CONJUNCTIVE OPERATION OF A SURFACE RESERVOIR AND OF GROUNDWATER STORAGE THROUGH A HYDRAULICALLY CONNECTED STREAM

by

Hubert J. Morel-Seytoux

February 1984

LORADO WATER RESOURCES

RESEARCH INSTITUTE

Colorado State University

Fort Collins, Colorado

Completion Report No. 130

Technical Completion Report

B-204-COLO

Agreement No. 14-34-0001-9147

CONJUNCTIVE OPERATION OF A SURFACE RESERVOIR AND OF GROUNDWATER STORAGE THROUGH A HYDRAULICALLY CONNECTED STREAM

by

Dr. Hubert J. Morel-Seytoux

Department of Civil Engineering
Colorado State University

Submitted to

Bureau of Reclamation
United States Department of the Interior
Washington, D.C. 20242

The research on which this report is based was financed in part by the U.S. Department of the Interior, as authorized by the Water Research and Development Act of 1978 (P.L. 95-467).

COLORADO WATER RESOURCES RESEARCH INSTITUTE
Colorado State University
Fort Collins, CO 80523

Norman A. Evans, Director

February 1984

ABSTRACT

Analytical solutions are described to represent the impact of net withdrawal from an aquifer on water table elevations and on induced seepage (negative return flow) from a river in hydraulic connection with the aquifer. These analytical solutions are prerequisite to the formulation and solution of a conjunctive optimal strategy of use of surface and ground waters for irrigation purposes. Optimal continuous time solutions are sought for rates of release from an upstream surface reservoir, for diversion rates of streamflows downstream from the dam and upstream of an irrigation area and for rates of pumping in the irrigation zone via the classical techniques of Calculus of Variations.

However instead of leading to an Euler-Lagrange system of partial differential equations the formulation leads to a system of Fredholm linear integral equations of the second kind. The clear economic meaning for the optimal strategy is a trade-off between two marginal costs: immediate value of not incurring a penalty for failing to meet a downstream legal right versus the capitalized cost of additional lift as a result of early pumping in the season.

FOREWORD

Maximum benefit from water use in irrigation is obtained by minimizing the cost of water (assuming cropping practices are fixed). The cost of groundwater is greater than the cost of surface water due to pumping costs. If surface supply is inadequate to meet full water requirements, some groundwater use is necessary. Furthermore, groundwater use may be a mandatory element in an efficient water-cycle system such as occurs in the South Platte River Basin. The management question which this research addresses is, "What is the correct mix of the two sources to optimize returns from the available water?"

A two-pronged approach was used in this study: (1) modify and adapt a hydrologic simulation technology developed with Department of Interior's partial support in a prior matching grant project (CR87) and, (2) develop the theory and procedure for incorporating optimization analysis into the hydrologic model.

The hydrologic system of interest is the South Platte River Basin in Colorado. Water in an alluvial aquifer in good hydraulic connection with the river is managed conjunctively with surface water. Groundwater pumping is permitted only if its impacts on surface stream flow is offset by augmentation water. Water users contemplate a main-stem storage reservoir and need new technology to find the best conjunctive reservoir and groundwater management strategy.

A previously developed hydrologic simulation model was modified to incorporate the presence of an upstream storage reservoir. Possible combinations of storage capacity, release rules for the reservoir and pumping rules for downstream aquifer were investigated with the model. The operational capability of the model to simulate this system on a weekly time scale was demonstrated. Its utility for testing and evaluating conjunctive management options was likewise demonstrated to be excellent.

A dissertation on the conjunctive surface-groundwater simulation model will be available from Colorado State University (Restrepo, 1984) in the future. A table of contents is appended at the end of this report. Technical details for an earlier version of model were previously reported in Completion Report No. 87 available from the Colorado Water Resources Research Institute and are not repeated in this report. More advanced modeling features were developed for the Colorado Commission of Higher Education, the Groundwater Users Association of the South Platte and the Ministry of Agriculture and Water of the Kingdom of Saudi Arabia (Illangasekare and Morel-Seytoux, 1983a,b; Morel-Seytoux and Illangasekare, 1983).

The second approach to meeting water user need for new technology is development of innovative methodology for incorporating optimization capability into the hydrologic model. A theory and procedure for finding an optimal strategy for managing surface storage conjunctively with groundwater pumping has been developed. This report gives details of the theory and the procedure. A hypothetical, idealized case is used to illustrate its application.

