Estimation of economic and hydrologic impacts of water management policies in the Yellowstone River Basin
by Derrell Sylvester Peel

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Applied Economics
Montana State University
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Vita

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Abstract

A partitioned linear programming model of the Yellowstone River Basin is developed. The model maximizes returns over variable costs to a vector of alternative irrigated agricultural crops. Demands for water in municipal use, energy production and minimum instream flows are included in the model as model constraints.

With the basic model as a benchmark, a number of scenarios reflecting alternative water management policies and changes in important variables are evaluated. Specific scenarios include increased levels of irrigation efficiency, increased irrigated acreage in the basin, below average levels of river flow which would be associated with dry years and increased levels of prices for agricultural products.

The results of the basic model indicate the presence of time and site specific water scarcities which are exaggerated in the scenarios of increased agricultural prices or below average flows. The results also indicate that water management policies designed to increase the level of irrigation water use efficiency will, within some range, result in increases in returns over variable costs to irrigated agricultural production. However, the costs of increasing irrigation efficiency are not calculated in the model. Model results indicate that increasing irrigation efficiency may result in significant income redistribution between sectors within the basin.

Chapter 1

Introduction

Issues regarding water resources have received much attention in the United States in recent years. Increasing scarcity of water due to increasing demands and/or decreasing quality has increased the conflicts among water users, environmental concerns and water for energy, agricultural, municipal and other industrial uses. This problem is particularly acute in many areas of the Western United States where a history of pure, abundant water supplies and a myriad of water related laws and legal issues, often confusing and conflicting and, in many cases, judicially tested for the first time only recently, have combined to bring water policy considerations to the forefront of public attention.

In a 1960 publication, Hirshleifer, DeHaven, and Milliman correctly noted that water related issues are often approached with more emotion than clear thinking. They state:

> Much nonsense has been written on the unique importance of water supply to the nation, or to particular regions. Granted that the nation, or any individual thereof, could not survive without water, that does not show uniqueness. No human can survive without food, without oxygen, and without a variety of other supporting

> environmental conditions many not even fully known today (p.4).

However, this does not imply that water resources are undeserving of scientific inquiry. While no more a "necessity" than many other goods, water resources are plagued with a certain uniqueness due to the many competing and overlapping uses of water, the externalities associated with water use, the absence of markets to allocate water in many cases, and the hazy nature of water ownership and use rights due to the spatial and intertemporal complexities of hydrologic systems.

Thus, as concern and attention to these issues increases and solutions become imperative, much information will be required for society to arrive at satisfactory solutions. Issues regarding water resources are invariably unique to a specific locality and complete solutions will involve site specific study. Accordingly this study is concentrated on specific river management alternatives in the Yellowstone River Basin in Montana. However, it is hoped that the methods used in this study will provide insights into water management issues that will apply to other areas as well.

Background

The Yellowstone River, a tributary of the Missouri River, has its headwaters in northwestern Wyoming, the site of Yellowstone National Park, and flows in a generally

northeasterly direction across southeastern Montana and a small portion of North Dakota to its confluence with the Missouri River. Free-flowing for the full 670 mile reach of the mainstem, the Yellowstone supports some of the finest sport fisheries in the United States. Some 550 miles of the mainstem are located in Montana. The major tributaries of the Yellowstone: the Clarks Fork of the Yellowstone, the Bighorn, the Tongue, and the Powder rivers likewise have their headwaters in Wyoming and flow northward into Montana before joining the Yellowstone. Thus, over one-half of the water supply of the Yellowstone River is produced in Wyoming.

The Yellowstone River Basin in Montana, with which this study is concerned, drains about 35,000 square miles which is roughly half of the total drainage of the basin. The basin is geographically a land of extremes ranging from the snow-capped peaks of the western portion, where the Yellowstone River enters Montana from Yellowstone Park, to the rolling plains of the eastern portion. Elevations range from over 12,000 feet in the mountains to about 2,000 feet where the river leaves Montana. The climate of the basin displays variation to match the geography. Average annual precipitation ranges from about 6.6 inches in part of Carbon County, the driest portion of the basin, to 24 inches in Park County, which has the highest average annual precipitation in the basin. Average temperatures range

from 15.2 degrees farenheit in the winter to 75 degrees farenheit in the summer. The basin thus maintains a vast number of different microclimates and supports a wide variety of flora and fauna.

The primary source of water for the Yellowstone river is snowpack that accumulates in the mountains of the headwaters. Average annual flow of the Yellowstone River at Sidney, Montana, for the years 1934-1980 is 8.9 mmaf (million acre-feet) with a variation of flows from 4.2 mmaf to 15.4 mmaf.[1] Snowmelt runoff in the basin usually begins about April and reaches a peak in May and June. Average monthly flows throughout the year will range from less than .4 mmaf to about 2 mmaf at Sidney with the low flows occurring in the late summer and fall.

The basin is a sparsely populated region covering some fourteen counties in the southcentral and southeastern part of the state. Billings, in Yellowstone county, is the largest city in the basin. There are two Indian reservations in the Yellowstone Basin; the Crow Reservation,

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[1]The use of averages can be very misleading. Average flows of the Yellowstone are extremely sensitive to the time period upon which they are based. For example, average annual flows at Sidney for the 5 year period 1934-1938 were 6.7 mmaf and for the 5 year period 1974-1978 were 10.6 mmaf. In addition, some authors prefer to adjust the raw historical average to reflect a particular level of development. The DNRC (1977a, pg. 17) report average flows at Sidney of 8.8 mmaf when adjusted to the 1970 level of development, and Boris and Krutilla (1980, pg. 62) report flows of 8.45 mmaf when adjusted for the 1975 level of development.

located in Bighorn and Yellowstone counties, and the Northern Cheyenne reservation, immediately adjacent to the Crow reservation to the east in Bighorn and Rosebud counties. Agriculture is the most important industry in the basin. Approximately 570,000 of the nearly 25,000,000 acres in the basin are presently under irrigation.[2] The Department of Natural Resources and Conservation (DNRC) (1977b) projects a maximum increase in economically feasible irrigated acreage of about 237,000 acres. Irrigated agriculture is by far the major user of water in the Yellowstone Basin with virtually all irrigation water coming from surface supplies. Present consumptive use of water for irrigation is about 1.1 mmaf/y.[3]

The other major primary industry in the basin is coal mining. Currently coal mining ranks far behind agriculture in economic importance but has the potential to become a very significant industry.[4] In 1977, some 29.3 million tons of coal were reported mined in the basin, representing about a 30-fold increase over mining 10 years previously. There are an estimated 50 billion tons of coal reserves in

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[2]These are fully irrigated acres as reported by the SCS (1978, Table IIIa), and do not include water spreading acreage.

[3]The 1.1 mmaf was reported by the SCS-USDA (1978, pg. 24). The DNRC (1977a, pg. 33) reports irrigated agricultural consumptive use as 1.5 mmaf.

[4]See DNRC (1977d, pp. 11-36) for energy related development projections.

eastern Montana, which are presently economically feasible to mine, indicating that the coal industry has much room to grow. Coal mining by itself uses almost no water.[5] In addition, current levels of instate energy production from coal is also a relatively insignificant water user. However, depending on the form of technology applied, energy production in the future could represent a significant demand for water (Boris and Krutilla, pp. 104-130). The situation appears particularly acute given that the bulk of Montana's coal reserves are located in the relatively water scarce Tongue and Powder sub-basins. Likewise, current water demands for municipal and other industrial uses are insignificant relative to agricultural uses.

Legal Issues

Ownership of Montana's water resources is a labyrinth of tangled legal issues at the state, interstate, and federal levels.[6]

State Water Law

All water in the state is declared to be public property by the state legislature although this is clouded by largely unspecified federal claims (discussed later in

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[5]See Boris and Krutilla (1980, pp. 94-104) for a description of the coal mining process and related water use.

[6]A good description of water related laws and legal issues can be found in Boris and Krutilla (1980, ch. 2 & 3) and DNRC (1977n, pp. 45-54).

this chapter) (Mont. Code Annot., 1979, 85-2-101, sect. 1). However, state law allows individuals and entities to establish the right to divert and use water in the state. Water use rights are based on the doctrine of prior appropriation. This doctrine, adopted in Montana in 1865, essentially states that rights to use water are chronologically ordered, with the oldest rights having the highest priority, i.e., "first in time, first in right". Use rights under prior appropriation are also subject to a number of other conditions, the primary one being that the water be put to "beneficial use", as defined by the state (Mont. Code Annot., 1979, 85-2-102, sect. 2). The process by which water rights are established has gone through some modifications over time. Many of the early water rights were established simply by putting the water to use (Bowman and Lessley, p. 4). In many cases there was no record of date or quantity of water associated with these rights. Later on, rights were established by posting notice of intent to divert water and filing the notice with the county clerk and recorder (Bowman and Lessley, p. 4). These use rights, accumulated over the years, are often confusing and overlapping. The Montana Water Use Act of 1973 set in motion a state-wide permit system for use rights and mandated a complete adjudication of existing water rights (Mont. Code Annot., 1979, 85-2, part 2).

The adjudication process requires that holders of water rights prior to July 1, 1973 file notice of such rights with the DNRC so that all rights existing as of that date can be evaluated and quantified simultaneously by a court proceeding. From that point on, new rights will be issued by the DNRC, and all applications will be handled by that agency.

The Water Use Act of 1973 also recognized and granted legal standing for instream uses of water and initiated the process whereby government agencies, but not individuals, could apply for reservation of water for present or future beneficial use. These reservations could apply to both instream and withdrawal use.

Federally Reserved Water

Further complicating the legal status of water resources is the existence of unspecified quantities of water reserved for the Crow and Northern Cheyenne Indian reservations. These reserved waters, hinged on the Winters Doctrine of 1908, essentially guarantee adequate water to meet the future demands of the reservation, whatever that future demand may be. This places potentially large demands on the water of the Yellowstone River and specifically on the Bighorn and Tongue sub-basins. The Wind River Indian Reservation in Northern Wyoming also has potential impacts on the inflow of the Bighorn River into Montana in this regard.

Other federal establishments in the basin, such as military reservations, national forests, wilderness areas, et cetera, are subject to water reservations in a similar manner.

The Yellowstone River Compact

The final complicating legal area with regard to the Yellowstone Basin is interstate competition for water. Primarily, the issue is that of deciding how the water of the Yellowstone and its tributaries should be divided between Montana and Wyoming. This issue is embodied in the Yellowstone River Compact (Mont. Code Annot., 1979, 85-20). The compact, ratified by Congress in 1951, is between the two states, but also included North Dakota as a signatory state since the actions of the other two states directly affect water available in North Dakota. The compact, and the commission set up to administer it, has these primary features: first, to recognize appropriative rights to beneficial uses of water in each signatory state as of January 1, 1950; second, to specify the shares of unappropriated water in the tributaries to be allocated to Montana and Wyoming; third, to give each signatory state veto power over transfers of water out of the basin.

Two consequences are important regarding the Yellowstone Compact. First, to date, the division of unappropriated water between Montana and Wyoming as specified in the compact has not been applied, but it appears

that the time is rapidly approaching when such application will be necessary. Secondly, the Compact has no impact on, or legal standing with, the waters reserved for the Indian Reservations in the basin, therefore the ability of the Compact to resolve interstate water issues is hindered.

The Water Problem

The question of the adequacy of water in the Yellowstone Basin to meet current and future demands is not an easy one. The adjudication of current water rights in the basin is under way but may take as long as 15-20 years to complete.[7] This makes resolution of new applications for rights very difficult in the interim. Thus, the existence of conflicts between present uses, new uses and water reserved for future use is unclear. It is clear, however, that the question of adequacy must be answered in the context of flows at specific locations and points in time. There are two time dimensions to be distinguished, temporal variations, i.e., variation in flow from year to year, and intertemporal variations, i.e., variation in flow within the year. Water shortages, to the extent that they exist or will develop, are time and site specific. While it may be true that there is enough water in the basin to meet

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[7]Preliminary results will be available in the immediate future but final legal decrees may be many years hence. (Telephone conversation with Mike McLane, Adjudication Program Manager, DNRC, September 13, 1982).

demands in total, it is true that there are areas in the basin that, at certain times during the year, presently appear to experience shortages of water.

In the plains region, critically low flows, approaching no flows in some streams, occasionally occur in the fall causing serious water availability problems for both irrigators and fish and wildlife (DNRC 1977a, p. 17). As demands for water grow these situations will worsen.

In the early 70's, about the time that the Montana Water Use Act was passed, coal development in the basin began growing at a rapid rate. This resulted in a wave of consternation regarding water resources in the basin and was the source of much research to identify possible solutions to conflicts among competing water users. Much of the research was carried on by the DNRC.[8] In recent years, the rate of coal development has slowed and while the panic-oriented concerns initially expressed have not materialized, there is every indication that coal development will continue to grow as will other industrial and agricultural uses. Thus, solutions to these problems are as important as ever. These solutions must deal with two components; the physical and hydrological characteristics of the basin, i.e., when and where water is available,

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[8]Much of this work is embodied in the Yellowstone Impact Study, a series of eleven technical reports (DNRC, 1977d-n) and a final report (DNRC, 1981). See also DNRC (1975, 1977a, 1977b, 1977c).

and the legal questions of the size and priority of rights to use the, at times, limited supply of water.

Possible Solutions

What kinds of solutions are available to solve these problems? The DNRC recognizes three possible solutions; water reservations, additional storage, and improved water management (1977a, p. 71).

The use of water reservations, provided for in the Water Use Act of 1973, allows public agencies to provide for future water demands and, importantly, recognizes and protects instream uses for fish and wildlife, health, and recreational purposes. Water reservations were designed to untangle some of the legal headaches and to provide a framework for allocating water among alternative uses.

Increased storage capacity provides a means of solving some of the spatial and intertemporal water distribution problems. However, the issue of increased storage capacity raises much concern over who will build, control, and administer the facilities, who will get to use the water and, particularly, the preservation of fisheries, wildlife habitat and low-lying agricultural lands. These issues make it appear that instream storage facilities are politically infeasible in virtually all areas of the

basin.[9] This requires the use of more expensive offstream storage to implement the storage alternative. It would appear that there is enough disagreement and discontent about increased storage that it will not be a viable alternative to solve all of the water problems in the Yellowstone Basin.

The third alternative proposes better management of water being currently used, primarily for irrigation, to conserve water and increase availability for other uses. Currently, overall irrigation efficiency in the Yellowstone River Basin is about 19 percent (SCS-USDA, 1978, Table IIIa). In other words, less than one-fifth of the water diverted from the river is used consumptively by agricultural crops. There is much concern over the other four-fifth's that is "lost". It would appear that there is indeed some room for water conservation through better river management. Increasing the level of irrigation efficiency would reduce the diversion requirement for irrigation. However, there are some implications of this conservation that have, at least to some extent, been overlooked. This study proposes to examine and develop, in

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[9]The Allenspur dam site, one of the more promising reservoir sites from a river management standpoint, was the subject of a joint resolution of the 1974 Montana Legislature as being contrary to state goals and objectives (DNRC, 1975, pg. 2).

some detail, these implications, and evaluate the economic impact of alternative river management policies on the Yellowstone Basin and the state of Montana.

Irrigation and Return Flows

As stated previously, approximately 80 percent of the water diverted from the river is lost from the irrigation system before being used by agronomic crops. However, roughly 90 percent of that "lost" water eventually returns to the river as return flows. The remaining water is truly "lost" to the surface flow system because it evaporates, percolates into deep groundwater aquifers, et cetera. The return flows enter the river after some time delay and downstream from the original diversion point.

These return flows, although subtle in their interaction with the hydrologic system, are nevertheless a significant factor in the flow of the river. It has long been recognized that water reentering the river as return flows can be reused. Teele, describing the Santa Ana River in California, in 1915, states; "It is thus evident that the same water, in passing from mountain to sea, a distance of not more than 100 miles, may be used at least eight times for power and irrigation (pp. 23-24)." Soil Conservation Service figures indicate that annual return flows in the Yellowstone are about 3.1 mmaf, over one-third of the average annual flow of the river as measured at Sidney (SCS-USDA, 1978).

More important are the implications for the distribution of water flow thoughout the year. The most critical period regarding water availability, at the present time, are the months of August and September when relatively low river flow is coupled with high diversion of water for irrigation. Given that return flows are delayed somewhat after diversion, the bulk of which occurs in the May to September interval, significant portions of the present levels of late summer flow of the river are due to return flows. The DNRC (1977a), recognizing the significance of return flows state, "In many areas water users have legal rights to water lost by irrigators above them, and their rights could be adversely affected by the use of more efficient irrigation practices (p. 72)".

Water Quality

The quality of return flow water is usually lower than it was before diversion due to the introduction of salts, pesticides, sedimentary material and/or organic matter.[10] In some areas of irrigated agriculture in the Western United States, this quality issue is critical. For example, portions of the Upper Rio Grande Valley and much of the Colorado River Basin are characterized by severe salinity problems and the quality component of the return

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[10]See Boone (1976) and DNRC (1977f, pp. 77-80) for more detailed discussions of water quality aspects of return flows.

flow issue is critical. The Yellowstone Basin is somewhat unique in this respect for two reasons. First, the basin is characterized by unusually high quality surface water in general, and second, there is a lack of indication of widespread water quality degradation throughout the basin. While certain areas of the basin may present potential quality problems it does not appear that treating return flows in the entire basin as primarily a quality issue is appropriate. For this reason this study will not deal with the quality issue and will concentrate instead on the quantity and distributional components of water in the Yellowstone Basin.

The conservation of water through better river management as a solution to the water problem in the Yellowstone Basin has recieved much attention. This is understandable because it appears to be an obvious alternative. It allows conservation of water for alternative uses and simultaneously contributes to the maintenance of water quality. In addition, it is not plagued with the legal and political controversies surrounding the water reservation and storage alternatives.

It appears that there are significant undesirable economic implications of proposed river management policies. Specifically, policies which are directed toward improving the overall efficiency of water used for irrigation may result in a reduction in the quantity of return

flow in the river, i.e., may change the distribution of river flow throughout the year. Therefore, policies of increased efficiency of water use may alter the adequacy of the river to meet withdrawal and instream uses, even at current economic levels and average river flows. Increased efficiency policies also have implications for other river management policies such as, irrigation project development and reservoir construction. These implications are even more exaggerated in light of other variables such as; variation in the physical system, i.e., runoff, precipitation, evaporation; future economic growth in the basin; and other economic conditions, i.e., level of prices for agricultural products.

Objectives

The purpose of this study is to examine the economic implications of current river management policies, in the Yellowstone River Basin. This will be accomplished by completing the following objectives:

(1) Development of a model of the Yellowstone River Basin, that incorporates the appropriate economic and hydrologic theory and policy factors to evaluate current management policies.

