water rights (OWRD, 1995). Only the Department of Fish and Wildlife, the Department of Environmental Quality and Department of Parks and Recreation may apply to OWRD to establish a new instream water right. Existing water rights can be converted into instream rights by any individual, and a minimum streamflow may be changed to an instream right through a review process. Most minimum streamflows have been converted to instream water rights since the 1987 law was established. As of November 1996, 1,315 instream water rights had been granted in Oregon (OWRD, 1997). Unless the instream rights have a senior priority date, however, they are of limited use in protecting streamflows in low water years.

Artificial flooding projects could prove to be an effective alternative in some areas. Because they do not require changes in water rights or irrigation technology, flooding projects may be more readily accepted by irrigators. In fact, flooding projects are likely to benefit irrigators in arid regions by reducing the risks associated with limited water supplies.

1.2 Problem Statement

Agricultural production in the lower Umatilla Basin relies heavily upon irrigation due to low annual rainfall and porous soils. Consequently, the hydrology of the region is linked to water use by the agricultural sector. Diversions and evapotranspiration reduce instream flows while the return flows from irrigation affect the quantity, quality, and temperature of surface flows in the Umatilla River. A study conducted by the Oregon Water Resources Department in 1985 and 1986 determined that return flows are an important component of streamflow during the late summer months in the Umatilla River. The study found that there was a two-week to a two-month delay from the time of water diversion for irrigation and the occurrence of return flow and that these flows ranged from 110 to 160 cfs during the irrigation season (Kraeg, 1991).

Terrestrial and aquatic species that depend upon riparian and wetland habitat have been affected both positively and negatively by irrigation. For example, waterfowl populations in the Columbia Basin benefit from food and wetlands associated with irrigated agriculture. However, salmon and steelhead populations in the Umatilla system and elsewhere in the area have declined significantly as a result of alterations to flows and temperatures.

Studies indicate that low flows and high water temperatures in the summer, combined with barriers to passage, represent the leading limiting factors to salmonid production in the Umatilla River (James, 1984). In low water years, sections of the river are completely dry while other stretches of the river experience temperatures in excess of 70 degrees Farenheit (lethal for most salmonids).

Tribal fishing for salmon ceased after the completion of Three-Mile Dam in 1915 which eliminated salmon runs. The Confederated Tribes of the Umatilla's desire to return salmon runs to historic levels intensified the water conflict in the basin. Without improving instream conditions for spawning and maturing fish, gains from hatchery programs will be limited. Water storage capacity in the basin is limited and irrigators often receive less than their full allocation of water. When faced with similar conflicts elsewhere between fisheries and agricultural production, the prescribed policy is to reduce the amount of water supplied to irrigation interests. For example, surface water deliveries to irrigators will be reduced in low-water years in the Klamath River Basin, in southern Oregon and northern California, to maintain lake levels in Upper Klamath Lake for the benefit of the Lost River and shortnosed suckers which were recently listed as endangered species (Cho, 1996). Such policies transfer much of the costs of fishery enhancement to the agricultural community.

In the Umatilla Basin, a group of irrigators and agriculturally dependent businesses, the Oregon Water Coalition, proposed a plan to provide additional flow during the summer months to benefit salmonids as well as irrigators (by reducing water application requirements and pumping lifts). The plan, which calls for spreading water on selected fields during periods of winter runoff, could be an innovative solution to future potential conflict between treaty reserved rights and irrigation interests and has the potential to benefit both parties.

To alleviate the effects of irrigation on streamflow in the Umatilla River, the Oregon Water Coalition proposed the flooding of selected fields in Echo Meadows during periods of winter runoff, when streamflow levels are at their highest. This artificial flooding is expected to mitigate the effects of irrigation in several ways:

a) by augmenting return flows and reducing temperatures in the Umatilla river during low-flow months in the summer and fall, for the benefit of immature and migrating adult salmonids;

b) by hydraulically flushing local aquifers, it will reduce ground water nitrate concentrations; and

c) by filling the soil profile in winter it will reduce the need for irrigation in the early spring.

Theoretically, the artificial flooding project would mimic, on a small scale, natural flood events that periodically occurred prior to development of the basin for irrigated agriculture. This project has received financial support from the EPA 319 grant program, administered through the Oregon Department of Environmental Quality. It is anticipated that the first flooding will begin during the winter of 1997-98.

The current scope of the proposed flooding entails less than 10,000 acre feet of water applied to approximately 2,500 acres of noncontiguous irrigated land. An analysis of the costs and benefits has not been conducted, so there is no information from which to assess the economic and hydrologic impacts of this proposed artificial flooding scheme. Understanding and quantifying the tradeoffs between agricultural production, the timing and magnitude of the flooding project, and the timing and quantity of return flows will provide important information that can improve the management of this and similar projects. In addition, the relative costs of the project can be compared to other water conservation strategies, such as improvements in irrigation conveyance and application efficiency, to determine the cost-effectiveness of artificial flooding.

1.3 Objectives

The main objective of this research is to evaluate the costs and selected environmental effects of the proposed artificial flooding project. The analysis will be based upon the proposed Echo Meadows project, but the results will be sufficiently general to assist in the evaluation of the potential of artificial flooding in other areas. Specific objectives include:

1) evaluate the impact of artificial flooding on returns to agricultural land within the study site under various project management schemes;

2) estimate the effect of artifical flooding on streamflow in the lower Umatilla River;

3) compare the effects (as measured by farm profits and streamflow) of various levels of the artificial flooding project to potential gains that could be achieved through other water conserving strategies.

To meet the first specific objective, a mathematical programming model was developed. This involved specification and estimation of a "representative farm" linear programming model which details the crops grown and management practices employed in the Echo Meadows area to assess the farm level impacts of the project. The overall modeling framework combined several representative farms to reflect variations in location, crops, soil, and management practices. In order to simulate the effects of the project under a variety of climatic conditions, uncertainty associated with surface water deliveries was incorporated into the model using historical water availability and crop water consumption.

Objective 2 involved linking artificial flooding and irrigation management decisions from the representative farm models to return flows in the Umatilla River. A simple mass-balance approach was used to conduct this portion of the analysis in lieu of a more detailed hydrology model for the area.

Objective 3 involved developing simulations of other management alternatives to identify tradeoffs between different management schemes. These economic and environmental tradeoffs are compared to the results obtained from changes in onfarm irrigation efficiency, and other water conservation strategies.

1.4 Justification

This research provides preliminary information regarding selected costs and benefits of the artificial flooding project in Echo Meadows. This information will be useful to irrigation districts, the Confederation of Indian Tribes, and resource managers in the area.

Irrigation districts will benefit from the analysis of the tradeoffs between the degree of artificial flooding and the subsequent effects upon irrigation requirements, crop yields, and profitability. Analysis of alternative plans that take into account both increases in acres flooded and amount of water applied will provide further information on the marginal benefits and costs of the project to irrigators. The analysis of return flows will estimate the timing and quantity of return flows to the lower Umatilla River and can be used to infer potential benefits to salmonid production. These latter potential benefits are of interest to the Confederation of Indian Tribes. When fisheries data become available, this information can be utilized (in subsequent research) to assess the effects on salmonid fecundity and survival, which in turn could be used in a bioeconomic assessment of the benefits of instream flow.

1.5 Study Area and Scope

The study area of this thesis is the Echo Meadows area of the lower Umatilla basin. Echo Meadows is located entirely within Umatilla County, Oregon. All delivered surface water is diverted from the mainstem of the Umatilla River above the town of

Echo through the Westland Main Canal (also known as Hunt Ditch) and is further diverted to individual farms through the Allen and Pioneer-Courtney ditches.

Echo Meadows is bounded by the Umatilla River on the east, Westland Main Canal to the south, Emigrant Buttes to the west, and Interstate 84 to the north. It encompasses approximately 6,000 acres, the majority of which are used in the production of irrigated crops and livestock. The terrain is fairly flat with some low rolling hills in the western portion of the meadows. Land that is not irrigated has little or no agricultural productivity.

This analysis focuses on the economic and hydrologic impacts of the Echo Meadows flooding project and therefore confines itself to Echo Meadows and the Umatilla River reach adjacent to the study area. This thesis ignores the impacts that the flooding project may have on downstream river users and does not attempt to value any fishery benefits to which it may contribute. In addition, the effects of artificial flooding upon groundwater nitrate levels will not be considered.

The central aim of this study is to estimate the changes in direct farm profits that result from the artificial flooding project. The study will also quantify the project's effect on surface flows at different times during the summer resulting from the interaction of agricultural producers and underlying hydrologic properties in the area.

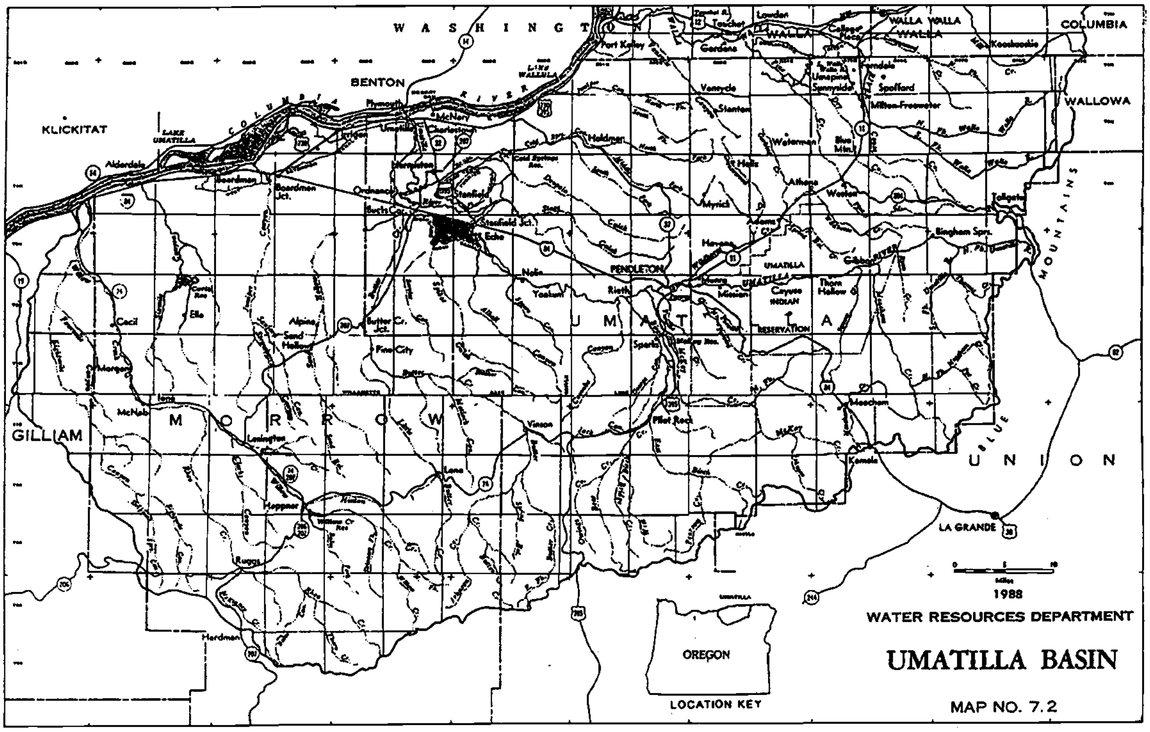
1.6 Thesis Organization

Chapter Two details the physical and institutional characteristics governing agriculture, water resources, and the environment in Umatilla County. Chapter Three contains a description of the economic assessment framework as well as a review of literature. Chapter Four deals with the estimation procedures employed here, including economic and hydrologic model descriptions and sources of data. Chapter Five contains a description of the simulation results and Chapter Six presents a summary and conclusion.

CHAPTER 2. STUDY AREA

The Umatilla River Basin is located in northeast Oregon and drains 2,545 square miles of land. The basin's major rivers and streams originate in the Blue Mountains and flow northward over the Deschutes-Umatilla Plateau until eventually draining into the Columbia River at the town of Umatilla. The mainstem Umatilla River extends 89 miles from the mouth to the confluence where the river separates into a North and South Fork which both extend another ten miles in length (OWRD, 1988). Figure 2.1 shows the Umatilla Basin and Echo Meadows (shaded area).

Figure 2.1 Umatilla Basin and Study Area



Annual precipitation ranges from 8 inches in the lower elevations to 45 inches in the Blue Mountains. The average temperature in the lower basin is 50 degrees Fahrenheit (F), however, temperatures frequently top 100°F in the summer months and drop below freezing during the winter.

Agricultural land, including both dryland and irrigated, comprise approximately 42% of the basin's area. Rangeland and range-forest transition areas account for another 42% of the basin while the remaining portion is 13% forest and 3% urban (OWRD, 1988). Total population in the basin was 42,415 in 1990.

The Umatilla Indian Reservation covers 169,406 acres and represents nearly six percent of the basin's total land area. Most of the reservation consists of a large block of land located in the southeastern portion of the Umatilla Basin near the headwaters of the Umatilla River. Smaller parcels are located along the southern boundary of the basin in the McKay and Birch Creek headwaters.

2.1 Agricultural Production

White settlers began entering the basin in the mid-1800's to raise livestock and pursue limited crop production. Full scale irrigation began in the early 1900's when the Federal Bureau of Reclamation constructed the Umatilla Project. By 1920, the Umatilla River was fully appropriated in the summer months.

In the 1960's, the introduction of pivot irrigation systems allowed land farther from the river to be irrigated with ground water. Shortly thereafter, however, rapid declines in the ground water level forced the state to designate a portion of the basin as the Ordnance Critical Ground Water Area. Since that time, three other sites in the basin have been designated as critical groundwater areas, including Stage Gulch which encompasses Echo Meadows. Designation of critical ground water areas prevents the development of new wells and can restrict both existing and future uses of the resource.

Estimates of the average annual recharge to aquifers in the Umatilla subbasin vary from 10,000 to 64,000 acre-feet. Annual pumping from the aquifer during 1980-85 averaged over 90,000 acre-feet. As a result of this mining, many irrigation wells have declined over 50 feet, while some water levels have dropped more than 200 feet. Ground water levels in the Stage Gulch area have dropped an average of 5 feet per year (OWRD, 1988).

The lower Umatilla Basin produces a variety of irrigated crops ranging from wheat to watermelons. Table 2.1 lists gross farm sales and harvested acreage for Umatilla County in 1995. Currently, Umatilla County contains over 400,000 acres of agricultural land that produced over $220 million worth of crops at the farm gate in 1995. The most commonly produced crops are wheat, corn, potatoes, and alfalfa.

Table 2.1 1995 Harvested Acreage and Gross Farm Sales, Umatilla County

Crop Group	Harvested Acreage	Gross Farm Sales ($,000)
Grains	285,600	100,842
Hay & Silage	38,600	9,520
Grass & Legume Seeds	6,685	5,569
Field Crops	27,320	43,335
Tree Fruits & Nuts	3,172	6,144
Small Fruits & Berries	40	132
Vegetable Crops	43,935	40,815
Spec. Prod.	250	13,750
All Crops	*405,602*	*220,127*

source: OSU Extension Service

The region is moderately cold in the winter and hot and dry in the summer. As a result, crop evapotranspiration demands are high and irrigation is required almost daily for moisture sensitive crops such as potatoes. Without added water and fertilizers, most of the land in the lower Umatilla Basin is suitable only for low volume grazing due to inadequate rainfall (20-30 cm annually) and low natural soil fertility (McMorran, 1996). Table 2.2 provides the average annual crop water use (ET) for seven major crops grown in Echo Meadows.

Table 2.2 Average Crop ET (acre-inches)

Crop	Avg. Annual ET (inches)
Winter Grain	21.41
Alfalfa	50.12
Corn	29.40
Potato	30.49
Pasture	43.15
Spearmint	25.78
Asparagus	29.64

Source: Agrimet, 1997

2.2 Water Resources

Four major reservoirs store water in the Umatilla Basin for irrigation, flood control, and industrial uses. Cold Springs Reservoir, located east of Hermiston, was established in 1908 to supply water for irrigation. The reservoir has a capacity of 50,000 acre-feet (AF). Another storage facility designed to meet irrigation needs is McKay Creek Reservoir. McKay Reservoir, located south of Pendleton, was completed in 1927 and has a capacity of 73,800 AF. Two other reservoirs, Willow Creek and Carty, were completed in the early 1980's to aid in flood control and provide cooling water for a coal-fired power plant, respectively.

Westland Irrigation District (WID) currently has 21,400 AF of recognized space in the McKay reservoir. In addition, the Bureau of Reclamation has some "reserved space", which is water storage that is not firmly contracted, that it typically supplies to WID. In 1996, WID received 7,130 AF of this reserved space (Esget, 1997).