The next step in development of this new combined hydrologic simulation-optimization technology will be to incorporate the optimization procedure with the simulation model. With this combination optimal reservoir release and groundwater pumping decisions can be made continuously throughout the season of operation. Of course, the new technology will be equally valuable for initial planning of project operations.

TABLE OF CONTENTS

	Page
RESEARCH OBJECTIVES	1
PART I - DRAWDOWN AND RETURN FLOW RESPONSES TO UNIFORM WITHDRAWAL IN A ONE-DIMENSIONAL HOMOGENEOUS SEMI-INFINITE AQUIFER	2
INITIAL CONDITIONS	2
BOUNDARY CONDITIONS	2
WITHDRAWAL EXCITATION	2
DRAWDOWN RESPONSE TO UNIFORM WITHDRAWAL	2
Verification	3
Drawdown Response to a General Excitation Rate per Unit Area.	3
RETURN FLOW RATE	4
Return Flow Rate Due to a General Withdrawal Pattern over the Irrigated Area	4
CUMULATIVE RETURN FLOW VOLUME	5
SIMPLIFICATION IN NOTATIONS	5
SUMMARY OF FORMULAE	6
Drawdown Unit Impuse Kernel Due to Uniform Withdrawal Rate per Unit Area	6
Representative Drawdown Due to a General Pattern of Withdrawal	6
Return Flow Rate Unit Impulse Kernel Due to Uniform Withdrawal Rate per Unit Area	6
Return Flow Rate from River Reach Due to a General Pattern of Withdrawal	7
REFERENCES	7
PART II - FORMULATION OF THE MINIMIZATION PROBLEM OF COST OPERATIONS FROM PUMPING AND SURFACE WATER DIVERSIONS FOR IRRIGATION..	8
INTRODUCTION	8
WATER COSTS	8
CONSTRAINTS	11
OPTIMIZATION FORMULATION	12
FORMULATION SUMMARY	15

SIMPLE SPECIAL CASE 16

Full Pumping Need Taken at End of Season 17
Full Pumping Need Taken at Beginning of Season 17
Use of Groundwater after Exhaustion of Surface Water Supply (last resort) 19
Pumping as Last Resort but with Continuous Satisfaction of Water Right 20
Pumping as Supplement to Surface Diversion with Continuous Satisfaction of Water Right 22
General Procedure (for still the simple case) 30

CONCLUSIONS 31

REFERENCES 32

APPENDIX Table of Contents of Restrepo's Dissertation............. 33

RESEARCH OBJECTIVES

The overall objective of the research was the development of a methodology to demonstrate the value of conjunctive management of an upstream surface reservoir with a downstream aquifer as water supplies. The methodology must incorporat properly the physical interactions between the stream, the aquifer and the wells as well as account for the agronomic (irrigation) and legal constraints. The methodology must be cost-effective so that it can be used for actual operations by various local groups of water users.

In this report only a brief review of a promising method of attack will be given. Generally speaking the thrust of the research has been in the direction of development of new and imaginative methods that will greatly reduce the cost of management studies of conjunctive use of surface and ground waters when in hydraulic connection without significant reduction in accuracy. In this regard the project was successful.

In a separate document, a dissertation (Restrepo, 1984) a more fully developed classical approach is used to provide specific quantitative answers to problems of management for a reach of the South Platte River. It addresses the problem of finding the optimal capacity and release rules of an upstream reservoir as well as the withdrawal rules for the downstream aquifer storage. A table of contents is appended at the end of this report.

PART I

DRAWDOWN AND RETURN FLOW RESPONSES TO UNIFORM WITHDRAWAL IN A ONE-DIMENSIONAL HOMOGENEOUS SEMI-INFINITE AQUIFER

INITIAL CONDITIONS

At time zero drawdown, s, is zero everywhere (i.e., for $0 \leq x \leq \infty$).

BOUNDARY CONDITIONS

At the river bank of a fully penetrating river drawdown remains zero at all times, i.e., s=0 at x=0 for all times. Abscissa x is measured in a direction perpendicular to river course with origin at river bank.

WITHDRAWAL EXCITATION

Withdrawal occurs uniformly over an interval of length a on each side of the fully penetrating river. The river reach length is L_r. Thus the area of withdrawal (which is also the cultivated irrigated area) is $A = aL_r$. The excitation (withdrawal) rate for the area A is Q (volume per unit time) or the excitation rate per unit area is q (depth per unit time). Naturally Q and q are related by the equation: Q=Aq.