(2) Evaluation of the economic impacts of increased efficiencies of water use by parametrically increasing the level of efficiency of water use in the model.

(3) Evaluation of current management policies in light of other physical and economic factors, such as lower-than-average river flows, alternative price levels and future agricultural development, and discussion of these implications in relation to other management alternatives.

Chapter 2

Economic and Hydrologic Theory

The purposes of this chapter are to set forth the hydrologic and economic theory appropriate to an understanding of the situation presented in Chapter 1 and to discuss (1) the implications and limitations of such theory in the light of data availability and other factors and (2) the adaptations necessary in order to use the theory to achieve quantification of the stated objectives.

Hydrologic Theory

An understanding of the economic impacts of alternative river management policies requires at least a cursory understanding of the hydrologic processes involved. The heart of the problem set forth in Chapter 1 is hydrology. Consequently, this section of the chapter will be devoted to a general introduction to hydrologic theory, a discussion of streamflow hydrology in particular, and an introduction to the responsiveness of the hydrologic system to human intervention.[1]

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[1]The general hydrology and runoff sections draw heavily on Ward (1975, chs. 1, 8).

Water occurs simultaneously on, under and above the earth's surface in a variety of forms, each of which is a component of a complex, continuously moving hydrologic cycle. Figure 1 depicts a simplified representation of the major components of the hydrologic cycle. This study is primarily concerned with the occurrence of water on or near the earth's surface and its availability for use.

Groundwater pumping in the Yellowstone Basin represents a relatively insignificant quantity of water and virtually no groundwater is pumped for irrigation. Therefore, adequate modeling of hydrology and water use in the Yellowstone Basin, for purposes of this study, can be accomplished with a hydrological model that concentrates on the streamflow or runoff component occurring in the basin. Ignoring groundwater pumping represents a significant simplification of the return flow problem because groundwater and streamflow systems are very often integrally related via the return flow mechanism. Burt (1964) presented the application of dynamic programming to problems of conjunctive ground and surface water. Young and Bredehoeft (1972) addressed issues of conjunctive ground and surface water use along the South Platte River in Colorado as did McConnen and Menon (1968) and Boyd (1968) in the Gallatin Valley, Montana.

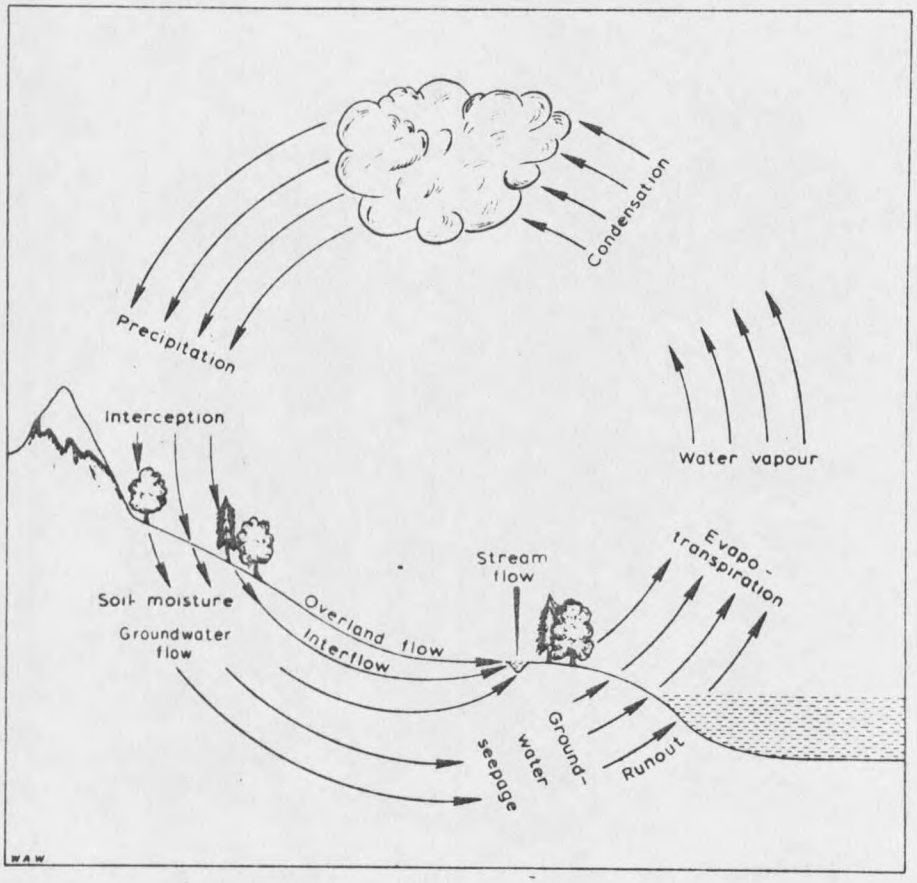

Figure 1. Simplified Diagram of the Hydrological Cycle. (From Ward, 1975)

Runoff

Runoff is the gravitationally motivated movement of water into and through channels on the earth's surface. Hydrologically, runoff occurs when precipitation exceeds evapotranspiration and storage in and on the ground surface. However, an important aspect of runoff is that, while the occurrence of precipitation tends to be very disjoint and irregular, the resulting streamflow tends to be relatively constant. This is due primarily to the storage capacity of the upper layers of soil on the earth which smooth and delay subsurface contributions to streamflow. Figure 2 presents a diagramatic representation of the specific components of runoff. These are channel precipitation, overland flow, interflow and groundwater flow.

Channel precipitation, i.e., precipitation directly onto the stream channel is usually a relatively small component of runoff, being directly proportional to the area of the catchment basin that is occupied by stream channels. In semi-arid regions like the Yellowstone Basin, this proportion is quite small. Overland flow occurs when water fails to infiltrate the soil and travels over the surface to the stream channel. Failure to infiltrate can occur for a number of reasons; impervious soil substance (bedrock, etc.), soil saturation during high precipitation or frozen soil surface. Overland flow is also usually a

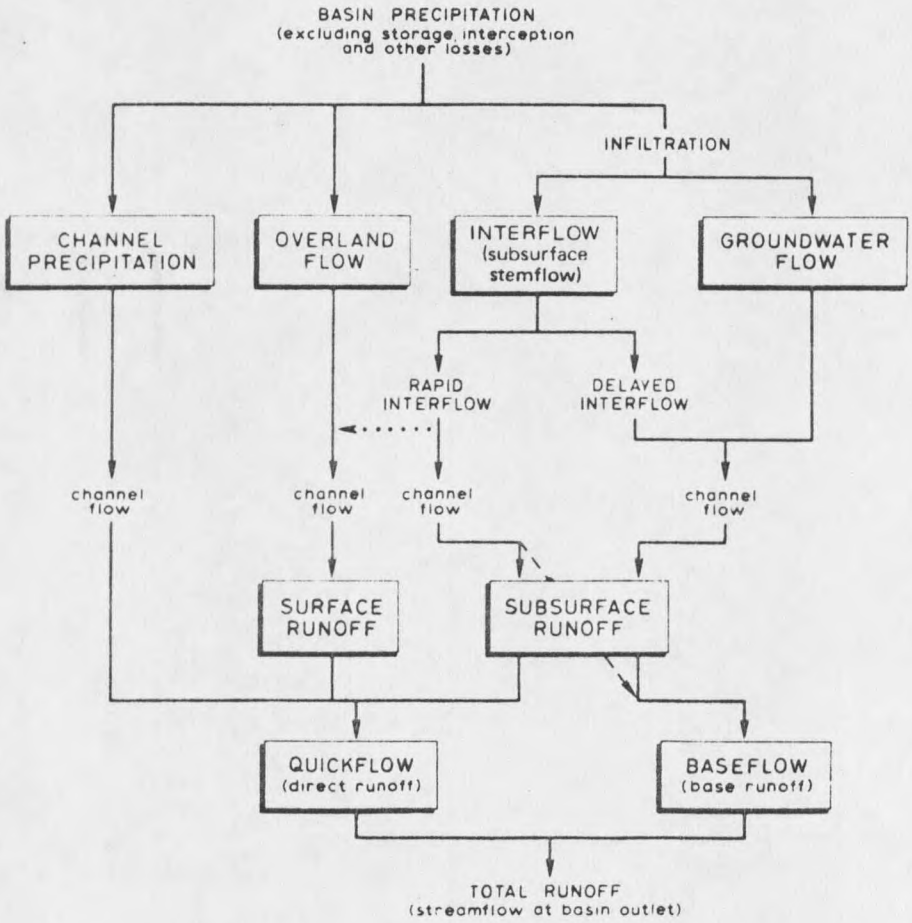

Figure 2. Diagrammatic Representation of the Runoff Process. (From Ward, 1975)

relatively small component of runoff because the aforementioned conditions rarely occur over large areas for extensive periods of time. However, floods, for example, indicate that there are important exceptions to this.

The water which infiltrates the soil will become either interflow, which is the shallow lateral movement of subsurface water, or groundwater. These two components are defined as subsurface runoff. Of all the runoff components, interflow is the most important contributor to total runoff, having impacts on immediate runoff (rapid interflow) and delayed runoff (delayed interflow). Ward cites empirical hydrologic studies which indicate that interflow may account for 85 percent of streamflow (Ward, p. 241).

Runoff is alternatively subdivided into quickflow or storm period runoff, which consists of channel precipitation, overland flow, and rapid interflow; and baseflow or dry period runoff, which consists of delayed interflow and groundwater contribution to streamflow. It is this baseflow which accounts for the relative constancy of streamflow despite intermittent precipitation patterns. These factors influence the annual distribution of streamflow typical of the Yellowstone and many other semi-arid regions of the West. Spring and early summer flows are very high, being predominantly quickflow resulting from snowmelt and seasonal rainfall in the spring and early

summer. Late summer, fall and winter flows are low as is precipitation during that period and streamflow is sustained almost entirely by baseflow.

Hydrographs

One of the tools used in runoff analysis is a hydrograph. A hydrograph is a graphical presentation of streamflow volume per unit time over time. Although used in other contexts, such as individual storm runoff analysis, the hydrograph is a very convenient way to illustrate river flow thoughout the year. The hydrograph of average monthly flows of the Yellowstone River at Sidney for the period 1934 to 1980 are presented in Figure 3.

Hydrographs, such as Figure 3, are an important foundation upon which water management and control policies are formulated. While hydrographs serve as a useful benchmark of available water supplies, it is imperative that other factors be considered in conjunction with the hydrograph. An understanding of the components included in flows measured in a hydrograph, the stochastic nature of runoff, and the variation in flows at different points along the river must be considered as well.

Streamflow and Irrigation

Historically, in many of the arid and semi-arid regions of the world, the quantity and distribution of streamflow placed quite restrictive limitations on the

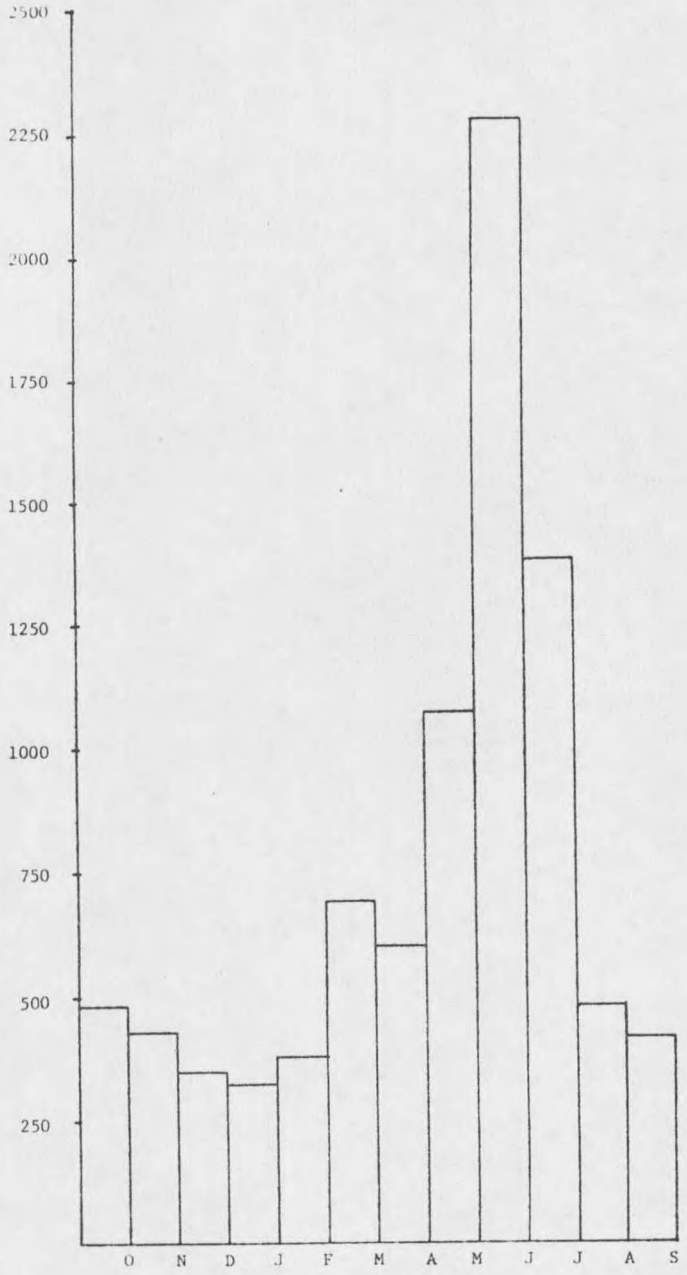

Figure 3. Average Monthly Flow of the Yellowstone River at Sidney, Montana, for Water Years 1934-1980.

nature and extent of economic activity. In much of the Western United States this is particularly true. Also very important, though less obvious, is the fact that human activities have impacts which feed back into the physical hydrologic system. An important example of this is irrigated agriculture.

Agricultural irrigation systems typically divert water from the river and convey it to fields through a network of canals, ditches and occasionally pipes. However, not all of the water diverted from the river is delivered to the field. Some is transpired by ditchbank flora, some is lost through operational spills, some seeps into subsurface aquifers and some evaporates. The efficiency of the physical delivery system, conveyance efficiency (E_c), is defined as the ratio of the quantity of water delivered to the field to the quantity of water diverted from the river or

$$E_c = \frac{\text{Water delivered to the field}}{\text{Water diverted from the river}}$$

Likewise, not all of the water delivered to the field will be beneficially used by crops. Some will run off due to effects of topography (slope), some will seep into subsurface aquifers and some will evaporate from the field surface. These effects can be exaggerated in some instances due to management inefficiency that results in improper irrigation timing and quantity of application.

The efficiency of this combination of physical and managerial factors at the farm level is defined as irrigation unit efficiency. This is sometimes referred to as field efficiency. Specifically irrigation unit efficiency (E_u) is the ratio of the quantity of water beneficially used by crops to the quantity of water delivered to the field or

$$E_u = \frac{\text{Water used by crops}}{\text{Water delivered to the field}}$$

E_c and E_u can be combined to express an overall irrigation efficiency (E_I) that is the ratio of the quantity of water beneficially used by crops to the quantity of water diverted from the river or

$$E_I = \frac{\text{Water used by crops}}{\text{Water diverted from the river}}$$

These efficiencies are based on definitions from Jensen (1967). Brosz (1981) provides a good summary of the factors involved in irrigation efficiency.

The numerous sources of losses from conveyance and field systems can be grouped into two categories; recoverable and nonrecoverable. Figure 4 shows the breakdown of irrigation system losses into the primary components and the resulting category of recoverable losses. Recoverable losses in this usage simply means those losses that will eventually return to the natural streamflow system. These are also known as return flows. Specifically return flows

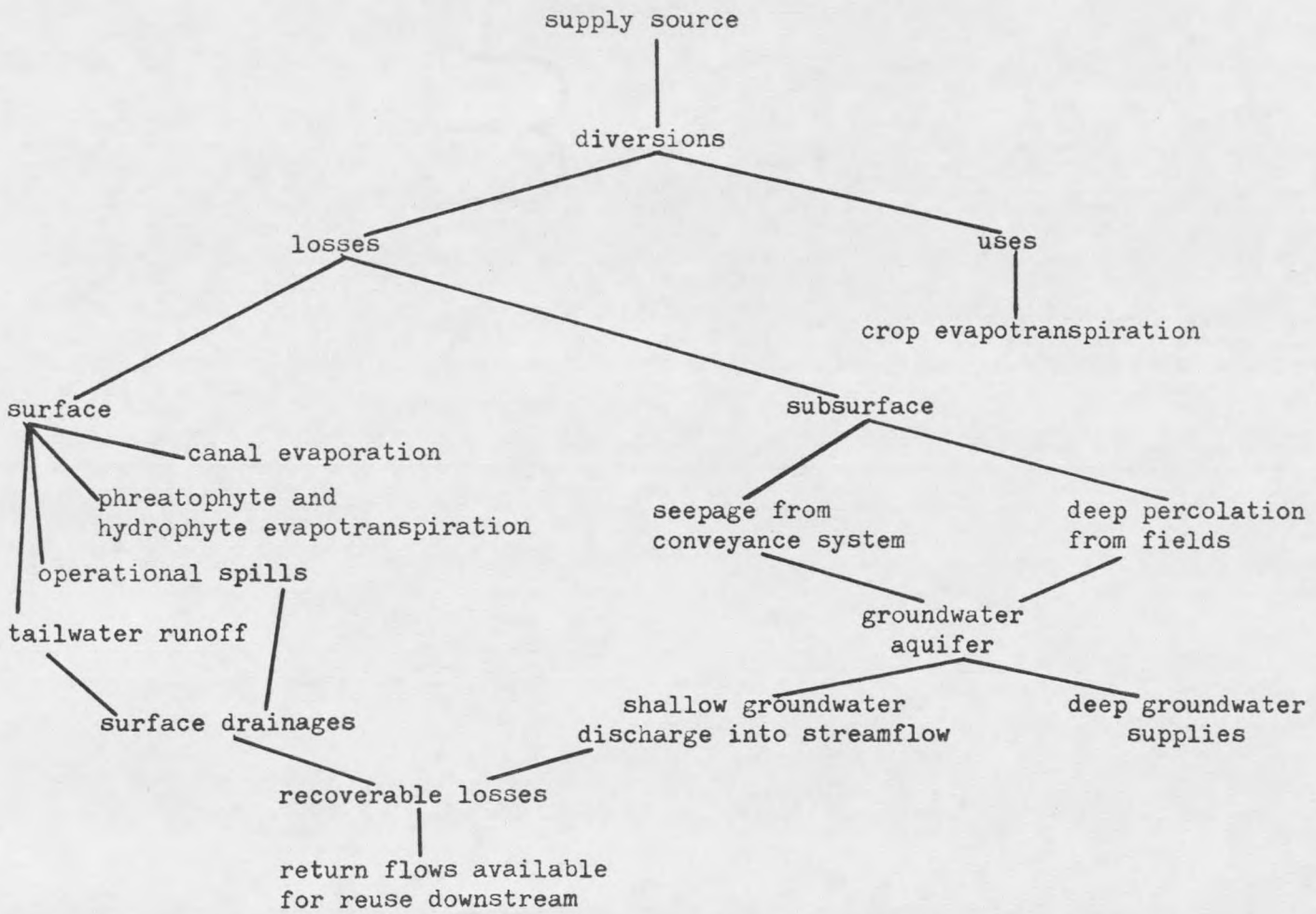

Figure 4. Components of Water Loss From Irrigation Systems.

are defined, for present purposes, as the sum of surface and subsurface losses from conveyance and field systems that reenter the streamflow system. Figure 5 provides a good representation of the irrigation and return flow systems and their relation to the river or streamflow system.

