Optimal use of ground and surface water in the Gallatin Valley, Montana
by Kenneth Boyd Young

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Agricultural Economics
Montana State University

Abstract:
Intraseasonal interaction of the ground and surface water system figures prominently in this irrigation-planning study of a river basin. A model for optimizing use of variable streamflows and supplemental groundwater reserves is developed that simultaneously evaluates economic interaction occurring within the ground and surface water system during four discrete periods of the irrigation season.

Development of the model encompasses three stages. First, the hydrologic system is analyzed and groundwater discharge is functionally related to water table height in eight hydrologic subareas over four time periods. Second, a nonstochastic model is developed to allocate intraseasonal surface supply and utilize supplemental groundwater subject to interspatial-intertemporal groundwater interactions determined by water table balances in each period. This model is used to compute well investment levels associated with assumed fixed surface supplies and different distribution efficiencies.

Third, the probability distribution of annual streamflow is evaluated and the optimal level of well investment (within the class of well developments computed above) is determined for each field efficiency condition with stochastic surface input.

Post-optimal analysis, including sensitivity analysis of variable pumping costs, well investment costs, tolerable water table heights, and crop allotment restrictions, is also applied.

Empirical results of the model indicated that with optimal surface water use, development of groundwater reserves for irrigation supply in the Gallatin Valley would increase average net annual irrigated income by $8 per acre or 18.2 percent on the 124,416 acres in the study area. If field efficiency can be raised from the present level to the recommended level, a comparable increase in irrigated income may be attained without groundwater development. Conjunctive use of ground and surface water together with increased field efficiency in irrigation would result in a potential annual income gain of $13 per acre of 30 percent overall.

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Approved:

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ABSTRACT

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CHAPTER I

INTRODUCTION

In many irrigation projects, the most limiting factor affecting productivity is a high water table resulting from a basic disequilibrium in the hydrologic system. The damage caused by excessive water tables has become a serious problem for irrigated agriculture in many parts of the world. In West Pakistan, for example, some 26 million acres of irrigated cropland has been damaged by waterlogging and salting, and the spread of salinity is continuing to force many more thousands of acres out of production every year. 1/

The full significance of this problem is often underestimated at the outset of irrigation development as the damage may not be evident until several years later. Accumulation of damage in the case of gradual soil salinization or loss of permeability has, generally, a very long time horizon. Damage is more easily assessed when farm income is directly affected by crop bogging or interference with harvesting.

In addition to artificial drainage, the most common method for controlling water tables, there are often several other strategies available for control of this problem. For example, the distribution system can be designed and water supply allocated so that percolation losses are minimized in the areas of the project that are most

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1/ D.E. Naylor, "Control of Waterlogging and Salinity in West Pakistan," International Journal of Agrarian Affairs, Vol. IV, No. 1, October 1963, pp. 1-12.

susceptible to bogging. Also, where groundwater can be used to supplement surface water, the water table may be controlled by concentrating pumping on lower lands of the project.

In most cases, however, the economic potential of employing these alternative strategies is not appreciated until after all irrigation structures are completed and some experience is obtained in operation of the irrigation system. At this stage, artificial drainage may be the only practical choice left for relieving high water tables although less costly control could have been attained formerly with another strategy, e.g., by changing the layout of the distribution system.

Nature of the Investigation

The economic significance of high water tables to irrigated agriculture and some alternative strategies for controlling this problem have been discussed in general. An important implication to be derived from this discussion is that a more systematic approach in planning irrigation systems is needed where high water table conditions are likely to be encountered. In view of the drainage problems experienced in some completed projects, e.g., in West Pakistan, 2/ it would appear that more comprehensive planning models would be advantageous even if based on relatively sparse hydrologic information.

2/ Ibid.

A general equilibrium model including all hydrologic relationships offers several advantages over partial equilibrium methods for analyzing water-table problems. For example, the evaluation of alternative strategies for water-table control may be directly incorporated within a composite criterion function for overall optimal system organization. This is not possible in the partial equilibrium approach. Allocation of water flows and the location of irrigation wells within a system can be important strategies in water-table control, particularly for localized problem areas. The use of a composite criterion function as postulated above greatly facilitates analysis of these more complex strategies for controlling water tables.