DRAWDOWN RESPONSE TO UNIFORM WITHDRAWAL

The drawdown response due to a unit impulse of uniform withdrawal per unit area over the interval (o,a) satisfying the initial condition of zero drawdown everywhere and zero drawdown at all times at the river bank is easily derived (e.g., Morel-Seytoux, 1977) from the knowledge of the Green's function for the one-dimensional linear Boussinesq equation. The solution is:

$$k_{s,q}(x,t) = \frac{1}{2\phi} \{\mathrm{erf}(\frac{a-x}{2\sqrt{\gamma t}}) - \mathrm{erf}(\frac{a+x}{2\sqrt{\gamma t}}) + 2\mathrm{erf}(\frac{x}{2\sqrt{\gamma t}})\} \qquad [1]$$

where ϕ is effective porosity, $\gamma = \frac{T}{\phi}$ is aquifer diffusivity and T is transmissivity.

Verification

For any x in the interval (o,a) at time zero (plus) Eq. [1] yields for drawdown the value:

$$k_{s,q}(x,,o) = \frac{1}{2\phi}\{\mathrm{erf}(\infty) - \mathrm{erf}(\infty) + 2\mathrm{erf}(\infty)\} = \frac{1}{2\phi}[1-1+2] = \frac{1}{\phi}$$

which is correct, representing the instantaneous drawdown to an impulse of withdrawal of one unit volume per unit area. For any $x > a$ at time zero (plus) Eq. [1] yields for drawdown the value:

$$k_{s,q}(x,o) = \frac{1}{2\phi}\{\mathrm{erf}(-\infty) - \mathrm{erf}(\infty) + 2\mathrm{erf}(\infty)\} = \frac{1}{2\phi}[-1-1+2] = 0$$

which is correct since water table is initially horizontal.

For any time at the river bank (x=0) Eq. [1] yields for drawdown the value:

$$k_{s,q}(o,t) = \frac{1}{2\phi}\{\mathrm{erf}(\frac{a}{2\sqrt{\gamma t}}) - \mathrm{erf}(\frac{a}{2\sqrt{\gamma t}}) + 2\mathrm{erf}(o)\} = \frac{1}{\phi}\mathrm{erf}(o) = 0$$

which again checks. Thus Eq. [1] provides correctly the response of drawdown to a uniform unit impulse withdrawal excitation over the interval (o,a).

Drawdown Response to a General Excitation (withdrawal) Rate per Unit Area

The general solution is as usual (Morel-Seytoux, 1979, p.16) of the form:

$$s(x,t) = \int_o^t \frac{1}{2\phi}\{\mathrm{erf}(\frac{a-x}{2\sqrt{\gamma(t-\tau)}}) - \mathrm{erf}(\frac{a+x}{2\sqrt{\gamma(t-\tau)}}) + 2\mathrm{erf}(\frac{x}{2\sqrt{\gamma(t-\tau)}})\}\ q(\tau)d\tau \qquad [2]$$

One obtains the response to the withdrawal discharge $Q(\tau)$ (volume per time) by simply replacing $q(\tau)$ by $\frac{Q(\tau)}{A}$ in Eq. [2] or explicitly:

$$s(x,t) = \frac{1}{2A\phi}\int_o^t \left[\operatorname{erf}\{\frac{a-x}{2\sqrt{\gamma(t-\tau)}}\} - \operatorname{erf}\{\frac{a+x}{2\sqrt{\gamma(t-\tau)}}\} + 2\operatorname{erf}\{\frac{x}{2\sqrt{\gamma(t-\tau)}}\} \right] Q(\tau)d\tau \qquad [3]$$

RETURN FLOW RATE

The return flow response per unit length of river reach (from one side of the river) due to a uniform unit impulse withdrawal rate per unit area is obtained as usual (e.g., Morel-Seytoux, 1979, p.53) by calculating the flux of water across the saturated thickness at river bank (x=0), namely:

$$- T \frac{\partial k_{s,q}(x,t)}{\partial x} \Big|_{x=0} = k_{q_r,q}(t) = - \sqrt{\frac{\gamma}{\pi}} \frac{(1 - e^{-\frac{a^2}{4\gamma t}})}{\sqrt{t}} \qquad [4]$$

Derivations of this result have been provided previously (Morel-Seytoux, 1977).