Return flows are a complex hydrological phenomenon. Consequently, while the primary components of return flow are identified, the complexity of return flows coupled with the complexity of the natural hydrologic system makes quantification of return flows difficult. Nicklin and Brustkern (1981) discuss the problems faced by hydrologists attempting to quantify return flows. This becomes important methodologically if one proposes to investigate the impact of return flows on the natural streamflow system.

Conceptually, return flows are an example of manmade overland flow and subsurface flow that contributes to quickflow and baseflow in hydrologically the same way as do natural sources. Of course, the quantity of return flow is proportional to the level of inefficiency in the conveyance and field systems and consequently can be controlled by changes in the level of technical efficiency of the irrigation system. However, one of the components of the hydrograph of river flows (Figure 3), is return flow. To the extent that a hydrograph is viewed as a "benchmark" of available water supplies, it can be misleading in this

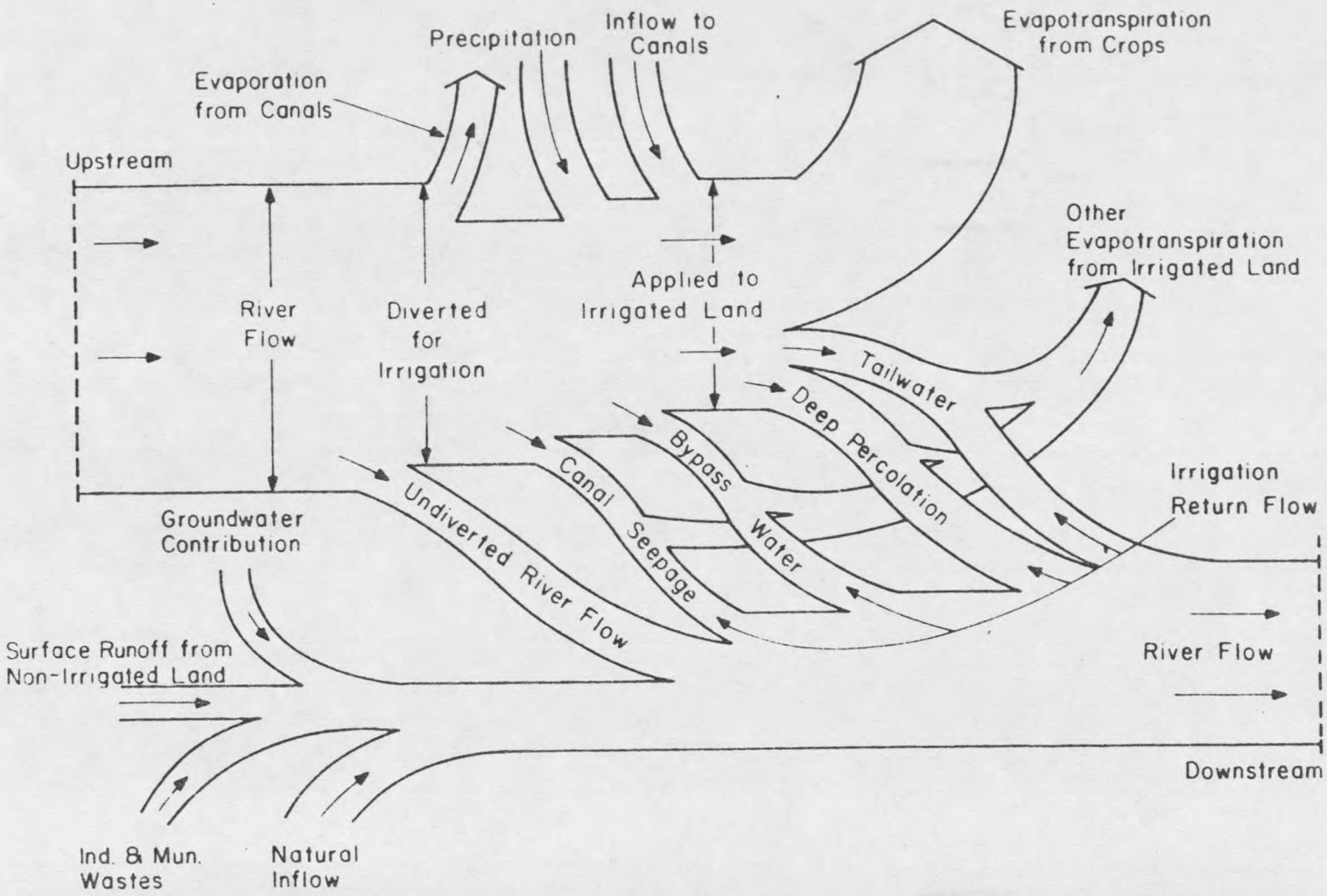

Figure 5. Conceptual Diagram of the Irrigation Return Flow System. (From Waller, 1976)

situation because the benchmark will change as the quantity of return flows in the system changes.

Economic Theory

The following section of economic theory should accomplish several goals. First, it should establish the general theoretical notion of water as an economic good with respect to both the quantity and quality aspects of water use. While this study abstracts from the quality issue, it is an important one that must ultimately be addressed and should be included in the theoretical framework. Second, the theory should establish the conceptual linkage between the level of irrigation efficiency (E_I) and the quantity and quality aspects of water use. Third, the theory should delineate between privately and publicly perceived impacts of changes in the level of E_I. Towards these ends, benefit/cost analysis provides an appropriate basis for evaluation of changes in the level of E_I.

Benefit/Cost Framework

When water is used as an input into the production process of some product (as opposed to its value as a consumption good) the demand for water is said to be a derived demand. That is, its value is derived from the value of the products for which water is an input. Thus, the demand for water in alternative uses is related to the marginal value productivity (MVP) of water in each use.

Specifically, the demand function for water as an input will be equal to the inverse marginal value productivity curve in the short run when only water is a variable factor. In the longer run, when other factors are variable and will be substituted for water, the demand function for water will be more elastic than the MVP curve. In a theoretical setting, where optimal allocation of water is assumed to occur, optimality is achieved when the marginal value productivity of water in all uses are equal. From the standpoint of water management policy, the demands for water are exogenously determined and are fixed in the short run.

It was expounded earlier that use of water depends on when and where water is available. In a more abstract sense, this can be restated to say that the value of water as perceived by the water policy planner, is dependent on quantity and quality of water available, given the exogenously determined demands for water, at a given time and place. Abstracting from the time and space dimensions, the total benefits of water can be defined, in general mathematical notation as

$$(1) \quad TB_W = f(Q_W, K_W)$$

where Q_W represents the quantity of water and K_W represents

the quality of water. Total costs of water can be defined in the same general nature as

$$(2) \quad TC_W = g(Q_W, K_W)$$

At this point, after making the usual assumptions about first and second order conditions, i.e., diminishing marginal benefits and increasing marginal costs, the marginal cost and benefit relationships can be defined as

$$(3) \quad MB_W = \frac{\partial TB_W}{\partial Q_W}$$

and

$$(4) \quad MC_W = \frac{\partial TC_W}{\partial Q_W}$$

This straightforward benefit/cost analysis (see Figure 6) has been recognized, for example, by the DNRC as pertaining to the Yellowstone River Basin (DNRC 1977n and 1981).

However, the specific impacts of the level of return flows and, therefore, the level of E_I are not formally taken into account in (3) and (4). Therefore, it is necessary to pursue further the quantity and quality aspects of water.

From previous sections on hydrology the major determinants of the quantity of water available are identified as natural streamflow or runoff, stream augmentation with

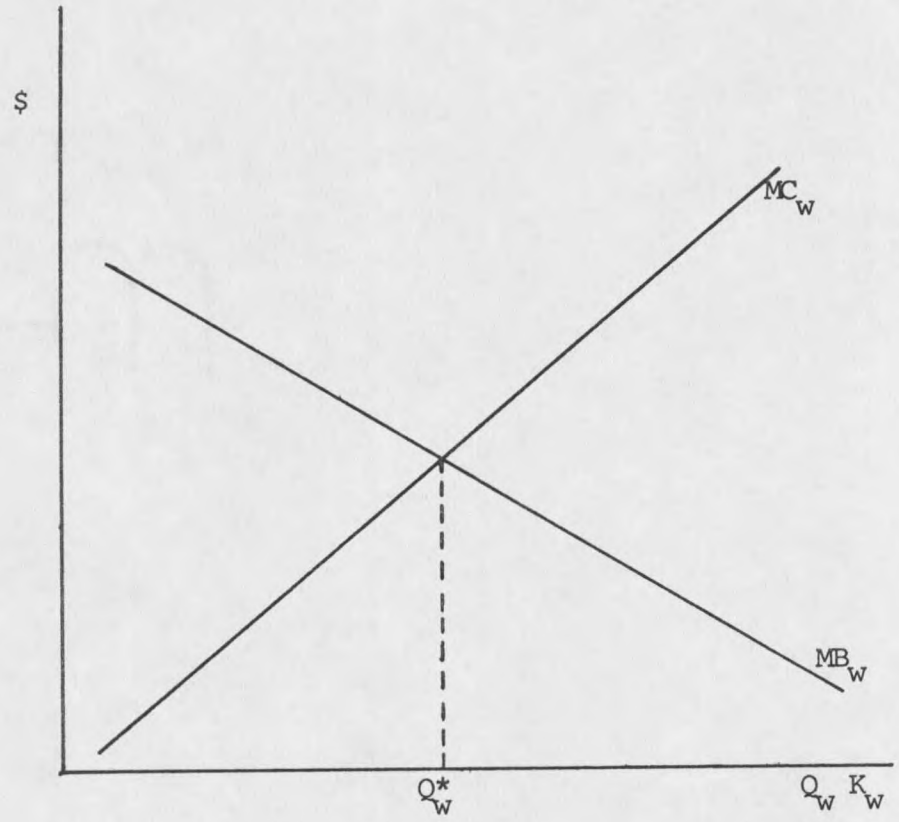

Figure 6. Marginal Benefits (MB_W) and Marginal Costs (MC_W) of Water Use.

storage facilities, and return flows from irrigation. That is,

$$(5) \quad Q_W = k(R, S, Rf)$$

where R represents natural runoff, S represents artificial storage and Rf represents return flow from irrigation.

Water quality is a function of natural quality conditions in the runoff system and artificial, ie., human, impacts that may be positive (water treatment) or negative (point and non-point sources of pollution). For present purposes, the quality impacts of return flow will be separated from other artificial quality impacts. Thus, water quality (K_W) can be expressed as

$$(6) \quad K_W = z(R, A, Rf)$$

where R represents quality factors in natural runoff, A represents artificial quality factors other than irrigation return flows, and Rf represents quality factors of return flows.

It was stated earlier that return flows (Rf) are directly proportional to the level of irrigation efficiency, or in general

$$(7) \quad Rf = h(E_I)$$

Consequently, the link between E_I and water benefits and costs is established. In general, substituting (7) into

(6) and (5) and substituting (6) and (5) into (1) and (2). results in

$$(8) \quad TB_W = f\{k[R, S, l(E_I)], z[R, A, h(E_I)]\}$$

$$(9) \quad TC_W = g\{k[R, S, l(E_I)], z[R, A, h(E_I)]\}$$

The marginal impacts of changes in the level of E_I can be appropriately defined as

$$(10) \quad MB_{E_I} = \frac{\partial TB_W}{\partial E_I}$$

and

$$(11) \quad MC_{E_I} = \frac{\partial TC_W}{\partial E_I}$$

This marginal analysis, (see Figure 7) in contrast with Figure 6, conceptualizes the optimal level of irrigation efficiency rather than the quantity of water use.

It is important to understand the distinction between privately and publicly percieved benefits and costs of the level of irrigation efficiency. The effects of both the positive and negative impacts, i.e., a better distribution through time and quality degradation, of a lower level of irrigation efficiency are almost entirely external to the individual water user. The preceeding benefit/cost analysis is multidimensioned in time and space and only in this light is the individual water user viewed in proper perspective to the entire basin. In economic parlance, there

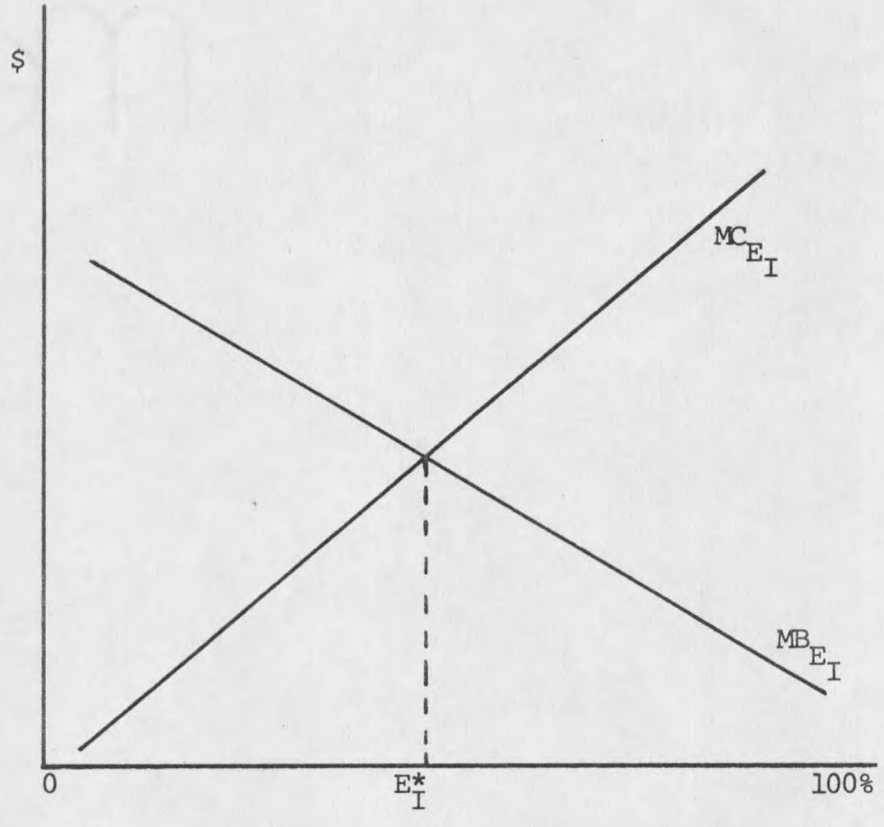

Figure 7. Marginal Benefits and Marginal Costs of Irrigation Efficiency (E_I).

are both positive and negative externalities associated with the level of E_I. Thus, there is a divergence in the public and private perceptions of both the marginal benefit and cost curves of Figure 7 as depicted in Figure 8.

There are two important implications implied in Figure 8. First, there is a divergence in the private and public marginal benefit and cost functions and therefore will result in a different level of E_I being viewed as optimal at the private and public levels, except in the unlikely case where they just happen to coincide. Second, given that there is a divergence in both the marginal benefit and cost functions, it is not obvious that there is a rigid, constant relationship in the two levels of E_I. In other words, it is not clear which one will be higher and whether or not the relationship between the two will always be the same. It is likely that site specific conditions, e.g., height of pumping, energy costs, whether or not the site is part of a publicly supported irrigation project, et cetera, will determine whether the private level of E_I is higher or lower than the publicly optimal level. In general, the predominantly nonmarket environment of water use as well as the nature of institutional regimes would likely result in privately determined levels of efficiency that are lower than would be publicly optimal.

There are a number of hydrologic and economic implications of policies which attempt to change the level of

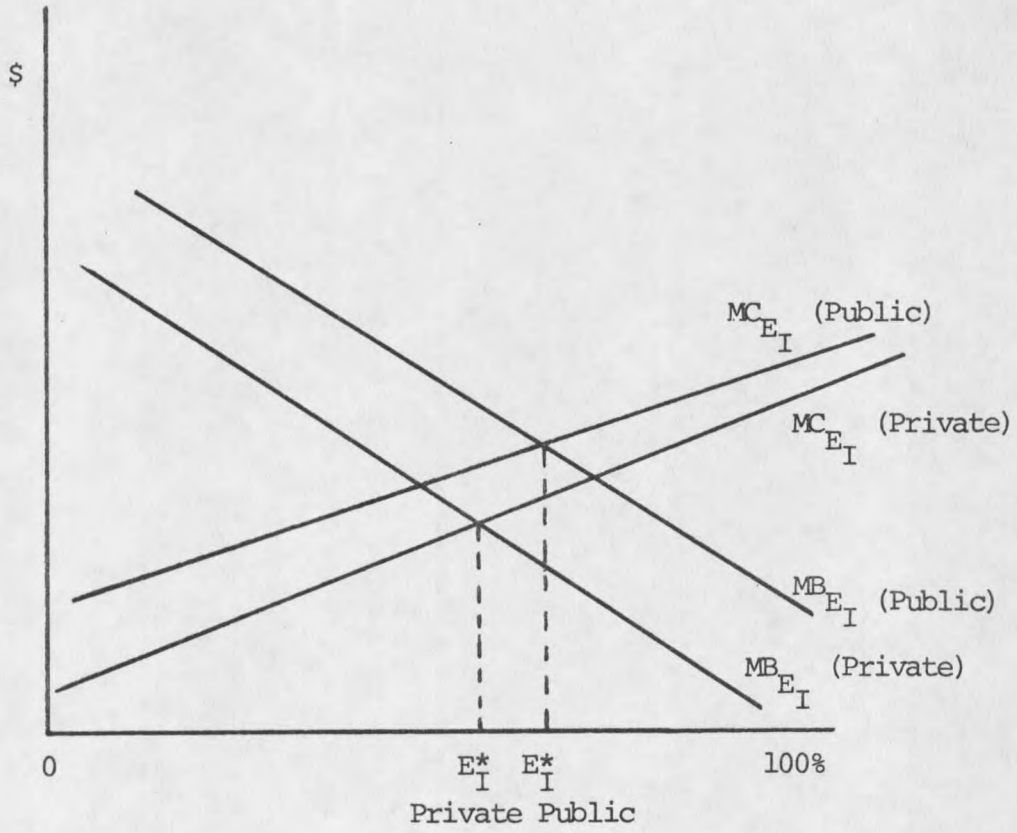

Figure 8. Public and Private Marginal Benefits and Marginal Costs of Irrigation Efficiency (E_I).

irrigation efficiency and subsequently change the level of return flows in the system. Anderson (1975) discusses the implications of return flows within a water rights regime of prior appropriation for irrigated agricultural producers. Johnson, Gisser and Werner (1981) deal with return flows in their discussion of a general model of efficient water allocation. Dudek and Horner (1981) discuss the effects of return flow control policies on income distribution among irrigators.

