Optimal allocation of water for agriculture and hydropower
by Larry David Cawfield

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

Abstract:
Wherever water users compete for a limited water supply, changes in use by one user are likely to affect others. In southwestern Montana, agriculture and hydropower compete for the bulk of available water. In the future, increased agricultural diversions for irrigation are possible, and increased irrigation efficiency is probable. The goal of this study was to develop a methodology to evaluate the economic gains and losses that would accrue to agricultural and hydropower water users from these changes in irrigation activity.

A computer model, which employed a form of dynamic programming, was developed and applied to the Canyon Ferry Basin and seven Montana Power Company Sites on the Missouri River. The purpose of the model was to determine optimal irrigation diversion levels so that agricultural and energy revenue from the system was maximized. The model has successfully yielded optimal diversion policies for a wide range of conditions (including but not limited to variations in energy and agricultural prices, interest rates, and irrigation efficiency) and has proven to be an effective management tool which could be applied wherever agriculture and hydropower compete for water.

In the Canyon Ferry system, the optimal diversion policy which maximizes energy and agricultural revenues is one which allows unlimited irrigation diversions during the irrigation season. Relatively high prices for agricultural products are the cause of this result. The optimal diversion policy which maximizes energy revenue alone is one in which diversions are less (32% less in one scenario) than current diversions. However, the energy revenues produced by the optimal diversions are only slightly higher (less than 3%) than the energy revenues which result from current diversions.

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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

Wherever water users compete for a limited water supply, changes in use by one user are likely to affect others. In southwestern Montana, agriculture and hydropower compete for the bulk of available water. In the future, increased agricultural diversions for irrigation are possible, and increased irrigation efficiency is probable. The goal of this study was to develop a methodology to evaluate the economic gains and losses that would accrue to agricultural and hydropower water users from these changes in irrigation activity.

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INTRODUCTION

One could argue that water is perhaps the single most important quantity in our lives. The first recorded history of civilization came from people who lived along the banks of the Euphrates and Nile Rivers. The great cities of the world are generally located adjacent to the great rivers of the world. About two-thirds of the human body is composed of water.

The reason that water plays such an important role in our lives is because its uses are many. Water is at once a liquid avenue of transportation, a cleaning solvent, a source of energy, and a vital component in the production of plant and animal matter. In fact, because water is so universally desired, there is often a greater demand than there is a supply of water. When water demand exceeds water supply, conflicts between competing users arise over the right of access and use of a water supply.

In the arid portions of the western United States, water has always limited the development of cities, industry, and agriculture. In Montana, irrigation and hydropower generation compete for the bulk of the available water within the state. Conflicts on the Missouri River and in the Canyon Ferry Basin in Southwestern Montana are typical of the conflicts between agricultural and hydropower interests and will be examined in detail in this thesis. The Bureau of Reclamation (which operates Canyon Ferry Dam) and Montana Power Company operate a number of hydropower facilities on the Missouri River. As the streamflows which feed these hydropower facilities are subject to upstream irrigation diversions, the ability of the hydropower facilities to generate energy is partially dependent on the timing and amount of these irrigation diversions. The study area is shown in Figure 1.

When an irrigator removes a portion of the flow from a river or stream, the irrigator has temporarily made the diverted portion of the streamflow unavailable for hydropower generation. However, only a portion of the diverted irrigation water is consumptively used. The remainder flows overland back into the stream or percolates to the groundwater system from which it generally returns slowly to the stream and becomes available for hydropower or irrigation. Figure 2 illustrates these elements of irrigation.

