Simulation of irrigation and reservoir water use in the Canyon Ferry drainage basin
by Denise Kelley DeLuca

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University

Abstract:
A water rights conflict exists between hydropower and proposed future irrigation water uses in the Canyon Ferry Reservoir drainage basin of southwestern Montana. The goal of this study was to determine how projected increases in upstream irrigation development would affect power production and spill volumes at the reservoir, and whether reservoir operating policies could be modified to produce more power and less spillage under both present and projected future irrigation conditions.

Two related computer models were developed to simulate irrigation water use in the basin and subsequent water use in the reservoir downstream. Three upstream irrigation conditions were simulated: (1) no irrigation, (2) present levels of irrigation, and (3) projected future levels of irrigation, representing a 100,000 acre increase in sprinkler irrigated land.

Based on 35 simulated years of data, it was found that a 15.8% increase in irrigated acreage would cause a 3% reduction in average annual reservoir inflow volume, a 1.3% reduction in average annual power production, and a 15.8% reduction in average annual spill volume. Average monthly inflows and power production, however, would become more uniform throughout the year. It was also found that more power and less spillage would be generated under both present and projected future irrigation conditions if the reservoir's spring target elevation were lowered and the summer fill date were delayed.

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Denise Kelley DeLuca

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

A water rights conflict exists between hydropower and proposed future irrigation water uses in the Canyon Ferry Reservoir drainage basin of southwestern Montana. The goal of this study was to determine how projected increases in upstream irrigation development would affect power production and spill volumes at the reservoir, and whether reservoir operating policies could be modified to produce more power and less spillage under both present and projected future irrigation conditions.

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Based on 35 simulated years of data, it was found that a 15.8% increase in irrigated acreage would cause a 3% reduction in average annual reservoir inflow volume, a 1.3% reduction in average annual power production, and a 15.8% reduction in average annual spill volume. Average monthly inflows and power production, however, would become more uniform throughout the year. It was also found that more power and less spillage would be generated under both present and projected future irrigation conditions if the reservoir's spring target elevation were lowered and the summer fill date were delayed.

CHAPTER 1

INTRODUCTION

Background

During the past several years, the Montana Department of Natural Resources and Conservation (DNRC) has deferred action on numerous applications for water-use permits in the Canyon Ferry drainage basin pending resolution of objections filed by downstream senior water rights holders. Under the Water Use Act (1973) the DNRC must confirm and insure protection of the existing water rights before it can grant any additional upstream water-use permits. The two major objectors, the Montana Power Company (MPC) and the U. S. Bureau of Reclamation (USBR), argue that there is no unappropriated water above Canyon Ferry reservoir, and that any additional appropriations would deplete water needed for hydropower and existing downstream irrigation. Both objectors agree that during certain months of some years water exists in excess of their rights; however, the quantity and regularity of water availability are still open to question.

Water availability studies for the basin above Canyon Ferry Reservoir have been carried out by several investigators. Fitz (1981) and Thompson (1983) reported on the water availability and MPC and USBR water usage in the Upper Missouri River basin. These reports outlined how much water is potentially available for future upstream irrigation appropriations. However, the hydrologic effects of each water use on the basin and its other water users are complex and are often not immediately apparent. For example, Flanagan (1983) found that improving upstream irrigation efficiency would result in more variable

Canyon Ferry inflows and subsequent reductions in average annual power production potential. Continuing this study, Brustkern (1986) found that increasing upstream irrigation would have "minimal and mixed impacts" on the Canyon Ferry reservoir operations. Specifically Brustkern concluded that although annual power production would be slightly reduced, spring flood control would be enhanced and winter power production would be increased. Increasing upstream irrigation efficiency, however, was found to both increase spring flood potential and decrease annual power production. This suggests that increasing irrigation efficiency would have almost the opposite effect of increasing irrigated acreage. Brustkern's study considered the individual impacts of increasing irrigation efficiency and irrigated acreage, leaving the combinations of such effects open to further investigation.