The problem of surface water-groundwater interaction in a hydrologic system may be simply explained by Darcy's Law governing linear flow of fluids. According to Darcy's Law, groundwater velocity for laminar flow is proportional to the hydraulic gradient along the path of flow. 3/

The following are two examples of interaction which may be explained by Darcy's Law:

3/ S.N. Davis and R. J. DeWiest, Hydrogeology, John Wiley & Sons, Inc., New York, 1966, p. 156.

1) If groundwater is pumped adjacent to a stream, water loss from the stream will tend to increase in proportion to the change in the hydraulic gradient between the stream level and the adjacent aquifer's declining water table level; and

2) If the water table in the adjacent aquifer is higher than the stream level, e.g., from heavy irrigation buildup, the surface water supply provided by the stream may be expanded by increased groundwater outflow from the adjacent aquifer.

The two examples cited are very simple cases of possible interaction between surface and groundwater. The analysis becomes more complicated when a water table change in one part of an aquifer region triggers a chain reaction of interactions throughout the rest of the system. A simulation model for evaluating this latter problem is presented in Chapter III.

In addition to the above physical interactions, some important economic interactions also take place between the ground and surface water system. A major source of interaction is the economic alternative of using the aquifer as a distribution system for irrigation supply instead of surface canals. This method of distribution is feasible in the present study as most of the aquifer area is located under agricultural land. Advantages in distribution efficiency coupled with low pumping lift associated with high water table levels make groundwater a relatively cheap alternative source of water supply in the Gallatin Valley. Reliability of groundwater supply is also assured because of the large volume currently in storage and the high annual rate of recharge to the aquifer in the Gallatin Valley.

It should be evident from the above discussion that high water-table levels are a primary cause of surface and groundwater interactions within a hydrologic system as well as a major threat to productivity of an irrigation project. This further justifies the use of a general equilibrium model for irrigation project planning which includes all hydrologic relationships of concern in optimal water allocation.

Purpose of the Study

This thesis involves the formulation, solution and evaluation of a general equilibrium model for conjunctive intraseasonal use of groundwater and surface water in the Gallatin Valley, Montana. The purpose of the model is to optimize the combined use of available surface and groundwater resources in the Gallatin Valley subject to specified intertemporal and interspatial hydrologic relationships that restrict the use of these resources. Since the major restriction on water use is the level of the water table, evaluation of water tables during the irrigation season enters prominently in construction of the model. The identification and quantification of hydrologic relationships affecting water table balance are important features of the methodology followed in this study. The analysis in Chapter III of this study is entirely devoted to specification and quantification of hydrologic relationships.

Specific empirical objectives of the present study are to determine the economic benefits of groundwater development in the Gallatin Valley, the value of improved irrigation efficiency resulting from better farm practices, ditch consolidation and/or lining, and the relative importance of current surface water supply in the study region. Empirical objectives also include an evaluation of optimal cropping patterns in different subareas of the Valley under different water supply conditions and the optimal level of well development in each subarea. A further objective is to identify what institutional changes will be required to provide flexibility in water exchange and encourage cooperation among water users so that optimal irrigation development may be obtained in the Gallatin Valley.

Justification for the Study

The primary reason for undertaking a comprehensive water study of the Gallatin Valley is that this region provides excellent opportunity for a systems analysis of interrelated drainage and water scarcity problems within the region. The higher lands in the

Valley generally run short of surface water early in July each season whereas the lower lands with the early water rights tend to have an abundance of surface water supply during all of the irrigation season. In the lower part of the valley, once fertile lands are now bogged due to misuse of water resources in this area. 4/ It would appear that major increases in economic efficiency should result from reallocation of the valley's water resources.

In addition to the need for a quantitative economic study of the Gallatin Valley, the study was made feasible by the relative abundance of empirical data available on water use and crop production in this region. A detailed investigation of the hydrology in the Gallatin Valley had been completed by USGS, 5/ and several feasibility studies of proposed water storage projects had been completed by the U.S. Bureau of Reclamation. 6/ The availability of this type of data plus considerable local crop production data at the Montana State University Experiment Station near Bozeman was an important consideration in undertaking a study of this nature.

4/ H.E. Murdock, Irrigation and Drainage Problems in the Gallatin Valley, Mont. Agr. Expt. Sta. Bulletin 195, Bozeman, November 1926, p. 1.