The earliest water right in the Umatilla basin was issued in 1860. Currently, over 4,000 water rights are held in the basin. Irrigation represents 83 percent of the total water rights (by volume) and amounts to 2,546 cfs (based on a 180 day irrigation season), of which 1,776 cfs are surface water rights and 770 cfs are ground water rights.

Irrigation began prior to 1909 in Echo Meadows and consequently water rights in the area represent some of the oldest issued in the basin. This land was among the first developed for irrigation because its topography allowed it to be irrigated with traditional methods and it has relatively good soil quality.

Irrigators in Echo Meadows are mainly supplied by water diverted through the Westland Main Canal which is operated by WID. Irrigation using "flood water" begins on March 15. Flood water is water that is diverted from the Umatilla River when it is running above 500 cfs. When the river flow drops below 500 cfs, irrigators begin using water that has been stored in McKay Reservoir. This typically occurs in early June. Table 2.3 provides historical McKay space, date of initial withdrawal, and allotment per acre for 1989 through 1996.

Table 2.3 Historical McKay Storage, 1989-1996

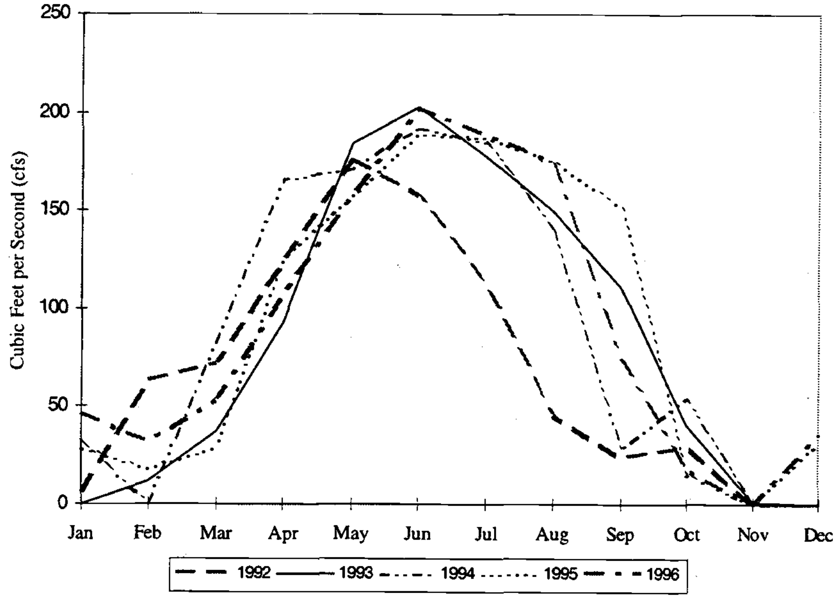
Year	McKay Reservoir Storage (acre-feet)	Date of First Diversion	Acre-Feet/ Acre Including Losses
1989	72,517	June 12	1.80
1990	51,378	June 20	1.03
1991	72,250	June 14	1.82
1992	55,562	June 9	1.35
1993	66,322	June 17	1.87
1994	61,857	June 9	1.46
1995	65,551	June 2	1.86
1996	66,391	June 6	1.83

source: Williams, 1997.

As shown in the table above, irrigators in Echo Meadows received a low of 1.03 af/acre in 1990 and a high of 1.87 af/acre in 1993. Irrigators in the area are typically limited by the amount of water stored in McKay Reservoir. As a result, both the storage level and date of first diversion are important factors affecting growers. In general, the larger the McKay allotment and the later the date of first diversion, the less binding is the water constraint on irrigator's managment decisions.

Figure 2.2 shows the mean monthly flows for Westland Main Canal, which has a capacity of 200 cfs, for the last five years. As the figure shows, the canal typically runs near or at capacity from May through July.

Figure 2.2 Westland Canal Mean Monthly Diversion, 1992-96



In the original Umatilla water rights decree, irrigators on silt loams in Echo Meadows received a duty of three acre-feet per acre, while irrigators on fine sand received six acre-feet per acre. With the construction of McKay Reservoir, supplemental irrigation water became available on much of the land in Echo Meadows. Supplemental irrigation water from McKay is given a duty of 4.5 af/acre/season but irrigators are limited by the duty shown on their primary right. Therefore, an irrigator with a primary duty of three af/acre that receives two af/acre from a primary source can divert 1 af/acre if supplemental water is available. Alternatively, an irrigator with a primary duty of six af/acre that receives two af/acre from a primary source can divert up to 2.5 af/acre if supplemental water is available

There are approximately 4,500 acres with primary water rights in Echo Meadows of which 3,600 acres also have supplemental water rights (WRIS, 1997). Approximately 15% of the primary water rights acreage is supplied from groundwater sources.

The Confederated Tribes of the Umatilla Indian Reservation have treaty rights to a quantity of water necessary to fulfill the purposes of the Tribal homeland, called a Winter's reserved right. The Winter's right includes both present and future needs but has not been quantified. In addition, because the Tribes have a sovereign government, they have full authority to manage water resources on the reservation. To date, the Tribes have chosen not to exercise their substantial treaty reserved rights and have instead pursued cooperative development strategies with irrigators and other water users in the Umatilla Basin.

In December 1985, minimum perennial streamflows were established on the Umatilla River. As a result, the Umatilla and its tributaries were withdrawn from further appropriation. The minimum flows were set to meet the lifecycle requirements of anadromous and resident salmonids in the system. Under Oregon law, minimum streamflows, like water rights, are regulated according to priority date. Minimum streamflows were set for various reaches and tributaries in 1985 and have a priority date of November 3, 1983.

Water quality in the lower 57 miles of the river frequently violates Department of Environmental Quality (DEQ) standards for contact recreation due to the presence of high levels of suspended solids and fecal coliform. The pollution mainly stems from urban effluent, livestock feedlots, and irrigation return flows. The quality standards are exceeded most frequently in the summer during low flow periods when water temperatures exceed 70^0F. The high temperatures, which are lethal to salmonids, lower the dissolved oxygen level and allow bacteria to grow.

2.3 Fishery Resources

Historically, the Umatilla River supported large runs of chinook and coho salmon, with the largest run of chinook salmon occurring in 1914. Following the completion of Three Mile Dam in 1915, however, the salmon runs quickly vanished. Currently the Umatilla River supports four species of anadromous fish: spring chinook, fall chinook, coho, and summer steelhead. The coho and chinook were reintroduced into the system in the early 1980's.

Three Mile Dam is the highest diversion facility on the Umatilla River and poses significant passage problems to migrating salmon. Little water flows through the fish ladder in low flow years and therefore does not effectively pass salmon over the dam. At the same time, water is spilled over the top of the dam creating a false attraction. Migration delay caused by the dam resulted in an estimated loss of 10 percent of the 1982-83 summer steelhead run (James, 1984). Recent projects have worked to improve the dam's bypass facilities but the success has not yet been evaluated.

Summer steelhead runs declined but were not eliminated due to the fact that they migrate at different times of the year, when flow levels are higher. Peak upstream steelhead migration occurs in February and March while peak spawning occurs in April.

Fall Chinook enter the Umatilla in late September and October and most spawning occurs in October and November.

Minimum streamflows for salmonids were recommended by state, federal, and tribal fish biologists below McKay Creek in 1983. The recommended minimum flow of 250-300 cfs was never achieved in the 43 years prior to 1983 during September 16-30 (James, 1984). These low summer flows resulted in increased stream temperature and allowed more temperature tolerant species such as suckers and squawfish to invade potential salmonid rearing habitat. Because the Umatilla River is overappropriated, minimum streamflows and instream water rights may not result in increased flows unless protected by legislation or senior water rights are purchased from irrigators.

The Umatilla Basin Project, a joint effort of the Confederated Tribes of Umatilla, local irrigators, and the federal government, was designed to restore the salmon runs in the Umatilla River that disappeared 70 years ago. While the native runs are gone, the goal of the project is to re-establish salmon that will reproduce naturally (Oregonian, 1995). The $80 million project pipes water from the Columbia river to replace irrigation water from the Umatilla that is left instream for salmon as well as investments to improve bank stability and stream habitat for spawning and rearing.

Recent efforts to reintroduce salmon to the Umatilla Basin have met with some success. During the period from 1982-1994, an average of 30 coho and 224 summer steelhead were harvested by sport anglers each year while no fall or spring Chinook had been harvested. Still, most of these fish are caught below river mile 3 (site of Three Mile Dam) and the others must be captured and transported by truck 20 miles upstream to areas of sufficient flow.

The following table provides the average adult returns for each species from 1981 through 1996.

Table 2.4 Average Adult Salmonid Returns, 1981-1996

Species	Average Adult Returns
Spring Chinook	1,130
Fall Chinook	305
Steelhead	1,254 (wild) 508 (hatchery)
Coho	1,437

Note: Steelhead, spring chinook and coho counts did not begin until 1990. Fall Chinook counts began in 1985.
Source: Leppink, 1997.

There exists a strong, positive relationship between streamflow and salmonid returns in the Umatilla River. Fisheries biologists correlated flows and the number of adult wild steelhead returning to the Umatilla River one, two and three years later for 27 years of flow and return records (1966-1992). Correlation coefficients of .913 and .869 were found between mean annual flows and mean spring flows, respectively, and wild steelhead returns two years subsequent (BPA, 1996). The Confederated Tribes have set a long range production goal of 38,000 salmon returns per year.

2.4 Soils in Echo Meadows

Soils are an important component of this study because they are a primary determinant of crop management and yield. Echo Meadows contains thirteen different soil classes (USDA, 1988). In this analysis, the soils are grouped into two categories according to crop potential and irrigation requirements. Soil class designation and location are critical to the development of the economic model of on-farm behavior. Specifically, as will be explained in section 4.3, the soil classes, irrigation technology, and crops are all used to distinguish representative farms in the economic model. The soil classes and physical properties are shown in Table 2.5.

Table 2.5 Soils in Echo Meadows

Soil Class	Name	Water Capacity (in/in)	Permeability (in/hr)	Elevation (ft)	Slope (percent)	Irrigation System	Crop Suitability
128A	Yakima Silt Loam	0.19 - 0.23	rapid (0.6-2.0) > 20 below 20"	600 to 1,600	0 to 3	Drip, Sprinkler, Furrow	Winter Wheat, Alfalfa
72A	Power Silt Loam	0.18 - 0.25	moderate (0.6-2.0)	500 to 1,300	0 to 3	Sprinkler, Flood	Alfalfa, Winter Wheat, Barley
65A	Pedigo Loamy Fine Sand	0.11 - .015	rapid to 12 inches	500 to 800	0 to 3	Sprinkler, Flood	Alfalfa, Pasture
119A	Wanser Loamy Fine Sand	0.10 - 0.12	rapid (6-20)	300 to 750	0 to 3	Sprinkler, Flood	Pasture, Hay
75B	Quincy Loamy Fine Sand	0.11 - 0.15	rapid (6-20)	300 to 1,100	0 to 5	Sprinkler, Drip	Winter Wheat, Alfalfa, Corn, Potatoes
66A	Pedigo Silt Loam	0.15 - .20	moderate (0.6-2.0)	500 to 1,800	0 to 3	Sprinkler, Flood	Alfalfa, Wheat, Barley
120C	Wanser-Quincy Complex	0.10 - 0.12	rapid (6-20)	300 to 750	0 to 12	Sprinkler, Flood	Pasture
74B	Quincy Fine Sand	0.08 - 0.11	rapid (6-20)	300 to 1,500	0 to 5	Sprinkler, Center Pivot	Alfalfa, Winter Wheat, Corn, Potatoes
28A	Freewater Gravelly Silt Loam	0.09 - 0.14	moderate (0.6-2.0)	800 to 1,400	0 to 3	Drip, Sprinkler, Furrow	Alfalfa, Small Grain, Asparagus
17A	Catherine Silt Loams	0.19 - 0.21	moderate (0.6-2.0)	600 to 1,300	0 to 3	Sprinkler	Pasture

Table 2.5 (Continued) Soils in Echo Meadows

Soil Class	Name	Water Capacity (in/in)	Permeability (in/hr)	Elevation (ft)	Slope (percent)	Irrigation System	Crop Suitability
75E	Quincy Loamy Fine Sand	0.11 - 0.15	rapid (6-20)		5 to 25	Sprinkler, Drip	Winter Wheat, Alfalfa
3A	Adkins Fine Sandy Loam	0.13 - 0.16	rapid (2.0-6.0)	400 - 1,100	0 to 3	Sprinkler	Pasture, Hay, Corn, Mint
87B	Sagehill Fine Sandy Loam	0.18 - 0.20	rapid (2.0-6.0)	500 - 1,100	2 to 5	Sprinkler, Drip	Alfalfa, Potatoes, Corn

2.5 Irrigation Systems

There are three main methods of irrigation: surface; sprinkler; and drip. Surface irrigation is the least capital-intensive system and typically relies upon gravity to deliver water to the crop. Border and furrow are two types of surface irrigation systems. Border irrigation utilizes two parallel levees which guide a stream of water moving down the slope. The land between two levees is called a border strip or a strip check and varies from 10 to 100 feet in width and from 300 to 2,600 feet in length. Border check-flood irrigation can be used on a variety of crops where the soil slope is less than 3 percent and there is uniform soil type.

Furrow irrigation uses narrow channels to distribute water rather than the wide channels used in border irrigation and is typically used for row crops, tree crops, and vineyards where the soil slope is less than 2 percent.

There are many different types of sprinkler irrigation systems and only a few will be mentioned here. The advantages of sprinkler systems over traditional irrigation methods are that water can be distributed evenly over a longer period of time thereby reducing runoff and deep percolation. In addition, high-valued crop producers frequently utilize sprinklers for frost and heat protection during the growing season. Most sprinkler irrigation systems can also be used to apply fertilizers and pesticides to crops.

High-valued tree crops and vineyards typically employ permanent set sprinklers which have relatively high investment costs but allow for the multiple uses mentioned above. Hose drag and hand move sprinklers involve the smallest initial investment costs of all the sprinkler systems but typically involve relatively large labor costs. Center pivot and wheel line sprinklers, which were developed to reduce the labor costs associated with hand move sprinklers, are propelled by a motor mounted on the sprinkler line. Sprinkler systems typically require an average water pressure of approximately 50 pounds per square inch (psi).

Drip (trickle) irrigation gained popularity in the late 1970s but still represents a small percentage of irrigation technology used in the West. This process utilizes emitters located near the plant root zone to slowly apply water. As a result, much of the water applied can be directly utilized by the crop. High investment costs and technical difficulties have prohibited the use of drip systems on most crop types. Drip systems typically require a water pressure of 15 psi.

Below is a partial list of the factors which influence the selection of one irrigation method over another. The purpose of the list is to show that there are many decision variables, aside from water price and availability, that determine the type of system employed by an irrigator. Section 2.6 describes the technology choice decision at the farm level.

- Slope of Ground
- Soil Depth
- Soil Intake Rate
- Soil Texture
- Water Availability and Cost
- Water Quality
- Type of Crop
- Climate

Each of the three irrigation system types applies water in a different manner and therefore has a different irrigation efficiency. Irrigation efficiency is the percent of applied irrigation water used by the crop after various losses occur. Encompassed in this efficiency measure is water-conveyance efficiency and water-application efficiency. Water-conveyance efficiency measures the loss that occurs as water is transported from source to destination. Estimated water-conveyance efficiencies range from 60-80 percent for earth ditches to 90-100 percent in pipelines. Water-application efficiency is the ratio of water stored in the root-zone of the soil and available to the plants compared to water delivered to the field. Common water-application efficiencies vary from 50-90 percent. The focus in this research is on water-application efficiencies of various systems. General efficiencies for selected irrigation systems are listed in Table 2.6.

Table 2.6 Irrigation Technology Efficiencies (percent)

Crop	Furrow/ Flood	Side Roll Sprinkler	Center Pivot
Alfalfa	57.5%	75.0%	75.0%
Wheat	50.0%	70.0%	85.0%
Pasture	50.0%	70.0%	92.5%
Asparagus	50.0%	70.0%	85.0%
Mint	60.0%	70.0%	85.0%
Field Corn	45.0%	72.5%	90.0%
Potatoes	32.5%	77.5%	85.0%

source: Whittlesey, 1986

The importance of efficiency levels can be seen by comparing the amounts of water required under alternative irrigation systems to meet a crop's water needs. For example, assuming that pasture's annual water requirement is 3.0 acre-feet, an irrigator will have to apply 6 acre-feet to the field using a flood irrigation system and only 3.53 acre-feet using a drip system.