Since virtually all of the land suitable for flood irrigation in the Canyon Ferry basin is in use, it is projected that any future irrigation development would be under the more efficient sprinkler type systems. Therefore, the combined effects of the projected increases in irrigated acreage with the corresponding increase in irrigation efficiency must be better understood. Accordingly, the goal of this project is to determine the effects of projected increases in upstream irrigation development on potential water uses at Canyon Ferry reservoir under different operating criteria.

Objectives

The project goal was attained by completing the following objectives: (1) determine how the projected levels of upstream irrigation development would modify the monthly and annual inflows to Canyon Ferry reservoir, (2) determine how the modified inflows would affect reservoir water uses, including monthly and annual power production and spillage, and (3) determine what modifications, if any, could be made in the current reservoir operating criteria to increase annual power production and/or decrease annual spillage under both current and projected future levels of upstream irrigation development.

These objectives were accomplished by developing separate computer simulation models for the water use area above Canyon Ferry Reservoir and for the reservoir itself. These models, which are based on a water balance over a monthly time step, were run in series. The water use model simulates the interactions between irrigation water use, groundwater storage and streamflows above Canyon Ferry, and subsequently develops monthly reservoir inflow sequences. Hence this model can determine the monthly inflow sequence to Canyon Ferry reservoir corresponding to any specified level of upstream irrigation development. This model represents an extension of the Brustkern (1986) model in that it, among other things, differentiates between numbers of flood and sprinkler irrigated acres. The second model takes the inflow sequences generated by the basin model, passes them through the Canyon Ferry reservoir, and computes the amount of power and the volume of spillage produced at the reservoir during each month. The Canyon Ferry reservoir model is also capable of simulating the effects of alternative reservoir operation policies. The steps taken in accomplishing the outlined objectives are summarized below.

Irrigation Water Use

Data Collection. The initial project step involved gathering information describing basin hydraulic and hydrologic characteristics and historical irrigation activities. These data are presented in Appendix A.

Development of the Irrigation Water Use Model. The basin water use model was developed to simulate the interactions between irrigation activities in the basin and basin outlet streamflows. This model consists of a series of water balance equations which account for streamflow, diversion, conveyance, evapotranspiration, and return flow on a monthly time step.

Generation of the Natural Reservoir Inflows. The natural inflows represent the inflows to Canyon Ferry reservoir that would have occurred under natural or "no-irrigation" conditions in the basin. They were developed by running the model in reverse with 35 years of historical monthly Canyon Ferry inflows and input parameters describing historical irrigation conditions in the basin. Once developed, the natural inflow sequence became part of the input parameter set for the basin model and was used throughout the rest of the simulation runs. The concept of using natural inflows was developed by Flanagan (1983) and Brustkern (1986).

Reservoir Operations

Data Collection. This step involved gathering information describing the hydraulic characteristics and operating policies of the Canyon Ferry reservoir. The major sources of these data were Brustkern

(1986) and the USBR Technical Report of Design and Construction for Canyon Ferry Dam and Power plant (1957).

Development of the Reservoir Operation Model. The reservoir operation model is also based on a series of water balance equations. Major output variables include monthly releases, spills, power production, and reservoir water surface elevations.

Simulation Runs

Simulation of Irrigation Water Use for Various Levels of Upstream Irrigation Development. The basin model was initially used to simulate six different levels of irrigation development in the basin by running the model with varying numbers of flood and sprinkler irrigated acres. The six conditions represented natural, historical, present, and present plus 25, 50, 75, and 100 thousand additional sprinkler irrigated acres. The "present" level of irrigation represents 1984 conditions when there were an estimated 493,985 acres under flood irrigation and 139,329 acres under sprinkler irrigation. After examining the resulting reservoir inflow sequences, it was decided that only the inflow sequences generated under the (1) "natural" (no-irrigation), (2) "present" irrigation, and (3) "projected future" (present + 100,000 acres) irrigation conditions should be run through the reservoir model, as the effects of other incremental levels were relatively minor.