Because irrigation affects both the timing and volume of streamflows available for downstream hydropower generation, those in charge of regulating water resources must be able to quantify the effect of proposed changes in irrigation practices on hydropower generation. Changes in irrigation practices in the study area are likely to come on two fronts: increasing irrigation efficiency and increasing

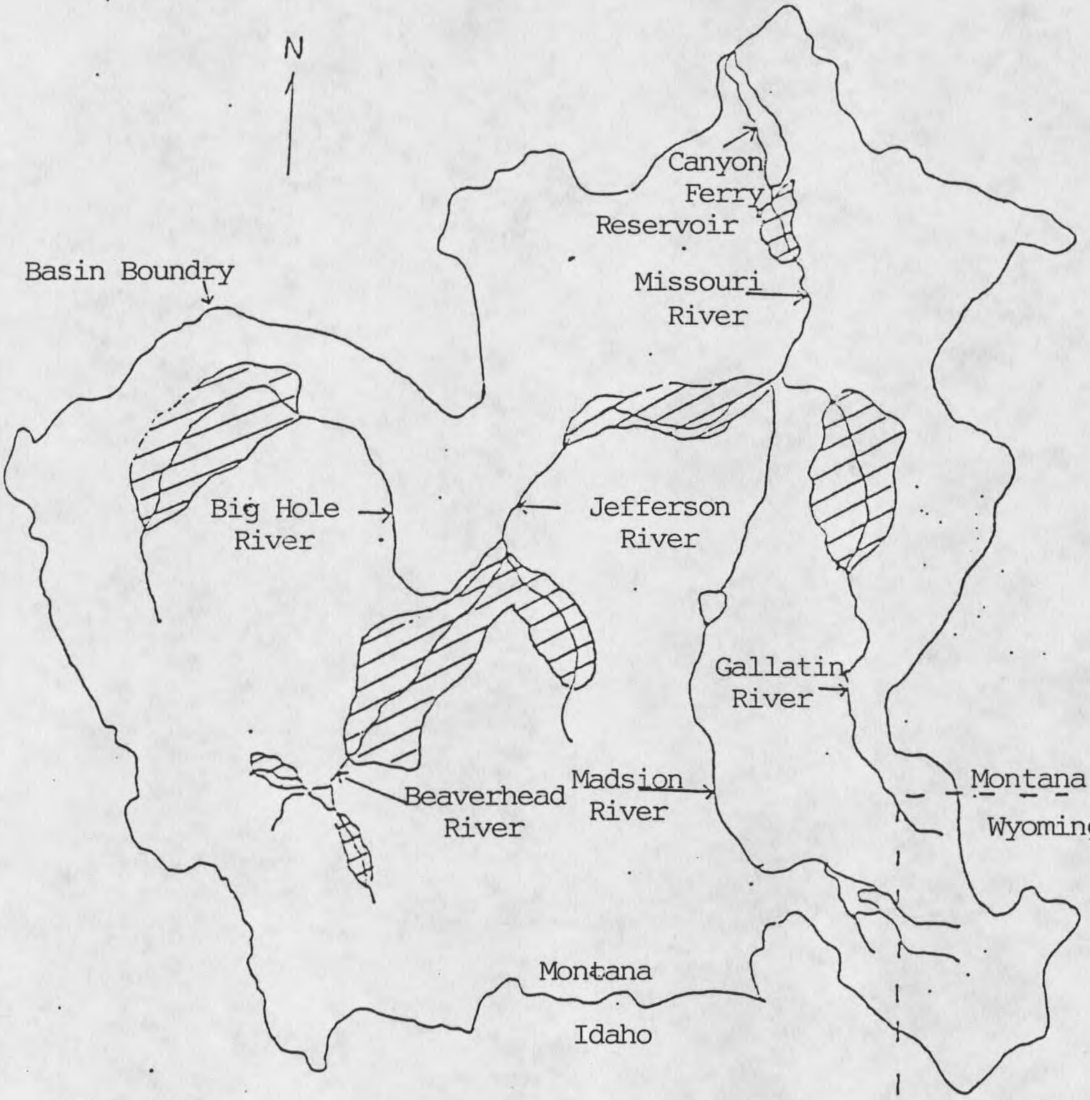

Figure 1. The Canyon Ferry Study Area. Montana Power Company Faciliites Not Shown. Shaded Areas Represent Areas of Major Irrigation Activity. (from Brustkern (1986))