5/ Hackett, et. al., Geology and Groundwater Resources of the Valley, Gallatin County, Montana, Geological Survey Water-Supply Paper 1482, U.S. Government Printing Office, Washington, D.C., 1960.

6/ United States Bureau of Reclamation, Report on Three Forks Division, Upper Missouri Project Office, Great Falls, Montana, 1958.

Statement of Hypotheses and Assumptions

The major hypothesis guiding this study is that a reallocation of surface water use in the Gallatin Valley, and in particular, development of groundwater pumping facilities for supplementing surface supply, would result in significant income gains and sizable improvements in efficient use of the Valley's natural resources. It is further hypothesized that the basic irrigation problem in the Gallatin Valley is resource management--making the right quantity of water available at the right place at the right time--as opposed to aggregate water shortages.

Important assumptions in the study which will not be tested are:

1) Evaluation of intertemporal and interspatial hydrologic relationships between surface and groundwater use will result in substantially more optimal use of these two resources in the Gallatin Valley than an optimization method which abstracts from this interaction between surface and groundwater use.

2) Groundwater depletion in the Gallatin Valley will not present a problem in this study as the probable annual withdrawal by pumping will not exceed annual recharge, on the average. Thus, the only effective storage function performed by the aquifer is an intra-seasonal one.

3) Irrigation use of surface water in the Gallatin Valley will have no perceptible effect on the volume or quality of water supply for downstream users located on the Missouri River.

4) Dewatering of streams adjacent to irrigated lands in the Gallatin Valley will have no significant economic effect on the fishery. 7/

Scope of the Study

Following a review of the literature in the subsequent chapter, considerable attention is devoted to the development of a simple hydrologic model for approximating groundwater discharge from eight subareas of the Gallatin Valley as a linear function of water table heights in these subareas. All discharge relationships regarding groundwater flows across subarea aquifer boundaries and interactions with stream flow are determined from historical hydrologic data on the Gallatin Valley utilizing fundamental principles of hydrology. The linear model for predicting groundwater discharge in the system is tested for empirical validity by comparing estimated groundwater discharge from subareas adjacent to the stream with

7/ This assumption could not be tested in this study as the value of the fishery is not known. The shadow prices associated with stream flow constraints in the model do provide a cost estimate of maintaining minimum stream flow levels for the fishery.

measured stream flow gains attributed to groundwater discharge. All subsequent groundwater discharge in the model is assumed to have the same linear relationship to other water table heights as for the particular class of water tables used in testing this model.

A theoretical general equilibrium model for irrigation optimization is formulated in Chapter IV with a nonlinear objective function and linear constraints largely determined from the hydrologic analysis in Chapter III. Evaluation of the relative economic importance of intertemporal and interspatial hydrologic relationships between ground and surface water use will constitute an important consideration in this theoretical model. Kuhn-Tucker theory is utilized to derive economic implications of the probable effects of surface-groundwater interactions which would result under different water supply conditions in the model. These theoretical interpretations provide a valuable guide for subsequent interpretation of the empirical results and sensitivity analysis of the empirical model.

Attention in Chapter V is mainly devoted to assembly of empirical data on water supply, crop water response and production cost for use in a linear programming model. A further methodological consideration is to utilize the soil reservoir for water storage during different time periods of the irrigation season for transferring water from high streamflow periods to periods later in the season when surface water is in relatively short supply. This particular strategy is of value in the Gallatin Valley as the volume of stream flow normally tends to recede as the irrigation season progresses. Also, storage capacity of the soil reservoir is relatively large compared with average monthly crop water requirements. Different soil water carryover levels are considered in defining various linear programming activities presented in Chapter V.

Formulation of the empirical linear programming model presented in Chapter VI is similar to the former theoretical model but simplified for ease in computation and accommodation of data. Measurement of net welfare in the applied criterion function is accomplished by delineating various segments of the concave theoretical objective function and defining separate activities of a linear program to be associated with these segments. Essentially, the same hydrologic constraints are retained as they are already linear in form. Additional constraints are also required for cropland acreage, wheat allotment restrictions, and crop rotation limitations in the eight subareas. The completed linear programming model contains 209 constraints, 458 activities, and 2,014 matrix entries.