Simulation of Reservoir Operations and Water Use. The three inflow sequences described above were run through the reservoir operations model using the current published operating criteria. The resulting average monthly power production and spill volume values were plotted and the full output record was examined for extremes in reservoir elevation, power production, and spill volumes.

Optimization of Reservoir Operating Criteria. After examination of the results of the reservoir water use simulation runs, it was decided that lowering the spring reservoir drawdown level and delaying the summer reservoir fill date would be desirable reservoir operation modifications to investigate. The present and projected future inflow sequences were run through the reservoir model a number of times, lowering the spring drawdown level by one foot with each run. This procedure was repeated using an August 1st rather than the original July 1st fill date.

The following report will describe the Canyon Ferry drainage basin study area, explain the development of the basin and reservoir models, present the results of each project objective, and finally discuss the conclusions drawn from the study results.

CHAPTER 2

STUDY AREA

The Canyon Ferry drainage basin covers the 15,900 square miles of southwestern Montana east of the Continental Divide and west of the Bridger and Gallatin ranges (Figure 1). Mountain snowmelt creates the many small streams that feed the Madison and Gallatin rivers along with the Big Hole and Beaverhead tributaries of the Jefferson river. Together these streams form the headwaters of the Missouri river and pour more than 4 million acre-feet of water into Canyon Ferry reservoir each year (USGS, 1984). The geography of the basin is characterized by its many mountain ranges, forests, and broad river valleys. The rigorous climate is considered semi-arid, with an average of 15" of precipitation falling in the river valleys annually (Flanagan, 1983).

Land use in the basin is dominated by agriculture. With the decline of the gold rush, and the passage of several federal land acts around the turn of the century, agriculture surpassed mining to become Montana's primary source of income. The most productive lands in the Canyon Ferry drainage are the irrigated areas on the valleys, benches, and alluvial fans along the headwater rivers. Although the growing season is short, the inherently fertile soils in this region lend themselves well to the production of small grain and forage crops.

Because of the dry climate these crops are irrigated where possible. Currently there are approximately 630,000 irrigated acres in the basin, although historically this value has ranged from a maximum