<u>Return Flow Rate Due to a General Withdrawal Pattern Over the Irrigated Area</u>

Again use of the convolution equation yields for the return flow along the river reach the expression:

$$Q_r(t) = - \frac{1}{a}\int_o^t \sqrt{\frac{\gamma}{\pi}} \left[\frac{1 - e^{-\frac{a^2}{4\gamma(t-\tau)}}}{\sqrt{t-\tau}} \right] Q(\tau)d\tau \qquad [5]$$

CUMULATIVE RETURN FLOW VOLUME

The cumulative return flow volume up to time t is defined as:

$$W_r = \int_o^t Q_r(\tau)d\tau \qquad [6]$$

The unit impulse response of cumulative return flow is obtained as usual (Morel-Seytoux, 1979, p.58) by integrating Eq. [4] with respect to time, namely:

$$k_{W_r,Q}(t) = -\frac{1}{a}\sqrt{\frac{\gamma}{\pi}}\int_o^t \left(\frac{1 - e^{-\frac{a^2}{4\gamma\tau}}}{\sqrt{\tau}}\right) d\tau \qquad [7]$$

or equivalently:

$$k_{W_r,q}(t) = -L_r\sqrt{\frac{\gamma}{\pi}}\int_o^t \left(\frac{1 - e^{-\frac{a^2}{4\gamma\tau}}}{\sqrt{\tau}}\right) d\tau \qquad [8]$$

SIMPLIFICATION IN NOTATIONS

In general drawdown will be evaluated only at a characteristic distance from the river where drawdown is roughly the average drawdown in the aquifer below the irrigated area. The unit impulse given by Eq. [1] when evaluated at that abscissa is denoted simply:

$$k_s(t) = \frac{1}{2\phi}\{\mathrm{erf}(\frac{a-x}{2\sqrt{\gamma t}}) - \mathrm{erf}(\frac{a+x}{2\sqrt{\gamma t}}) + 2\mathrm{erf}(\frac{x}{2\sqrt{\gamma t}})\} \qquad [9]$$

where x has a particular value (e.g., $\frac{a}{2}$) and the excitation is that per unit area. Thus the representative (average) drawdown at the selected abscissa is given by the equation:

$$\bar{s}(t) = \int_0^t k_s(t-\tau)q(\tau)d\tau = \frac{1}{A}\int_0^t k_s(t-\tau)Q(\tau)d\tau \qquad [10]$$

Similarly the unit impulse kernel of return flow rate is simply denoted $k_r(t)$ and defined by the equation:

$$k_r(t) = -\frac{1}{a}\sqrt{\frac{\gamma}{\pi}}\,\frac{(1 - e^{-\frac{a^2}{4\gamma t}})}{\sqrt{t}} \qquad [11]$$

and the return flow rate is given in general by the expression:

$$Q_r(t) = \int_0^t k_r(t-\tau)Q(\tau)d\tau \qquad [12]$$

SUMMARY OF FORMULAE

Drawdown Unit Impulse Kernel Due to Uniform Withdrawal Rate per Unit Area

$$k_s(t) = \frac{1}{2\phi}\{\mathrm{erf}(\frac{a-x}{2\sqrt{\gamma t}}) - \mathrm{erf}(\frac{a+x}{2\sqrt{\gamma t}}) + 2\mathrm{erf}(\frac{x}{2\sqrt{\gamma t}})\} \qquad [13]$$

Representative (mean) Drawdown Due to a General Pattern of Withdrawal

$$\bar{s}(t) = \frac{1}{A}\int_0^t k_s(t-\tau)Q(\tau)d\tau \qquad [14]$$

Return Flow Rate Unit Impulse Kernel Due to Uniform Withdrawal Rate Per Unit Area

$$k_r(t) = -\frac{1}{a}\sqrt{\frac{\gamma}{\pi}}\,\frac{(1 - e^{-\frac{a^2}{4\gamma t}})}{\sqrt{t}} \qquad [15]$$

Return Flow Rate from River Reach Due to a General Pattern of Withdrawal

$$Q_r(t) = \int_o^t k_r(t-\tau)Q(\tau)d\tau \qquad [16]$$

REFERENCES

Morel-Seytoux, H. J. 1977. "Natural Redistribution of Water Table Levels in a One-Dimensional Semi-Infinite Aquifer," Handout No. 14, Class Notes for Course CE 632 Optimal Ground Water Management, Department of Civil Engineering, Colorado State University, Fall 1977, 6 pages.