The linear programming model is first analyzed as a deterministic model using the algorithm of parametric programming to evaluate 16 optimal levels of well development associated with eight different surface water supplies and two different distribution efficiencies for water supply. Probability of these surface water supplies is determined by fitting a gamma function to historical inter-seasonal streamflows. Intraseasonal flow in each of four irrigation time periods during each season is assumed to be a constant proportion of total annual flow. Expected value and standard deviation of net income are computed for each of several well development levels. These two statistics for net income in the Gallatin Valley are evaluated under various hypothesized situations and are the main quantitative measures from the economic analysis.

The two distribution efficiencies represent estimated present low field efficiency in the study area and a recommended higher field efficiency level that may potentially be adopted under a changed institutional system allowing more flexibility in water exchange. Parametric changes in distribution efficiency provide estimates of the value of ditch consolidation in the study region as well as an estimate of benefits emanating from improvements in on-farm irrigation efficiency.

CHAPTER II

IRRIGATION DEVELOPMENT IN THE GALLATIN VALLEY

A Literature Review

This chapter is divided into three major parts. Part I is a brief review of the historical development of irrigation in this region. Part II is a more exhaustive review of previous studies by government agencies and researchers at Montana State University on proposed irrigation development of the Gallatin Valley. Part III is a survey of some of the methodology employed and results obtained in other area studies involving related problems.

Part I. Historical Development

Irrigation ditches were first excavated during 1864 in the Gallatin Valley. 1/ As the area became more populated, new settlers continued to add on more ditches and appropriate water rights in the local streams with little regard to the overall benefit of the irrigation system. The outcome of this *ad hoc* piece-meal development policy is a wasteful distribution system and an over-appropriated surface water supply. Many of these ditches still in use parallel each other and have other construction defects. Severe water shortages were reported as early as 1919. 2/

1/ *Water Resources Survey, Gallatin County*, State Engineer's Office, Helena, Montana, January 1953, p. 6.

2/ Murdock, H.E., *Irrigation and Drainage Problems in the Gallatin Valley*, Agr. Expt. Sta., Montana State University, Bulletin 195, Bozeman, November 1926.

Irrigation management has also been inefficient in the Gallatin Valley. This is in part associated with early use of the western appropriation doctrine in the acquisition of water rights. 3/ Management was considered to be one of the key problems in 1953 in the Gallatin Valley by the State Engineer: 4/

> Poor irrigation practices on the part of some users is causing a waste of water and depriving other land of its use. The waste of water on higher areas, and seepage from the too numerous ditches is causing some land in the valley bottoms to become water-logged. This once productive land is now of no use except as pasture, some of it growing nothing more than swamp grass.

Under the institutionally-fixed ownership of water rights, little incentive exists for users with early surface rights to be efficient in their use of this resource or to take proper care of their ditches. Some, in fact, deliberately use excess water during heavy run-off periods to build up their water tables for sub-irrigation in other periods. This aggravates the bogging problem on lower lands.

This cursive review on historical irrigation development in the Gallatin Valley is intended to highlight current problems in the area and to explain their evolvement. What are some of the past proposals for solving these problems?

13/ Gopalakrishnan, C., The Economics of Water Transfer: An Institutional Appraisal, Ph.D. Thesis, Montana State University, Bozeman, 1967.

14/ Water Resources Survey, op. cit., p. 14.

Part II: Proposals for Development

A severe drought in 1919 provided impetus for an early extensive investigation of irrigation and drainage problems in the Gallatin Valley. 5/ Murdock's recommendations for relieving the water shortage problem were: (1) build storage reservoirs in the mountains; (2) line the irrigation canals; (3) change the irrigation system; and (4) drain the seeped lands and use this water for irrigation. These proposals were investigated in more depth in later studies and will be evaluated in turn along with other possible alternatives.

Surface Storage

A series of studies were begun in 1938 by the Bureau of Reclamation: (1) on the feasibility of diverting water from Hebgen Reservoir on the Upper Madison River to the Gallatin Valley; 6/ and (2) constructing a dam on the West Gallatin River below Spanish Creek for storing irrigation water. 7/ The latter alternative was later found to be more practical and the Hebgen diversion project was abandoned. Four alternate storage schemes at the Spanish Creek site were compared; the most optimal plan having a benefit-cost ratio of 1.52. In the course of this investigation, the Bureau also evaluated

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5/ Murdock, op. cit.