The growers in Echo Meadows typically employ flood, sprinkler, and center pivot irrigation depending upon the elevation, slope of the land, and soil characteristics. In the lowlands, flood irrigation is used due to the fact that the fields are fairly level and can be gravity fed from the Westland Main Canal. In addition, the soils in these regions typically have permeabilities that are amenable to flood irrigation. Land with more varied slopes, porous soils, and in higher elevations requires the use of sprinkler irrigation systems. Wheel line and center pivot systems are commonly used in these areas to irrigate alfalfa, potatoes, and other crops due to the pumping lift necessary to deliver water to the field as well as the low water holding capacity of the soils. Sprinkler systems allow more control over water applications and therefore compensate somewhat for the high permeability of the soil.

2.6 Irrigation Technology Choice

Assuming farmers are profit-maximizers, the choice among irrigation methods is driven by which system generates the highest quasi-rent per acre. Irrigation cost per acre for a given technology (C_i) and land quality (L_q) can be given by Equation 2.1 (adapted from Caswell and Zilberman, 1986):

$$C_i (L_q) = I_i + \{[1.024 (H_i/\varepsilon)] P_e + P_d\} * AR_i \qquad (2.1)$$

I_i is the fixed irrigation cost per acre and AR is the application rate (acre-feet/acre) of water to the crop for the length of the growing season. P_e is the price of energy ($/kWh) and P_d is the district charge per acre-foot. The term in brackets describes the relationship between energy, water lift (and pressurization), and pumping efficiency. H_i is the total required lift (ft.) and ε is the efficiency of the pumping system expressed as a decimal. The pressurization requirements for center pivot and wheel line systems are converted into feet of lift (1 lb./sq. in. = 2.31 ft. of lift) and added to the elevation lift requirement to determine H_i (Ley, 1994).

From Equation 2.1, it is clear that flood irrigation methods have lower water application costs per unit of water but may have higher costs per acre due to low irrigation efficiencies (high application rates). It is also important to note that irrigation costs are a function of land quality, where land quality reflects soil type, slope of the land, and can be extended to include climate variables as well.

The type of crop produced is an integral component of technology choice because different crops have different ETs and root depths. The ability of a given tract of land to produce a particular crop is dependent, in part, upon effective water (application rate * irrigation efficiency). Effective water then is a function of water applied (AR_i), land quality (L_q), and irrigation technology. Technology choice is given by Equation 2.2 where "i" refers to the irrigation system under consideration and Π represents profit:

$$\text{maximize} \quad \Pi_i = P_y\, f[AR_i{*}\alpha_i\,(L_q)] - C_i\,(L_q) \qquad (2.2)$$

P_y is the price of output and the bracketed term is the crop production function where α_i is the irrigation efficiency of the system under consideration. The first-order conditions ensure that for each system possibility, the irrigator will maximize profits by applying water up to the point where the value of the marginal product of water is equated with the marginal cost of water. The technology that maximizes the function will be chosen.

From Equation 2.2, it is apparent that under conditions where land quality is good, the price of electricity is low, and lift requirements are relatively small, flood and furrow irrigation have higher per acre profits and therefore are more likely to be chosen by the grower. Modern irrigation technologies, such as wheel line sprinklers and center pivot systems, become relatively more attractive despite their higher capital costs when: land quality degrades; lift requirements increase; and the price of electricity is high. Therefore, as the cost per acre-foot of water increases, either through an increase in electricity price or an increase in the lift requirement, profit-maximizing farmers will shift toward more efficient technologies. As Caswell and Zilberman note, "It is found that modern irrigation technologies are more likely used in locations with relatively low land quality and expensive water, while traditional surface irrigation technologies are more likely used in locations with heavy, leveled soils and cheap water". In addition, modern irrigation technologies are typically yield increasing, which also improves the likelihood of adoption (Zilberman et al., 1994).

Other factors aside from profit maximization objectives can influence irrigation technology choice. For instance, farmers may be risk-averse and therefore apply high discount rates (require short payback periods) to irrigation equipment which tends to reduce adoption. Human capital, such as age and education, can also be an important factor in the choice of irrigation method (Huffman, 1977).

Recent research has demonstrated that producers are often more influenced by quantity of water than price of water, because for most producers the allotment of water is more constraining than price (Moore and Dinar, 1995). These results have important implications for water policies designed to improve irrigation efficiency such as the Allocation of Conserved Water Program in Oregon. One particularly relevant point is that small increases in the price of water are unlikely to alter producer decisions and influence the adoption of more efficient irrigation techniques because the productive value of a unit of water is substantially higher than its observed price in most cases.

Increasing the price or reducing the quantity of surface water can increase the diffusion of efficient irrigation technology. However, if irrigators are able to substitute groundwater for higher-priced surface water, effects on technology adoption may be minimal. For example, in California, landowners drilled 10,000 new wells as surface water supplies were reduced as a result of the 1976-77 drought (Gaffney, 1992). Consequently, surface water was "saved" at the expense of unpriced groundwater. In many areas, the two are hydrologically linked however, and depletion of groundwater reservoirs will ultimately reduce streamflows.

The artificial flooding project in Echo Meadows will provide additional water supplies to irrigators in the area by reducing the amount of water that needs to be applied early in the growing season. As a result, a portion of the surface water allotment can be "saved" for use at a later date. The reduced scarcity of water will tend to work against the adoption of more efficient irrigation technologies.

CHAPTER 3. ECONOMIC ASSESSMENT FRAMEWORK AND LITERATURE REVIEW

The economic analysis is based on the representative farm model representation of irrigation management decisions, which seek to maximize farm profits subject to technical and resource constraints on production. This modeling framework links economic theory with biophysical data and relationships to provide a benchmark from which to assess proposed changes in the agricultural system.

This chapter discusses the framework and assumptions behind economic optimization models. It includes a section which describes the linear programming method used to optimize the representative farm models. In addition, the chapter details the assumptions implicit in linear programming and discusses their relevance to the formulation and solution of agricultural production problems.

3.1 Classical Optimization Theory

The general constrained optimization expression for a profit maximization problem can be written as:

$$\Pi = \sum_i p_i q_i - \sum_j r_j x_j \qquad (3.1)$$

subject to the production function

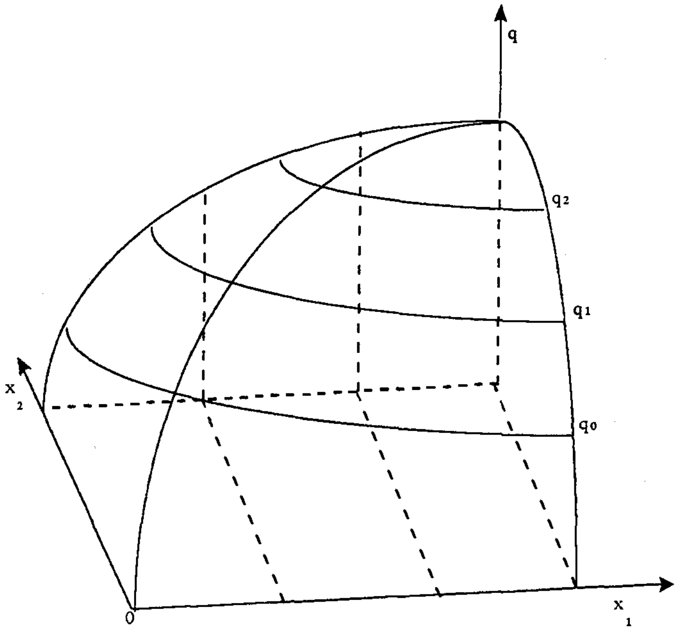
$$f(q_1 \ldots q_s, x_1 \ldots x_t) = 0 \qquad (3.2)$$

where Π represents the profit function
p_i is the unit price of output q_i
r_j is the unit price of input x_j

$f(.)$ is the production function written in implicit form.

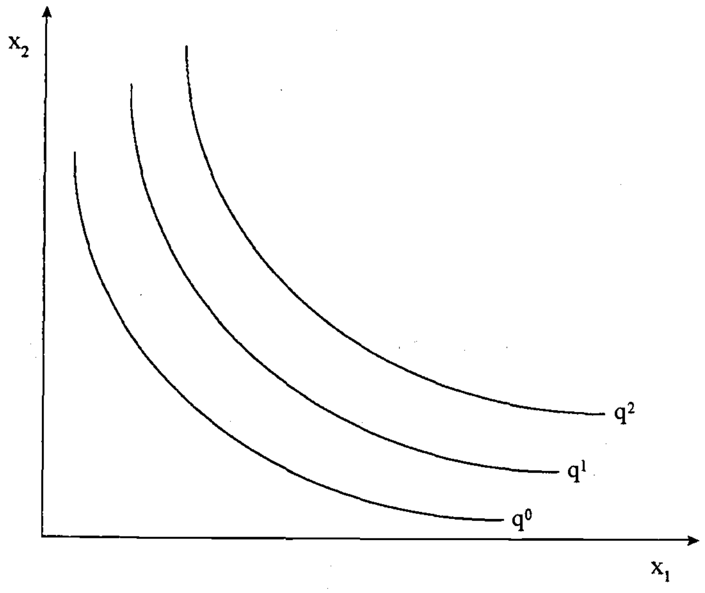
The production function, $f(q_1...q_s,x_1...x_t)$, describes the relationship between inputs and outputs. Specifically, technical efficiency is embedded in the function so that it provides the maximum output obtainable from a given combination of inputs (Henderson and Quandt, 1980). It is defined only for nonnegative values of inputs and outputs and is assumed to be increasing (i.e., $f' > 0$) and strictly quasi-convex over the relevant domain. Furthermore, the production function is assumed to have continuous first and second-order partial derivatives. Figure 3.1 provides an example of a production function with two inputs (x_1 and x_2) and one output (q).

Figure 3.1 Production Function with Two Inputs



An isoquant is the minimum locus of all combinations of inputs which yield a specified output level. Isoquant maps show the possible substitution of one input for another in the production function. In reference to the figure above, an isoquant is a horizontal "slice" of the production function (labeled with q's in the figure). Figure 3.2 shows an isoquant map for two inputs (x_1 and x_2) and one output (q).

Figure 3.2 Isoquant Map



Since the production function is assumed to be continuous, there are an infinite number of combinations of inputs that can satisfy a given output level. This assumption gives classical isoquants their smooth shape.

Mathematically, an isoquant is represented by Equation 3.3 where q^0 represents a specified output level.

$$q^0 = f(x_1, x_2) \qquad (3.3)$$

The slope of an isoquant, which measures the rate at which one input can be substituted for another input while holding output constant, is referred to as the rate of technical substitution (RTS).

$$RTS = -\frac{\partial x_2}{\partial x_1}\bigg|_{q = q^0} \qquad (3.4)$$

Rewritten as an unconstrained Lagrangian function ($\mathcal{L}$), Equations 3.1 and 3.2 appear as follows,

$$\mathcal{L} = \sum_{i=1}^{s} p_i q_i - \sum_{j=1}^{n} r_j x_j + \lambda f\,(q_1 \ldots q_s, x_1 \ldots x_n)\,. \qquad (3.5)$$

Setting each first-order partial derivative equal to zero

$$\partial\mathcal{L}/\partial\lambda = f(q_1,\ldots,x_n) = 0 \qquad (3.6)$$

$$\partial\mathcal{L}/\partial q_i = p_i - \lambda(\partial f/\partial q_i) = 0 \qquad i = 1,\ldots,s \qquad (3.7)$$

$$\partial\mathcal{L}/\partial x_j = -r_j - \lambda(\partial f/\partial x_{s+j}) = 0 \qquad j = 1,\ldots,n \qquad (3.8)$$

and solving via Cramer's Rule results in the optimal values of the q's, x's, and λ's. The value of the Lagrangian multiplier (λ) is commonly referred to as the "shadow value". Shadow values provide the change in the objective function that would arise from a unit change in a constraint. Rearranging any pair of partial derivatives with respect to quantity, while holding all other inputs and outputs constant, reveals that, at the optimal solution, the rate of product transformation (RPT) equals the ratio of their prices.

$$\frac{p_j}{p_k} = \frac{f_j}{f_k} = -\frac{\partial q_k}{\partial q_j} \qquad j, k = 1,\ldots,s \qquad (3.9)$$

From Equations 3.6 and 3.7 it can be shown that for the *k*th ouput and the *j*th input the value of the marginal product (VMP) must equal the input price. VMP is the price of the output multiplied by the addition to output created by a one unit increase in an input.

$$\frac{r_j}{p_k} = \frac{f_{s+j}}{f_k} = \frac{\partial q_k}{\partial q_j} \quad \text{or} \quad r_j = p_k \frac{\partial q_k}{\partial x_j} = VMP \quad k = 1,\ldots,s \quad j = 1,\ldots,n \tag{3.10}$$

where f_i(i=1,...,s+n =m) is the partial derivative of the production function with respect to its *i*th argument.

Lastly, from Equation 3.8, the rate of technical substitution (RTS) for every pair of inputs, holding all other inputs and outputs constant, must equal the ratio of their prices.

$$\frac{r_j}{r_k} = -\frac{\partial x_k}{\partial x_j} \qquad j, k = 1,\ldots,n \tag{3.11}$$

The second-order conditions for profit maximization require that the bordered Hessian determinants alternate in sign:

$$\begin{vmatrix} \lambda f_{11} & \lambda f_{12} & f_1 \\ \lambda f_{21} & \lambda f_{22} & f_2 \\ f_1 & f_2 & 0 \end{vmatrix} > 0, \ldots, (-1)^m \begin{vmatrix} \lambda f_{11} & \ldots & \lambda f_{1m} & f_1 \\ \cdots & \cdots & \cdots & \cdots \\ \lambda f_{m1} & \ldots & \lambda f_{mm} & f_m \\ f_1 & \ldots & f_m & 0 \end{vmatrix} > 0 \tag{3.12}$$

Because the Lagrange multiplier (λ) is negative and a constant, it can be manipulated outside of the determinant. The second-order conditions for a maximum can then be simplified as follows,

$$\begin{vmatrix} f_{11} & f_{12} & f_1 \\ f_{21} & f_{22} & f_2 \\ f_1 & f_2 & 0 \end{vmatrix} < 0 \qquad \begin{vmatrix} f_{11} & \ldots & f_{1m} & f_1 \\ \cdots & \cdots & \cdots & \cdots \\ f_{m1} & \ldots & f_{mm} & f_m \\ f_1 & \ldots & f_m & 0 \end{vmatrix} < 0 \cdot \tag{3.13}$$

As mentioned above, these conditions are met when the production function is assumed to be strictly quasi-convex over the relevant domain.

3.2 Mathematical Programming

Classical optimization relies upon calculus and therefore requires that problems be framed in terms of equality constraints. In order to add flexibility and reality to problem solving techniques, economists applied mathematical programming techniques to economic optimization problems. Mathematical programming has the advantage of allowing inequality constraints as well as allowing the number of constraints to exceed the choice set, which more closely approximates true decision-making behavior (Chiang, 1984). This analysis employs linear programming (LP), a subset of mathematical programming, to optimize the economic models. The following section discusses the framework and assumptions underlying LP.

In linear programming, both the objective function and the constraints must be specified as linear functions. This requirement does not pose great limitations, however, as most nonlinear functions can be linearized without a significant change in solution results. This is especially true of models in which constraints, rather than the objective function, are the source of nonlinearity (McCarl and Onal, 1989). A general linear programming problem can be expressed in summation notation as:

$$Maximize \quad \pi = \sum_{j=1}^{n} C_j X_j$$

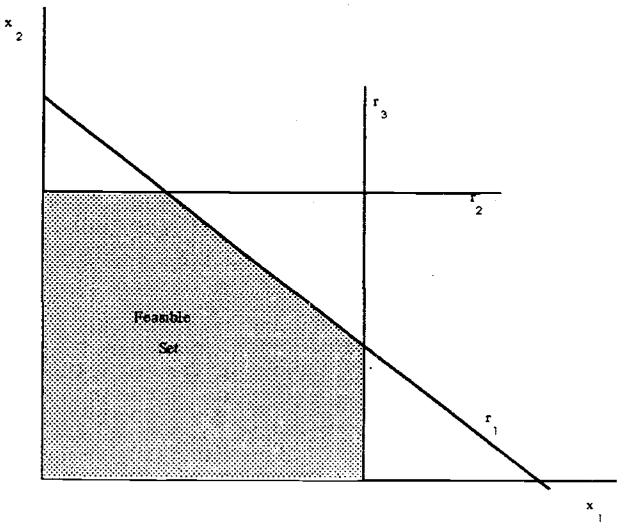
$$\text{Subject to } \sum_{j=1}^{n} a_{ij} x_j \le r_i \qquad (i = 1,2,\ldots,m)$$

$$\text{and} \quad x_j \ge 0 \qquad (j = 1,2,\ldots,n) \qquad (3.14)$$

The model determines the level of x_j that maximizes π (profit) subject to resource and nonnegativity constraints.