An Alternative Methodological Approach

Conceptually the foregoing theory is straightforward. However, empirical application of the theory would require a ponderous amount of data including; definition and valuation of all water uses, knowledge and modeling capability of both quantity and quality aspects of the hydrologic system, data regarding the cost and maintenance of irrigation conveyance and field systems at alternative levels of efficiency, and the definition of an appropriate planning horizon and discount factor to implement benefit/cost analysis. The complexities and stochastic nature of the hydrologic system, the fact that water resources operate in a predominantly non-market environment and consequently preclude reliable valuation data, and the nebulus nature of some uses, i.e., aesthetics etc., make this a more onerous task than can be adequately handled in this study.

An alternative modeling approach that will present an appreciation of the impacts of the level of efficiency and related factors while precluding an actual determination of costs and benefits is to use a "typical year" model. The "typical year" model, based loosely on the Marshallian concept of a representative firm in production theory, allows us to abstract, initially at least, from the stochastic nature of the hydrologic system, and the problems of planning horizons, discounting, and defining, valuing and projecting levels of all water uses.[6] This approach utilizes a linear programming framework to model a "typical year" that concentrates on irrigated agriculture, the primary consumptive user of water, and average levels of river flow in the basin. Other, less clearly defined uses of water are entered as constraints in the model, but not explicitly valued. Snyder (1976) utilized linear programming in his model to determine the value of water for irrigation in the Yellowstone River Basin. The partitioned linear programming framework was also utilized by Boyd (1968) and McConnen and Menon (1968) in water modeling applications.

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[2]Concerning the representative firm, Rima (1967) states, "The firm is not an actual firm, but rather an analytical tool which Marshall concieved..."

Chapter 3

The Model

In order to construct an analytical model according to the guidelines of Chapter 2, which will fulfill the objectives of Chapter 1, three precepts served as guidelines. First, the model must adequately simulate the hydrology of the basin. While the objectives prescribe an economic evaluation of the impact of alternative river management policies, such impacts are the result of interactions with the physical hydrologic system. Therefore, economic evaluation is contingent upon satisfactorily modeling the hydrologic processes. Second, economic evaluation of river management policies is contingent upon satisfactorily establishing the linkage between the economic phenomenon, which in this study is irrigated agriculture, and the hydrology of the basin. Third, the conceptual ideas in Chapter 2 indicate a number of applied policy issues which are beyond the scope of this thesis, but merit further investigation. Accordingly, the model was developed with enough flexibility to allow these issues to be dealt with at a later date without significant modification of the basic model presented here.

The remainder of this chapter is directed towards presenting the general linear programming framework and the adaptation of this framework to the specific problem dealt with in this study.

The Standard Linear Programming Problem

Linear programming (LP) is a mathematical technique that seeks to optimize a specific criterion over a vector of alternative activities subject to a set of linear constraints.

Let $j=(1,2,3,\ldots N)$ represent a set of N activities, where x_j is the quantity of the jth activity and $i=(1,2,3,\ldots M)$ represent a set of M resources or inputs into the N activities where b_i is the level of the ith resource available. The interdependencies between the x_j's and b_i's can be expressed as a system of M x N linear equations of the form:

$$\begin{aligned}
a_{11}x_1 + a_{12}x_2 + \ldots a_{1n}x_n &= b_1 \\
a_{12}x_1 + a_{22}x_2 + \ldots a_{2n}x_n &= b_2 \\
&\vdots \\
a_{m1}x_1 + a_{m2}x_2 + \ldots a_{mn}x_n &= b_m
\end{aligned}$$

where

$$x_j \geq 0, \quad j=(1,2,\ldots N)$$

The a_{ij}'s are the coefficients of proportionality, ie., the technical coefficients relating the ith input to the jth activity. The solution to the system of equations is obtained using an algorithm known as the simplex procedure (Dantzig, 1963).

The system of equations are optimized according to a specific objective function Z. For example, to maximize a set of activities x_j, (j=1,2,...N), each with a value of c_j, (j=1,2,...N), the objective function is

$$\max (Z) = \sum_{j=1}^{N} c_j x_j$$

The standard linear programming problem is subject to four general assumptions (Dantzig, 1963, pp. 32-33).

(1) Proportionality: In the LP model, the levels of resources used are always porportional to the activity level.

(2) Nonnegativity: Activities are always restricted to zero or positive levels.

(3) Additivity: The additivity assumption requires that each resource or input be completely accounted for in the model, ie. the total amount of individual resource use implied by the sum of all activities must be equal to the total amount of each resource available.

(4) Linear Objective Function: Each of the activities in the LP problem must contribute to the objective function in a linear fashion regardless of the level of the activity.

In addition, the general LP framework implies that there are a finite number of activities and resources and that these are infinitely divisible.

In addition to determining the optimal allocation of scarce resources among alternative uses, the LP solution will include calculated shadow prices for each resource constraint. These shadow prices represent the imputed values of a marginal unit of each of the resources. More specifically, the shadow price of a particular resource is the value of an additional unit of the resource used in the highest valued activity minus the opportunity cost of the resource in alternative uses. Therefore, in light of an optimal allocation of resources, the calculated shadow price of a resource represents the marginal value of that resource. The validity of the shadow price as an estimate of the true marginal value of that resource to society depends on the completeness of the model in reflecting social opportunity costs.

The linear programming framework is well suited to the needs of the study. As a methodological approach it fulfills two critical needs of the study. First, it is a model of the allocation of a scarce resource among a number of alternative uses. Second, by optimizing a specific criterion, it provides the mechanism whereby the impacts of factors affecting the scarce resource can be measured. However, as established in Chapters 1 and 2, both the

scarcity of water resources and the impacts of return flows in tne Yellowstone Basin are functions of time and space dimensions. Thus the adaptation of the linear programming model to include these dimensions is a first prerequisite.

Spatial Dimension

To facilitate the modeling of an area as vast as the Yellowstone Basin, the region is divided into nine sub-basins. These nine sub-basins (see Figure 9 and Table 1) represent the major tributary and mainstem regions of the Yellowstone Basin and are based on aggregations of hydrologic subdrainages used by the DNRC (1970). The drainage basin composition of the nine areas are also listed in Table 1.

Each of the nine sub-basins is modeled individually in the linear programming framework and combined, along with appropriate linkages among the sub-basins, in a partitioned linear programming framework. The Yellowstone River Basin, in tne context of mainstem river flow and tributary inflow, can be viewed spatially as a network similar to Figure 10 and, when adapted to the partitioned LP framework, results in a matrix format similar to Figure 11 where the sub-basin submatrices are sequentially linked to form the basin-wide model.

The linear programming model which was developed treats all activities within a sub-basin as if they occur at one point in space. Thus the model acts as if the nine

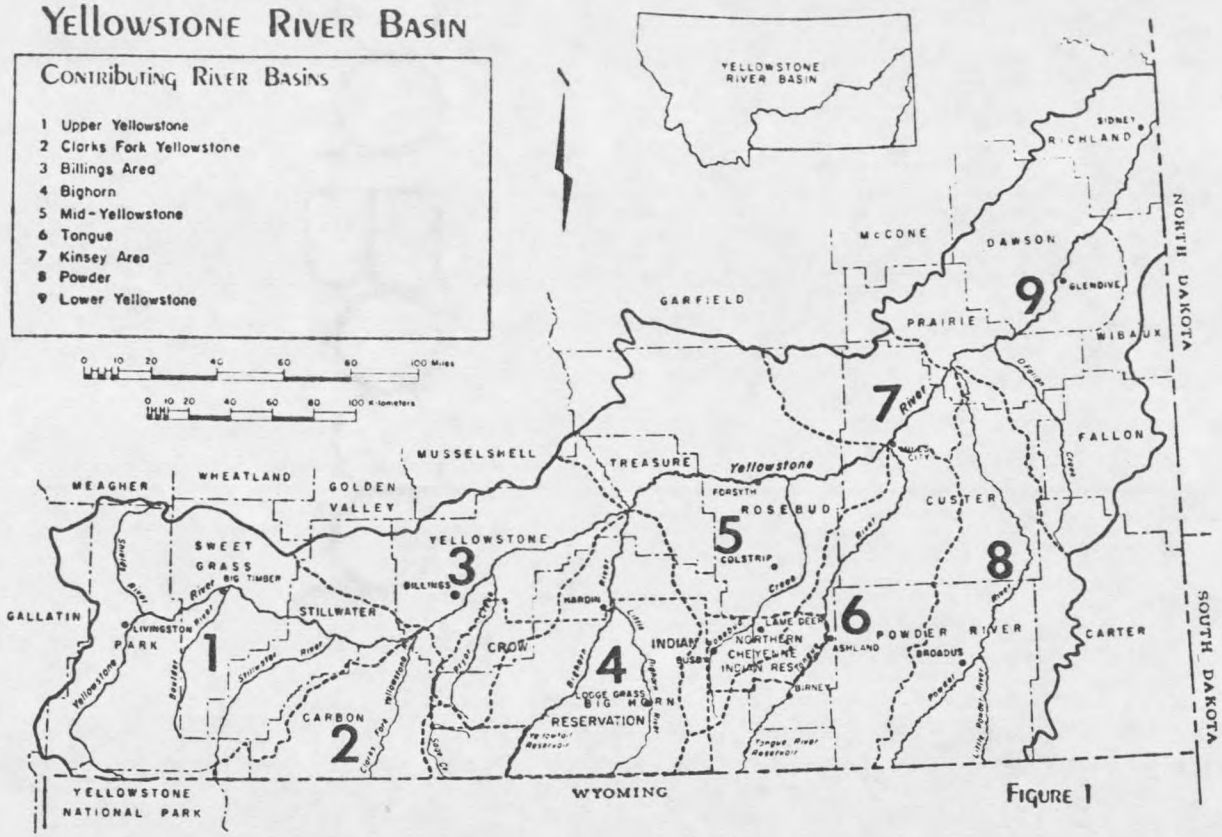

FIGURE 1

Figure 9. The Nine Planning Sub-basins of the Yellowstone River Basin. (From DNRC, 1977d)

Table 1. The Nine Sub-basins of the Yellowstone River Basin and Associated Hydrologic Drainages.

Sub-basin	Name	Hydrologic Basin
1	Upper Yellowstone	43A, 43B, 43C, 43BV, 43BJ, 43QJ
2	Clarks Fork	43D
3	Billings	43Q, 43E
4	Bighorn	43N, 43P, 43O
5	Mid-Yellowstone	43KJ, 42A
6	Tongue	42B, 42C
7	Kinsey	42K
8	Powder	42I, 42J
9	Lower Yellowstone	42L, 42M

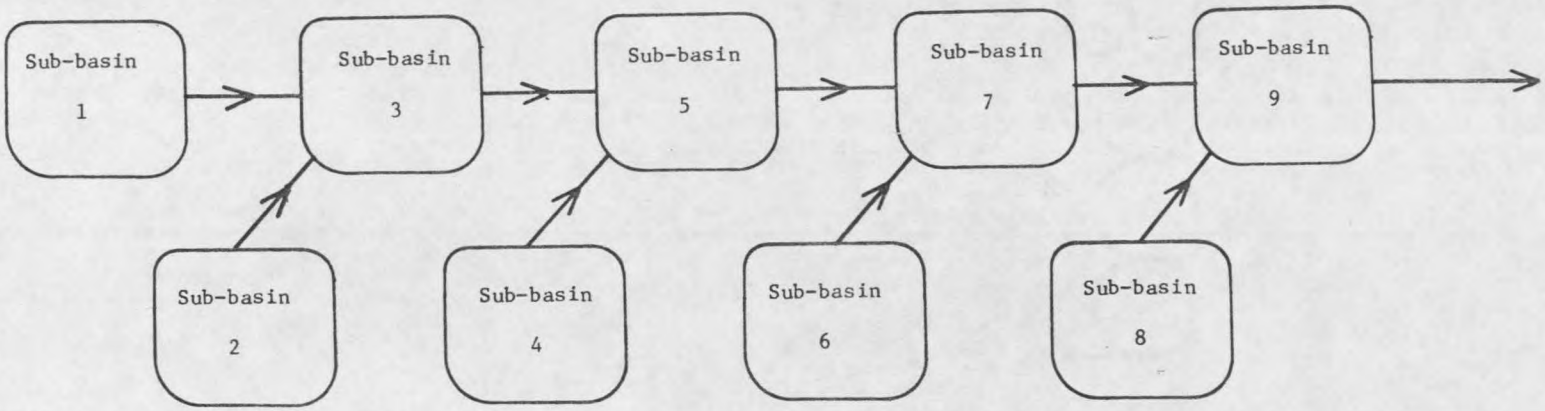

Figure 10. The Nine Planning Sub-basins as a Network.

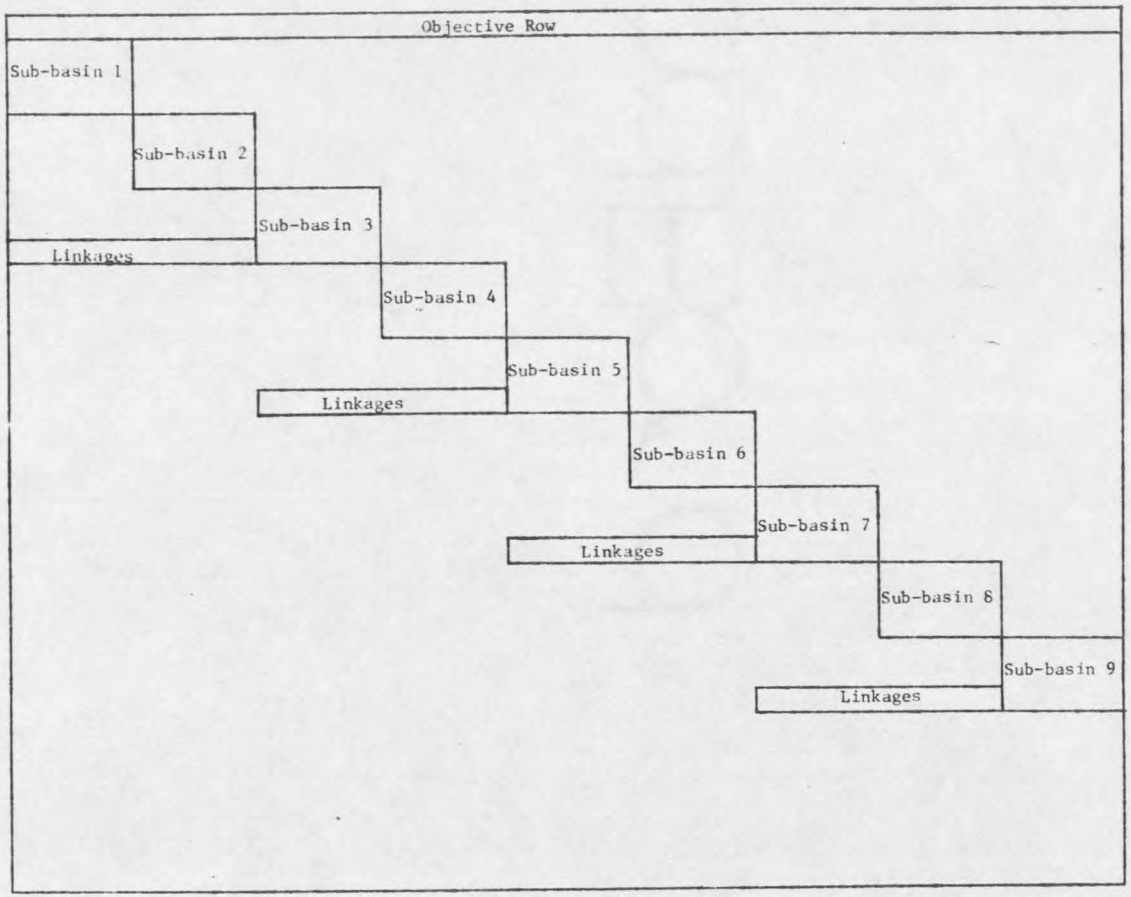

Figure 11. The Nine Sub-basins Submatrices in the Partitioned Linear Programming Framework.

sub-basins of the Yellowstone Basin are nine individual points in space. Further spatial realism could be added to the model by further dividing the sub-basins into smaller regions.

The nine area breakdown was chosen for three reasons. First, the nine area breakdown is compatible with other analytical work done in the Yellowstone Basin (Boris and Krutilla, 1980 and DNRC, 1977d). Therefore, the results of this study will be compatible with those of other studies. This will facilitate the ability of water planning officials to interpret the results presented here. Second, the nine area breakdown works quite well to facilitate the meshing of alternative data sources. Much of the economic and agricultural data are county based whereas the hydrologic data are based on hydrologic sub-basins. Third, each additional sub-basin substantially increases the size of the basin-wide model. Therefore, in order to conserve on both computational time and time spent in model construction, the model should be no larger than required to deal with the problem under investigation.

Time Dimension

While it is the intent of this study to utilize an annual "typical year" type model utilizing average levels of annual river flows, the nature of the hydrologic and agricultural processes necessitate modeling the characteristics of flow within the year. This is accomplished in

the LP model by replacing single activities and constraints based on annual values with a series representing monthly values. For purposes of this study the LP model contains 5 time intervals representing the 5 months, May through September, thereby representing the majority of the irrigation season. Instead of one (annual) water balance equation for each sub-basin, there are five balance equations, one for each of the five months of the irrigation season. The hydrology of the basin requires that these five time intervals be interrelated due to the nature of return flows and crop consumptive use of water. Expansion of the model to encompass all periods of the year is straightforward and could be accomplished by an increase in dimension of the model.

The Hydrologic Model

The movement of water through time and space is simulated mathematically by material balance equations.