6/ Senate Document No. 191, Missouri River Basin, 1944.

7/ U.S. Department of the Interior, Report on Three Forks Division, Bureau of Reclamation, Upper Missouri Project Office, Great Falls, Montana, Appendix M.

a groundwater pumping plan. This had a benefit-cost ratio of 2.41. Consequently, the Bureau recommended that the groundwater plan be adopted in place of a surface water storage project.

A storage reservoir with 8,000 acre-feet capacity was constructed in 1948 on Middle Creek, a Gallatin River tributary, by the Montana State Water Board.

Ditch Consolidation and Lining

Murdock's recommendations for ditch lining and consolidation have not been pursued further or promoted any related construction to the writer's knowledge. This may be a promising area for further research.

Drainage

Subsurface drainage of bogged lands in Central Park and Belgrade subareas has been investigated by the United States Soil Conservation Service. 8/ SCS recommended that deep-interception drains be constructed at one-mile intervals in these subareas and that provision be made for one-half mile spacing should shorter spacing be necessary.

Artificial drainage of this scale is an expensive undertaking. Since the bogging problem has been attributed to apparent gross

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8/ U.S. Soil Conservation Service, Preliminary Examination Report on Water Supply and Distribution Investigation, Gallatin Valley Area, Gallatin County, 1948 and Survey Report on Central Park Drainage Project, Three Rivers Soil Conservation District in Gallatin County, Montana, 1950.

inefficiencies in surface water distribution and management, correction of these inefficiencies may alleviate much of the problem. At least this matter could be investigated before drainage commitments are made in the future. The present study will be concerned with effects of groundwater pumping and variation in surface water distribution in the valley on bogged areas.

Use of Groundwater

The Bureau of Reclamation plan to pump groundwater in the Gallatin Valley has been investigated further by McConnen and Mennon, 9/ Sammons, 10/ and Boyd. 11/

The Bureau proposed to pump about 92,300 acre-feet annually from 193 wells overlying the aquifer region into established ditches now diverting from West and East Gallatin Rivers. The pumped water would be used to replace surface water reallocated to other water-deficit lands outside the aquifer region.

9/ McConnen, R.J. and G.M. Mennon, Planning the Integrated Use of Ground and Surface Water: A Linear Programming Study of the Gallatin Valley, Montana, Mont. Agr. Expt. Sta, Bul. 616, Bozeman, 1967.

10/ Sammons, R.W., Irrigation Development: Institutional Blocks to Ground-Surface Water Integration in the Gallatin Valley, Montana, Ph.D. Thesis, Montana State University, Bozeman, 1964.

11/ Boyd, D.W., Simulation Via Time-Partitioned Linear Programming: A Ground and Surface Water Allocation Model for the Gallatin Valley of Montana, Report No. 10, Montana Water Resources Center, Bozeman, June 1968.

McConnen and Mennon used a linear programming model to evaluate net benefits of transferring surface water from surplus to deficit areas and replacing this water with pumped water in ditches as proposed by the Bureau. They estimated that net annual farm income under assumed Cooperative District organization in the Gallatin Valley would increase by $210,738 with the use of 190 wells.

Sammons did a case study of Highline Canal in the Gallatin System and investigated the cost of supplementing canal flows by pumping during the period July 15 to September 1 when surface water supplies are generally short. He estimated that 25 wells would be needed to meet the supplementary requirements of 7,875 acre-feet at a cost per season of $32,878, or $4.17 per acre-foot. He also analyzed institutional blocks to groundwater integration in the area. A recommendation for institutional change was: 12/

> A model of an institutional organization that would allow farmers to exchange surface water for groundwater without endangering their present water rights is needed. This institutional structure would delineate legal responsibilities for both parties during its operation and dissolution.

Boyd used linear programming to allocate water among competing uses in the Gallatin Valley: agricultural, municipal, industrial and recreational; and between surface and sub-surface storage. Adjustments were made in parameters of the model to simulate stream flow over 30 years of record during the testing phase. Pumping was

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12/ Sammons, *op. cit.*, p. 103.

employed to supplement surface water at a cost of $2 per acre-foot. Boyd did not analyze effects of pumping on the water table in different subareas or the optimal allocation of water among the different subareas of the valley.