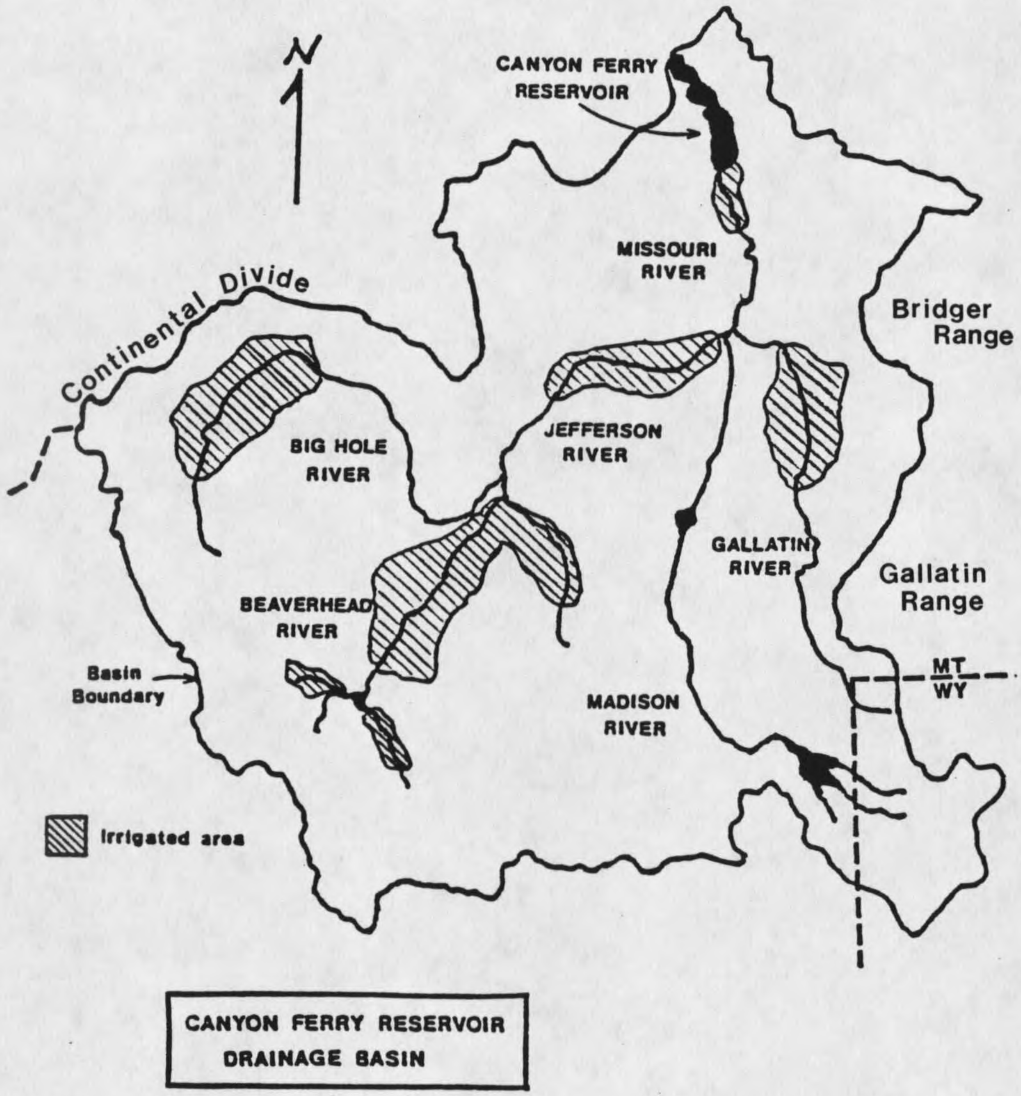

Figure 1. Major rivers and irrigated areas in the Canyon Ferry Reservoir drainage basin

of 713,000 acres in 1954 down to 525,000 acres in 1983 (Figure 2)(MBSA, 198-). About 90% of the irrigated land is devoted to forage crops, with the rest planted in small grains, potatoes, and various small horticultural crops (MT Ag. Stats., 1985). Until the mid-1950's, flood-type irrigation systems covered virtually all of the irrigated acreage in the basin. Since then the more efficient sprinkler type systems have become increasingly popular and now account for over 20% of the basin's irrigation (MBSA, 198-). Although irrigated fields can be found along streams located throughout the basin, the irrigation practices and subsequent hydrologic responses of these different areas are quite similar, as described below.

The irrigation process begins when water is diverted from a local stream into a typically unlined canal for conveyance to the fields. Approximately twice as much water is diverted from the stream as will be applied to the fields (SCS, 1978). Some of the diverted water, called carriage water, is necessary to maintain water levels that permit diversions from the canals. The carriage water runs through the conveyance system then returns to the source stream. The rest of the excess diverted water is either not used and returned with the carriage water, infiltrated through the canal beds into the surrounding soil, or consumed by phreatophytes and evaporation.

The portion of irrigation water that reaches the field is applied by either surface or sprinkler irrigation methods (Figure 3). Gilley et al. (1982), discusses what happens to the water once it is applied to the field using both surface and sprinkler irrigation systems. With surface irrigation, water flows by gravity from the upper to the lower