1) $\text{Outflow}_t = \text{Inflow}_t - \text{Use}_t$

Equation 1 is a simple version of such a balance equation which says that the outflow of water from a sub-basin in time interval t must be equal to the inflow minus the use in time interval t. In this example, inflow and outflow must be interpreted more broadly than just streamflow to include "effective" inflow and outflow such as internal precipitation, temporary groundwater infiltration, and

storage. Of course "Use_t" can be separated into categories for any number of alternative uses. Rewriting equation 1 as

1a) $Use_t + Outflow_t = Inflow_t$

sets the stage for incorporation of the material balance equation into the linear programming framework where inflow is a specified right-hand side (RHS) and uses and outflow are activities. By forcing the strict equality, the outflow becomes a residual activity such that, any water not "used", must become outflow and move into the next sub-basin downstream; thus simulating the "flow" of the river.

Figure 12 is a representation of the major components of the model used in this study. All of the water which enters a sub-basin must either be diverted for irrigation, used for energy production, municipal, or minimum flow (instream) requirements or sent downstream as undiverted flow. In this case, the undiverted flow is the residual activity to ensure that the water equation balances, and therefore is a component of outflow. Minimum flow represents minimum river levels required to maintain wildlife habitat and water quality and is one of three categories of exogenous uses, but, as it is an instream use it is also a component of outflow.

The exogenous use categories; energy production, municipal, and minimum flow enter the model at specified

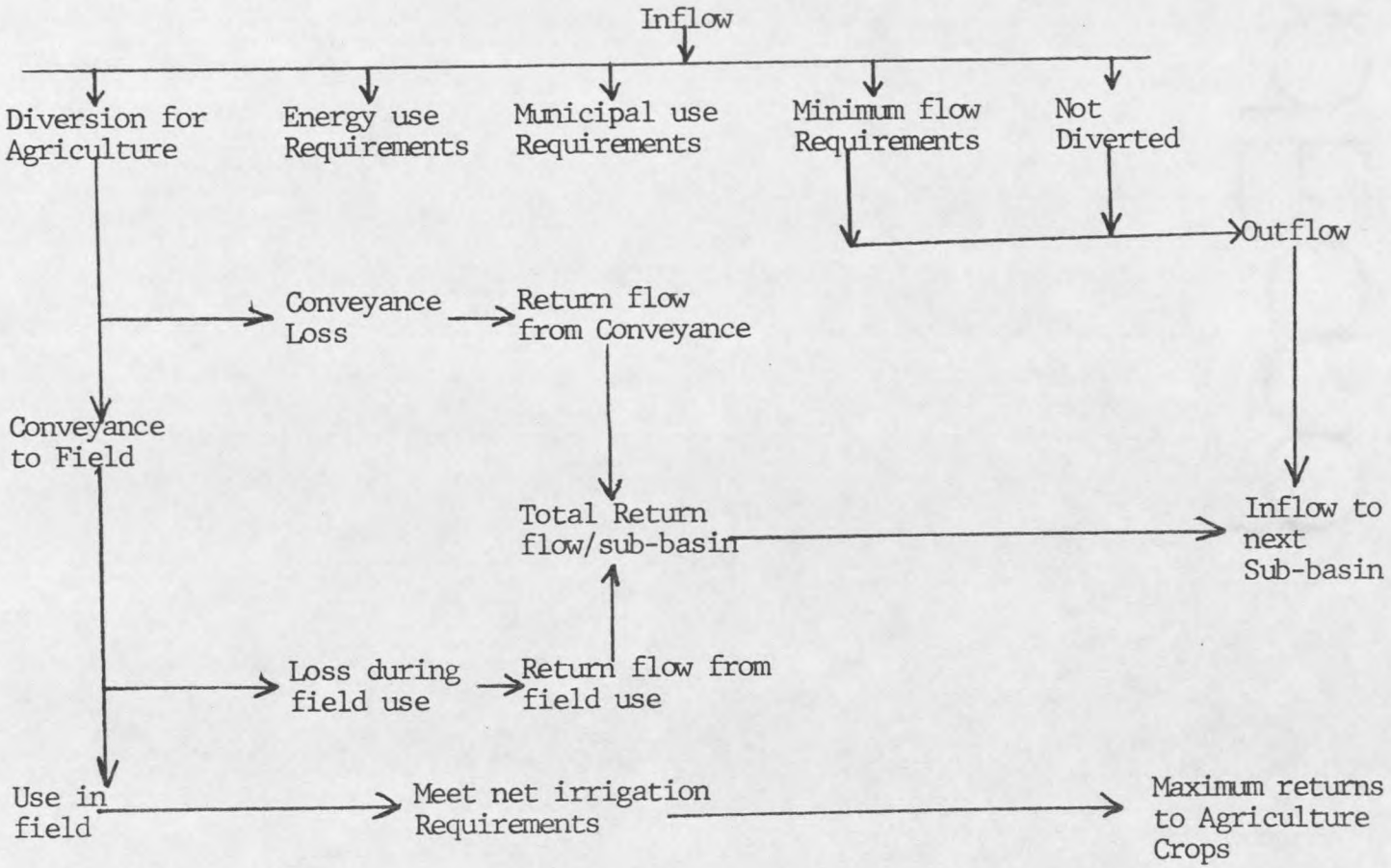

Figure 12. Flow Chart of the Principal Components of the LP Model.

levels, by time interval and sub-basin, in the form of row constraints which must be satisfied. Minimum flow constraints, based on instream reservations for fish, wildlife and water quality maintenance granted by the Board of Natural Resources and Conservation, represent a significant portion of the water available in the river. Energy and municipal use of water at the present time are small relative to total river flow. However, the inclusion of these components in the model greatly increases its flexibility to simulate scenarios of increased levels of these alternative uses.

The Irrigated Agriculture Model

Modeling the movement of irrigation water from the river to the plant through the conveyance and field systems is accomplished via a network of transfer activities and balance equations. The conveyance and field use processes are simulated with transfer activities which divert water from the "river", (the water balance equation), and deliver a portion of that water to the plant for its use. Not all of the diverted water is delivered because of conveyance and field losses, that is, because conveyance and field efficiencies are less than 100 percent. The diversion, conveyance, field use, and crop net irrigation requirement portion of the linear programming model is depicted conceptually in the tableau presented in Figure 13. The tableau presents, as detached coefficients, those portions of the

	Divert Water	Field Use of Water	Crop Activity			RHS
Water Balance Equation	1				=	Inflow
Conveyance Equation	$-E_c$	1			=	0
Field Use Equation		$-E_u$	N.I.R.		=	0

E_c = conveyance efficiency
E_u = irrigation unit efficiency
N.I.R. = net irrigation requirements

Figure 13. "Movement" of Water From the River to Crops in the LP Model.

relevant equations which show how the model establishes the linkage between the cropping activities and river flow via the conveyance and field systems. Thus, in an abstract sense, the "movement" of water from the river to the crop is modeled as depicted by the directional arrows. For illustration ease, the tableau only shows the equations for a single time interval.

Referring to Figure 13, and assuming for simplicity that conveyance efficiency (E_c) and irrigation unit (field) efficiency (E_u) are both 50 percent, if one acre-foot of water is diverted from the river, then one-half acre-foot will be delivered to the field. Of the water delivered to the field, one-half will be delivered to the plant for consumptive use. Thus, of the original one acre-foot diverted from the river, only one-quarter acre-foot was ultimately used by the plant. A different set of these rows and activities exists for each time interval (month) and sub-basin. Alternative irrigated crops can be produced in the sub-basins. The cropping activities are linked to the hydrologic model via net irrigation requirements for each crop which are specified by month and must be satisfied in order to "grow" a particular crop. In this sense the model is limited to a single irrigation scheme for each crop in each sub-basin. In other words, the current model does not permit a crop to have a lower yield and hence

require less water. However, the model could be expanded to include such alternatives if data were available.

The model does not attempt to simulate the entire agricultural production process for each of the crops. With the exception of water, the model assumes that all other production inputs are available and production requirements are satisfied for each crop. The total number of irrigated acres in each sub-basin are constrained, but the optimum cropping pattern is determined by the linear programming model.

The model implicitly assumes that each sub-basin is characterized by homogeneous soil types, farming systems, management levels, etc. Thus, it tacitly assumes that each sub-basin is composed of a series of average or typical farms that are all alike.

The Objective Function

The objective function is the driving force of the linear programming model. In this model, the objective function is specified to maximize returns over variable costs to the vector of crops in each area. In addition the objective function contains a nominal charge of $5.00 per acre-foot for diversion activities. This is constant for all sub-basins and is not an actual diversion cost but is intended to insure that the model is efficient, ie., doesn't divert any more water than necessary for crop use.

The Basin-wide Model

The linkages between the nine sub-basins that result in a basin-wide model of river flow consist of two components; instream flow between sub-basins and return flows from irrigation. River flow from an upstream sub-basin to an immediately downstream sub-basin consists of two outflow components. The two outflow components of a sub-basin are the undiverted water which satisfies the minimum flow requirements and the residual activity, i.e., other undiverted flow. These occur in the linear programming model as a transfer between the water balance equations of the upstream and downstream sub-basins by time interval. Figure 14 is a conceptual tableau representing this transfer of instream flow from an upstream sub-basin to an immediately downstream sub-basin for a given time interval. The tableau is a simplified representation of this transfer process and includes only the necessary portions of the equations involved.

Thus, in Figure 14, each acre-foot of water engaged by the minimum flow activity of the upstream area, to meet the minimum flow constraints for that sub-basin, will be transferred to the balance equation of the sub-basin immediately downstream. Similarly, for each acre-foot of water engaged by the residual undiverted flow activity of the upstream sub-basin, to balance the water balance equation, an

	Minimum Flow	"Not Diverted"		RHS	
Water Balance Equation	1	1	=	Inflow	Upstream Sub-basin
	•	•			
	•	•			
Water Balance Equation	- 1	- 1	=	Inflow	Downstream Sub-basin

Figure 14. "Movement" of Instream Flow From an Upstream Sub-basin to an Immediately Downstream Sub-basin.

acre-foot will be transferred to the water balance equation of the sub-basin immediately downstream.

The sign convention of the LP model in this study uses positive coefficients to represent "demanders" and negative coefficients to represent "suppliers" for transfer activities and balance equations. Therefore the minimum flow and the residual undiverted flow activities are "demanding" water from the upstream sub-basin and "supplying" water to the sub-basin immediately downstream. If the downstream sub-basin has no internal streamflow source, then the RHS of the water balance equation will be zero since the inflow into that sub-basin enters on the left side of the water balance equation, i.e., the outflow from the upstream sub-basin. All of the tributary sub-basins and the upper mainstem have water entering across the state line from Wyoming and/or generate significant quantities of streamflow within the sub-basin and therefore have positive RHS on the water balance equations. However, most of the mainstem sub-basins are located in the plains region of the basin, i.e., they are not headwater areas, and therefore do not make significant contributions to streamflow.[1]

The return flows that reenter the surface flow system are somewhat more complicated both with regard to the time

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[1]This assumption is modified somewhat in the calibration procedure described in Chapter 5.

and space dimensions. Spatially, it is assumed in this model that in the tributary and upper mainstem sub-basins, (1,2,4,6,8), water is diverted by individual users which are scattered homogeneously throughout the sub-basins such that virtually all of the return flow from irrigation is available for reuse by an irrigator in that same sub-basin. Most of the mainstem sub-basins (3,5,7,9), in contrast, are characterized by distinct diversion points for large irrigation projects and consequently return flows are not available until the next sub-basin downstream. The major exception to this assumption is sub-basin 3, the Billings area, which is something of a transition area. Consequently, in the Billings sub-basin it is assumed that 60 percent of its internally generated return flows are available for rediversion within sub-basin 3 and 40 percent will not be available for reuse until sub-basin 5, which is immediately downstream.

Return flows also cross over time intervals because of their delayed nature. Thus, return flows from a May diversion, for example, will contribute to the May water balance equation, the June water balance equation, et cetera.

Reservoirs

The model also includes simulations of the two largest reservoirs in the basin, the Yellowtail Dam on the Big Horn River (sub-basin 4) and the Tongue Reservoir on the Tongue River (sub-basin 6).

The actions of a reservoir are simulated by a series of transfer activities and balance equations. Figure 15 depicts conceptually the simulation of reservoir activities for a particular time interval. For example, in time interval t, the water "supplied" to the reservoir comes from either water held in the previous time interval and not released or water held from river flow in this time interval. The balance equation for reservoir use in each time interval are subject to a strict equality, i.e., all of the water "supplied" must be demanded in some activity. Thus, the water "supplied" to the reservoir, in each time interval, can be "demanded" for either reuse in that same sub-basin, release to the sub-basin immediately downstream, or transferred to the next time interval as reservoir storage. In other words, the reservoir balance equation for a particular time interval says that the sum of the quantity of water held over from the previous time interval plus the quantity held from river flow in this time interval must equal the amount of water used in the sub-basin in this time interval plus the amount released downstream in this time interval plus the amount held over into the next time interval.

The use of positive and negative C_j's in the objective function allows the model to simulate any number of possible reservoir management scenarios, which may be desired, again contributing to the flexibility of the model.

	Transfer water from t-1 to t	Store water in t	Release water downstream in t	Release water back into sub-basin in t	Transfer water from t to t+1		RHS
Water Balance Equation (t)		1				=	Inflow
Reservoir Balance Equation (t-1)	1					=	0
Reservoir Balance Equation (t)	-1	-1	1	1	1	=	0
Reservoir Balance Equation (t+1)					-1	=	0

t = time interval

Figure 15. Simulation of Reservoir Actions in the LP Model.

Chapter 4

Data Sources and Preparation

The Basic Model

The linear programming model requires three basic types of data; the values of the resource constraints (the right hand sides, RHS), the values of the matrix coefficients (the a_{ij}'s), and the values in the objective function (the C_j's). The major resource constraints for this model are; the water flowing into the the basin, i.e., the RHS of the water balance equations, acreage restrictions, and the values of the exogenous use activities. These include minimum instream flow for fish and wildlife habitat and water quality maintenance, water used in energy production, and water for municipal use. The primary a_{ij}'s are the conveyance and field efficiencies, return flow coefficients, the net irrigation requirements for the cropping activities and those for land use. The rest of the a_{ij}'s are required for the functioning of material balance equations and transfer activities. The major objective function values are the returns over variable costs (ROVC) for each of the crops grown in each sub-basin.

Hydrologic Data

Streamflow gauging data on the Yellowstone River was obtained from the U. S. Geological Survey's computerized data bank. The years 1963 to 1977 were used as a base period for the calibration model and as the basis of comparison for subsequent applied runs. The time period of 1963-1977 is not in keeping with the assumption about a "typical year", in terms of river flows, since the average flows for this period of years is greater than the long run average of river flows.[1] The problems in determining "average" flows were discussed in Chapter 1. This particular base period was chosen because it coincided with the base period of other hydrologic data and with available cropping data and thereby facilitated the calibration procedure.

The model requires that the "inflows" into the tributary and mainstem sub-basins be specified as RHS. However, the mathematical nature of linear programming treats each sub-basin as a point in space, i.e., inflows and outflows occur at the same point. Thus, in a realistic sense, it is necessary to treat the water which flows out of a particular sub-basin as being available for diversion throughout that sub-basin and therefore is treated as inflow. In

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[1]The 1963-1977 average annual flow at Sidney was 10.3 mmaf compared with the 1934-1980 average annual flow of 8.9 mmaf.

sub-basins where very little streamflow is generated within the sub-basin and outflow, in the absence of human influences, is nearly the same as inflow, treating outflow as inflow is of little consequence. However, in sub-basins where there is substantial internal runoff, limiting specified inflow to measured stream inflow would seriously underestimate the water available in that sub-basin.

In conjunction with the previous notion, it is imperative to keep in mind that the historically measured outflow from a sub-basin, on a monthly basis, already reflects a historical pattern of diversion and return flow which occurred in that sub-basin. More correctly, it reflects the net difference of diversion in that month and return flows that returned in that month. Thus, what is really required as a RHS is the pristine flow of the river, that is, the flow of the river in the absence of human influences. Estimates of pristine river flows were provided by Phil Farnes of the Montana office of Soil Conservation Service, U.S. Department of Agriculture.

Conveyance and Field Efficiencies

Conveyance and field efficiencies for the nine sub-basins were obtained from SCS-USDA (1978). Current levels of conveyance and field efficiencies used in the basic model are presented in Table 2 along with increased levels of efficiencies for the other scenarios which are discussed later in this chapter.

Table 2. Current and Future Levels of Conveyance and Field Efficiencies. (From SCS-USDA, 1978)

Model / Scenario	Sub-basin 1	2	3	4	5	6	7	8	9
					Conveyance				
B1 (1980)	43	40	50	50	50	50	50	50	32
E1 (1990)	56	54	59	59	59	59	60	60	44
E2 (2000)	68	67	68	68	68	68	69	69	56
E3 (2010)	81	81	77	77	77	77	79	79	68
					Field				
B1 (1980)	40	40	46	42	45	45	51	50	51
E1 (1990)	47	51	51	48	50	50	58	57	53
E2 (2000)	54	61	55	54	54	54	64	64	55
E3 (2010)	61	72	60	60	59	59	71	71	57

Return Flows

The determination of the general pattern of return flows was a most difficult empirical task. To the extent that there has been hydrologic work to determine return flow patterns, it has always been extremely site-specific studies where hydrologists can account for factors such as soil types, topography, and the geomorphology of the locality. What was needed for this study was a general pattern of return flows, i.e., a pattern which represents the average return flow pattern over the range of soil types and topographical features found in a basin.

Substantial time was spent in conjunction with this study attempting to empirically estimate a general pattern of return flow for the Yellowstone Basin. While not entirely successful, work did lead to indications of the pattern of return flows found in the Yellowstone Basin. These indications tended to be confirmed by data from the Bureau of Reclamation-USDI about return flow patterns in the Shoshone Project in Wyoming and led to the adoption of the return flow pattern shown in Table 3 for use in this study.[2]

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[2]The Bureau of Reclamation-USDI data is contained in a letter from the Upper Missouri Regional office, Bureau of Reclamation-USDI, Billings, Montana, August 13, 1982.

Table 3. Return Flow Pattern Used in the LP Model.

Return flow occurring:	Percent of total losses:
Same month as diversion	40
1st month after diversion	12
2nd month after diversion	10.4
3rd month after diversion	6.4
4th month after diversion	3.2
5 month total[3]	72.

Minimum Flow Requirements

The minimum flow requirements for each area, for each of the five months in the model, are listed in Table 4. The values used are the instream reservation amounts granted by the Board of Natural Resources and Conservation.[4]

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[3] In other words, 72 percent of the losses from conveyance and field systems has returned in 5 months. The remaining 28 percent is composed of losses which are either non-recoverable or will return after the fifth month.

[4] Minimum flow requirements are based on the final instream reservations published in Boris and Krutilla (1980, Table 7-1) except for the Billings Area where recent adjustments have been made. The values for the Billings Area are contained in a letter from Richard Moy, Chief, Water Management Bureau, DNRC, September 14, 1982.