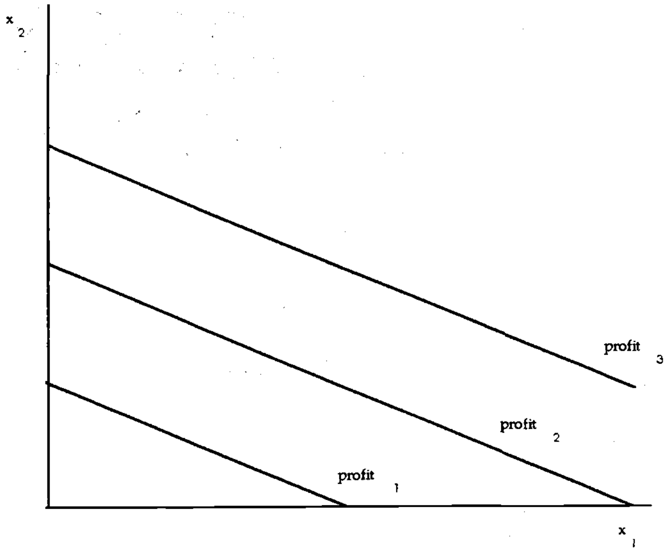
In the case of two activities, LP solutions can easily be illustrated graphically. Consider the following situation in which there are three linear resource constraints (r_1, r_2, and r_3) associated with activities x_1 and x_2. The shaded region in Figure 3.3 represents the production possibilities set. All points outside this set are unattainable given the resource constraints.

Figure 3.3 Production Possibilities Set



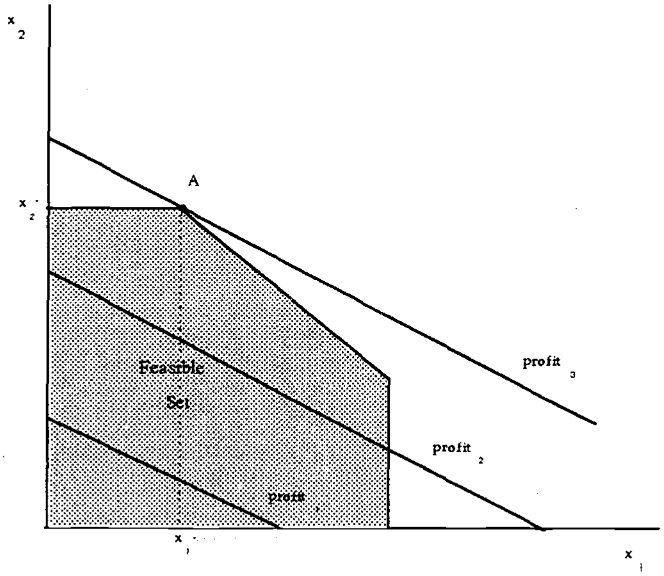
The objective function, which is also linear, can be represented by a map of isorevenue lines. Isorevenue lines show the various combinations of outputs that produce a given profit level. In Figure 3.4, larger profits are indicated by those isorevenue lines that lie further to the northeast.

Figure 3.4. Isorevenue Lines



Superimposing Figure 3.3 on Figure 3.4 locates the profit maximizing solution. The optimal solution occurs at point A, where an isorevenue line is tangent to the production possibilities set. Quantities x_1^* and x_2^* represent the profit maximizing output levels.

Figure 3.5 Graphical Representation of an Optimal LP Solution



Most LP algorithms follow a step-by-step solution procedure, called the simplex method, in which each step moves closer to the optimal solution of the objective function. First the feasible solution set is identified and an initial solution is chosen. Next, the algorithm determines whether the current solution is the optimal by iteratively searching for other possible solutions, keeping the one which most closely meets the criteria specified in the objective function. This process continues until the basic feasible solution cannot be improved upon.

There are a number of assumptions regarding the production process and resources that are implicit in LP models (Hazell and Norton, 1986). They include:

1) *Optimization.* It is assumed that the producers goal is to maximize or minimize the process specified in the objective function and that the objective function correctly identifies the various alternatives available to the producer.

2) *Fixedness*. At least one constraint has a nonzero right hand side coefficient.

3) *Finiteness*. It is assumed that there are only a finite number of activities and constraints to be considered.

4) *Determinism*. All coefficients in the models are assumed to be known with certainty.

5) *Continuity*. Both resources and activities can be used and produced in fractional units.

6) *Homogeneity*. All units of the same resource or activity are identical.

7) *Additivity*. No interactive effects between activities exists - that is, total production is the sum of each individual activity.

8) *Proportionality*. An activity's contribution to the objective function and resource usage are assumed to be constant regardless of the level of the activity (perfectly elastic demand curve and a Leontief production function).

If any of these conditions are thought to be inappropriate, linear programming should not be employed in the analysis.

3.3 Choice Problems Cast as LP Models

Assumptions 7 and 8 define a production function that has both constant returns to scale and fixed input ratios. Constant returns to scale refers to a production process in which a *k*-fold change in input levels results in a *k*-fold change in output. That is,

$$f(kb) = kf(b) = kZ \qquad (3.15)$$

where f(b) represents the production function and Z is the objective function value. The assumption of a Leontief production process rules out the possibility of input substitution. This inflexible assumption can be overcome by introducing additional activities for a

This inflexible assumption can be overcome by introducing additional activities for a product that account for production processes that utilize different input ratios (Chiang, 1984).

As is evident from Figure 3.6, the fixed proportions assumption differs significantly from the classical isoquant presented earlier (Figure 3.2). The dashed line represents the least-cost expansion path for a firm with a single production process requiring fixed input proportions.

Figure 3.6 Single Production Process Isoquants

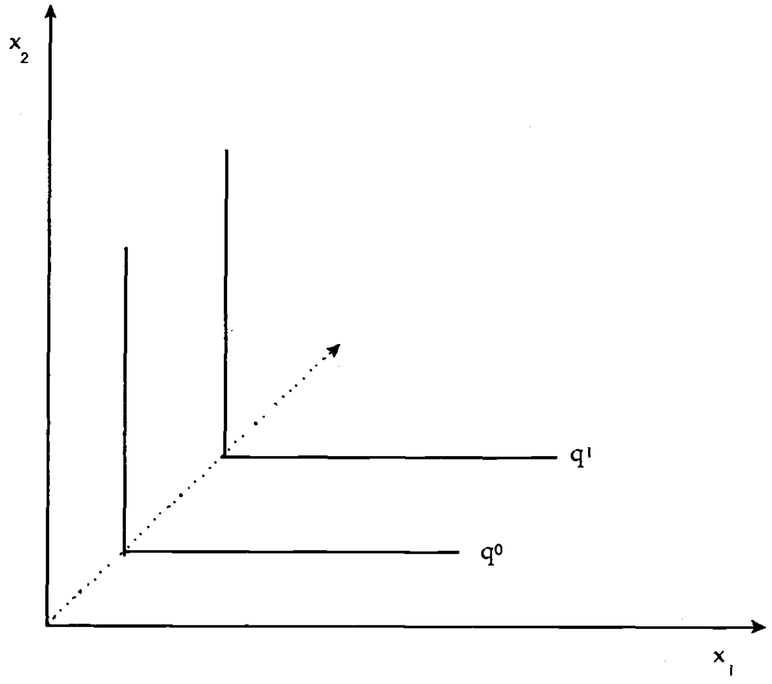
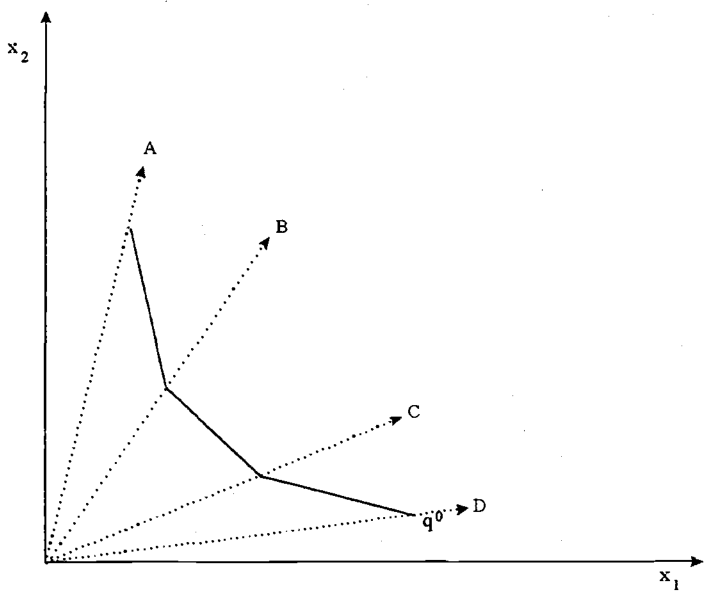


Figure 3.7 depicts a firm with four fixed proportion production processes, labeled A through D. As multiprocess production is introduced into the LP model, the isoquants

begin to resemble the classical shape, where it is assumed that the firm has an infinite number of production processes available. For example, processes A through D could represent four different irrigation technologies which require different combinations of inputs x_1 and x_2 (e.g. water and electricity). The optimal expansion path, and therefore irrigation technology, is determined by the relative prices of the two inputs.

Figure 3.7 Isoquants Under Multi-Process Production



3.4 Mathematical Programming Applications in Agriculture

Application of mathematical programming to the agricultural sector has been widespread. Hildreth and Reiter (1948) are credited with the first application of LP in agriculture with their analysis of optimal crop rotations. Over the last half-century, discussion solely considers selected methods and studies which applied mathematical programming to water-related issues in agriculture. The section is divided into three main themes: irrigation policy models; uncertainty models; and bioeconomic models. In all of the studies reviewed, the maximization of profits was assumed to be the objective of agricultural producers.

3.4.1 Irrigation Policy

Mathematical programming has been widely used in irrigation policy analysis because it allows the researcher to predict policy impacts *ex ante* by explicitly modeling the production process and all relevant production alternatives. Agricultural policies which restrict inputs, such as surface water supplies or agricultural externalities, such as non-point source effluent, are typically included in the mathematical program in the form of constraints on the production process.

Weinberg et al. (1993) use a nonlinear programming model to predict agricultural production and water sales decisions in response to hypothetical water market prices in the San Joaquin Valley, California. Agricultural effluent is a major source of water pollution in the San Joaquin Valley. The main objective was to demonstrate improvements in water quality that could result from introducing a regional water market. The water conservation opportunities included in the model were: (i) deficit irrigation; (ii) increased irrigation efficiency; and (iii) crop substitution. Constraints were included to reflect supply limits on water and land as well as to impose restrictions on crop substitution possibilities. The authors found that a policy objective of a 30 percent reduction in agricultural drainage could be achieved with an exogenously determined water market price of $96 per acre-foot.

Eckert and Wang (1993) used LP to analyze farm level response to uncertain surface water supplies in crop-livestock operations in Conejos County, Colorado. The model was adjusted to reflect those growers with high, medium, and low-priority water rights to determine the optimal management strategy for each under differing surface water supplies. In addition, the LP was run with and without groundwater pumping capability for each of the three representative farms. Net income per acre ranged from $67 to $12.50 for farms with high priority water rights and access to groundwater and farms with low priority water rights with no access to groundwater, respectively. The authors found that as surface water supplies were reduced, farmers first seek to maintain their livestock operations and therefore maintain minimum feed production levels at the expense of fallowing other crops such as barley and high-yield alfalfa. The availability of groundwater, however, allows growers to continue to produce barley because profits outweigh the pumping costs. In all cases except the high-priority one, farmers switched from two-cut alfalfa to one-cut alfalfa due to the reduced water requirements. The shadow price of surface water during May through August varied from $1.16 to $1,300 per acre inch for high priority and low priority farms without groundwater, respectively.

In an earlier irrigation policy study, Hamilton, Whittlesey, and Halverson (1989) examined the potential for an interruptible water market to move water from irrigation to hydropower production and streamflow maintenance during low-flow periods in the Snake River basin of Idaho. Seven representative farm models were developed based on differences in water application systems, crop mix, pump lift, and location, and were optimized over twenty-five years through the use of linear programming. As in Weinberg et al. (1993), growers could respond to decreased water supply by changing crop mix, adjusting applied water, and increasing irrigation efficiency. The model estimated that hydropower benefits are ten times greater than reductions in farm income, indicating that the water market is economically feasible.

3.4.2 Uncertainty in the Farm Model

Traditional LP specifications assume risk neutrality and profit maximization. In practice, however, agricultural production involves substantial risk. Sources of risk include price, yield, climate, and resources. Not incorporating risk into a linear programming model can lead to upward biases in the supply of risky crops and valuation of resources. The decision of whether or not to include risk in the farm model depends, in part, upon the availability of data describing risk. Furthermore, as McCarl and Spreen note, the most fundamental motivation for modeling risk occurs when the optimal risk neutral "solution (obtained from the model) diverges from reality because the decision maker in reality has somehow considered risk". This implies that a risk neutral model should first be developed and assessed against actual behavior before the decision is made to include risk. If risk is deemed an important factor, the next step involves choosing the appropriate modeling method. The following section discusses several of the risk modeling techniques and relevant literature applied to agriculture.

The extent to which risk and uncertainty need to be incorporated into a farm production model depends upon the objectives of the study. The treatment of risk in agricultural economic models has ranged from simply varying the constraint level on a resource to models which include utility function assumptions and stochastic variables.

3.4.3 Risk Aversion (Objective Function Risk)

Ignoring risk-averse behavior can also result in the model solution having little resemblance to the decisions that farmers actually make. For example, suppose a farmer has a utility function that can be characterized by the following quadratic function (Y represents income):

$$U(Y) = \alpha Y + \beta Y^2 \qquad (3.16)$$

One established method of dealing with risk is through expected utility. When choosing between alternative farm plans, the farmer is concerned with the expected value of income associated with each alternative. Taking the expected value of Equation 3.16 makes the choice between risk and return apparent.

$$E[U(Y)] = \alpha E[Y] + \beta v[Y] + \beta E[Y]^2 \qquad (3.17)$$

$v[Y]$ is the variance of Y. Assuming α is positive and β is negative, the farmer would prefer plans with lower variances and higher incomes (Hazell and Norton, 1986). Under these conditions, the farmer would restrict plans to those in which the income variance is minimized for a given expected income level.

The expected value-variance (E-V) and minimum total absolute deviation (MOTAD) models are popular methods used to incorporate risk associated with objective function coefficients (McCarl and Spreen). These models assume that the decision maker is willing to forego income in order to reduce the variance associated with expected income. The objective function contains the expected coefficient values and adds a risk aversion parameter (which is typically varied) that takes into account the variance associated with each coefficient.

There are several methods that are used for the specification of the risk aversion parameter in E-V and MOTAD models. One method involves solving the objective function for a range of parameter values; this leads to the development of a frontier of efficient choices. Some researchers have estimated values by minimizing the difference between observed behavior and the model solution. Other methods involve assumptions regarding the functional form of utility.

In one study incorporating objective function risk, Harris and Mapp (1986) used mathematical programming to identify risk-efficient irrigation strategies for farmers using groundwater on the Oklahoma Panhandle. Mining of the Ogalalla aquifer has increased well depths while, simultaneously, rising energy prices have reduced the profitability of irrigated agriculture. The authors employ a plant growth simulation model that considers the interactions of stochastic weather conditions, soil water, plant growth and development, and irrigation decisions. Approximately fifteen irrigation-scheduling strategies were considered in the model and 23 years of weather data were used to develop expected net returns and variance of net returns (risk). Stochastic dominance revealed three strategies that were return increasing and variance reducing with respect to the traditional practice of intensive irrigation. The authors concluded that risk-aversion (a strategy of applying an excessive amount of water to the crop in order to avoid declines in yields) was not the only explanation for the intensive irrigation taking place on the

Oklahoma Panhandle. They conclude that a more plausible explanation is the low cost of pumping groundwater relative to the returns from irrigation.

In another study, El-Nazer and McCarl (1986) developed a "disequilibrium unknown life" model to determine the optimal long-run crop rotation on a northeastern Oregon farm under risk-neutrality and risk-aversion. This type of model has the advantage of allowing the model to determine the optimal rotation scheme rather than exogenously placing rotation restrictions on the model but requires detailed data on the yields of crops under different rotational schemes. The model specifies that crops chosen in year t are dependent upon the acreage and crops in year t-1 and that current yields are dependent upon the rotational scheme followed. The authors incorporate risk-aversion into the model through the MOTAD framework and found that, in general, as the risk aversion coefficient increased, crop diversification increased. El-Nazer and McCarl point out that this diversification results from the complementary relationships among crops as well as from risk considerations.