Morel-Seytoux, H. J. 1979. "Cost-Effective Methodology for Stream-Aquifer Interaction Modeling and Use in Management of Large Scale Systems," HYDROWAR Program, Colorado State University, Fort Collins, CO 80523, December 1979, 75 pages.

PART 2

FORMULATION OF THE MINIMIZATION PROBLEM OF COST OPERATIONS FROM PUMPING AND SURFACE WATER DIVERSIONS FOR IRRIGATION

INTRODUCTION

For a system already constructed (i.e., with existing reservoirs, canals, wells, etc.) and capable of delivering enough water from combined surface and underground supply to meet crop need for optimal crop yield, the maximization of profits from water use is simply obtained by minimization of the cost of water acquisition. In this case the income from the sale of the crops is fixed. It is the sum of the products of price by optimal yield for the various crops. Generally the cost of groundwater is greater than that of surface water as a result of the energy cost for lifting the water. Thus profit can be maximized by minimizing the cost of water. This is achieved by using the right amount of surface and ground waters at the right time in order not to drawdown the aquifer too much. This is of course accomplished by using the surface supply whenever available and groundwater only as a supplemental source. However surface water availability may be limited by the demand of senior downstream surface water rights. The minimization problem arises as a result of such constraints.

WATER COSTS

Diversion amounts per unit time will be expressed either as discharges or velocities (i.e., depths per unit time, which is volume per unit area per unit time). The function $D(t)$ represents the diversion rate (expressed as depth per unit time) from the stream at a diversion point upstream of the irrigation area. Figure 1 displays the