This perusal of previous studies on proposed irrigation development suggests that further investigation is needed on the following issues before an overall optimal development plan can be implemented in the Gallatin Valley:

1) What is the optimal allocation of ground and surface water during the irrigation season among various subareas of the valley having different access to these resources?

2) How is the optimal allocation of ground and surface water use affected by the presence of high water table conditions in different subareas? Can bogging be controlled by utilizing wells for irrigation of low lands and restricting the use of surface water?

3) What value would ditch consolidation and lining have for conserving use of water in the system and alleviating the bogging problem?

4) What institutional changes are needed to permit comprehensive reallocation of water supplies, both ground and surface, within the valley to conform with results of an optimization model?

Answers are required to these important questions before optimal use can be made of water resources in the Gallatin Valley.

The following literature review is of selected studies where related questions have been investigated in other subareas. Methodology employed and results obtained in these studies will furnish valuable guidance for the present study.

Part III: A Survey of Selected Studies

Water Resource Allocation

A sizable literature has evolved on the use of allocation models and alternate methods of systems analysis in water resource studies during the past 15 years.

The Harvard Water Resources Group discusses a number of systems analysis techniques applied to allocation problems. 13/ Recent favored allocation models are inventory models and dynamic programming first used in water resource studies by Massé and Little. 14/ An example of an inventory model applied in optimal use of a reservoir with stochastic input is a 1963 Israeli study. 15/

13/ Maass, A.M., R. Hufschmidt, H.A. Dorfman, Thomas S. Marglin, Jr. and G. Fair, Design of Water Resource Systems (Cambridge, Mass.: Harvard University Press, 1962).

14/ The idea of using dynamic programming to determine temporal allocation of water from a reservoir is attributed to Pierre Massé, Rept. to the Societe de Statistique de Paris, Berger-Levrault, Paris, June 21, 1944. The first known application of the model in water research is reported in J.D.C. Little, "The Use of Storage Water in a Hydroelectric System," J. Operations Research Soc. of America, Vol. 3, May 1955.

15/ Avi-Itzak, B. and S. Ben-Tuvia, "A Problem of Optimizing a Collecting Reservoir System," Operations Research, Vol. II, No. 1, 1963, p. 122.

Allocation studies on conjunctive use of ground and surface water have been done by Burt, 16/17/ Leonard, 18/ Dracup, 19/ Aron, 20/ and Buras. 21/ Buras used dynamic programming in an engineering study to derive operating rules which determine the amounts of water to be allocated from a surface reservoir and a groundwater aquifer to several irrigation uses and to recharge. Burt also used this tool to derive decision rules for surface and groundwater use in an economic study. In another study, Burt considers optimal use of

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16/ Burt, O.R., Economics of Conjunctive Use of Ground and Surface Water, Ph.D. Thesis, University of California, Berkeley, 1962.

17/ Burt, O.R., "Economics of Conjunctive Use of Ground and Surface Water," Hilgardia, Journal of Agricultural Science, University of California, Vol. 36, No. 2, December 1964.

18/ Leonard, R.L., Integrated Management of Ground and Surface Water in Relation to Water Importation: The Experience of Los Angeles County, Ph.D. Thesis, University of California, Berkeley, 1963 (unpublished).

19/ Dracup, J.A., The Optimum Use of Groundwater and Surface Water System: A Parametric Linear Programming Approach, Water Resources Center, University of California, Berkeley, Report 6-24, July 1, 1966.

20/ Aron, G., Optimization of Conjunctively Managed Surface and Groundwater Resources by Dynamic Programming, Water Resources Center, University of California, Davis, Project No. W132, June 1969.

21/ Buras, N., "Conjunctive Operation of Dams and Aquifers," Journal of the Hydraulics Division, American Society of Civil Engineers, Vol. 89, No. HY6, November 1963, pp. 111-131. There are some important distinctions between the study by Buras and the above studies by Burt concerning the evaluation of groundwater storage and the use of recharge under declining aquifer conditions. Discussion of these differences is omitted as the problem of groundwater depletion will not be an issue in the present study.

a single resource, groundwater, which may be in fixed supply o partially renewable. By using the recursion relationship which results from application of Bellman's "Principle of Optimality," Burt derives approximate decision rules for determining groundwater use as a function of current supply. 22/

In general, these allocation studies tend to have a long-run planning horizon and treat surface and groundwater as independent physical resources related only through their joint contribution to economic output. Under high water table conditions, as found in the Gallatin Valley, surface supplies are not independent of groundwater use during irrigation periods. Evaluation of these dependencies in an intra-seasonal optimization model should serve to distinguish the present study from most former allocation studies.