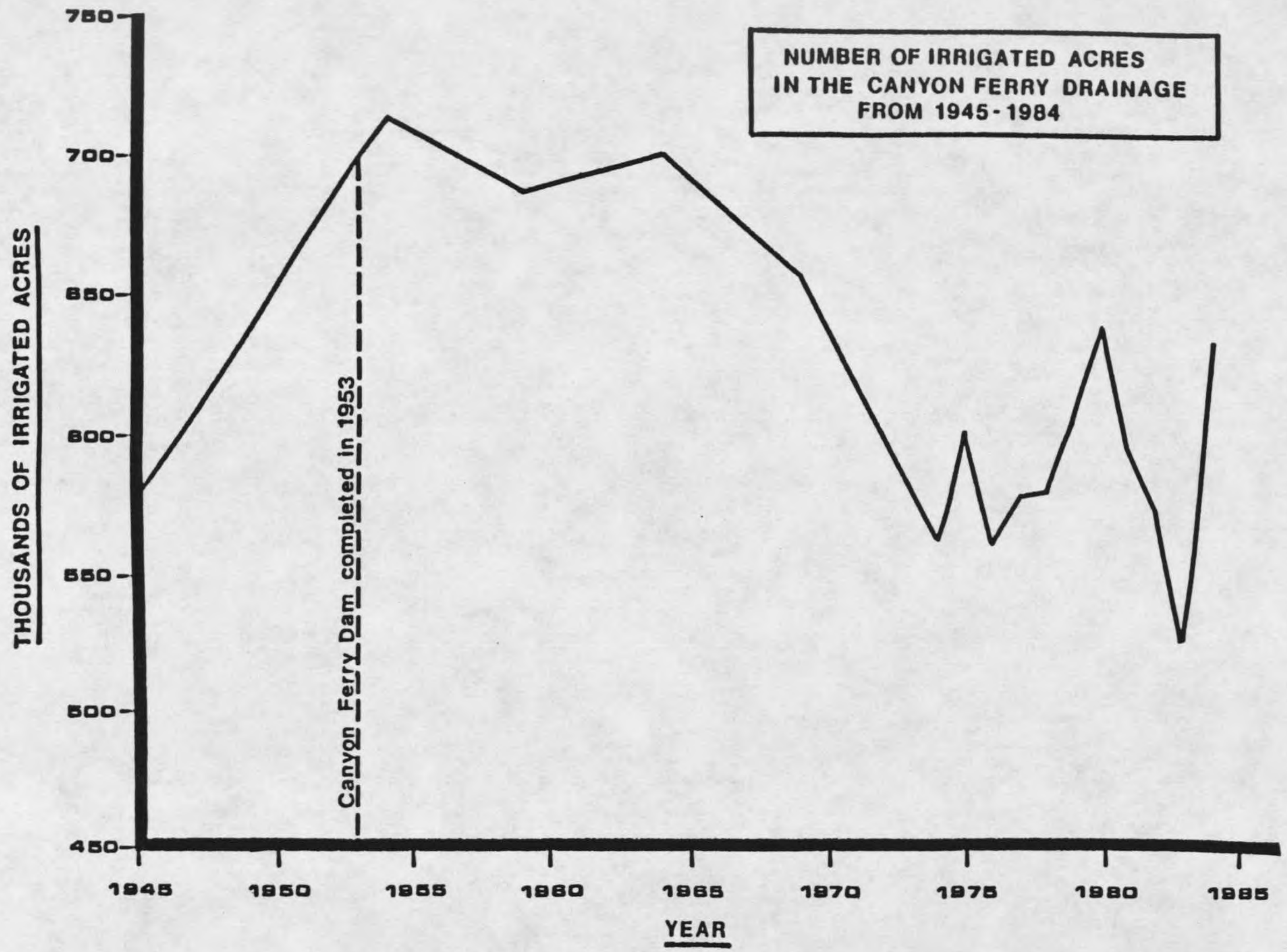

Figure 2. Total numbers of irrigated acres in the Canyon Ferry drainage basin between 1945 and 1984