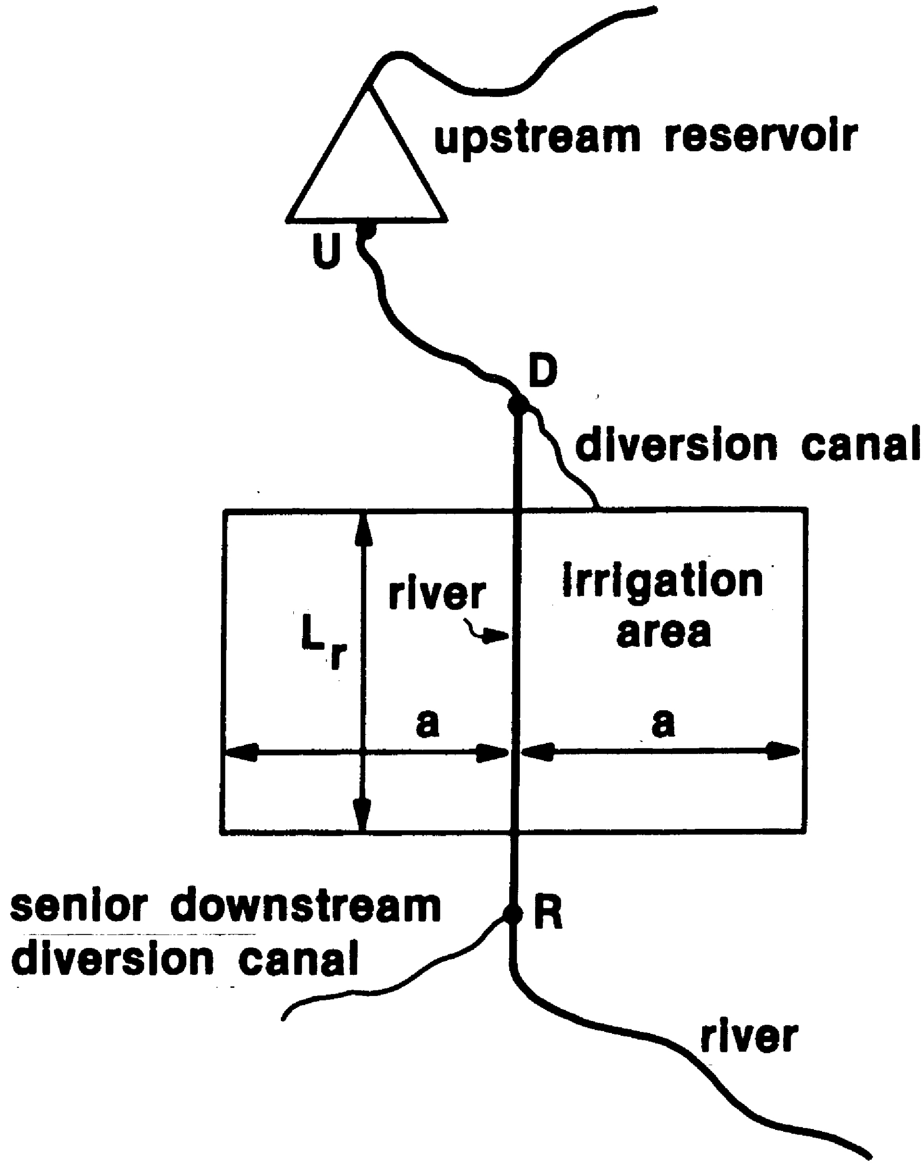

Figure 1. Overall Configuration of System with Upstream Reservoir, Stream, Irrigation Area and Senior Downstream Diversion

overall configuration of the system. Water is released at a rate (velocity) $x(t)$ at point U (upstream point of system of interest). Without any loss this flow reaches point D (diversion point) where a certain amount $D(t)$ (velocity) is diverted. The remaining flow in the river (i.e., $x(t)-D(t)$) will then continue through the irrigation area. Through the reach of length L_r the river is in hydraulic connection with the aquifer. As a result the outgoing flow rate at point R will have increased (algebraically) by the return flow for the reach, $q_r(t)$ expressed as a velocity. Naturally all discharges are converted to velocities by dividing them by the total irrigation area, A.

If c_s denotes the unit cost of surface water diversion then instantaneous cost of diversion is $c_s D(t) A$ and the total cost over the irrigation season is its integral over the irrigation season. The unit cost c_s does not vary within the season (an assumption).

The cost of groundwater is more complex, as it depends on the lift. Drawdown being measured from the initial position of the water table at beginning of irrigation season, used as origin of time, the lifting cost depends on the total lift, which is the initial lift plus the additional lift due to further drawdown during the season. If c_o represents the initial unit cost of pumping and c_m the marginal cost of pumping (i.e., cost per unit pumped volume per additional unit of drawdown) then the total groundwater cost during the irrigation season of duration T plus the total surface diversion cost, is given by the expression:

$$Z = \int_o^T \left[c_o + c_m \bar{s}(t)\right] Q(t)dt + \int_o^T c_s AD(t)dt \qquad [1]$$

where $\bar{s}(t)$ is a representative drawdown for the area and $Q(t)$ is the pumped discharge. The drawdown $\bar{s}(t)$ being a linear function of pumped discharges, it is clear from Eq. [1] that the total water cost will be a quadratic function of pumping rates and a linear one of surface diversion rates.

CONSTRAINTS

There are limitations to the availability of water from the surface reservoir. Denoting by X_T the total available volume of water for the season from the reservoir per unit of irrigation area then clearly the total volume of release cannot be greater than that amount. However, because cost of surface water is relatively cheap, that total volume will indeed be used. Consequently the constraint takes the form:

$$\int_0^T x(t)dt = X_T \qquad [2]$$

where T is the duration of the irrigation season. There is a downstream water right which is a total volumetric right for the season, denoted W_T when expressed per unit area of irrigation. Consequently since river outflow from the irrigation area is instantaneously $x(t)-D(t) + q_r(t)$, the mathematical expression of the required total satisfaction of water right is:

$$\int_0^T \left[x(t) - D(t) + q_r(t)\right]dt = W_T \qquad [3]$$

The equality is justified by the fact that the upstream users have no interest in losing cheap water to downstream users.

To produce a crop abundantly and of good quality, a proper amount of water has to be delivered to the crop. This amount varies and is denoted e(t) (for evapotranspiration need). This function is a known function of time. Not all the water diverted will reach the plant (in its specific location in a furrow, etc.). Some of it is lost by seepage before it gets to the field. The fraction of diverted water that will actually reach the fields is denoted E_f. Of that amount which reaches the fields only a fraction denoted E_p will actually reach the plant and be transpired. In other words to meet the plant need e(t) an amount D(t) is to be diverted which is $e(t)/E_fE_p$, an amount which can be substantially greater than the plant need. Pumped water can also be used to meet that need. Being withdrawn right on the field, pumped water suffers only one inefficiency. The constraint (requirement) that plant need be met takes the mathematical form:

$$E_fE_pD(t) + E_pq(t) = e(t) \qquad [4]$$

OPTIMIZATION FORMULATION

The optimization problem is one of minimization of the objective function defined by Eq. [1]. This objective function is not fully explicited because $\bar{s}(t)$ is a function of the net withdrawal rate (per unit area). This net withdrawal rate is the difference between pumped rate and aquifer recharge from water application. The net withdrawal rate (velocity) is thus:

$$q_n(t) = q(t) - (1-E_p)q(t) - (1-E_fE_p)D(t) \qquad [5]$$

or defining for simplicity $E_{fp} = E_f E_p$ and $E_r = 1-E_{fp}$, which is the recharge efficiency of the surface diversion:

$$q_n(t) = E_p q(t) - E_r D(t) \qquad [6]$$

From the theory of linear systems the drawdown $\bar{s}(t)$ is expressed as a convolution integral:

$$\bar{s}(t) = \int_o^t k_s(t-\tau) q_n(\tau) d\tau \qquad [7]$$

The specific form of the kernel depends upon the representation of the aquifer behavior and its characteristics. For a very simple situation the kernel $k_s(\cdot)$ was derived earlier (see Eq. [13] in Part I). Substitution of Eq. [7] into the objective function transforms the optimization problem in the explicit form:

$$\text{Minimize } \{\int_o^T \{c_o + c_m \int_o^t k_s(t-\tau) \left[E_p q(\tau) - E_r D(\tau)\right]\} q(t) dt + c_s \int_o^T D(t) dt\} \qquad [8]$$

subject to the various constraints defined by Eqs. [2], [3] and [4]. There are three decision functions: $x(t)$, $D(t)$, and $q(t)$. Two of them are not really independent due to constraint Eq. [4]. That equation can be used to express $D(t)$ in terms of $q(t)$ and $e(t)$, namely:

$$D(t) = \frac{e(t)}{E_{fp}} - \frac{q(t)}{E_f} \qquad [9]$$

and in turn Eq. [9] can be used to eliminate $D(t)$ from the objective function in Eq. [8]. After substitution the objective function takes the form:

$$z = c_o \int_o^T q(t)dt + c_s \int_o^T D(t)dt + c_m \int_o^T \{\int_o^t k_s(t-\tau)$$
$$\left[E_p q(\tau) - \frac{E_r e(\tau)}{1-E_r} + \frac{E_r}{E_f} q(\tau)\right] d\tau\} q(t)dt$$

or:

$$z = c_o \int_o^T q(t)dt + c_s \int_o^T D(t)dt + c_m \int_o^T \{\int_o^t k_s(t-\tau)\left[\frac{q(\tau)}{E_f} - f(\tau)\right] d\tau\} q(t)\ dt \qquad [10]$$

where for simplicity the known function $\frac{E_r}{1-E_r}\ e(\cdot)$ has been redefined, temporarily, as $f(\cdot)$. Thus the optimization of the objective function depends now explicitly on two arbitrary functions: $x(t)$ and $q(t)$. To complete the elimination of $D(t)$ from the objective function its integral has to be rewritten in the form:

$$\int_o^T D(t)dt = \int_o^T \frac{e(t)dt}{E_{fp}} - \int_o^T \frac{q(t)dt}{E_f}$$

Substitution of this expression into the objective function yields:

$$z = (c_o - \frac{c_s}{E_f}) \int_o^T q(t)dt + \frac{c_s}{E_{fp}} \int_o^T e(t)dt +$$
$$c_m \int_o^T \{\int_o^t k_s(t-\tau) \left[\frac{q(\tau)}{E_f} - f(\tau)\right] d\tau\}\ q(t)dt \qquad [11]$$

The problem, once more, is to minimize this objective function with respect to the unknown functions $q(t)$ and $x(t)$ subject to the constraints defined by Eqs. [2] and [3]. After elimination of $D(t)$ from Eq. [3] that constraint takes the form:

$$\int_0^T \{x(t) - \left[\frac{e(t)}{1-E_f} - \frac{q(t)}{E_f}\right] + q_r(t)\}\ dt = W_T$$

or, defining the total depths of evapotranspiration crop need, of water right and of pumpage as:

$$E_T = \int_0^T e(t)dt$$

$$Q_T = \int_0^T q(t)dt$$

and $$W_T = \int_0^T w(t)dt$$

where w(t) is the downstream surface water right rate (velocity), finally:

$$- E_f \int_0^T q(t)dt - \frac{1}{E_f} \int_0^T \{k_r(t-\tau)q(\tau)d\tau\}dt = X_T - W_T$$

$$- \frac{1}{1-E_r} E_T - \int_0^T \{\int_0^t k_r(t-\tau)f(\tau)d\tau\}dt \qquad [12]$$

Note that the kernel of return flow due to withdrawal is a negative function so that the second term on the left hand side is actually positive. The same comment applies for the last term on the right hand side.