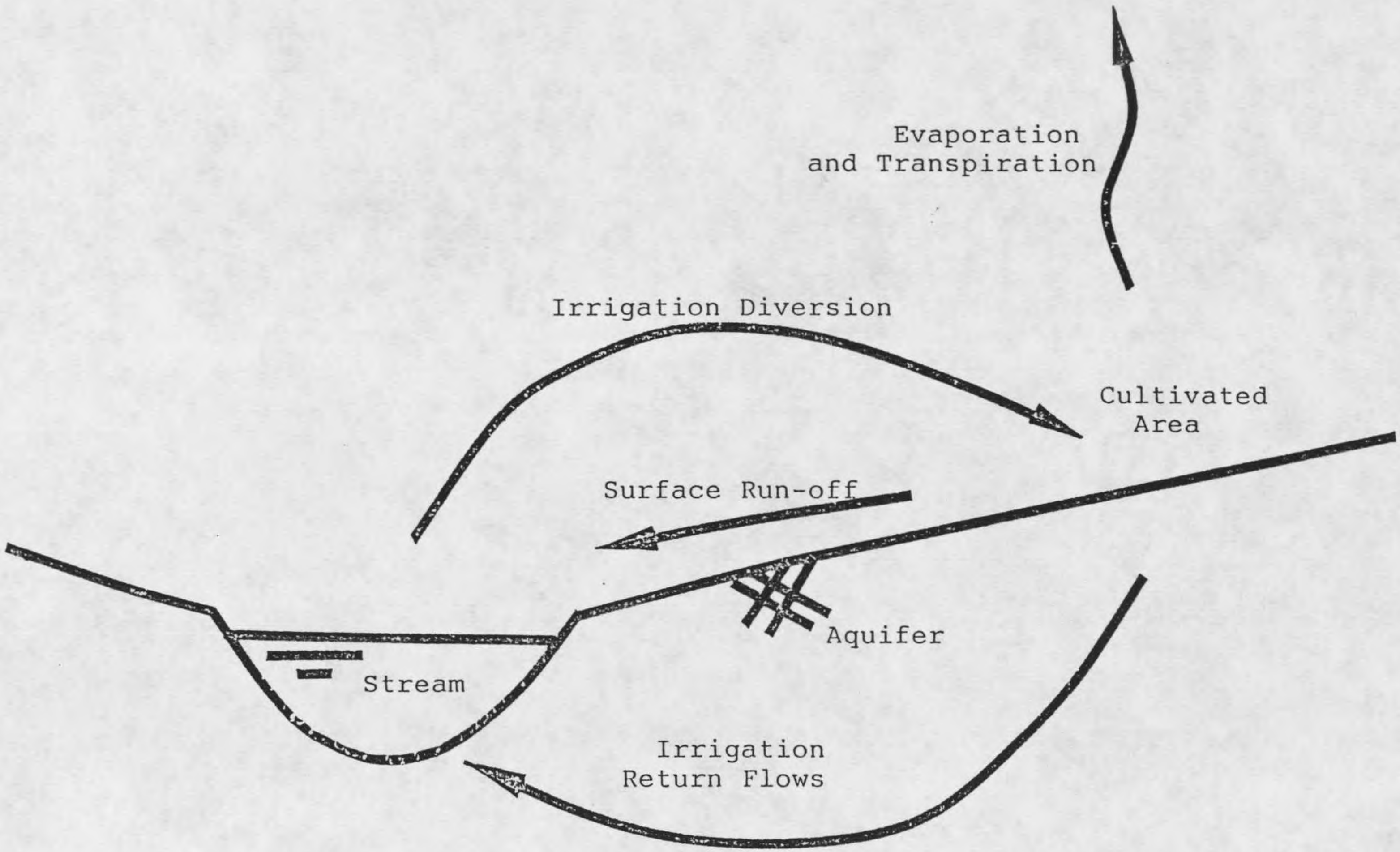

Figure 2. Elements of Irrigation Water

diversions to irrigate more land. The Soil Conservation Service (1978) predicts that as a result of improved conveyance systems, better water management, and increased sprinkler irrigation, overall irrigation efficiency will increase dramatically in Montana in future years. In addition, irrigators have applied for numerous permits to expand irrigation operations in the Canyon Ferry drainage basin. The Montana Department of Natural Resources and Conservation, which administers water rights in Montana, has delayed any action on the permits because of objections by Montana Power Company and the Bureau of Reclamation. Montana Power Company and the Bureau of Reclamation claim that any additional water use in the Canyon Ferry drainage basin would impair the ability of downstream dams to generate hydropower. This report will attempt to quantify the effects that changes in irrigation efficiency and diversions have on energy production.

Flanagan (1983) studied the effects of hypothesized increases in irrigation efficiency in the upper Missouri River Basin and found that increases in irrigation efficiency result in a decrease in the hydropower generation at Canyon Ferry Dam. An approximate doubling of irrigation efficiency from the current level to 40% resulted in a 4.1% reduction in the average annual energy production at Canyon Ferry Dam. Likewise, an increase in efficiency from the current level to 60% resulted in a 8.5% reduction in the average annual energy production at Canyon Ferry Dam. Likewise, an increase in efficiency from the current level to 60% resulted in a 8.5% reduction in the average annual energy production at Canyon Ferry Dam. Brustkern (1986) employed a more sophisticated version of Flanagan's work and obtained similar results. Additionally, Brustkern evaluated the effects of hypothesized increases in the irrigated acreage (at constant irrigation efficiency) and found that annual energy production at Canyon Ferry was reduced with an increase in irrigated acreage. However, Brustkern found that energy production during winter months (when energy is potentially more valuable) actually increased with an increase in the irrigated acreage. Hence, increasing irrigated acreage might be desireable to both agriculture and energy generating interests.