The decision of whether to incorporate risk relies upon the subjective judgment of the researcher. In general, including risk in a farm model makes the model larger and more complex and as a result, harder to interpret, explain and deal with (McCarl and Spreen). In some cases, risk may be confounded with improper farm model specification. For instance, Baker and McCarl (1982) analyzed the effects of aggregating farm resource availability over time in linear programs. In representative farm models, resource constraints are often included on an annual basis. The authors argue that the choice of time disaggregation can have a large influence on the results obtained from the model and in some cases can result in optimal solutions that are infeasible in reality. Furthermore, annual models typically require the use of average data, thereby masking intraseasonal variations which can influence crop selection and management. Baker and McCarl tested the effects of time disaggregation by developing four models, ranging from one to 22 periods, using the MOTAD framework. They found that, in the risk-neutral specification, the higher period models contained a greater degree of diversification In addition, as the risk-aversion parameter was increased, the results of the small-period models tended to approach the results obtained from the 22-period model, indicating that small period risk models may overstate the importance of risk. One important finding was that the 22-period model which did not incorporate risk performed better than all other model specifications. The authors concluded that time disaggregation is an important modeling consideration and that researchers should use information on resource substitutability during the year when determining the number of periods to include in a linear program.

3.4.4 Risk in Inputs (Right Hand Side Risk)

In addition to the objective function, risk can also enter into the right-hand side (RHS) parameters (or inputs). For example, farm models often incorporate the risk associated with seasonal water supply variations. Chance-constrained programming is a nonrecourse method of introducing the uncertainty associated with inputs into the production process. Nonrecourse refers to models in which risk is assessed by the farmer at the beginning of the season and all production decisions are based upon this preseason risk assessment. Essentially, the risk component is introduced to the model through a transformation of the average resource availability.

$$\sum_j a_{ij}X_j \leq \overline{b_i} + Z_\alpha \sigma_{b_i} \qquad (3.18)$$

where $\alpha_{ij}X_j$ represents the useage of the resource in production, b_j is the average availability of the resource; Z_α is the standard normal coefficient (at α-level of probability) and σ is the standard deviation of resource availability.

The chance-constrained model adds little to the computational requirements of a general linear programming model and has been applied to a number of problem settings in agriculture. Its use has been controversial, however, due to its limited theoretical support and the fact that it offers no guidelines when the recommended solution is found to be infeasible. Generally, recourse models (discrete stochastic programming), which deal with risk in a sequential manner, have been reviewed as a more favorable method of dealing with RHS uncertainty (Rae, 1971).

3.4.5 Bioeconomic Models

Bioeconomic models specify natural processes and predict the effects that human management decisions have on those natural processes. Interactions within agriculture production have been modeled to understand the effects of new policies and technologies on farm profits and environmental systems simultaneously. Traditionally, the focus of bioeconomic models applied to agriculture has been on the impacts of a new policy or technology and its effects on the economic performance of standard management practices of an "average" farm (Kling et al., 1993).

Rehnals and Bras (1981) employed a stochastic dynamic program tied to soil moisture and crop yield models to analyze the irrigation scheduling problem in the South Platte River irrigation area. Their analysis was unique in that it included potential evapotranspiration (PET) as a stochastic variable. The reasoning behind this was that it is impossible to make exact predictions of PET. The model was separated into N weeks over the irrigation season, rather than separating the model by growth stage of the crop as has been done in other studies. This arbitrary separation was chosen to make the model amenable to the decision stages required in dynamic programming models. The contribution of crop growth in week k was determined by an algorithm relating actual evapotranspiration (difference between average soil moisture and the permanent wilting point in week k), PET (difference between field capacity and permanent wilting point in week k), and the maximum attainable yield. The objective function maximized net benefits across the N weeks in the irrigation season. The authors tested model results using stochastic and deterministic measures of PET and found insignificant differences between the two models. They further reason that in areas where PET is not highly variable, it is unnecessary to include PET uncertainty in the model.

Yaron and Dinar (1982) used soil moisture response functions combined with mathematical programming to determine the optimal allocation of water on a farm during the irrigation season. The first stage of their analysis involved developing a representative farm LP model which separated the irrigation season into ten day increments subject to seasonal and incremental production and resource constraints. Shadow prices were determined by the LP and inserted into a dynamic program (DP) which found the optimal amount and timing of applied water during the irrigation season based upon soil moisture and crop response algorithms. Specifically, the DP identified the crop responses to alternative irrigation scheduling programs while the LP calculated the profits associated with each alternative. This LP-DP loop process continued until an optimal solution was found. The results indicate that there exists large potential for irrigation scheduling to increase farm profits.

Another example of this approach is Bernardo et al. (1987). The authors use a two stage mathematical programming model to determine the optimal intraseasonal allocation of irrigation water under varying water supply constraints on a representative farm in Washington State's Columbia River Basin. The model allows irrigation technology changes, crop substitution, and fallowing crop land as production alternatives. In order to represent accurately the yield effects of changes in water applications, a crop simulation model was incorporated into the analysis. The crop simulation model accounts for the fact that yield is affected by the degree of water deficit and that the magnitude of the yield reduction is dependent upon the growth stage in which the deficit occurs. The mathematical program modeled a single season broken down into several growth stages of the four crops considered. It was found that reductions in water allotments, either seasonal or intermittent, had limited effects upon crop yields and farm profits due to the substitution options available to the farm. Yield reductions associated with reduced water supplies were minimized by adopting more efficient irrigation technologies and changing the timing of irrigation such that the deficit occurs in the final growth stage, when the crops are less susceptible to water stress.

Taylor et al. (1992) used the Erosion-Productivity Impact Calculator (EPIC) model to generate twenty-five years of yield and environmental output data associated with the major crops and soil classes in the Willamette Valley, Oregon. These results were linked to five representative farm LP's to estimate the impacts of different agricultural effluent control strategies. Five policy options were tested within the bioeconomic model: a per unit tax on leached nitrates; a tax on nitrogen fertilizer; per acre effluent standards; a no-till drills requirement on small grains and grass seed production; and a ban on fall fertilizer applications. The authors generated least-cost abatement frontiers by restricting each representative farm to a particular per acre abatement level. These solutions were compared to the five policy options mentioned above. In general, the effectiveness of each policy as it related to the least-cost solution varied across the representative farms, indicating the importance of site-specific characteristics in non-point source pollution policy design. The results suggest that a single policy for a single pollutant aimed at all farms will not reduce overall effluent and can result in increases in other pollution problems as well.

3.5 Selection of Representative Farms

Because it is generally not feasible to model every farm (or firm) separately in a region, it is necessary to classify farms into homogeneous groups called representative farms. The designation of representative farms is based upon physical, technological, and managerial characteristics (Hazell and Norton, 1986). This construction allows the ouput of each farm to be aggregated to provide measures of the regional consequences (e.g. changes in profits, resource use, etc.) associated with the problem addressed in the LP model solution. The number of representative farms included in the model is determined by the degree of heterogeneity present in the area of study. Ignoring differences among farms can have a large effect on the optimal solution obtained from a model. Modeling separate farms as one large unit overstates resource mobility and therefore allows the grouped unit to earn higher profits than the sum of profits across individual farms. This is referred to as "aggregation bias".

Aggregation bias can be minimized by closely following specific guidelines when grouping the representative farms. In practice these guidelines include grouping farms with:

1) similar resource endowments (size class).
2) similar yields.
3) similar technologies.

Like all models, the representative farm model is a simplification of reality and therefore does not exactly coincide with goals and management strategies on a specific farm. However, when constructed carefully, such models provide reasonable accurate predictions of changes at the aggregate level.

CHAPTER 4. PROCEDURES AND DATA

This chapter describes the formulation of the representative farm models as well as the hydrology model used to estimate the impacts of the artificial flooding project on farm profits and return flows. It also discusses how the two models are linked to capture the interdependence of water applications, crop water consumption, and movement of groundwater in the alluvial aquifer.

4.1 General Procedures

This research can be separated into three components: economic modeling of farms in Echo Meadows; simulating the hydrology of the area; and linking the two models to develop the relationship between water applications and the timing and quantity of return flows to the Umatilla River. The steps involved in this procedure are as follows:

1) use physical, economic, and agricultural characteristics of the area to create representative farms;

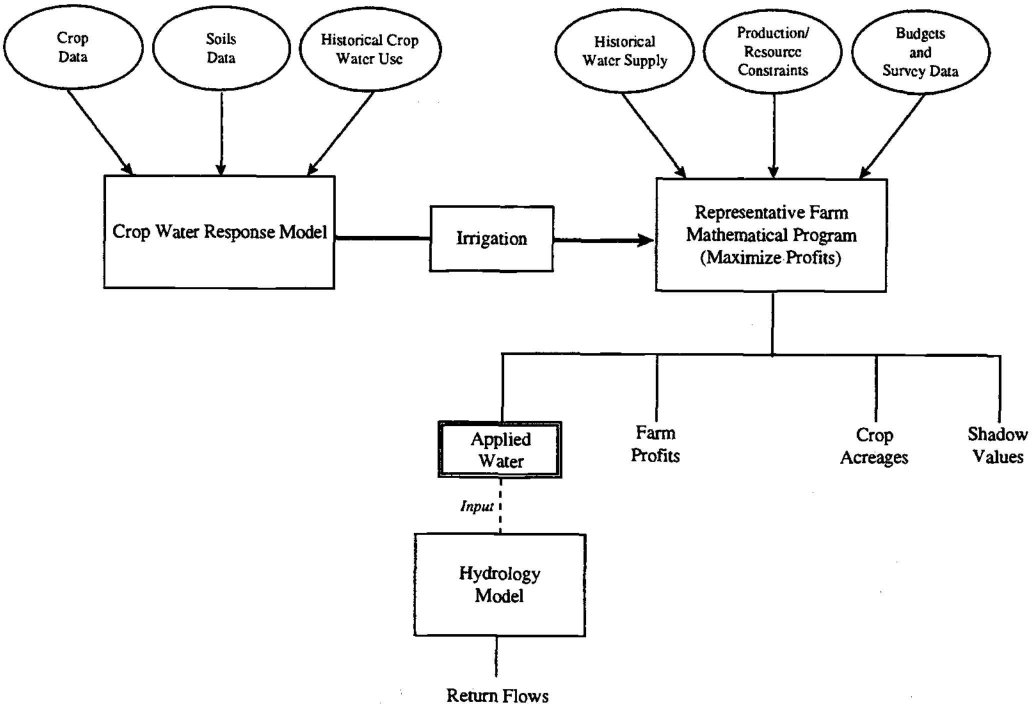
2) construct a mathematical program which maximizes farm profits and allows the grower to practice deficit irrigation, crop substitution (including fallowing land), and change irrigation application technology in response to changes in water supply;

3) use water applications determined by the representative farm model to estimate the quantity of return flows to the Umatilla River; and

4) incorporate alternative water conserving strategies into the representative farm models and compare these results with those obtained from the artificial flooding project.

Figure 4.1 shows how the data and models are linked in the analysis. The representative farm model contains parameters and constraints developed from OSU Enterprise Budgets, survey data, and U.S. Bureau of Reclamation historical surface water deliveries to Echo Meadows. The yield response model, which is a sub-component of the representative farm model, utilizes crop, soils, and historical crop water use in the Echo Meadows area to estimate the relationship between water applications and yield for each representative farm. The mathematical program provides shadow values for the resources used in production, farm profits, crop acreages, and irrigation.

Figure 4.1 Model Design and Data



4.2 Data Sources

Data on agricultural practices in the area were obtained from a mail-administered grower survey (see Appendix A), OSU Enterprise Budgets, and conversations with local growers and agricultural extension agents. Annual crop reports for Umatilla County (OSU Extension Service, Hermiston) provided yields and unit prices for the crops included in the model.

Table 4.1 summarizes the results of the survey of irrigators in the area. The survey was sent to thirteen growers in Echo Meadows. Ten surveys were returned and nine were determined useable.

Table 4.1 Results of Echo Meadows Survey (Acres)

Crop	Flood	Flood with Level	Wheel/Hand Sprinkler	Center Pivot	Total	Percent
Alfalfa	150	280	25	655	*1,110*	*28.4%*
Asparagus				75	*75*	*1.5%*
Corn				180	*180*	*4.6%*
Mint[a]		300			*300*	*6.1%*
Pasture	230	887	133	375	*1,625*	*41.6%*
Potatoes[b]				180	*180*	*4.6%*
Wheat	50	100	20	270	*440*	*11.25%*
Total	*430*	*1,567*	*178*	*1,735*	*3,910*	
Percent	*11.0%*	*40.1%*	*4.6%*	*44.4%*		

[a] No mint production was reported on the surveys. Acreage was determined from an on-site conversation with the grower.

[b] No potato production was reported on the surveys. Acreage was estimated from rotation information provided on the survey.

Eighty-five percent of the acreage with water rights in Echo Meadows is represented in the table above. This was a higher proportion than the sample frame and can be explained by the fact that much of the land in the study area is harvested by a few of the larger growers who responded to the survey.

In addition to acreages by crop and technology, growers were asked to provide information on typical crop rotations. For flood irrigated acreage, the typical rotation is four years of alfalfa followed by one year of wheat or corn, then back to alfalfa. The typical rotation under sprinkler technologies is four years of alflalfa, one year of wheat, one year of potatoes or corn, then back to alfalfa.

Prices and yields were taken from Umatilla County Crop Production Reports for 1992-1996, while Enterprise Budgets published by OSU Extension Service were used to obtain estimates of the costs of production for each crop. Table 4.2 provides the average prices and maximum yields for each crop included in the representative farm models.

Table 4.2 Crop Prices and Yields

Crop	Price[a] ($/unit)	Yield[b] (per acre)	Unit
Alfalfa	93.80	8	ton
Asparagus	49.00	30	cwt
Corn	2.91	245	bushel
Mint	14.38	75	lb
Pasture	20.00	10.5	aum
Potatoes	4.74	530	cwt
Wheat	3.83	120	bushel

[a] Five-year average price, 1992-96.

[b] Yield obtainable if full crop water requirements are met (source: McMorran).

4.3 Representative Farm Models

Representative farms in the region were selected according to soil characteristics, crops produced, and irrigation technology. For example, the thirteen soil series in Echo Meadows identified by the USDA, NRCS Soil Survey were combined according to water holding capacity, permeability, and crop potential into two general soil groups.

This breakdown was relatively natural considering the two distinct soil groups in the area. One group consists of the silt loams which are located in the eastern portion of Echo Meadows and have water holding capacities which range from 0.15 to 0.23 inches per inch of soil and moderate permeability (0.6-2.0 inches per hour). Growers on these soils produce a variety of field crops as well as operate integrated pasture/livestock operations. Approximately 60% of the irrigated acreage in Echo Meadows has silt loam soils.

The second group consists of the fine sands that are generally found in the western section of Echo Meadows. These soils have lower water holding capacities (0.08-0.14 in/in) and rapid permeability (6.0 to 20.0 in/hr). Due to these soil qualities, much of the land is used in the production of alfalfa and irrigated pasture for livestock grazing. Land which is used to produce other crops are generally under center pivot or wheel line irrigation due to rapid permeability and uneven terrain. Flood irrigation is used to produce pasture and alfalfa on more level lands. Approximately 40% of the acreage in Echo Meadows has fine sand soils.

To account for the heterogeneity among producers in the region, three representative farms were constructed. The characteristics of each are described in Table 4.3.

Table 4.3 Characteristics of the Representative Farms

Representative Farm	Soil Type	Crops Harvested	Farm Size	Representative Acreage
Farm 1	Silt Loam	Alfalfa Wheat Corn Potatoes Pasture	300 Acres	2,240 Acres
Farm 2	Silt Loam	Mint Pasture Asparagus	500 Acres	500 Acres
Farm 3	Fine Sand	Alfalfa Wheat Corn Potatoes Pasture	500 Acres	1,820 Acres

Farm 1 represents a typical farm on the eastern edge of Echo Meadows near the Umatilla River. Most of the acreage nearest the Westland Main Canal is flood irrigated while wheel line and center pivot systems are more common to the north (near I-84). Farm 2 produces mint, asparagus, and pasture on silt loam soils. Currently, there are 300 acres of mint and 75 acres of asparagus in Echo Meadows. A separate representative farm was created to account for profits earned from these relatively high-valued crops. Farm 3 represents a typical farm in the western portion of Echo Meadows of which nearly half of the land is used to produce pasture.