Table 4. Minimum Instream Flows (acre-feet).

	Sub-basin								
	1	2	3	4	5	6	7	8	9
May	180,454	1,000	469,309	233,600	755,000	4,600	755,000	26,000	735,500
June	489,800	3,420	1,093,122	309,300	1,558,000	4,500	1,558,000	11,000	1,496,000
July	232,000	1,400	370,392	221,000	632,000	4,600	632,000	4,000	647,000
August	120,000	381	215,205	172,000	237,000	4,600	237,000	900	164,000
September	92,508	346	184,878	155,000	267,000	4,500	267,000	500	195,000

Municipal & Energy Related Water Use

At the present time, water used for municipal and energy related activities is insignificant relative to total flow. Values for these uses are based on estimates of water use in these categories by Boris and Krutilla (1980).[5] Energy requirements of 3500 acre-feet/month are used in sub-basins 5, 6, and 8 which encompass present locations of coal related industry in the basin. All other sub-basins have zero energy related water use. Requirements for municipal use are 500 acre-feet/month for the Upper Yellowstone, 3000 acre-feet/month for the Billings Area, 120 acre-feet/month for the Mid-Yellowstone and 140 acre-feet/month for the Lower Yellowstone. The inclusion of both of these activities is far more important methodologically than for reasons of present significance as discussed in Chapter 3.

Irrigated Acres

Irrigated acreage for each of the nine sub-basins is based on estimates obtained from SCS-USDA (1978). These estimates tend to be higher than actual measurements of

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[5]The energy related water use values in the model are based on estimated coal production in the immediate future (approximately 72 million tons), see Boris and Krutilla (1980, Table 5-7). The values for water for municipal use are based on water reservations granted for municpal use and a depletion rate of 50 percent of diversion, see Boris and Krutilla (1980, Table 6-8).

irrigated acres in any given year that would be obtained from the Montana Department of Agriculture because it includes acres that are irrigated intermittently.[6] The higher estimates were used because it was felt that it more correctly represents the currently irrigable acreage in the basin. A total of 569,100 irrigated acres are used in the model. The irrigated acres for each sub-basin are presented in Table 5.

Irrigated Crops

The vector of alternative irrigated crops for each of the nine sub-basins was chosen, based on historical data, to be tnose principal crops which, collectively, will account for approximately 95 percent or more of the irrigated acres in the county. This was based on data from the Montana Department of Agriculture for all crops except irrigated pasture which was based on information from the Bureau of Census. The alternative crops for each of the nine sub-basins are listed in Table 6.

It is appropriate to view the barley cropping activity as a proxy for all irrigated spring grains (oats, spring wheat, et cetera) because of close similarities of the crops with regard to irrigated production. For the calibration model, where a historical cropping pattern was specified as

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[6]For example, the 1977 Montana Agricultural Statistics lists a total of 434,555 irrigated acres in the Yellowstone Basin.

Table 5. Irrigated Acreages of the Nine Sub-basins Used in the LP Model. (From SCS-USDA, 1978)

#	Sub-basin Name	Irrigated Acres
1	Upper Yellowstone	148,208
2	Clarks Fork	93,532
3	Billings	94,490
4	Bighorn	61,110
5	Mid-Yellowstone	58,800
6	Tongue	11,635
7	Kinsey	19,590
8	Powder	11,075
9	Lower Yellowstone	70,660
	Basin Total	569,100

Table 6. Alternative Crops for the Nine Sub-basins.

Upper Yellowstone	barley, alfalfa hay, other hay, pasture, sugar beets
Clarks Fork	barley, alfalfa hay, other hay pasture, sugar beets, beans, corn silage
Billings	barley, alfalfa hay, other hay, pasture, sugar beets, corn (grain), corn silage, beans
Bighorn	barley, alfalfa hay, other hay, pasture, sugar beets, corn (grain), corn silage, beans
Mid-Yellowstone	barley, alfalfa hay, other hay, pasture, sugar beets, corn (grain), corn silage, beans
Tongue	barley, alfalfa hay, other hay pasture, corn silage
Kinsey	barley, alfalfa hay, other hay, pasture, sugar beets, corn (grain), corn silage, beans
Powder	barley, alfalfa hay, other hay, pasture, sugar beets, corn (grain), corn silage
Lower Yellowstone	barley, alfalfa hay, other hay, pasture, sugar beets, corn (grain), corn silage, beans

a part of the calibration procedure, the barley activity was explicitly a proxy and included acreages of oats and spring wheat in the calculation of the cropping pattern.

Returns Over Variable Cost (ROVC)

The objective function of the model is to maximize ROVC's of the different crops which can be grown in the basin. The ROVC's used in this model are based on modified enterprise budgets prepared by the Cooperative Extension Service. The modified budgets are listed in Appendix A.

Sugar Beet and Bean Acreage Restrictions

In addition to the overall acreage restrictions in a sub-basin, restrictions were placed on the maximum acreages of beans and sugar beets. Both sugar beets and beans are specialized crops grown under intensive management and production regimes. The large objective function values of these crops would result in abnormally high acreages if they were left unrestricted. Therefore exogenous constraints were used to restrict acreages of those two crops to more realistic levels. Sugar beet acreage is limited to the number of acres contracted with the buyer in the Yellowstone basin. Therefore sugar beet acreage in the model is limited to the average historical acreages which approximates the number of contract acres. Beans are also limited to the average historical acreage in the basin.

Net Irrigation Requirements

The quantity of water required for each crop for each month of the growing season are based on the net irrigation requirements published by the SCS-USDA. This leaves intact the SCS assumptions about the occurrence of effective rainfall that are implicit in that publication. Each of the nine sub-basins had to be classified according to climatic zone (see Appendix B) and then net irrigation requirements for each crop in each area are determined. These requirements are presented in Appendix B.

Since irrigation requirements are not published for the "other hay" category, (grass and native hay) it was assumed that "other hay" is irrigated exactly like alfalfa hay except that irrigation stops at the end of July after one cutting has been harvested. While it is undoubtedly true that some portion of this category is irrigated after July, at least for pasture, it also seems likely that many "other hay" acres are irrigated from streams where flows are restricted in late summer.

Alternative Scenarios

Increased Irrigation Efficiency Scenarios

Estimates of current levels of conveyance and field efficiencies along with estimates of increases to be achieved by the year 2000 were taken from SCS-USDA (1978). An intermediate level was extrapolated by taking the

current level plus half the distance between the current and year 2000 level. Also, a high level was extrapolated as being equal to the year 2000 level plus half the distance between the current and year 2000 levels. This provides three scenarios for increased irrigation efficiency in addition to the current values. While there is no guarantee that these increased levels will be achieved at the implied times, approximately years 1990, 2000, and 2010, they provide a reasonable basis for speculation about attainable levels from a technical standpoint. The values of conveyance and field efficiencies used in these scenarios are listed in Table 2.

Dry Year Scenarios

Variation in available water supplies from year to year is a critical factor affecting the possibilities for river management. Thus, it was deemed important to indicate the impacts of dry years. The physical impact of dry years are simulated in two joint aspects of the model, decreased river flows and increased net irrigation requirements. The increased net irrigation requirements were necessary in this model because the basic model incorporates the assumption of normal levels of effective rainfall in determining the net irrigation requirements.

For present purposes, adjustments were made in river flows and rainfall that would be indicative of the impacts involved. Using annual flows of the Yellowstone River for

a period of 55 years at Sidney as a guide, and assuming a normal distribution of river flows, it is estimated that flows greater than 6.9 mmaf would occur more than 90 percent of the time and flows greater than 8.87 mmaf would occur more than 80 percent of the time. In reality, the river flows do not appear to be distributed normally. Actual frequency calculations from the 55 year period indicate that flows greater than or equal to the specified flows would occur about 75 and 54 percent of the time respectively. In other words, flows less than the "driest" flow used these scenarios (6.9 mmaf) actually occurred 46 percent of the time in the historical period.

Using data provided by Caprio, Snyder, and Grunwald (1980), reductions in rainfall which would occur 90 and 80 percent of the time were also estimated. The estimates of the net irrigation requirements were then adjusted according to the lower levels of rainfall.

The adjustments in river flow and rainfall were generalized into constant percentage changes in river flows and net irrigation requirements and applied proportionally in all sub-basins. The first dry year scenario is based on decreases in river flows of 14 percent and increases in net irrigation requirements of 13 percent. The second dry year scenario is based on river flow decreases of 33 percent and increases in net irrigation requirements of 21 percent.

Increased Level of Agricultural Prices

Values associated with water for irrigated agricultural use are imputed values derived from the value of the agricultural products produced with water. Thus, a change in the level of prices for agricultural products will change the value of water and will have economic impacts pertinent to water management policies if water is a scarce resource. Adjustments in prices were made based on ratios of the prices paid and prices recieved indices. For example, as an approximation to the level of returns to agriculture which prevailed in 1973, the ratio of the 1973 prices recieved and prices paid indices were compared to the 1980 ratio of these indices and then the adjustments of the prices recieved in the 1980 budgets in order to approximate the 1974 ratio can be calculated. This procedure resulted in increased prices recieved in the 1980 budgets of about 42 percent. This was used as the first higher agricultural prices scenario. A second scenario based loosely on projections of the prices paid and recieved indices which would exist if there was an increase in the prices of agricultural crops in the 1980 budgets of about 70 percent.

Indexing the prices recieved alone also results in changes in the relative values of crops as well, which is to be expected. However, it is desirable in this analysis to look at the impact of higher levels of agricultural

returns ceteris peribus, i.e., holding everything else, including the relative ranking of the ROVC's of the crops constant. Therefore, the increases in prices received were translated into constant percentage changes in the ROVC's and applied to all crops. The two scenarios resulted in proportionate increases in ROVC's of 78 and 134 percent respectively.

Increased Irrigated Acreage Scenarios

Three scenarios of additional irrigated acreage were also developed. The first two scenarios are based on projections of economically feasible additional acreage at a "low" and "intermediate" level of future development done by the DNRC (1977d). These two scenarios represent additional irrigated acreages of 79,160 and 158,310 acres respectively. A third scenario, which represents an increase in irrigated acreage even beyond the DNRC "high" level (237,480 acres), is based on the total number of additional acres for which water reservations have been granted, 265,881 acres. In each of these scenarios the additional acres are distributed throughout the basin according to the distribution of currently irrigated acres.

Chapter 5

Results

The results of using the LP model to generate a solution for the basic Yellowstone River Basin model and for a series of alternative scenarios are presented in this chapter. The alternative scenarios involve factors which affect either physical or economic variables which have implications for water management policies. Each of the scenarios is based on a variation of one major component of the model while the remaining components are held constant. The purpose is to analyze the impact of changes of that component on the rest of the system.

The following is a summary of the basic model and the scenarios which were developed in Chapters 3 and 4 and the notation used in presenting the results.

The Basic Model

B1 This is the model of the Yellowstone River Basin at the present time. It incorporates current levels of conveyance and field efficiencies (representing a basin-wide irrigation efficiency of 19 percent), currently irrigated acres, returns over variable costs based on 1980 crop budgets, specified return flow pattern, current minimum instream flow requirements, and adjusted river flow values from the calibration phase.

Increased Irrigation Efficiency Scenarios

E1 Conveyance and field efficiencies are increased about 43 percent over the basic model levels to a basin-wide irrigation efficiency 28 percent.

E2 Conveyance and field efficiencies are increased about 92 percent over the basic model levels to a basin-wide irrigation efficiency of 37 percent. This level of efficiency is that projected by the SCS to be achieved for the year 2000.

E3 Conveyance and field efficiencies are increased about 150 percent over the basic model levels to a basin-wide irrigation efficiency of 48.5 percent.

Dry Year Scenarios (compared to the basic model which is based on an annual flow at Sidney of 10.2 mmaf, the average flow for the 1963-1977 period.)

D1 Specified river flows are decreased 14 percent and net irrigation requirements increased 13 percent from the basic model. This represents an annual flow of 8.87 mmaf at Sidney which is only slightly below the 1934-1980 historical average of 8.9 mmaf. Flows lower than this level occurred historically 23 out of 55 years in the 1924-1980 period.

D2 Specified river flows are decreased 33 percent and net irrigation requirements increased 21 percent from the basic model. This represents an annual flow at Sidney of 6.9 mmaf. Flows lower than this level occurred historically 13 out of 55 years in the 1924-1980 period.

Increased Irrigated Acreage Scenarios

A1 Irrigated acreage of the basin is increased by 79,160 acres, about 14 percent over the basic model.

A2 Irrigated acreage of the basin is increased by 158,310 acres, about 28 percent over the basic model.

A3 Irrigated acreage of the basin is increased by 265,881 acres, about 47 percent over the basic model.

Increased Agricultural Prices Scenarios

P1 Returns over variable costs of all crops are increased 78 percent over the basic model levels. This approximates the level of ROVC's for agricultural products in 1973.

P2 Returns over variable costs of all crops are increased 134 percent over the basic model levels.

Calibrating The Model

The Yellowstone River Basin is fed by a multitude of ungauged streams which contribute to streamflow as stream augmentation. Also, river flow is subject to losses due to deep percolation from the river bed and evaporation from the stream surface. Net stream augmentation (NSA) is defined as the sum of stream augmentation and stream losses, for a particular reach of river and time interval. Net stream augmentation can be either positive or negative depending on whether the losses outweigh the augmentations in a given time interval. Inspection of gauging data shows that in winter months actual measured outflows from some areas are less than inflows indicating that net stream augmentation can become negative at certain times.

Neither stream augmentations or stream losses have been empirically measured along the Yellowstone River. A balance equation of river flow for a particular time

interval that accounts for net stream augmentation and return flows is

$$\text{Outflow} - (\text{Inflow} + \text{Diversion}) = (\text{NSA} + \text{Return flow})$$

Reasonable estimates of the quantity (NSA + Return flow) can be obtained using observed values of inflow and outflow and calculated diversions, which are based on estimated irrigation efficiencies, net irrigation requirements, and historically observed cropping patterns. However, it is not possible to separate net stream augmentations and return flows into their respective magnitudes unless one or the other is known. In this case, net stream augmentation was treated as an unknown variable to be estimated as a residual when the return flow pattern was specified. The return flow coefficients were based on return flow patterns estimated at other locations.

In some of the sub-basins, such as the Upper Yellowstone and the Clarks Fork, it appears that net stream augmentation is positive and significant in the summer. In the lower portion of the basin however, net stream augmentation may be either positive, negative or nearly zero during the summer months. The calibration process makes an estimate of net stream augmentation during the calibration phase, and thereafter it is tacitly assumed that net stream augmentation stays constant throughout all of the scenarios

except the dry year scenarios where net stream augmentation is adjusted downward proportionately with river flows.

The LP model was calibrated to average levels of river flow for the period 1963-1977. In calibrating the model, the following were specified; the return flow pattern, the net irrigation requirements for crops, the levels of conveyance and field efficiencies and a cropping pattern (an average cropping pattern for the years 1959-1978 was used for calibration). Then estimates of net stream augmentation were adjusted so that the model generated river flows which corresponded to the average measured flows of the river for the 1963-1977 period. Calibration was based on USGS measurements of river flows at three checkpoints on the mainstem; Billings, Miles City, and Sidney. The average annual flow of the river at Sidney for this period was 10.2 mmaf. The calibration process accomplished two purposes; first, it was used to adjust the model to account for net stream augmentation and second, it was used to improve the internal consistency of the model.

Results of the calibration run are reasonable when compared to values approximated by the SCS-USDA (1978) in the Yellowstone Basin. For example; the average diversion per acre of the calibrated model is 6.63 acre-feet per acre (af/acre), about 92 percent of the SCS value of 7.22 af/acre; crop irrigation requirements are about 1.29 af/acre, about 88 percent of the SCS value of 1.46 af/acre;

and return flows for the May to September interval are about 3.23 af/acre, compared to the SCS value of 3.94 af/acre.

Certain parameters specified during the calibration process were modified in order to run the basic model and the subsequent scenarios. The cropping pattern was released in order to allow the LP model to select the crop rotation that would maximize returns to agriculture according to the objective function. Irrigated acreage constraints were changed from the historical levels used in the calibration process to current values. In addition, minimum instream flow restrictions, which were not in place during the historical calibration period, were imposed on the model.

Results of the Basic Model

The results of the basic model and the scenarios are presented in a series of tables which are listed below.

Table 7. Basin-wide Summary of the Basic Model.
Table 8. Total Diversions and Return Flows.
Table 9. Diversions by Sub-basin.
Table 10. Return Flows by Sub-basin.
Table 11. Basin-wide Cropping Patterns.
Table 12. Returns to Agriculture.
Table 13. Shadow Prices of Water.
Table 14. Shadow Prices of Irrigated Acres.

A summary of the basin-wide results of the basic model are presented in Table 7. Diversions and return flows for the individual sub-basins are presented in Tables 9 and 10. Returns to agriculture for the individual sub-basins in the basic model are presented in the first column of Table 12. To the extent that water is scarce in the basin, the model will reflect economic scarcity as a nonzero shadow price. The shadow prices for water in the basic model, by time interval and sub-basin, are listed in the first column of Table 13. Thus, the model detects economic scarcity of water in August (time interval 3) in sub-basins 1, 2, 3, and 8. The value of the shadow prices represent the value of an additional acre-foot of water at the margin, i.e., what one additional acre-foot of water would contribute to the value of the objective function.

Table 7. Basin-wide Summary of the Basic Model (B1).

	Total	Per Acre
Diversion (ac-ft)	4,119,824	7.24
Return Flow (ac-ft)	1,976,081	3.47
Returns to Agriculture	111,640,157	196.17

Table 8. Total Diversions and Return Flows (May to September in Acre-feet).

	Basic Model	Increased Irrigation Efficiency Scenarios			Dry Year Scenarios		Increased Irrigation Acreage Scenarios		
	B1	E1	E2	E3	D1	D2	A1	A2	A3
Diversions	4,119,824	2,959,940	2,226,478	1,713,727	4,423,701	3,391,670	4,608,296	5,096,076	5,758,717
Return Flows	1,976,081	1,256,926	818,641	518,496	2,141,693	1,618,514	2,217,433	2,459,427	2,788,187

Table 9. Diversions by Sub-basin (May to September in Acre-feet).