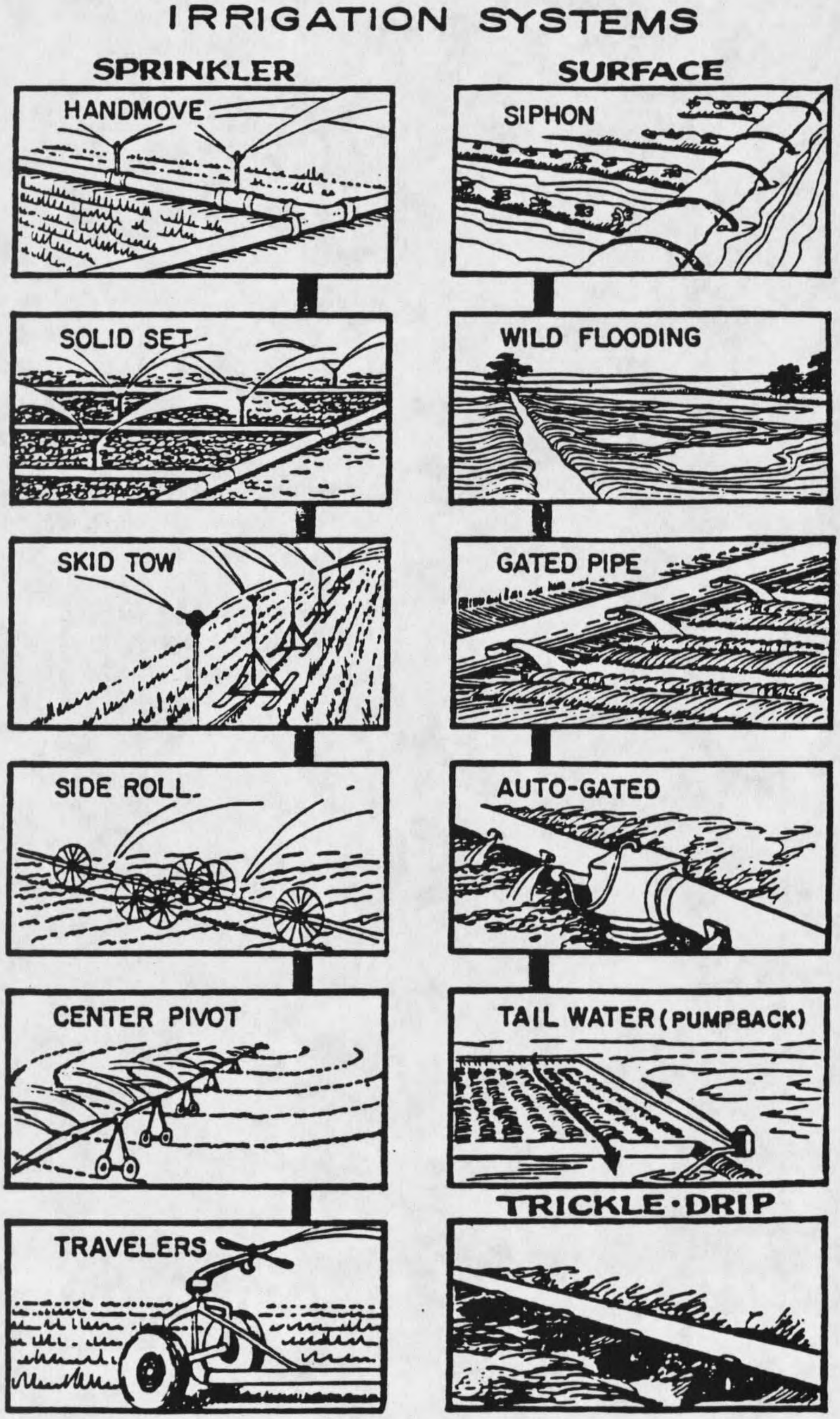

Figure 3. Examples of surface and sprinkler irrigation systems (Gilley et al.,1982)

end of the field. The simplest version of this method is called "wild flooding." In this case the end of the irrigation ditch is blocked, causing the water to flow out over the sides of the ditch and across the field. Other surface methods allow better control by employing siphon tubes to transfer the water to either furrow or border irrigated fields.

With sprinkler methods, water is pumped from the irrigation ditch to the sprinkler system where it is then sprayed on the field through a set of nozzles. The sprinkler apparatus can be moved over the field manually or automatically to uniformly distribute the water during a given irrigation cycle. With either the surface or sprinkler methods, the amount of water applied to a field must be somewhat greater than the net crop water requirement in order to compensate for unavoidable losses to surface runoff, deep percolation, nonuniformity of application, and, in the case of sprinkler systems, evaporation and wind drift losses during application. In a well-run system, the rate of irrigation water application is proportional to factors such as soil infiltration rate, field size and slope, crop type and maturity, and current climatic conditions.