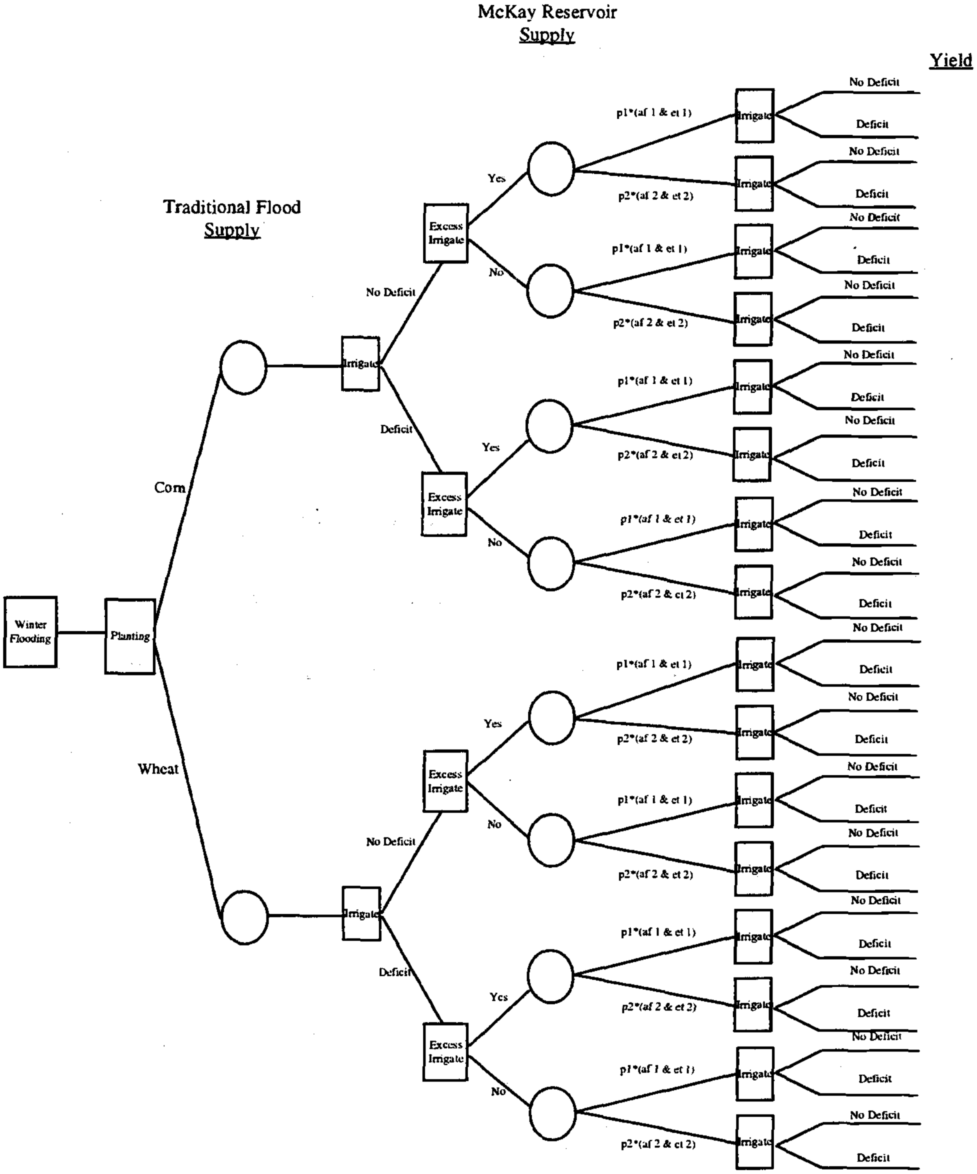
4.4 Stochastic Programming with Recourse Model

To account for the uncertainty surrounding seasonal water supply, a stochastic programming model with recourse (SPR) was developed. In SPR models, decision-makers have full knowledge regarding the outcomes of decisions made during earlier model periods but only probabilistic knowledge on the outcomes of future events (Rae, 1971). Consequently, the model seeks to maximize expected profits.

SPR is used when production involves sequential decisions and RHS risk (i.e. risk related to input supplies and other right-hand-side variables). For instance, at the beginning of the growing season, weather conditions and water supply are uncertain. As a result, growers must make planting decisions in the face of this uncertainty. As the season progresses, the uncertainty is resolved but growers can only adjust through short-run water saving strategies such as fallowing acreage and deficit irrigation in low water supply years. In this manner, SPR models "depict adaptive decisions along with fixity of earlier decisions" (McCarl and Spreen). As Turner and Perry (1997) point out, SPR "incorporates elements of mathematical programming, decision tree analysis and stochastic dynamic programming."

In the context of management decisions in Echo Meadows, growers determine acreages of crops and irrigation technology at the beginning of the season. Acreages of crops and technologies are determined with the knowledge of historical water supply and weather conditions. That is, growers attempt to maximize profits based upon expected seasonal water supply and weather conditions. As a result, the SPR model identifies an optimal "first decision" (in this case plantings under a given technology) given the uncertainty surrounding weather and water supply. Figure 4.2 provides a simple decision tree representation of the SPR model used in this analysis.

Figure 4.2 Decision Tree of SPR Model (2 Crops, 1 Technology, 1 Deficit Level)



In late winter or early spring, artificial flooding project water is diverted from the mainstem Umatilla River through the Westland Main Canal and applied to fields using flood irrigation technology. The next decision in the model involves the choice of crops to plant and irrigation technologies to employ. Figure 4.2 includes two crops, one technology, one deficit irrigation level, and two water supply/weather states-of-nature (the actual representative farm models include as many as five crops, four technologies, ten deficit irrigation levels, and nine water supply/weather states-of-nature).

Following planting, irrigators in Echo Meadows irrigate with "flood flows" from the Umatilla River (labeled as "traditional flood supply"). Irrigators may withdraw water from the Umatilla River as long as the flow is at or above 500 cfs. During this stage, they can choose to deficit irrigate to meet average crop ET.[1] In addition, because seasonal water supply is typically limited by the storage in McKay Reservoir, irrigators can choose to apply excess water during the flood flow stage to ensure that they enter the McKay supply stage of the model with a full soil profile, thereby pushing back the date on which they must begin withdrawing from their McKay allotment.[2] As shown in Table 2.3, irrigators in the Echo Meadows area typically switch from flood flows to McKay water supply in early June.

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[1] Average crop ET during the flood flow stage was calculated by determining the number of days each crop is irrigated using flood flows (dependent upon the crop's growing season) and multiplying by the average ET per day from March through May. To account for seasonal variations in the number of days irrigators use flood flows, the "date on" dates reported in Table 2.3 were used to calculate a probability weighted average number of days under flood flows.

[2] It was assumed that soil water was 40% depeleted for each crop and soil type at the time of excess irrigation.

The McKay stage of the modeling process accounts for uncertain water supplies and variations in weather conditions by assigning probabilities to each state. Figure 4.2 shows two states of nature with probability p1 and p2, respectively. In the representative farm models, nine states were included and are shown in the table below.

Table 4.4 Probabilities Associated with Each State of Nature

	McKay Supply (acre-feet/acre)		
	1.00	1.40	1.80
High ET	3.13%	6.25%	15.63%
Normal ET	6.25%	12.5%	31.25%
Low ET	3.13%	6.25%	15.63%

Using published ET data for Hermiston (OSU, 1992), high, normal, and low ET levels for each crop were identified. High ET refers to a hot, dry growing season while low ET refers to a cool, wet growing season. Using historical weather data, a normal ET year was defined as an ET level which would meet or exceed a crop's water consumption in five out of ten years. High ET and low ET were defined as an ET level which would meet or exceed a crop's water consumption in eight out of ten years and two out of ten years, respectively. The published numbers were generated using a normal distribution; probabilities assigned were .25, .5, and .25 for high, normal, and low ET levels, respectively. Using the McKay supply information listed in Table 2.3 , the probabilities of each supply level are .125, .25, and .625 for supply levels of 1.0, 1.4, and 1.8 af/acre, respectively. The probabilities shown in Table 4.4 were calculated by multiplying each weather state (ET level) by each supply level.

4.5 Mathematical Formulation of Representative Farm Models

Mathematically, the representative farm models were formulated as follows:

$$\begin{aligned}
Max\ Z = {} & \sum_{w}\sum_{b}\sum_{t}\sum_{d}\sum_{f}\sum_{g} YLD_{bdfg}(WATER_{wbtdfg})\, ACRS_{wbtdfg}\, VAL_{b} \\
& - \sum_{w}\sum_{b}\sum_{t} PLACRS_{wbt}\, PRD_{bt} \\
& - \sum_{w}\sum_{b}\sum_{t}\sum_{d} ACRS1_{wbtd}\, WTR1_{wbtd}\, CWTR_{wbt} \\
& - \sum_{w}\sum_{b}\sum_{t}\sum_{d}\sum_{f}\sum_{g} ACRS_{wbtdfg}\, WTR_{wbtdfg}\, CWTR_{wbt} \\
& - LBR \sum_{w}\sum_{b}\sum_{t}\sum_{d} \left[ACRS1_{wbtd}\, IRAP1_{wbtd}\right] LBHR_{t} \\
& - LBR \sum_{w}\sum_{b}\sum_{t}\sum_{d}\sum_{f}\sum_{g} \left[ACRS_{wbtdfg}\, IRAP_{wbtdfg}\right] LBHR_{t} \\
& - LBR \sum_{b}\sum_{t} FLACRS'_{s'bt}\, LBHR_{t} \\
& + \sum_{b}\sum_{t} \left(FLACRS'_{s'bt}\, {}^{SOILP_{b}}\!\big/_{EFF'_{s'bt}}\right) WID \\
& - \sum_{w}\sum_{b}\sum_{t}\sum_{d}\sum_{f}\sum_{g} HH_{b}(YLD_{bdfg})\, ACRS_{wbtdfg} \qquad (4.1)
\end{aligned}$$

where

Z = annual net profits
w = water source (ground = ‘g’ or surface = ‘s’)
b = crop (b = alfalfa, pasture, wheat, mint, asparagus, potatoes, corn)
t = irrigation technology (t = flood, flood with level, wheel line, center pivot)
d = deficit irrigation during flood water supply stage (d = .60, .65, .70, .75, .80, .85, .90, .95, 1.0)
f = states of nature during McKay water supply stage
g = deficit irrigation during McKay water supply stage (g = .60, .65, .70, .75, .85, .90, .95, 1.0)
YLD = crop yield per acre
WATER = seasonal water applied
ACRS = acres by crop and model option during the McKay water supply stage
VAL = crop price
PLACRS = planted acreage
PRD = planting and irrigation system fixed costs per acre
ACRS1 = acres by crop and model option during the flood flow supply stage
WTR1 = water applied to crops during the flood flow water supply stage
CWTR1 = irrigation water costs
WTR = water applied to crops during the McKay water supply stage

LBR = labor cost per hour
LBHR = labor hours per acre required for each irrigation
IRAP1 = number of irrigations during flood flow water supply stage
IRAP = number of irrigations during McKay water supply stage
FLACRS = artificially flooded acreage
WID = district water charge
SOILP = artificial flooding water that remains in the soil profile
HH = harvest and hauling cost per acre

The solution to the mathematical program defined above finds the combination of acres of crops and irrigation options that maximizes expected profit. The objective shows that crop yield is a function of seasonal water applications (discussed in section 4.6). In addition, harvest and hauling costs vary with crop yield, while the number of irrigations during each stage of the model depends upon crop, deficit option, and soil type. In general, as the water holding capacity of the soil increases, the number of irrigations decreases. It is assumed that the irrigation interval for a given crop is the same for each technology but that the water applied at each irrigation varies by irrigation system efficiency. In each of the representative farm models, labor was charged at $15 per hour.

The costs of irrigation water depend upon the irrigation technology employed, the pressurization requirement of the irrigation system, the depth of the well (if ground water is used), and the irrigation district charge. CWATR and CWATR1 are calculated according to Equation 2.1. A pump efficiency of 60% is assumed (Ley, 1994). Electricity and irrigation district charges are $.03/kWh and $17/af, respectively (Ashbeck, 1997).

Activities in the model were constrained to reflect the management practices and resource availability in Echo Meadows. In all three farm models, total acres were constrained to limit the size of the farm to those acreage levels reported in Table 4.3.

Equation 4.2 restricts planted acres across crops and irrigation technologies by the acreages that can be serviced by groundwater and surface water in a given year. From the Water Rights Information System (WRIS) database, it was found that fifteen percent of the acres in Echo Meadows have groundwater rights while the remainder are supplied by surface water sources.

$$\sum_{b}\sum_{t} PLACRS_{wbt} \leq TACRS_{w} \quad \forall w \qquad (4.2)$$

where TACRES = total acres supplied by each water source

Equation 4.3 is the seasonal water supply constraint. It limits the amount of water that can be applied throughout the season to the duty defined by the water right. The constraint allows irrigators to apply excess water to the crop before entering the water limiting McKay supply stage. In addition, Equation 4.3 accounts for reductions in irrigation requirements brought about by the artificial flooding project.[3] Specifically, the irrigation requirements are reduced by the amount of applied artificial flooding water that remains in the soil profile at the beginning of the irrigation season (SOILP). SOILP is divided by the water application efficiency of each crop/irrigation system combination (EFF) to account for the amount of water that would have to be applied if no artificial flooding were to take place. Because precipitation during the winter months can add to water in the soil profile it was necessary to determine effective rainfall on each soil type. Effective rainfall is defined as the portion of rainfall that contributes to meeting the ET requirements of a crop. Using average monthly rainfall data for the town of Echo and nongrowing season ET estimates (Wright, 1993), effective rainfall for each crop and soil type was read from estimates developed by Doorenbos and Pruit (1977). SOILP was calculated as the difference between available water storage capacity of the soil and the winter precipitation not consumed by the crop.[4]

$$\sum_{b}\sum_{t}\sum_{d} WTR1_{wbtd}\, ACRS1_{wbtd} - \sum_{b}\sum_{t} FLACRS_{bt}\, SOILP_{b} / EFF_{bt} + \sum_{b}\sum_{t}\sum_{e} XS_{wbte}\, EXCS_{b} + \sum_{b}\sum_{t}\sum_{d}\sum_{f}\sum_{g} ACRS_{wbtdfg}\, WATR_{wbtdfg} \le DUTY_{w}\, TACRS_{w} \quad \forall w \qquad (4.3)$$

where EXCS = excess water applications (af/acre).
DUTY = the seasonal water allotment (af/acre) defined by the water right

In addition to the seasonal water supply constraint, a constraint was included to reflect water availability during the McKay stage of the model. Equation 4.4 limits water supply in each of the nine states of nature to those reported in Table 4.4.

$$\sum_{b}\sum_{t}\sum_{d}\sum_{f}\sum_{g} WATR'_{s'btfg}\, ACRS'_{s'btdfg} - \sum_{b}\sum_{t}\sum_{e} XS'_{s'bte}\, EXCS_{b} \le \sum_{f} P_{f}\, MKSP_{f}\, ACRS'_{s'} \qquad (4.4)$$

where P = probabilities associated with each state of nature
MKSUP = McKay supply (af/acre) under each state of nature

Equation 4.5 is a balance constraint included to ensure that planted acres by water source, crop, and irrigation technology are less than or equal to the acres in the corresponding activities during the flood flow supply stage.

$$-PLACRS_{wbt} + \sum_{d} ACRS1_{wbtd} \le 0 \quad \forall w,b,t \qquad (4.5)$$

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[3] The water used in the artificial flooding project does not count against the seasonal water duty.

[4] Wright (1993) found that grass has an average ET of 18.4 mm and bare ground and average ET of 17 mm during the winter months. An average ET of 25 mm was used for all crops in order to match the results reported by Doorenbos and Pruitt (1977).

Like Equation 4.5, Equation 4.6 is a balance constraint that limits the production of crops in the McKay stage to those planted during the flood flow supply stage. These constraints reflect the fixity of decisions made during the planting stage of the model.

$$-ACRS1_{wbtd} + \sum_{g} (1/P_f) ACRS_{wbtdfg} \le 0 \quad \forall w,b,t,d,f \qquad (4.6)$$

Excess irrigation during the flood flow supply stage is explicitly modeled only for crops irrigated with surface water because groundwater crops are not subject to the same water supply limitations during the McKay stage. Equation 4.7 is a balance equation that allows surface water crops during the flood stage to receive excess irrigation water. Without this option, the model would select water applications levels just equal to the ET requirements of the crop during the flood flow supply stage.

$$-\sum_{d} ACRS1_{'s'btd} + \sum_{e} XS_{'s'bte} \le 0 \quad \forall b,t \qquad (4.7)$$

Equations 4.8, 4.9, and 4.10 are rotational constraints that reflect the common crop rotations used in Echo Meadows. Pasture, mint, and asparagus are treated as permanent crops.[5]

$$\begin{aligned} -0.5 \sum_{w}\sum_{t} PLACRS_{w'alf't} &+ \sum_{w}\sum_{t} PLACRS_{w'wht't} + \sum_{w}\sum_{t} PLACRS_{w'crn't} \\ &+ \sum_{w}\sum_{t} PLACRS_{w'pot't} \le 0 \end{aligned} \qquad (4.8)$$

$$\sum_{w}\sum_{t} PLACRS_{w'wht't} - \sum_{w}\sum_{t} PLACRS_{w'crn't} - \sum_{w}\sum_{t} PLACRS_{w'pot't} \le 0 \qquad (4.9)$$

$$-\sum_{w}\sum_{t} PLACRS_{w'crn't} + \sum_{w}\sum_{t} PLACRS_{w'pot't} \le 0 \qquad (4.10)$$

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[5] Upper bound constraints were applied to permanent crops based upon acreages reported in the survey.