Sub-basin	Basic Model	Increased Irrigation Efficiency Scenarios			Dry Year Scenarios		Increased Irrigation Acreage Scenarios		
	B1	E1	E2	E3	D1	D2	A1	A2	A3
1	1,248,464	815,864	584,793	434,600	1,411,195	947,958	1,421,974	1,595,460	1,831,237
2	678,074	539,701	363,675	254,860	691,523	104,198	693,542	775,485	886,849
3	648,609	472,501	398,877	322,901	577,078	583,844	739,677	763,627	796,177
4	463,887	343,984	265,295	210,858	524,351	561,259	529,227	594,560	683,350
5	340,403	259,629	208,580	168,591	384,755	412,021	386,065	431,716	493,485
6	65,155	49,695	39,924	32,269	73,638	78,861	74,464	83,777	96,428
7	100,439	73,598	57,997	45,664	113,527	121,573	114,131	127,819	146,423
8	55,220	41,356	32,030	25,216	60,244	62,383	61,737	68,253	77,112
9	519,573	363,612	275,307	218,768	587,390	519,573	587,479	655,379	747,656

Table 10. Return Flows by Sub-basin (May to September in Acre-feet).

Sub-basin	Basic Model	Increased Irrigation Efficiency Scenarios			Dry Year Scenarios		Increased Irrigation Acreage Scenarios		
	B1	E1	E2	E3	D1	D2	A1	A2	A3
1	614,767	357,711	220,177	130,802	694,817	512,192	700,238	785,697	901,841
2	360,724	232,961	127,504	62,971	377,268	50,391	379,202	424,740	486,629
3	294,879	196,299	147,042	102,570	271,958	253,941	336,688	352,097	373,038
4	216,598	145,693	99,198	67,052	244,854	262,066	247,301	278,000	319,724
5	148,759	103,206	74,412	51,876	168,160	180,037	168,694	188,627	215,595
6	28,448	21,076	14,232	9,920	32,154	34,426	32,511	36,577	42,100
7	42,163	27,035	18,245	11,297	47,663	51,030	47,910	53,655	61,464
8	23,802	15,242	10,074	6,237	26,744	28,490	26,928	30,055	34,305
9	245,941	157,703	107,757	75,771	278,075	245,941	277,961	309,979	353,491

Table 11. Basin-wide Cropping Patterns (acres).

Crop	Basic Model	Increased Irrigation Efficiency Scenarios		Dry Year Scenarios		Additional Irrigated Acreage Scenarios		
		E1	E2,E3	D1	D2	A1	A2	A3
Barley	0	0	0	0	0	0	0	0
Alfalfa Hay	292,963	384,156	358,769	227,339	60,584	317,199	335,482	360,330
Other Hay	65,806	0	0	83,244	133,097	96,226	109,207	126,849
Pasture	0	0	0	0	0	0	0	0
Sugar Beets	57,975	57,975	57,975	57,975	57,975	57,975	57,975	57,975
Corn Silage	138,264	139,878	139,878	135,993	210,135	160,985	183,703	214,527
Beans	12,478	12,478	12,478	12,478	12,478	12,478	12,478	12,478
Corn	1,614	10,613	0	52,071	5,997	3,398	28,567	62,773
Total Irrigated Acreage	569,100	569,100	569,100	569,100	480,266	648,261	727,412	834,932
Slack					88,834			

Table 12. Returns to Agriculture (dollars).

Sub-basin	Basic Model	Increased Irrigation Efficiency Secenarios		Dry Year Scenarios		Increased Irrigation Acreage Scenarios			Increased Agricultural Prices Scenarios	
	B1	E1	E2,E3	D1	D2	A1	A2	A3	P1	P2
1	31,022,840	31,022,840	31,022,840	31,022,840	13,186,888	35,318,921	39,614,376	45,452,137	55,220,744	72,593,712
2	12,110,118	20,351,661	20,351,661	9,926,183	2,976,141	11,010,050	12,093,834	13,566,764	21,555,877	28,337,937
3	21,132,004	19,967,652	21,132,004	15,845,518	18,825,321	23,817,986	23,937,981	24,101,125	37,615,017	49,449,038
4	13,425,043	13,425,043	13,425,043	13,425,043	13,425,043	15,192,986	16,960,720	19,363,203	23,896,609	31,414,700
5	11,379,765	11,379,765	11,379,765	11,379,765	11,379,765	12,835,091	14,290,060	16,258,694	20,255,761	26,628,493
6	2,076,615	2,076,615	2,076,615	2,076,615	2,076,615	2,373,249	2,670,061	3,073,247	3,696,323	4,859,241
7	3,785,619	3,785,619	3,785,619	3,785,619	3,785,619	4,280,187	4,774,577	5,446,554	6,738,329	8,858,297
8	1,900,175	2,028,423	2,028,423	1,719,721	1,551,902	2,068,092	2,236,009	2,464,151	3,382,295	4,446,386
9	14,807,978	14,807,978	14,807,978	14,807,978	14,807,978	16,574,038	18,339,919	20,739,761	26,357,984	34,650,520
	111,640,157	118,845,596	120,009,948	103,989,282	82,105,272	123,470,600	134,917,537	150,465,536	198,718,939	261,238,324

Table 13. Shadow Prices of Water (dollars).

Sub-basin	Time Interval	Basic Model B1	Increased Irrigation Efficiency Scenarios* E1	Dry Year Scenarios D1	Dry Year Scenarios D2	Additional Irrigated Acreage Scenarios A1	Additional Irrigated Acreage Scenarios A2	Additional Irrigated Acreage Scenarios A3	Increased Agricultural Prices Scenarios P1	Increased Agricultural Prices Scenarios P2
1	May				1.00			1.00		
	June				69.82					
	July				1.00			1.00		
	August	59.50	94.98	62.26	57.58	71.68	71.68	71.53	114.24	153.54
	September									
2	May				1.00			1.00		
	June				69.82					
	July				1.00			1.00		
	August	59.50	94.98	62.26	57.88	71.68	71.68	71.53	114.24	153.54
	September									
3	May				1.00			1.00		
	June				69.82					
	July				1.00			1.00		
	August	59.50	94.98	62.26	57.88	71.68	71.68	71.53	114.24	153.54
	September									
4	May				1.00			1.00		
	June				1.00			1.00		
	July				1.00			1.00		
	August				1.00			1.00		
	September				1.00			1.00		
5	May				1.00			1.00		
	June									
	July				1.00			1.00		
	August							1.00		
	September									
6	May									
	June									
	July				1.00			1.00		
	August				1.00			1.00		
	September				1.00			1.00		
7	May									
	June									
	July				1.00			1.00		
	August							1.00		
	September									
8	May									
	June									
	July				1.00			1.00		
	August	57.37		50.40	46.72	57.37	57.37	57.30	104.61	138.54
	September									
9	May									
	June									
	July				1.00			1.00		
	August							1.00		
	September									

*E2 and E3 scenarios were not included in this table because all shadow prices were zero.

Table 14. Shadow Prices of Irrigated Acres (dollars).

Sub-basin	Basic Model	Increased Irrigation Efficiency Scenarios			Dry Year Scenarios		Additional Irrigated Acreage Scenarios			Increased Agricultural Prices Scenarios	
	B1	E1	E2	E3	D1	D2	A1	A2	A3	P1	Pq
1	103.74	107.42	188.99	194.06	86.69	-0-	90.88	90.88	88.78	208.73	284.11
2	84.82	100.62	188.91	194.84	86.72	-0-	91.55	91.55	88.78	180.21	248.69
3	95.42	82.78	187.07	191.20	76.57	20.14	79.44	79.44	78.02	186.38	251.69
4	170.16	180.13	186.67	191.20	165.13	157.12	170.16	170.16	166.07	332.97	449.86
5	150.48	157.12	161.32	164.61	146.84	142.76	150.48	150.48	147.77	289.69	389.64
6	150.48	157.12	161.32	164.61	146.84	141.31	150.48	150.48	147.77	289.69	389.64
7	153.77	160.38	164.21	167.25	150.56	147.07	153.77	153.77	151.44	292.98	392.93
8	89.96	160.06	164.21	167.25	87.17	84.03	89.96	89.96	88.79	177.05	239.55
9	144.17	154.47	160.30	164.03	139.69	141.53	144.17	144.17	138.90	283.38	383.33

The shadow prices for irrigated acres in the basic model are presented in the first column of Table 14. These values indicate what an additional acre of irrigated land would contribute to the value of the objective function.

The results of the basic model are the benchmark by which the results of the scenarios will be compared. Thus, the scenarios become a series of "what-if" questions, i.e., given the results of the basic model, what if a particular component changes?

Results of Increased Irrigation Efficiency Scenarios

One of the primary objectives of this study was to evaluate the economic and hydrologic implications of river management policies which are aimed at increasing irrigation efficiencies.

Hydrologic Impacts

As the level of irrigation efficiency increases, the quantities of diversions and return flows decrease and the distribution of river flow throughout the year is altered. In the E1 scenario, diversion is reduced by 28 percent and return flows for the May to September interval are reduced by 36.4 percent. In the E2 scenario, diversions and return flows for the May to September interval are reduced by 46 and 58.6 percent respectively from the basic model. In the E3 scenario, diversions and return flows for the May to September interval are reduced by 58.4 and 73.8 percent

respectively from the basic model. Basin-wide quantities for diversions and May to September return flows for the basic model and the scenarios are listed in Table 8 and diversions and return flows for the individual sub-basins are listed in Tables 9 and 10 respectively. Basin-wide cropping patterns for the E1, E2, and E3 scenarios are listed in Table 11. Cropping patterns for the individual sub-basins are listed in Appendix C.

Economic Impacts

Returns to agriculture for the E1, E2, and E3 scenarios are listed in Table 12. The cropping pattern is the same in scenarios E2 and E3 and therefore the returns to agriculture does not change. The returns to agriculture do not include diversion costs. Thus, the value of the objective function is greater for the E3 scenario than for the E2 scenario since less water has been diverted. Total returns to agriculture for the entire basin increased 6.5 percent over the basic model in the E1 scenario. Total returns to agriculture basin-wide increased 7.5 percent over the basic model in the E2 and E3 scenarios.

The shadow price for water in sub-basins 1, 2, and 3 for the month of August increased from $59.50 to $94.98 and the shadow price of water in sub-basin 8 for the month of August decreased from $57.37 to 0 in the E1 scenario (shown in Table 13). Shadow prices for water in all other months and sub-basins were 0 in the E1 scenario. The E2 and E3

scenarios had shadow prices of water that were 0 in all months and sub-basins and consequently were not included in Table 13. The shadow prices of irrigated acres are presented for each sub-basin in Table 14.

Results of the Dry Year Scenarios

In the D1 scenario, which represents an annual flow at Sidney of 8.87 mmaf, diversions increased by 7.3 percent over the basic model and return flows increased by 8.4 percent. In the D2 scenario, which represents an average annual flow at Sidney of 6.9 mmaf, diversions decreased by 2.5 percent and return flows decreased by 2.9 percent from the basic model levels. Total diversions and return flows are listed in Table 8, while diversions and return flows by sub-basin are located in Tables 9 and 10. Basin-wide cropping patterns are presented in Table 11 and cropping patterns for the individual sub-basins are listed in Appendix C.

In the D2 scenario, sub-basins 1 and 2 had slack or idle irrigated acreage of 5,590 and 83,244 acres respectively. Also the Yellowtail and Tongue reservoirs ended the fifth time interval, i.e., September, at less than full capacity in this scenario. The two reservoirs were left at 11 and 89 percent less than capacity respectively. While the inability to fill the reservoirs at the end of the irrigation season may or may not be a desired reservoir management goal, the fact that this scenario deviates from

the others is indicative of the severity of the water shortage in this scenario.

Basin-wide returns to agriculture decreased by 6.85 percent and 26.5 percent from the basic model in the D1 and D2 scenarios respectively. Returns to agriculture are listed in Table 12. Shadow prices of water and irrigated acres are listed in Tables 13 and 14 respectively.

Results of Increased Irrigated Acreage Scenarios

Taking into account the increased acreage in the A1, A2, and A3 scenarios, diversions on a per acre basis were 7.11, 7.01, and 6.90 acre-feet per acre compared to 7.24 acre-feet per acre in the basic model. This occurs because the cropping pattern which accompanied the additional acres included less water intensive crops. However, the additional acreage resulted in increases in total diversions of 12 percent, 23.7 percent, and 39.8 percent respectively for the A1, A2, and A3 scenarios over the level of the basic model (see Table 8).

Returns to agriculture increased by 10.6 percent, 20.9 percent, and 34.8 percent for the A1, A2, and A3 scenarios respectively. Returns to agriculture for each sub-basin are listed in Table 12 but should not be viewed as projections of potential irrigated agricultural development in the individual sub-basins as the additional acres were distributed according to the distribution of currently

irrigated acres and not according to any projections of where development could be expected to occur. Shadow prices for water, by time interval and sub-basin, and irrigated acres by sub-basin are listed in Tables 13 and 14 respectively.

Results of the Increased Agricultural Prices Scenarios

Since the relative value of the crops were not changed as a result of increasing the level of returns over variable cost, the cropping pattern did not change from that of the basic model and consequently neither did diversions or return flows. The increased level of prices received resulted in impacts on other economic variables. The changes in returns to agriculture are listed in Table 12. Tables 13 and 14 contain the shadow prices of water, by time interval and sub-basin, and irrigated acreage, by sub-basin.

Caveats and Limitations of This Study

Any model, by definition, must make certain simplifying assumptions as a part of the modeling process. These assumptions invariably introduce some potential for error in parameter values used in the model. It is imperative that the results of any model be evaluated in light of the assumptions that were incorporated in the construction of the model.

One of several important assumptions of this model is that it is limited to one irrigation scheme for each crop. In other words, the crop is grown only if there is enough water to meet one set of net irrigation requirements which are specified for each time interval. This tends to overestimate the economic impacts associated with water scarcity because it does not allow the crop to be grown under a diminished water regime with a corresponding reduction in yield. Thus, if water is scarce and there is not enough water to grow alfalfa hay, for example, at the stated irrigation requirements the model must revert to some other crop which uses less water and most likely has a substantially lower objective function value. Accomodation of multiple irrigation schemes in the model is straightforward but the required data is presently unavailable.

It is important to remember that this model uses returns to agriculture in the objective function, i.e., returns over variable costs. Thus, the results presented here represent a short run solution rather than a long run solution. More importantly, the use of ROVC's overestimates the economic values in the results presented in this chapter. Thus, the shadow prices associated with water and irrigated acres are overstated due to the use of ROVC's because fixed costs have not been considered.

It should be remembered also that the basic model was calibrated to a recent historic period of time when the

average flows of the Yellowstone River were higher than the long run average. Thus, the model would tend to understate the physical scarcities of water that would be present at a lower level of flow. However, the D1 scenario represents a flow much closer to the the long run average flow and therefore corrects this situation somewhat.

Suggested Refinements of This Model

As with any model, an almost infinite number of refinements could be incorporated and would be desirable in some sense. However, some refinements for this particular model could easily be made and would greatly increase the flexibility of this model.

The use of net returns rather than returns over variable costs as objective function values for the agricultural crops would result in long run solutions and would simplify interpretation of the shadow prices associated with the various resources. The expansion of this model from five monthly intervals to one which would include the entire year would significantly increase the value of the model. It would facilitate use of the model in scenarios of future development and the impact of river management policies on factors other than irrigated agriculture, such as fish and wildlife habitat, municipal use, and energy and other industrial uses of water which are not limited to the summer months.

It would be useful to incorporate other factors associated with irrigated agricultural production more realistically into the model. This would include such production factors as multiple irrigation schemes, different distribution and application systems for irrigation, different farming systems, different levels of management and physical factors such as the variety of soil types found in the basin.

Chapter 6

Conclusions, Policy Implications and Suggestions for Further Research

This study has been devoted to modeling the Yellowstone River Basin in Montana so that the economic and hydrologic implications of alternative water management policies could be estimated. The initial emphasis of this study was to evaluate the implications of increasing the technical efficiency of water used for irrigation. As the study progressed, opportunities to evaluate other alternative scenarios were recognized and exploited. The vast complexities of the hydrologic and economic systems in the basin as well as the maze of legal and other institutional factors which influence water use all combine to suggest that a comprehensive understanding of water management implications would be, at the very least, taxing. Not all of the issues are resolved by this study, but a framework was developed whereby many of these issues can be investigated in future work.

Conclusions and Policy Implications

The results of the basic model indicate that while there is an abundance of water in most places most of the time, site and time specific shortages of water do occur in

the Yellowstone Basin as indicated by the nonzero shadow prices of water in four of the nine sub-basins. As the level of irrigation efficiency increases in the irrigation efficiency scenarios, returns to agriculture increase over the level of the basic model in E1 and E2, while holding constant from E2 to E3. This indicates that there are gains to be made by increasing the level of irrigation efficiency, at least marginally, above current levels.

However, a closer examination of the individual sub-basins indicates that marginal increases in irrigation efficiency do result in detrimental economic impacts to certain irrigators. At the level of irrigation efficiency implied by the E1 scenario, if water is used optimally as determined in the model, water becomes more scarce in sub-basins 1, 2, and 3 than is true for the basic model. This is indicated by the increased shadow price of water in those sub-basins. A comparision of the returns to agriculture in those sub-basins between the basic model and the E1 scenario shows a significant redistribution of income as a result of the increased irrigation efficiency. Returns to agriculture in sub-basin 3 are reduced while those in sub-basin 2 are increased. The increases in sub-basin 2 are more than enough to offset the decreases in sub-basin 3, so the result is an increase in returns to the entire basin. In sub-basin 8 however, the shadow price of water falls to zero in the E1 scenario indicating that water scarcity has

been eliminated by the increase in irrigation efficiency and a higher level of returns to agriculture is achieved as a result.

Achieving the level of irrigation efficency implied by the E2 scenario indicates that all water scarcities have been eliminated when the 1963-1977 average flow occurs. Thus, in some sub-basins, as the level of irrigation efficiency is increased the result will be first an increasing and then a decreasing level of shadow prices of water.

The explanation to this phenomenon is fairly straightforward though not initially obvious. In those sub-basins where the basic model generates nonzero shadow prices, water is a binding constraint on the level of agricultural production. Initial increases in the level of irrigation efficiency, with everything else constant, will result effectively in more water being made available due to decreased diversion requirements. However, in those sub-basins which are initially short of water, the increased water availability will result in a move towards a more optimal cropping pattern. Thus, either the increased net irrigation requirements associated with the new cropping pattern, which occurs because the highest valued crops tend to be the most water intensive, or the increased economic value associated with the new cropping pattern or a combination of both results in the increased value of water as reflected in higher shadow prices.

Increases in returns to agriculture will continue until enough water becomes available to allow the constrained globally optimum cropping pattern implied in the model to be achieved. The constrained globally optimum cropping pattern is that which is achieved when water is not a binding constraint in any sub-basin and time interval. The globally optimum cropping has been achieved at the point where irrigation efficiency is increased to the level of the E2 scenario. The cropping patterns for the individual sub-basins which collectively make up the constrained globally optimum cropping pattern were achieved in some sub-basins at the level of irrigation efficiency in the basic model, in sub-basin 8 at the level of irrigation efficiency in the E1 scenario, and in the rest of the sub-basins at the level of irrigation efficiency in the E2 scenario.