These results should immediately inspire the well-informed and wise water manager to pose such questions as "For the existing irrigation system efficiency and existing hydropower systems, what level of irrigation activity (as measured by irrigated acres) produces the most combined benefit to irrigators and energy producers?" or "As time goes by and irrigation efficiency increases, what level of irrigation activity produces the most combined benefits to irrigators and energy producers?". The purpose of this report is to answer the above questions by presenting a method for determining optimal irrigation diversion activities in the study area. In addition, the method will be applied to a number of scenarios and the results will be analyzed to verify the method.

An optimization model, using a form of dynamic programming, is developed and applied to seven Montana Power Company hydropower installations on the Missouri River, Canyon Ferry Dam, and the Missouri River Basin above Canyon Ferry Dam. As dynamic programming is most suited to computer application, a FORTRAN computer program which contains the optimization model has been written for the purposes of this report. A copy of the computer program is contained in Appendix A. (In some scenarios considered in this report, optimal policies are found for non-zero interest rates. The computer program which contains the optimization model when non-zero interest rates are considered is slightly different than the computer program in Appendix A.)

The optimization model is intended for use in determining the best or optimal combination of irrigation diversions and irrigation efficiency and to evaluate the economic gains that would accrue to users as a result of the implementation of these optimal policies. Although the empirical results obtained in this report are highly site specific, the methodology by which the results are obtained is completely general and could be applied by water managers and planners wherever hydropower and agriculture compete for a limited water supply.

The optimization model used in this report consists of two distinct components -- a simulation component and an optimization component. The simulation component uses the basic model (with minor modifications) reported by Brustkern (1986). The model simulates operation of the irrigation and hydropower activities within the basin. The simulation determines the amount of revenue which would be produced by agriculture and by hydropower production for specified levels of irrigation activity during each of the years from 1956 to 1984. (Canyon Ferry was constructed prior to 1956 and was filled for the entire year for the first time in 1956.) The optimization component uses the results of the simulation component to select other levels of irrigation activity so that the optimal level of irrigation activity may be identified.