4.6 Crop Water Response Component

In each of the representative farm models described above, the grower chooses the quantity of water to apply throughout the course of the growing season, the method of application, and the crops produced. The crop-water response model is built on the assumption that crop yields are a function of applied water. Crop yields decline when soil moisture falls below a threshold level, defined by the drought tolerance of a specific crop.

Following the Food and Agriculture Organization approach (Doorenbos and Kassam, 1979), crop yield response to changes in water applications were modeled according to Equation 4.11.

$$Yield = Y_m\left[1 - k_b\left(1 - \frac{ET_a}{ET_m}\right)\right] \tag{4.11}$$

Y_m is the maximum yield of the crop, k_b is the yield response factor, ET_a is actual crop evapotranspiration and ET_m is the maximum crop evapotranspiration. If the ratio of actual to maximum evapotranspiration is one, the crop achieves maximum yield. When $ET_a < ET_m$, actual yield is reduced proportionally to maximum yield. To interface the crop yield response to water applications with the representative farm model and to ensure model tractability, specific water deficits of zero to 40 percent (in five percent increments) were investigated.[6] A zero water deficit corresponds to water applications meeting the full consumptive requirements of the crop. As a result, each crop/technology

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[6] It was assumed that deficits in excess of 40 percent result in complete crop failure (English, 1997).

option has nine associated deficit options available during each irrigation stage of the model.[7]

4.7 Hydrology Model

One of the objectives of this research is to estimate potential changes in instream flows arising from artificial flooding and other on-farm irrigation adjustments. This requires a model of subsurface water movement. Idealy, a daily time-step hydrology model should be linked with irrigation to determine the timing, quantity, and location of return flows in the Umatilla River adjacent to Echo Meadows. Designing and implementation of this type of model proved intractable at this point in time. In lieu of a more detailed hydrology model, a simple "mass balance" approach is employed to provide a an estimate of the effects of artificial flooding on return flows. The mass balance approach considers the amount of water applied at the surface (artificial flooding and irrigation) and subtracts that component that is consumed by the crop or lost to the atmosphere through evaporation. The residual, or net amount of water from such a mass balance accounting is an upper bound estimate of possible return flows.

Three soil tests conducted in different areas of Echo Meadows found that the water table depth ranged from four to seven feet (Hoeffel, 1997). In the southeastern portion of Echo Meadows, preliminary analysis showed that water flows from the river into the water table underlying lands adjacent to the river (English, 1997). In lands

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[7] Past analyses have found that high valued crops are not deficit irrigated under reasonable water supply levels (Connor, 1995; Turner, 1996). Consequently, deficit irrigation was

further from the river, groundwater generally flows north toward the Umatilla River. Without a detailed hydrology model, it is impossible to quantify the amount and speed of groundwater movement in the alluvial aquifer underlying Echo Meadows. As a result, this analysis only considers irrigation and return flows on a seasonal basis. The estimates therefore represent an upper bound on the annual return flows generated from the combination of winter flooding and irrigation in Echo Meadows.

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not included as a model choice for potatoes, mint, and asparagus.

CHAPTER 5. RESULTS AND IMPLICATIONS

Chapters 3 and 4 presented the economic theory and modeling techniques chosen to analyze the effects of artificial flooding and other alternatives on farm profit and return flows in Echo Meadows. This chapter details the results and implications of the model solutions. The first part of the chapter discusses base case model results. The remaining sections discuss the impacts of the artificial flooding project and other streamflow augmentation plans.

5.1 Base Case Model Results

The base case model was developed to replicate existing conditions in Echo Meadows. The results for the base case analysis provide a benchmark against which the artificial flooding project and alternative streamflow augmenting strategies can be compared. To assess the performance of the representative farm models, key model outputs were compared to actual levels obtains from the on-farm survey. Table 5.1 reports the optimal (profit maximizing) acreages obtained from the base model and compares them to the actual acreages obtained from the survey.

Table 5.1 Comparison of Model Acreage to Actual Acreage by Crop

Crops	Modeled Acreage[a]	Actual Acreage[b]
Alfalfa	1,583	1,314
Asparagus	54	75
Corn	200	213
Mint	300	300
Pasture	1,580	1,924
Potatoes	200	213
Wheat	392	521
Total	4,317	4,560

[a] Sum of acres across the three farm models.
[b] Adjusted upward to reflect total acreage in Echo Meadows.

Overall, the model performs well, predicting total harvested acreage in Echo Meadows within five percent of actual total irrigated acres in the area. To meet the crop water requirements of higher valued crops such as potatoes and mint, the model chose to deficit irrigate pasture during the McKay water delivery stage on both soil types, as well as fallow some pasture acreage. This fallowed acreage accounts for the difference between reported and predicted total acres in Table 5.1. Because there is only one year of survey information, there is no range associated with actual acreage. In reality, acreages for crops in rotation fluctuate somewhat from year to year. Permanent crops such as pasture, mint, and asparagus fluctuate less due to contracts and cattle feed requirements.

The representative farm models adequately predict total crop acreages under the four irrigation systems. As reported in Table 5.2, the models perform the poorest when predicting total crop acres under flood irrigation. For example, the models predict that no crops would be produced under flood irrigation systems (due to its relative inefficiency). In general, sprinkler irrigation systems are under-represented in the modeled solutions, while flood irrigation systems are over-represented. This stems from the fact that the models do not include information on specific field slope and terrain which can impact irrigation technology choice.

Table 5.2 Comparison of Model Acreage to Actual Acreage, by Irrigation System

Crop	Modeled Acreage	Actual Acreage
Flood	0	509
Flood (Level)	3,017	1,800
Wheel Line	146	211
Center Pivot	1,154	2,040

Total annual profits under the base case solution across representative farms in Echo Meadows are $494,968, or approximately $109 per acre.

5.1.1 Individual Farm Model Results

The results for farm model 1 are presented in Table 5.3. Total farm profits in the base case solution are $40,929, or approximately $136 per acre. Eighty-five percent of the acreage is under flood irrigation systems and forty-three percent of the planted acreage is in alfalfa. Because pasture is a permanent crop, it was necessary to include a lower acreage bound to bring it into solution.[8] Without this lower bound, the model would choose to produce other crops in lieu of pasture due to its relatively low profitability. This suggests that farmers in the area have influences aside from profit maximization when producing pasture or that the value assigned to a unit of pasture ($ per AUM) is too low. In addition, the model does not explicitly value pasture as a risk-reducing input to cattle production, which could explain why pasture appears relatively unprofitable in the model.

Table 5.3 Farm Model 1: Base Case Solution

Crop	Flood	Flood (Level)	Wheel Line	Center Pivot	Total
Alfalfa		113		*20*	133
Corn		8		*9*	17
Pasture		100			100
Potatoes				*17*	17
Wheat		33			33
Total	0	254	0	46	300

Note: Acres supplied by groundwater are in italics.

Excess irrigation water is applied during the flood water supply stage to all wheat, corn, pasture and alfalfa acreage that is irrigated with surface water. All potato acreage is supplied by groundwater and therefore receives no excess irrigation applications during the flood water supply stage. Unlike surface water supplied crops, crops which are irrigated with groundwater have stable water supplies during the growing season. Consequently there is no advantage to be gained from excess irrigation during the flood water supply stage. In addition, pasture and wheat acreage is deficit irrigated during the late summer months to ensure that higher valued crops receive their full water requirement.

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[8] The lower bound on pasture in the three farm models was set at 80% of the reported acreage.

Farm 2 produces asparagus, mint, and pasture. Profits in the base case solution are $110,985 or $222 per acre. Mint is the highest valued crop produced in Echo Meadows. As such, the model chooses to plant as much acreage in mint as the acreage constraints allow. In order to meet the water requirements of mint, 41 acres of relatively less valuable cropland is left idle. Again, a lower bound was placed on pasture acreage to guarantee that it enters the model solution. Eighty-four percent of the crops planted are irrigated with flood irrigation on level fields, while the remaining crops are irrigated with center pivot systems.

Table 5.4 Farm Model 2: Base Case Solution

Crop	Flood	Flood (Level)	Wheel Line	Center Pivot	Total
Asparagus				*54*	54
Mint		279		*21*	300
Pasture		105			105
Total		384		75	459

Note: Acres supplied by groundwater are in italics.

All pasture acreage is deficit irrigated during the late summer months to meet the full ET requirements of mint and asparagus. In addition, excess water is applied during the flood water supply stage to all surface water irrigated crops.

Farm 3 represents farms in the western portion of Echo Meadows where soils are sandy and the terrain is less level. Total profits for Farm 3 under the base case solution are $21,608 or $44 per acre. The sandy soils require more frequent irrigations, which promotes the adoption of higher efficiency and less labor intensive irrigation technologies such as wheel line and center pivot systems. Forty-five percent of the planted acreage used flood irrigation with level fields, while nine percent and forty-six percent use wheel line and center pivot systems, respectively.

Table 5.5 Farm Model 3: Base Case Solution

Crop	Flood	Flood (Level)	Wheel Line	Center Pivot	Total
Alfalfa				101 *61*	162
Corn				20	20
Pasture		200			200
Potatoes				20	20
Wheat			40		40
Total	0	200	40	202	442

Note: Acres supplied by groundwater are in italics.

5.1.2 Base Case Return Flows Analysis

Return flows from irrigation are an important component of streamflow in the Umatilla River during summer months. A review of the Umatilla River hydrograph indicates that July and August are extreme low flow months with average flows of 21 and 23 cfs, respectively. In contrast, the Umatilla River flows at an average of 1,089 and 1,153 cfs in March and April, respectively.

Table 5.6 provides irrigation applications and return flows generated by each representative farm.

Table 5.6 Irrigation Applications and Return Flows by Representative Farm

Representative Farm	Irrigation Applications (AF)	Return Flows (AF)
Farm 1	1,037	362
Farm 2	1,478	539
Farm 3	1,430	342

Farm 1 applies a total of 1,037 af during the growing season. 675 af are used to meet crop ET requirements while the remaining 362 af remain in the alluvial aquifer and eventually enter the Umatilla River as return flows. The ratio of ET to total irrigation applications implies an overall efficiency of 65 percent for Farm 1. Farms 2 and 3 have overall efficiencies of 63 and 76 percent, respectively. Expanding the information in Table 5.6 to account for the total acreage in Echo Meadows results in total irrigation applications of 14,430 af and total return flows of 4,488 af. Assuming that all of the return flows enter the Umatilla River at a steady rate during the growing season (180 days), they account for 12.6 cfs of the summer flows in the river.

5.2 Artificial Flooding

A portion of the artificial flooding project water remains in the soil profile and therefore reduces irrigation requirements during the early part of the growing season. This "effective" artificial flooding water (water added to the soil profile), denoted as SOILP, varies by soil type and crop and is shown in Table 5.7.

Table 5.7 Effective Artificial Flooding (SOILP) Coefficients (inches)

Crop	Silt Loam	Fine Sand
Alfalfa	10.2	6.0
Asparagus	4.1	2.4
Corn	8.16	4.8
Mint	4.1	2.4
Pasture	4.1	2.4
Potatoes	4.1	2.4
Wheat	6.1	3.6

Effective artificial flooding is higher for deeper rooted crops and loam soils. Because precipitation in the winter months is low in the Echo Meadows area, rainfall is either consumed by perennial crops or lost to evaporation. As a result, effective artificial flooding is the same for normal and dry winters.

As shown in Table 5.8, artificial flooding did not affect the overall crop mix for Farm 1 from the base case solution. However, the irrigation technology mix changed somewhat. Specifically, eighteen acres that were irrigated under center pivot systems shifted to flood irrigation on level fields. Artificial flooding reduced crop irrigation requirements and therefore promoted the use of less technically efficient but more economically efficient irrigation systems in the same manner as an increase in water supply. It is important to note that these results represent a long-run solution that would occur if artificial flooding were continued for many consecutive years. It is unlikely that an irrigator would idle a center pivot system after a single year of artificial flooding.

The switch to less costly irrigation systems increased overall profits for Farm 1 to \$45,541. Part of this increase in profits also stemmed from the fact that irrigators were able to substitute artificial flooding water, which has no associated charge, for surface water supplied by the irrigation district. Pasture supplied by groundwater is deficit irrigated during both model periods. In the late summer months, all wheat, all pasture, and 98 acres of alfalfa are deficit irrigated.

Table 5.8 Farm Model 1: Solution with Artificial Flooding

Crop	Flood	Flood (Level)	Wheel Line	Center Pivot	Total
Alfalfa		113			133
		21			
Corn		17			17
Pasture		92		*8*	100
Potatoes				*17*	17
Wheat		33			33
Total	0	273	0	27	300

Note: Acres supplied by groundwater are in italics.

Profits on Farm 2 improved to $113,594 as a result of artificial flooding. The overall crop mix remained unchanged when artificial flooding was introduced into the model but it did promote the use of less expensive irrigation technology. Specifically, five acres of pasture switched from a center pivot system to flood irrigation. In addition, artificial flooding caused five acres of groundwater supplied mint under center pivot to move into surface water supplied flood irrigation and five acres of surface water supplied pasture to move into groundwater supplied flood irrigated acreage.

Table 5.9 Farm Model 2: Solution with Artificial Flooding

Crop	Flood	Flood (Level)	Wheel Line	Center Pivot	Total
Asparagus				*54*	54
Mint		284		*16*	300
Pasture	*5*	100			105
Total	5	384	0	70	459

Note: Acres supplied by groundwater are in italics.

Artificial flooding caused profits on Farm 3 to increase by $166, to $21,774. Optimal acreages by crop and technology remained the same as the base case solution, however. Farm 3 is located on fine sand soils which have less water holding capacity than silt loams. As a result, the effect of artificial flooding on water storage in the soil profile is lower and irrigation requirements are reduced only slightly.

Overall, the profits in Echo Meadows under the artificial flooding project are $532,587, $37,620 more than without the project.

5.2.1 Return Flows With Artificial Flooding

The proposed artificial flooding project calls for 2.5 af of water to be applied to each acre using traditional flood irrigation technologies. All artificial flooding water that is not consumed by crops or lost to evaporation is assumed to enter the river as return flows. As shown in Table 5.10, return flows generated when including artficial flooding in the model are considerably higher than without. This analysis predicts that a total of 11,110 af of return flows are generated by 3,179 acres of flooded land when the model solutions are expanded to account for all of the acreage in Echo Meadows. Assuming that return flows enter the Umatilla River at a steady rate during the growing season, artificial flooding contributes 31 cfs to summer flows, an increase of 18.4 cfs over the model solution without winter flooding.

Table 5.10 Return Flows by Representative Farm with Artificial Flooding

Representative Farm	Land Artificially Flooded (Acres)	Return Flows (AF)
Farm 1	276	910
Farm 2	389	1,393
Farm 3	200	802

5.2.2 Sensitivity of Results to Effective Artificial Flooding Coefficients

In order to assess the impact of the effective artificial flooding coefficients on the model results, the model was run for four different levels. Table 5.11 shows the results of the model runs. An effective artificial flooding level of 100% refers to the levels reported in Table 5.6. The other levels in Table 5.10 refer to 75, 50, and 25 percent of the effective artificial flooding coefficients reported in Table 5.6. Effective artificial flooding would decline during wet winters when precipitation exceeded crop water requirements and evaporation.

Table 5.11 Model Results Under Different Effective Artificial Flooding Coefficient Levels

Effective Artificial Flooding Level	Profits	Artificially Flooded Acres	Return Flows (acre-feet)
100%(SOILP)	$532,587	3,179	11,110
75%(SOILP)	$514,499	3,019	10,988
50%(SOILP)	$500,629	2,268	9,572
25%(SOILP)	$489,838	2,022	9,264

As shown in the table, total profits decline as the amount of artificial flooding water captured in the soil profile declines. Profits on Farm 3 actually fall below the Base Case level when SOILP is reduced to the 50 percent level. This occurs because the reduced irrigation requirements brought about by artificial flooding are outweighed by the labor costs required to spread the flood water.[9] Table 5.11 also shows that as SOILP declines, flooded acres and return flows decline as well. When SOILP declines, the farms tend to plant more acreage under wheel line and center pivot irrigation systems. Consequently, the acreage that is artificially flooded declines. Return flows decline as a result of the reduced amount of artificial flooding and increased irrigation efficiency.