A recent Harvard study by Rogers and Smith 23/ includes an evaluation of water table balance for a single irrigated area in East Pakistan. It is assumed in this study that part of the diverted surface water is lost to groundwater recharge, nonbeneficial evapotranspiration, and surface runoff in each decision period. The remainder is

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22/ Burt, O.R., "Optimal Resource Use Over Time with an Application to Groundwater," Management Science, Vol. 11, No. 1, September 1964, pp. 80-93.

23/ Rogers, Peter, and D.V. Smith, "The Integrated Use of Ground and Surface Water in Irrigation Project Planning," American Journal of Agricultural Economics, Vol. 52, No. 1, February 1970, pp. 13-24.

employed for crop use. It is noted that tube wells are utilized for both supplemental irrigation supply and removing excess subsurface water. The model applied is assumed to be in a steady state thus simplifying the computation of fixed investment in canal facilities and wells.

A primary distinction between the above Harvard study and the current study is that stochastic variation in interseasonal surface water supply is an important consideration in determining the optimal level of well investment. Allowances are also made for the effects of intraseasonal water shortages upon crop response. All water table levels in eight subareas of the present model are evaluated explicitly in each decision period and all groundwater movement related to water table conditions is simulated.

An intraseasonal irrigation planning study involving allocation of limited surface water among competing irrigated crops in different time periods of the irrigation season was recently completed by Anderson, 24/ also reported by Anderson and Maass. 25/ Anderson

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24/ Anderson, R.L., "A Simulation Program to Establish Optimum Crop Patterns on Irrigated Farms Based on Preseason Estimates of Water Supply," American Journal of Agricultural Economics, Vol. 50, No. 5, December 1968, pp. 1586-1590.

25/ Anderson, R.L., and A. Maass, "A Simulation Technique to Estimate Crop Production of Irrigation Projects, Based on Crop Response to Varying Schedules of Irrigation Water," International Commission on Irrigation and Drainage, R34, Question 23, pp. 547-558.

used a computer simulation program to allocate water supply initially among farms and then among crops on each farm during two-week intervals of the crop-growing season. Plant response to water supply in each period was estimated from evapotranspiration studies. Irrigation timing is also an important consideration in the current study.

Water Relationships

The literature on intraseasonal surface and groundwater relationships is relatively sparse. Some engineering studies have appeared on groundwater basin behavior, e.g., Tyson and Weber. 26/

Tyson and Weber simulated groundwater flows in an aquifer region divided into "polygonal zones" using an electric analog model. Equations for continuity and Darcy's Law were used in estimating flow relationships. The aquifer was not known to interact with surface water streams as is the case in the Gallatin Valley.

Ditch Consolidation Studies

A recent feasibility study on ditch consolidation was completed by Huszar 27/ in Colorado which has application to the present study.

26/ Tyson, H.N., Jr., and E.M. Weber, "Groundwater Management for the Nation's Future--Computer Simulation of Groundwater Basins," Journal of The Hydraulics Division, Proceedings ASCE, Vol. 90, No. HY4, July 1964, pp. 59-77.

27/ Huszar, P.C., Economics of Irrigation System Consolidation, M.S. Thesis, Colorado State University, Fort Collins, March 1969.

Huszar evaluated the expected benefits of a local irrigation system (upper system) and the expected loss to downstream users (lower system) resulting from proposed consolidation in the upper system. Consolidation was found to be infeasible because of the reduction in important return flows to the lower system.

Institutional Studies

Institutional problems of ground-surface water transfers have been investigated by Hartman, 28/ Hartman and Seastone, 29/30/31/ Bittinger, 32/ Smith, 33/ and Snyder. 34/

28/ Hartman, L.M., "Economics and Groundwater Development," Groundwater, Vol. 3, No. 2, April 1965.

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