Increased irrigation efficiency beyond the level of E2 will not increase returns to agriculture but will increase the value of objective function value as diversion costs continue to decrease. This suggests that policies designed to increase the level of irrigation efficiency must be based on, first, determining the level of efficiency which is desired as a goal and determining the potential economic impacts within each sub-basin of achieving that goal. Such analysis should be completed prior to implementation of these policies.

Determination of the optimal level of irrigation efficiency is implied by the benefit/cost analysis presented in Chapter 2. The results of this work are indicative of the impacts of increases in irrigation efficiency but do not suggest what level of efficiency is desirable.

While this study made no attempt to determine the cost of achieving and maintaining alternative levels of irrigation efficiency, an examination of the returns to agriculture associated with the increased irrigation efficiency scenarios does suggest the limits to economically feasible improvements. The increase in efficiency from the basic model to the E1 scenario results in increased returns to agriculture of about $7.2 million or $12.66 per acre. Thus, the cost of achieving the efficiency increase from 19 to 28 percent is economically feasible only if it can be accomplished at a cost of less than $12.66 per acre. This figure is on an annual basis and is stated in the absence of present value calculations which would reduce the value of annual contributions in future years of the planning horizon. Subtracting fixed costs from the objective function values would also reduce the values stated here. The diminishing returns associated with increased irrigation efficiency is illustrated by the fact that efficiency increases from the E1 to E2 levels, i.e., 28 to 37 percent, is accompanied by increased returns to agriculture of only

$2.05 per acre. The increase from E2 to E3 does not increase the returns to agriculture.

There is no a priori reason to believe that the optimal level of irrigation efficiency will necessarily be higher than the level which overcomes the redistributive impacts presented in these results in a particular sub-basin. The redistributive impacts may be only transitory if the optimal irrigation efficiency level is high enough but will be permanent if it is not. The specific level of the impacts will be unique to each individual sub-basin. Thus it is not clear that general or nonspecific policies of increased irrigation efficiency can be accomplished without significant detrimental economic impacts to certain water users. These impacts may be either temporary or permanent depending on particular circumstances. There appears to be a tendency among water planning officials to believe that whatever level of irrigation efficiency can be achieved above current levels will be beneficial to all water users. This belief is contrary to the results of this study.

The dry year scenarios indicated, as might be expected, that water scarcities are increased in low flow years. The D1 scenario is based on annual river flows at Sidney of 8.87 mmaf which is only slightly below the 1934-1980 average of 8.9 mmaf. Thus, the D1 scenario is more nearly the long run average level of river flow than that used in the

basic model, which was based on the average flow for the years 1963-1977 of 10.2 mmaf. The dry year scenarios, in particular, illustrate the implications of having or not having storage facilities on the river.

The wide fluctuations in returns to agriculture in the three upper sub-basins are indicative of the value of storage and also of the decreases in risk to water users associated with the availability of storage facilities. Depending on the institutional regime, the upstream users may have first use of the water in which case water would not be going to the highest valued use. In that situation the value of storage would be greater than that implied by the results of this study. A comprehensive benefit/cost analysis would be necessary to accurately determine the net social value of storage in the basin. An examination of the shadow prices of irrigated acreage for the dry year scenarios indicates that the value of irrigated land is very dependant on a reliable water source throughout the irrigation season.

In the D2 and also in the A3 scenarios, shadow prices of water of $1.00 appear in various time intervals and sub-basins. These result from the fact that the reservoirs are not filled at the end of the irrigation season in these scenarios. The two reservoirs, the Yellowtail dam in sub-basin 4 and the Tongue dam in sub-basin 6, have an activity which places a value on the carry-over of water beyond the

irrigation season. This activity was given a $1.00 per acre-foot objective function value as an incentive to the model so that it would not drain the reservoirs at the end of the irrigation season. Thus, in the D2 and A3 scenarios, where water is very scarce, the $1.00 becomes the opportunity cost of not having an additional acre-foot of water to leave in the reservoirs.

Interpretation of the results of the dry year scenarios must be made in light of the tacit assumption of a priori knowledge of diminished river flows. The fact that the D2 scenario results in irrigated acres being taken out of production in sub-basins 1 and 2 suggests the seriousness of the potential conflict which may arise in the Yellowstone Basin during low flow years. In the event that water becomes very scarce, the agricultural demand for water will be in conflict with the current minimum instream reservations for the available water supplies. In reality, unless the diminished water supplies were known in advance with certainty, irrigated acres would not actually stand idle but would be utilized in diminished irrigated production. However, the fact that the model calls for decreases in cropped acreage by over 80,000 acres is indicative of the potential conflict involved and the potential economic impacts.

The results of the increased prices and additional irrigated acreage scenarios as variations of the basic

model did not present any unexpected results. However, the increased agricultural prices scenarios did illustrate an obvious but often overlooked fact that the value of water to irrigated agriculture is not static but is dependent on the value of the agricultural products produced. The increased agricultural prices and irrigated acreage scenarios are more significant when considered in joint occurrence with the other scenarios thereby exaggerating the implications of various water management policies.

Suggestions for Further Research

The results of the basic model and the scenarios are all presented in the context of a *ceteris paribus* assumption, i.e., each of the scenarios is in the framework of what if one variable changes and everything else remains constant? The most obvious extensions of the work presented in this study would be to relax the *ceteris paribus* assumption and investigate the impacts of combinations of factors affecting river management policies. Such work would result in the determination of potential economic impacts of increased irrigation efficiency over a wider range of variables. Simultaneously, investigation based on the stochastic nature of the occurrence and magnitude of physical and economic variables both independently and jointly would provide useful information to policy makers.

In addition, more detailed analysis of the site specific factors on the potential economic impacts would

provide information about the kind and extent of water management which can be applied in each of the sub-basins. This, in turn, may have implications, for example, on the socially desirable nature and extent of federal and state support for irrigation project development. In addition, benefit/cost studies related to increases in irrigation efficiency as well as storage facilities and other water management alternatives are indicated by the results of this study.

Further work in modeling the hydrology of the basin would be desirable. Empirical determination of return flow patterns has proven to be a very difficult task and additional work to define return flow patterns as well as sensitivity analysis of the results presented here with regard to alternative return flow patterns would contribute much to the possibility of well informed water management policies. In addition, issues regarding water quality must be addressed on a site specific basis as a part of an overall water management plan.

The results presented in this work are done in the absence of the legal and institutional framework in the basin. For example, the income redistribution which occurs as irrigation efficiency increases may be exaggerated or diminished by the water rights regime and other institutional factors within the basin. Further work is necessary

to evaluate the impact of the institutional and legal mechanisms on the results reported here.

APPENDICES

APPENDIX A

BUDGETS

Table 15. Irrigated Alfalfa for Sub-basins 1, 2, 3, and 4.

RETURNS		
Yield (5 Tons x $60.00)	(1)	$300.00
VARIABLE COSTS		
Fertilizer and Application	(2)	$ 11.90
Crop Chemicals	(3)	3.60
Irrigation Labor	(4)	6.00
Machinery: Fuel, Oil, Repairs	(5)	31.03
Pickup Variable Costs	(6)	5.00
Miscellaneous Expense	(7)	7.17
Other (twine)	(8)	6.60
Interest on Operating Capital	(9)	1.37
Machinery Labor (4.65 hr. x $4.00)	(10)	18.60
TOTAL VARIABLE COSTS	(11)	$ 91.27
RETURN OVER VARIABLE COST	(12)	$208.73

Based on data from Fogle and Luft (1980).

Table 16. Irrigated Alfalfa for Sub-basins 5 and 7.

RETURNS		
Yield (4 tons x $60.00)	(1)	$240.00
VARIABLE COSTS		
Stand Establishment	(2)	$ 9.02
Fertilizer and Application	(3)	28.44
Crop Chemicals	(4)	4.77
Irrigation Labor	(5)	4.50
Machinery: Fuel, Oil, Repairs	(6)	31.73
Pickup Variable Cost	(7)	3.50
Miscellaneous Expense	(8)	13.79
Interest on Operating Capital	(9)	2.96
Machinery Labor	(10)	15.82
TOTAL VARIABLE COSTS	(11)	$115.27
RETURNS OVER VARIABLE COST	(12)	$124.73

Based on data from Griffith, Schaefer and Luft (1978).

Table 17. Irrigated Alfalfa for Sub-basins 6, 8, and 9.

RETURNS		
Yield (4 tons x $60.00)	(1)	$240.00
VARIABLE COSTS		
Stand Establishment	(2)	$ 9.84
Fertilizer and Application	(3)	19.01
Crop Chemicals	(4)	4.47
Custom Stack	(5)	23.40
Irrigation Labor	(6)	6.98
Machinery: Fuel, Oil, Repairs	(7)	12.23
Pickup Variable Cost	(8)	5.59
Miscellaneous Expense	(9)	7.35
Twine	(10)	4.96
Interest on Operating Capital	(11)	1.70
Machinery Labor	(12)	7.62
TOTAL VARIABLE COSTS	(13)	$103.15
RETURN OVER VARIABLE COST	(14)	$136.85

Based on data from Schaefer, Griffith and Luft (1978).

Table 18. Irrigated Corn for Grain for All Sub-basins.

RETURNS		
Yield (100 bu. x $3.25)	(1)	$325.00
VARIABLE COSTS		
Seed (16.7 lb. x $1.05/lb.)	(2)	$ 17.53
Fertilizer and Application	(3)	38.40
Crop Chemicals	(4)	11.25
Custom Hire (Corn Drying)	(5)	55.00
Irrigation Labor	(6)	6.00
Machinery: Fuel, Oil, Repairs	(7)	47.59
Pickup Variable Costs	(8)	5.00
Miscellaneous Expense	(9)	13.19
Interest on Operating Capital	(10)	7.22
Machinery Labor (6.2 hr. x $4.00)	(11)	24.80
TOTAL VARIABLE COSTS	(12)	$225.98
RETURN OVER VARIABLE COST	(13)	$ 99.02

Based on data from Fogle and Luft (1980).

Table 19. Irrigated Feed Barley for All Sub-basins.

RETURNS		
Yield (80 bu. x $2.00)	(1)	$160.00
VARIABLE COSTS		
Seed (90 lb. @ $4.50/bu.)	(2)	$ 8.46
Fertilizer and Application	(3)	24.50
Crop Chemicals	(4)	3.25
Irrigation Labor	(5)	4.00
Machinery: Fuel, Oil, Repairs	(6)	26.07
Pickup Variable Cost	(7)	5.00
Miscellaneous Expense	(8)	7.82
Interest on Operating Capital	(9)	3.17
Machinery Labor (4.47 hr. x $4.00)	(10)	17.87
TOTAL VARIABLE COSTS	(11)	$100.14
RETURN OVER VARIABLE COST	(12)	$ 59.86

Based on data from Fogle and Luft (1980).

Table 20. Irrigated Beans for All Sub-basins.

RETURNS		
Yield (20 cwt. x $23.00)	(1)	$460.00
VARIABLE COSTS		
Seed (50 lb. x $48.00/cwt.)	(2)	$ 24.00
Fertilizer and Application	(3)	11.10
Crop Chemicals	(4)	4.12
Irrigation Labor	(5)	6.40
Machinery: Fuel, Oil, Repairs	(6)	60.09
Pickup Variable Cost	(7)	5.00
Miscellaneous Expense	(8)	10.95
Interest on Operating Capital	(9)	4.61
Machinery Labor (7.58 hr. x $4.00)	(10)	30.32
TOTAL VARIABLE COSTS	(11)	$156.59
RETURN OVER VARIABLE COST	(12)	$303.41

Based on data from Fogle and Luft (1980).

Table 21. Irrigated Sugar Beets for All Sub-basins.

RETURNS		
Yield (18 ton x $32.00)	(1)	$576.00
VARIABLE COSTS		
Seed (2.1 lb. x $9.50/lb.)	(2)	$ 19.95
Fertilizer and Application	(3)	58.25
Crop Chemicals	(4)	9.45
Custom Hire (Hoe Beets)	(5)	24.00
Irrigation Labor	(6)	11.40
Machinery: Fuel, Oil, Repairs	(7)	93.42
Pickup Variable Cost	(8)	5.00
Miscellaneous Expense	(9)	20.75
Interest on Operating Capital	(10)	7.64
Machinery Labor (10.93 hr. x $4.00)	(11)	43.73
TOTAL VARIABLE COSTS	(12)	$293.59
RETURN OVER VARIABLE COST	(13)	$282.41

Based on data from Fogle and Luft (1980).

Table 22. Irrigated Corn Silage for All Sub-basins.

RETURNS		
Yield (20 ton x $18.00)	(1)	$360.00
VARIABLE COSTS		
Seed (16.7 lb. x $1.05/lb.)	(2)	$ 17.53
Fertilizer and Application	(3)	38.40
Crop Chemicals	(4)	11.25
Irrigation Labor	(5)	6.00
Machinery: Fuel, Oil, Repairs	(6)	56.05
Pickup Variable Cost	(7)	5.00
Miscellaneous Expense	(8)	12.18
Interest on Operating Capital	(9)	7.47
Machinery Labor (6.91 hr. x $4.00)	(10)	27.64
TOTAL VARIABLE COSTS	(11)	$181.52
RETURN OVER VARIABLE COST	(12)	$178.48

Based on data from Fogle and Luft (1980).

APPENDIX B

NET IRRIGATION REQUIREMENTS

Table 23. Climatic Zones for the Nine Sub-basins.

Climatic Zone	Sub-basins
1	5, 6, 7 and 8
2	2, 3, 4 and 9
3	1

Table 24. Net Irrigation Requirements (May to September in acre-feet).

Month	Alfalfa	Beans	Sugar Beets	Corn Silage	Corn Grain	Pasture	Barley
			Climatic Zone 1				
M	.23	.04	.06	.03	.15	.18	.32
J	.33	.24	.19	.12	.38	.25	.32
J	.57	.54	.55	.47	.48	.46	.05
A	.47	.24	.56	.47	.04	.40	
S	.23		.28	.17		.20	
			Climatic Zone 2				
M	.20	.03	.05	.02	.12	.16	.28
J	.29	.21	.16	.10	.33	.22	.28
J	.52	.54	.52	.43	.46	.42	.04
A	.43	.27	.52	.43	.05	.36	
S	.18		.23	.14		.17	
			Climatic Zone 3				
M	.16		.04			.03	.25
J	.27		.15			.14	.25
J	.48		.47			.39	.04
A	.39		.46			.35	
S	.15		.19			.15	

APPENDIX C

CROPPING PATTERNS

Table 25. Cropping Patterns by Sub-basin for the Basic Model (B1) and the P1 and P2 Scenarios (acres).

Crops	Sub-basins 1	2	3	4	5	6	7	8	9
Barley									
Alfalfa Hay	147,022	17,438	52,249						
Other Hay		65,806							
Pasture									
Sugar Beets	1,186	6,921	15,118	8,067	7,174		2,547	498	16,464
Corn Silage					50,509	11,635	16,847	8,963	50,310
Beans		3,367	3,118	794	1,117		196		3,886
Corn								1,614	

Table 26. Cropping Patterns by Sub-basin for the El Scenario (acres).

Crops	Sub-basins 1	2	3	4	5	6	7	8	9
Barley									
Alfalfa Hay	147,022	83,244	65,641	52,249					
Other Hay									
Pasture									
Sugar Beets	1,186	6,921	15,118	8,067	7,174		2,547	498	16,464
Corn Silage					50,509	11,635	16,847	10,577	50,310
Beans		3,367	3,118	794	1,117		196		3,886
Corn		10,613							

Table 27. Cropping Patterns by Sub-basin for the E2 and E3 Scenarios (acres).

Crops	Sub-basins 1	2	3	4	5	6	7	8	9
Barley									
Alfalfa Hay	147,022	83,244	76,254	52,249					
Other Hay									
Pasture									
Sugar Beets	1,186	6,921	15,118	8,067	7,174		2,547	498	16,464
Corn Silage					50,509	11,635	16,847	10,577	50,310
Beans		3,367	3,118	794	1,117		196		3,886
Corn									

Table 28. Cropping Patterns by Sub-basin for the D1 Scenario (acres).

Crops	Sub-basins 1	2	3	4	5	6	7	8	9
Barley									
Alfalfa Hay	147,022		28,068	52,249					
Other Hay		83,244							
Pasture									
Sugar Beets	1,186	6,921	15,118	8,067	7,174		2,547	498	16,464
Corn Silage					50,509	11,635	16,847	6,692	50,310
Beans		3,367	3,118	794	1,117		196		3,886
Corn			48,186					3,885	

Table 29. Cropping Patterns by Sub-basin for the D2 Scenario (acres).

Crops	Sub-basins 1	2	3	4	5	6	7	8	9
Barley									
Alfalfa Hay	8,335			52,249					
Other Hay	133,097								
Pasture									
Sugar Beets	1,186	6,921	15,118	8,067	7,174		2,547	498	16,464
Corn Silage			76,254		50,509	11,635	16,847	4,580	50,310
Beans		3,367	3,118	794	1,117		196		3,886
Corn								5,997	

Table 30. Cropping Patterns by Sub-basin for the A1 Scenario (acres).

Crops	Sub-basins 1	2	3	4	5	6	7	8	9
Barley									
Alfalfa Hay	167,604		88,876	60,719					
Other Hay		96,226							
Pasture									
Sugar Beets	1,186	6,921	15,118	8,067	7,174		2,547	498	16,464
Corn Silage					58,663	13,297	19,618	9,202	60,205
Beans		3,367	3,118	794	1,117		196		3,886
Corn			519					2,879	

Table 31. Cropping Patterns by Sub-basin for the A2 Scenario (acres).

Crops	Sub-basins 1	2	3	4	5	6	7	8	9
Barley									
Alfalfa Hay	188,183		78,111	69,188					
Other Hay		109,207							
Pasture									
Sugar Beets	1,186	6,921	15,118	8,067	7,174		2,547	498	16,464
Corn Silage					66,815	14,960	22,388	9,441	70,099
Beans		3,367	3,118	794	1,117		196		3,886
Corn			24,423					4,144	

Table 32. Cropping Patterns by Sub-basin for the A3 Scenario (acres).

Crops	Sub-basins 1	2	3	4	5	6	7	8	9
Barley									
Alfalfa Hay	216,151		63,481	80,698					
Other Hay		126,849							
Pasture									
Sugar Beets	1,186	6,921	15,118	8,067	7,174		2,547	498	16,464
Corn Silage					77,845	17,219	26,153	9,765	83,545
Beans		3,367	3,118	794	1,117		196		3,886
Corn			56,909					5,864	

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