Most of the inefficiencies in these systems arise from over irrigation caused by excessively high application rates and irrigation run lengths. When the irrigation application is greater than the soil infiltration capacity, excess water starts to collect on the soil surface. Most of the accumulated water eventually becomes surface water runoff, although some will stay on the soil surface and infiltrate after the irrigation period. Most of the excess infiltrated water percolates below the root zone and thus cannot be used by the growing crops.

Irrigation water that is consumed by crops, phreatophytes, and evaporation is lost to the basin system. About 60% of the water diverted for irrigation in the Canyon Ferry basin is consumed (SCS, 1978). The remaining 40% of the diverted water is classified as either "surface" or "subsurface" irrigation losses. This water is lost to the irrigator, but not lost to the basin as a whole. For example, the carriage water and tailwater that comprise surface losses return to the source streams relatively quickly, and can be rediverted by another irrigator downstream. The subsurface losses percolate through the soil to the underlying aquifer where they become part of the groundwater system. This water also returns to the source streams, though not as quickly as do the surface losses. The aquifer acts as an underground reservoir for this water, letting it return back to the stream over a long period of time. The actual rate of return depends on the distance from the point of irrigation application to the stream and on local aquifer properties. In the Canyon Ferry basin it has been estimated that about 22% of the irrigation water that reaches the groundwater in a given month returns to the stream within that month, and that about 75% returns within 6 months (Brustkern, 1986).

CHAPTER 3

IRRIGATION WATER USE

Data Collection

Developing a detailed model to simulate the effects of basin-wide irrigation on basin outlet streamflows requires collecting geologic, hydrologic, and geographic information to describe the basin. Specifically, data are needed to define sizes and locations of irrigated fields, crop and soil types, rainfall quantities, irrigation system types and efficiencies, conveyance efficiencies, aquifer locations and properties, and streamflow patterns. In the case of the Canyon Ferry water-use model, the types and quantities of data available substantially dictated model design. Sufficient information was found to develop parameter values that could describe average annual or average monthly irrigation conditions for the basin as a whole. For the interested reader, the specific data used to develop model parameters and variables are presented in Appendix A. Since data were not available for individual farms, the model design had to represent the basin as one large, aggregated area which could be described only by generalized parameters. Even if it had been possible to model each irrigated field separately, the desired model results did not warrant such detail.

In light of the data limitations, there are several reasons why this lumped parameter representation of the basin is acceptable and even desirable. First, the purpose of the model was to generate the sequence of monthly basin outflow volumes that would occur under a specified number of irrigated acres in the basin. Since this study was not concerned with the streamflow patterns occurring in the upper reaches of the basin, there is no reason to consider the local impacts of individual farms separately. Second, it has been shown that certain descriptive parameters, such as irrigation efficiency, can vary radically from one farm to the next in the basin, and even from one irrigation run to the next on the same field (USBR, 1970-71). To successfully use a single value to describe such a variable parameter, it would have to be used to represent the average of several fields and several irrigation runs. This is accomplished by the model by combining the many irrigated fields into just two large fields and making computations with a monthly time-step. Since the travel times for the basin are less than 5 days (Brustkern, 1986), the monthly time step can cover several irrigation runs, and thus successfully mask the individual impacts of each farm. Finally, the irrigation practices and corresponding hydrologic responses on the various farms in the basin are, in general, quite similar. This supports the use of generalized parameter values to describe the hydrologic behavior of the Canyon Ferry Drainage basin. Without such simplifying assumptions, little progress can be made towards improving water resources management. As Glover (1960) points out in the introduction to his Transient Groundwater Hydraulics text, "if the criticisms leveled at those useful assumptions were to be taken seriously, we should find ourselves obligated to discard the great bulk of engineering formulas used so successfully over the past 200 years, since a close scrutiny of their