5.2.3 Water Supply Reduction Scenario

The results reported above indicate that artificial flooding is a "win-win" situation. That is, growers in Echo Meadows benefit from reduced irrigation requirements while there are potential benefits to salmonids from the increased streamflow. An alternative method of augmenting streamflow in the Umatilla River would be to reduce the water supply to irrigators in Echo Meadows. To compare this scenario with the artificial flooding project, water supply was restricted by an amount equal to the difference between return flows with and without the artificial flooding project. This amounts to a reduction in seasonal surface water supply of 1.45 af/acre (6,622 af/4,506 acres). Assuming such a reduction is politically and technically feasible, the Oregon Water Resources Department could hold back this water in McKay Reservoir and release it as needed to maintain adequate streamflows.

Profits and planted acreage for each representative farm are shown in Table 5.12.

Table 5.12 Profits and Planted Acreage Under Water Supply Reduction Scenario

Representative Farm	Profits	Planted Acreage
Farm 1	$31,359	223
Farm 2	$109,333	443
Farm 3	$19,846	403

Total farm profits for Echo Meadows under the water supply reduction scenario are $415,824, $79,144 less than the base case solution, and $116,763 less than profits with the artificial flooding project. As shown in Table 5.12, the water supply reduction caused all farms to fallow land in order to meet the water requirements of valuable crops. To help stretch short water supplies, the farms adopted water-saving irrigation technologies for all crops other than pasture. Overall, farm water application efficiencies

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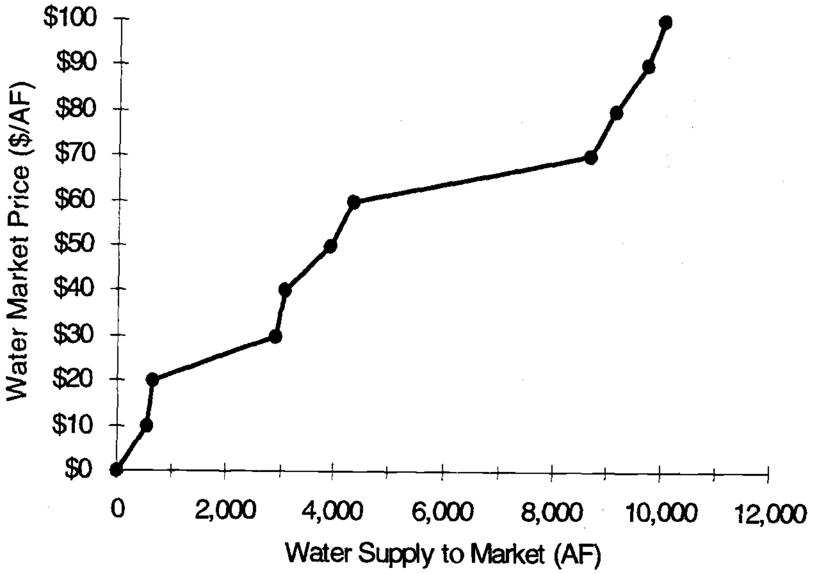
[9] The model was constrained to require that Farm 3 artificially flood all acres using traditional flood irrigation technologies.

increased to 69, 65, and 78 percent (from 65, 63, and 76 percent) for farms 1, 2, and 3, respectively.

5.2.4 *Instream Flow Water Market Scenario*

Another possible way to provide water for instream flows is to introduce a water market to Echo Meadows in which the Oregon Water Resources Department and other interested groups could purchase irrigation water from growers in Echo Meadows to meet instream flow needs. In this scenario, the base case models were adjusted to allow water to be applied to crops or sold at the beginning of the season into the water market at an exogenously set price level. This is not a true water market because it does not allow irrigators to sell water to other irrigators. By including a fixed, exogenous water price, this scenario represents the offer price necessary to induce irrigators in Echo Meadows to supply water obtained by increasing irrigation efficiency and idling cropland. The water market price was increased from zero to one hundred dollars in ten dollar increments. The results are presented in Figure 5.1.

Figure 5.1 Hypothetical Water Market Supply



At low prices, irrigators respond to the water market by increasing irrigation efficiency and selling the conserved water in the market. As the price rises and irrigation efficiency gain opportunities are exploited, growers begin to fallow low valued cropland because the profits earned in the water market are higher than value of the water in crop production. At a water market price of $10, irrigators in Echo Meadows choose to sell 563 af. At $100, the highest price considered in the analysis, irrigators choose to supply 10,011 af. In order to match the return flows generated by the artificial flooding project, the water market price would need to be approximately $65 per acre-foot. At this price, the total cost of meeting the increased flows generated by artificial flooding would be over $430,000 per year.

It should be noted that the lower bound on pasture included in the base case models precludes water applied to pasture from being sold in the water market. Because pasture is a relatively low value crop, it is reasonable to expect that growers will fallow pasture before other crops in response to a water market. In the base case solution, growers applied 5,459 af to pasture. The average shadow value of water applied to pasture across the three farm models is $12.37/af. If it is assumed that irrigators must receive twice this amount to fallow pasture and sell to the water market, the 6,622 af required could be obtained for approximately $160,642.[10]

5.3 Implications

The results presented in the analysis above suggest that the artificial flooding project proposed for Echo Meadows is a "win-win" situation. Salmon production would benefit from habitat improvement streamflow during critical low-flow periods, as well as cooler water temperatures resulting from increased inflow of groundwater to the river. Irrigators in Echo Meadows would benefit from a reduction in early season irrigation requirements equal to the amount of artificial flooding water held in the crop's root zone. Only after exceptionally wet winters, when the soil profile is essentially full, would the artificial flooding project detrimentally affect farm profits. This is unlikely to occur however, because the artificial flooding project would probably not take place in these years.

Total return flows with the artificial flooding project are 6,622 af higher than return flows without the project. Assuming that this water enters the Umatilla River at a steady rate during a 180 day growing season, the project increases streamflows below

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[10] 5,459 af * $24.74 + (6,622 af - 5,459) * $22 = $160,642

Echo Meadows by 18.6 cfs. Average monthly summer streamflows in the Umatilla River at the towns of Yoakum and Umatilla are shown in Table 5.13.

Table 5.13 Average Monthly Summer Streamflows (CFS) at Umatilla and Yoakum Gages

Gage	June	July	August	September	October
Yoakum	501	355	308	166	91
Umatilla	121	21	23	36	80

The Yoakum gage is located approximately ten miles upstream of Echo Meadows while the Umatilla gage is located near the mouth of the river, approximately twenty miles below the study site. As shown in the table, summer flows drop to nearly twenty cfs in July and August at the town of Umatilla. If the 18.5 cfs generated by the artificial flooding project were prevented from being diverted by downstream users, it could have a significant impact on summer flows.

Even modest gains in streamflow and reductions in stream temperatures could have a significant impact on the population of resident and anadromous salmonids. For example, a recent study on the John Day River, in northeastern Oregon, found that a ten percent increase in streamflow would increase juvenile steelhead production by between eight and 74 percent, depending upon the reach of river being considered (R.M. Adams et al., 1993). In addition, the study found that reductions in stream temperature would substantially improve juvenile steelhead productivity as well. In an earlier study, Johnson and Adams (1988) estimated that the value of an additional acre-foot of water in the production of steelhead on the John Day River was $2.36. While this value is less than the marginal value of an acre-foot of water in crop production, it is important to recognize, as the authors point out, that the use of water to produce fish has no detrimental effects upon downstream users. In short, the increased summer flow resulting from the artificial flooding project is likely to have positive impacts on the recreational fishing value of the Umatilla River.

In addition, as shown above, the costs associated with artificial flooding are much less than the alternative plans considered. Since the artificial flooding project does not affect an irrigator's water right, it is likely to be more politically feasible to implement the water markets or other measures that reduce or eliminate water rights

CHAPTER 6. SUMMARY AND CONCLUSIONS

Chapter five presented the SPR model results and implications of artificial flooding and other streamflow augmentation plans. The first section of this chapter summarizes the research problem, method of analysis, and model results. The next section presents the limitations of this thesis and identifies future research needs. The last section draws conclusions from the results obtained in this analysis.

6.1 Summary of Research

Low summer flows, high temperatures, and barriers to migration in the Umatilla River have contributed to the decline of anadromous salmonid returns to the river. This has promoted conflict between agricultural producers in the area and groups interested in improving conditions for spawning and rearing salmon. In response to the conflict and risk of legislative action, the Oregon Water Coalition proposed artificially flooding selected cropland in the late winter in an attempt to recharge the alluvial aquifer and boost return flows during critical low flow periods. A preliminary economic analysis can help to determine the impacts of the flooding project on agricultural production in the area. This information can also help identify the costs and benefits of the project and aid in the design of a plan which can meet the joint goal of improving salmonid productivity while maintaining the economic viability of agricultural producers in the area.

Specifically, this thesis sought to 1) evaluate the impact of artificial flooding on returns to agricultural land within the study site; 2) predict the effect of artificial flooding on streamflow in the lower Umatilla River; and 3) compare the artificial flooding project to other water conservation options.

Chapter two described the study area of this thesis. Echo Meadows is located in the lower Umatilla Basin, Oregon and was first developed for agriculture in the early 1900s. Average annual precipitation in the area is less than nine inches per year and all crops produced must be irrigated. Presently, Echo Meadows produces alfalfa, asparagus, corn, mint, pasture, potatoes, and wheat. The water resources section of Chapter two described the basin's reservoir storage capacity, permitted water rights, and streamflow conditions in the Umatilla River. Following this, historical and current salmonid returns were described and barriers to productivity of the fishery resource were identified. Lastly, soil characteristics in Echo Meadows and irrigation technology choice were presented. The quality of the soil is an important determinant of the crops which can be produced and the choice of irrigation technology to employ.

Chapter three contained the economic assessment framework and a review of relevant literature. Classical optimization theory was discussed in the first section of the chapter. The next section presented the assumptions and optimization procedures associated with linear programming. The remaining sections reviewed the procedures and results of economic studies which employed mathematical programming to identify optimal solutions to a variety of problems associated with agricultural production. In addition, the merits and methods of incorporating risk into linear programs were discussed.

Chapter four developed the procedures employed in this analysis and described the data used in the linear program. The general procedures followed in this research were 1) use physical and agricultural characteristics of the area to create representative farms; 2) construct a mathematical program which maximizes farm profits and allows the grower to practice deficit irrigation, crop substitution, and change irrigation application technology in response to changes in water supply; 3) use water applications determined by the representative farm model to estimate the quantity of return flows to the Umatilla River; and 4) incorporate alternative water conserving strategies into the representative farm models and compare these results with those obtained from the artificial flooding project.

The representative farm models were constructed based on information concerning soil characteristics and production practices obtained from a survey of growers in Echo Meadows. The results from each model identified the profit maximizing acres, crops, irrigation technologies, and deficit irrigation levels for each scenario considered. Risk associated with water supply and growing season weather was incorporated into the representative farm models through the use of the stochastic programming with recourse (SPR) framework. The three representative farms were developed to account for the heterogeneity among agricultural production and physical characteristics in Echo Meadows.

The results from the simulations presented in chapter five indicate that:

1) artificial flooding will increase farm profits in Echo Meadows by nearly $40,000 and increase streamflows in the Umatilla River below Echo Meadows by over 18 cfs;

2) in the long-run, artificial flooding will tend to promote the use of less costly but also less technically efficient irrigation technologies;

3) conversely, obtaining water for instream flow by reducing the water supply to irrigators will promote the use of water-saving irrigation technologies but reduces farm profits by nearly $80,000, annually;

4) introducing a water market in the area designed to increase streamflows will increase onfarm irrigation efficiency as well as increase total farm profits. In order to generate a flow increase comparable to the artificial flooding project, the Department of Water Resources or interest groups would need to pay between $160,000 and $400,000, annually to purchase water from farmers;

5) both the water supply restriction and water market scenarios reduce the planted acreage in Echo Meadows, which would negatively affect secondary agricultural industries in the area. The artificial flooding project would avoid this loss in agricultural output.

6.2 Limitations of Research

The modeling framework used in this analysis assumes that growers in Echo Meadows can adjust instantaneously to changes in resource availability. In reality, growers are constrained by long-term contracts and cash-flow limitations. Consequently, the results presented in this thesis can only be interpreted as long-run solutions.

Artificial flooding could raise the water table in Echo Meadows and therefore reduce pumping lift requirements for wells is the area. This researched lacked a detailed hydrology model that could estimate the dynamics of water movement in the alluvial aquifer underlying Echo Meadows and therefore ignored this possible benefit of the flooding project.

Perhaps the most important factor omitted from this analysis is the timing of return flows to the Umatilla River. Without the benefit of a daily or similar time step hydrology model it was impossible to estimate where and when water applied to land in Echo Meadows would reappear in the Umatilla River. Incorporating this detail would add valuable information concerning the tradeoffs between the timing and depth of artificial flood water and the timing and quantity of return flows. With this information, water managers would be able to affect streamfows during the most critical low-flow periods.

Further research should also be conducted on the effects of streamflow and water temperature on salmonid productivity in the Umatilla River. From this information, an economic valuation of recreational fishing in the Umatilla River could be conducted. This information would help in designing an artificial flooding plan that maximizes potential benefits in terms of salmonid productivity.

6.3 Conclusions

This thesis presents some insights concerning the impacts of a proposed artificial flooding project in the Echo Meadows reach of the Umatilla River. Specifically, the results suggest that the artificial flooding project is beneficial to agricultural producers *and* of potential benefit to salmon. It therefore represents a rare situation in which competing water user groups can work together to improve streamflow conditions without one side bearing a significant portion of the costs. As such, the artificial flooding project would not suffer from the enforcement costs and animosity associated with plans which reduce an irrigator's water supply.

If the artificial flooding project is to be successful in improving salmonid habitat, it is vital that the flows generated by the project are protected from diversion by downstream water users. If the flows are not protected, the benefits of the project will only go to meet the water requirements of crops located downstream from Echo Meadows. Furthermore, the project can only be viewed as a partial solution to the problem. Other obstacles to salmonid survival, such as Three Mile Dam, other low-flow sections, and habitat degradation must be addressed as well.

The artificial flooding project represents an innovative use of natural systems to improve the productivity of economically and culturally valuable outputs from a fixed water supply. Competition for Oregon's water resources will continue to grow in the future; projects such as the one presented in this analysis will become increasingly important as methods to meet rising demand. In addition, laws governing the allocation of water, which were developed during a period of relatively low water demand, will need to be altered to reflect the changes in social attitudes regarding water resources and the variety of benefits that are derived from them.

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APPENDIX

APPENDIX Echo Meadows Survey

Echo Meadows Survey

Please fill out the following survey to the best of your knowledge. In addition, feel free to write comments or add detail where you feel it is appropriate.

1. Please fill in the following table regarding the acreages, average yield, average price, fertilizer, and weed control of crops harvested on your farm:

Crop	Planted Acreage	Average Yield (per acre)	Average Price	Fertilizer Applied Annually (lbs per acre)			Annual Cost of Herbicide ($/acre)	Annual Cost of Insecticide ($/acre)
				N	P	K		
Native Pasture								
Improved Pasture								
Meadow Hay								
Grass Hay								
Alfalfa								
Corn								
Spearmint								
Asparagus								
Potatoes								
Barley								
Oats								
Wheat								
Others (specify):								

2. Briefly describe the typical crop rotations that you follow including the time of year crops are planted and whether or not a cover crop is typically planted.

3. The following questions deal with the management of cattle:

3a. How many head of cattle do you graze on your land annually? ________

3b. How long and at what time of year are cattle typically grazed on your pasture land?

____

____ .

3c. How many hay cuttings do you usually get before you graze? __________ .

4. Indicate the number of irrigations and the acres irrigated by flood, flood with field leveling, wheel/hand line, and center pivots in the table below (use blank column to fill in any other irrigation methods you use):

Crop	Average Number of Irrigations	Flood Irrigation (acres)	Flood w/ Field Leveling (acres)	Wheel/Hand Line Sprinkler (acres)	Center Pivot (acres)	Other ______ (acres)
Native Pasture						
Improved Pasture						
Meadow Hay						
Grass Hay						
Alfalfa						
Corn						
Spearmint						
Asparagus						
Potatoes						
Barley						
Oats						
Wheat						
Others (specify):						

5. Estimate the annual costs per acre of operating each irrigation system:

Irrigation system	Labor	Electricity/ Fuel	Maintenance /Repair	Ditch Maintenance	System Setup	Other Annual Costs
Flood						
Flood w/ Leveling						
Wheel Line						
Center Pivot						
Other						

6. In a normal year, what percentage of your irrigation water comes from:
ground water? __________
surface water? __________

7. If you use ground water, please provide the following well information:

Average Depth of Well (feet)	Pump Capacity (GPM)	Operating Pressure (PSI)

8. Is the winter flooding project likely to change your current management practice or crop production in any way? If yes, please explain.

9. What do you view as the major costs and benefits of the project?

THANK YOU FOR YOUR TIME AND COOPERATION