LITERATURE REVIEW

The foundations of operations research were laid during World War II when teams of scientists were employed to scientifically determine how to best allocate scarce resources to various military operations. These early operations research teams received some of the credit for the victory of the Air Battle of Britain and for many other victories during World War II. Since that time, the value of operations research has been recognized not only for military operations but also for business, management, government, manufacturing, electronics, and financial applications as well.

Operations research is a scientific technique which observes the relationship between components of an operation and the outcome or result of the operation. By creating and examining a mathematical model which embodies the relationship between the components of an operation, one can employ operations research techniques to extract information about the real, physical operation from the mathematical model. Additionally, operations research is directed toward improving the operation in question by resolving conflicts of interest among the components of the operation in a manner that most benefits the operation. The optimal decisions or policies which most benefit the operation as a whole are found and expressed for application to the real, physical operation.

The application of operations research techniques to different fields has led to considerable refinement and improvement of the original operations research techniques. In 1952, George Dantzig perfected the simplex method of linear programming for application to general, linear systems. Since then, linear programming has become one of the most widely applied operations research techniques. In 1957 Richard Bellman formulated the principle of dynamic programming for application to general, multi-stage decision processes. Bellman's principle simply and elegantly states that an optimal policy has the property that "regardless of the initial state and decision, the remaining decisions must constitute an optimal policy with regard to the first decision." This thesis will employ dynamic programming principles, and consequently Bellman's principle will be discussed at length in the methodology section of this report. The theory of queues as advanced by Moran (1959) and others has also been used in operations research.

Operations research has been applied extensively to water resource problems since the early applications of operations research. Dynamic programming has proven to be particularly useful for application to water resource problems. In fact, Bellman's landmark text on dynamic programming describes problems in which wastewater treatment plant location and wastewater treatment level are analyzed with the objective of minimizing costs.

Buras (1972) describes the application of dynamic programming to the design of a major irrigation canal system on the Ghazvin Plain in Iran. The route of the aquaduct and the location of lateral canals were determined by dynamic programming techniques. The optimal design resulted in minimum construction and operation costs. Buras also briefly describes the application of dynamic programming to the revegetation of a watershed for the purposes of improving water yield and grazing.

Dudley and Burt (1973) applied dynamic programming to the joint operation of a reservoir and irrigated acreage. The reservoir capacity and irrigation water distribution system capacity were considered fixed so that the timing and amount of irrigation water application, the amount of acreage to irrigate, and whether or not to irrigate all cultivated acreage for the duration of the growing season were left to be determined. The total crop water demand was treated as a stochastic variable; this treatment is considerably more refined than the treatment afforded crop water demand in this report.

An important distinction in the type of data employed in dynamic programming applications emerges in the literature of the subject. While some researchers have developed applications for stochastic inputs or demand, others have developed applications for deterministic inputs or demands. There is little difference between the approaches as far as the underlying principles of dynamic programming, but stochastic applications are generally computationally more difficult.

Hall and Dracup (1970) applied dynamic programming to find the optimal irrigation timing and the optimal irrigated area for a region which was occasionally deficient in water supply.

Applications of dynamic programming to determine reservoir operating rules are numerous. Only a few of the publications are reviewed here. Kottegoda (1980) discusses the application of dynamic programming to the conjunctive operation of a surface reservoir and a groundwater reservoir to satisfy downstream water requirements. The surface inflows to the reservoir are stochastic while the downstream demand is deterministic.

Butcher (1971) finds optimal reservoir operating policies for multi-purpose reservoirs assuming that inflows to the reservoirs are stochastic and exhibit the properties of a Markov Chain -- that is, the flow in any period is a good indicator of the flow in the next period.

Hall and Howell (1963) present a method for determining the optimal size of one single-purpose reservoir. Optimal operating policies for different sized reservoirs are determined in order that the optimum size reservoir may be chosen for a particular application. Inflows to the reservoir are synthetically generated and deterministic.

Since Bellman first formulated his principle of dynamic programming, others have extended and improved dynamic programming with the intent of avoiding the 'curse of dimensionality' that attends dynamic programming as described by Bellman. The technique which follows most readily from Bellman's Principle of dynamic programming is now called discrete dynamic programming. Differential dynamic programming, discrete differential dynamic programming, state incremental dynamic programming, and the policy iteration technique are all versions of discrete dynamic programming and are designed to sidestep the 'curse of dimensionality' that limits the value of discrete dynamic programming.

Yakowitz (1982) provides an excellent review of each of these techniques and in the general application of dynamic programming to water resources. Readers unfamiliar with this topic would be well advised to review Yakowitz's article carefully. Yakowitz speculates that differential dynamic programming has the most promise as an effective management tool in water resources. However, for the relatively small problem investigated herein, this author has found the simple and elegant approach of the policy iteration technique more than satisfactory.

Butcher (1971) and Mawer and Thorn (1974) have employed the policy iteration technique in problems of optimal operation of water resource systems. However it appears as if these researchers have not fully utilized computational power provided by the policy iteration technique. Furthermore, these researchers considered stochastic streamflows while deterministic streamflows are employed in this thesis.

The bulk of the dynamic programming applications that deal with reservoir operations and irrigation practices seek to identify the optimal reservoir size and the optimal operating policy of that reservoir so that downstream irrigation demands (or multipurpose demands) can be met. This thesis differs from these applications (and may be unique) in that the optimal irrigation policy is sought for irrigation districts upstream of a system of energy producing reservoirs. The policy maximizes revenue production. The operating policy at the reservoir is considered fixed and is not subject to optimization.

The Canyon Ferry System (specifically the irrigation and hydropower operations within the basin) has been studied extensively in the recent past. Flanagan (1983) was the first of several researchers from the Civil Engineering Department at Montana State University to study irrigation and hydropower operations in the Canyon Ferry Basin. Flanagan developed a model which simulated the irrigation operations within the Canyon Ferry Basin and which predicted the monthly inflows to Canyon Ferry for various combinations of irrigation efficiency and irrigation diversions. Flanagan also developed a crude model of the hydropower operations at Canyon Ferry and, on the basis of this model, found that increases in irrigation efficiency within the Canyon Ferry Basin would result in decreases in the average annual energy production at Canyon Ferry Dam. As previously indicated in the introduction, Flanagan found that when irrigation efficiency approximately doubled and tripled to 40% and 60% from current levels average annual energy production decreased by 4.1% and 8.5% respectively.

Brustkern extended and refined Flanagan's work. His more sophisticated version of Flanagan's model also predicted decreases in average annual energy production with assumed increases in irrigation efficiency. Specifically, his work indicates that decreases in average annual energy production of 7.0% and 11.1% occur when irrigation efficiency approximately doubled and tripled from of the current levels to 40% and 60% respectively. Brustkern also investigated the consequences of increasing the amount of irrigated acreage in the basin while maintaining irrigation efficiency at the present level. His results indicate that increases of 5% and 10% in the amount of irrigated acreage resulted in average annual energy production decreases of 0.3% and 0.99% respectively. However, it was observed that increases in irrigated acreage resulted in changes in the time distribution of energy production such that more energy was produced during the winter months when energy is potentially more valuable.

DeLuca (1987a) refined further the simulation of irrigation operations in the Canyon Ferry Basin by separating the effects of sprinkler and flood irrigation and by employing a more sophisticated accounting method for the diverted irrigation water. DeLuca also simulated the operation of Canyon Ferry Reservoir but used a model which differed significantly from that of both Flanagan and Brustkern. DeLuca found that an increase of 15.8% in the basin's irrigated acreage resulted in a decrease in average annual energy production of 1.3%. The 15.8% increase in irrigated acreage was accompanied by an increase in irrigation efficiency because the increased acreage was assumed to be more efficiently irrigated by sprinkler irrigation. DeLuca also varied the operating policy at Canyon Ferry Reservoir Dam and found that certain policies resulted in improved energy production potential at Canyon Ferry.