FORMULATION SUMMARY

The minimization problem involves the objective function:

$$z = (c_o - \frac{c_s}{E_f}) \int_0^T q(t)dt + \frac{c_s}{E_f E_p} \int_0^T e(t)dt + c_m \int_0^T \{\int_0^t k_s(t-\tau)\left[\frac{q(\tau)}{E_f} - \frac{E_r e(\tau)}{1-E_r}\right]d\tau\}q(t)dt \qquad [13]$$

and the equality constraint:

$$X_T - W_T - \frac{E_T}{1-E_r} + E_f \int_o^T q(t)dt + \int_o^T \{\int_o^t k_r(t-\tau)\left[\frac{q(\tau)}{E_f} - \frac{E_r e(\tau)}{1-E_r}\right]d\tau\}dt = 0 \qquad [14]$$

There are two unknown functions, q(t) and x(t), but only one appears in Eqs. [13] and [14]. The problem appears to be one in classical Calculus of Variations. In order to discover (hopefully) a general method of solution a simple limiting case will be investigated first.

SIMPLE SPECIAL CASE

Let us assume that the cost of surface water is very cheap (i.e., $c_s = 0$ for practical purposes), that initial cost of pumping is very small (i.e., $c_o = 0$), and that efficiencies E_f and E_p are both one. Then in this case the objective function reduces to:

$$z_s = c_m \int_o^T \{\int_o^t k_s(t-\tau)q(\tau)d\tau\}q(t)dt \qquad [15]$$

and the equality constraint reduces to:

$$X_T - W_T - E_T + \int_o^T q(t)dt + \int_o^T \{\int_o^t k_r(t-\tau)q(\tau)d\tau\}dt = 0 \qquad [16]$$

One possible strategy of operation is not to pump at all. In that case the cost is minimal (zero). However such strategy is feasible only if $X_T - W_T - E_T \geq 0$ that is if the irrigation requirement E_T and W_T can both be met by seasonal surface storage availability X_T. If such volume is not sufficient then the need will have to be supplied by depleting the aquifer somewhat. Thus in the situation of a deficit in surface water availability (i.e., $X_T < E_T + W_T$) it will be necessary to draw water from the aquifer. In order to get a feeling about the problem and its solution, let us consider the effect of different strategies: for example, withdrawal of full pumping need at beginning of season, at the end of the season or continuously throughout the season.

Full Pumping Need Taken at End of Season

In this case the withdrawal is a unit impulse of magnitude Q_T (expressed as a depth). The objective function of Eq. [15] becomes:

$$z_{se} = c_m \int_o^T \{\int_o^t k_s(t-\tau)Q_T D_\delta(T-\tau)d\tau\}Q_T D_\delta(T-t)dt \qquad [17]$$

(The subscript e refers to the strategy of pumping at end of season) where $D_\delta(\cdot)$ is the Dirac delta function singular at time T. The inner integral is zero except at τ=t=T, where it takes the value $\frac{1}{2}k_s(o)Q_T$, and the total pumping cost is:

$$z_{se} = \frac{1}{2}\, c_m k_s(o)Q_T^2 = \frac{c_m}{2\phi}\, Q_T^2 \qquad [18]$$

In this case $Q_T = E_T+W_T-X_T$ so that the total cost is explicitly:

$$z_{se} = \frac{c_m}{2\phi}\,(E_T+W_T-X_T)^2 \qquad [19]$$

Full Pumping Need Taken at Beginning of Season

The withdrawal is a unit impulse of magnitude Q_T but occurring at time 0. The objective function of Eq. [15] takes the form:

$$z_{sb} = c_m \int_o^T \{\int_o^t k_s(t-\tau) Q_T D_\delta(\tau) d\tau\} Q_T D_\delta(t) dt$$

or

$$z_{sb} = c \int_o^T \frac{1}{2} Q_T k_s(t) Q_T D_\delta(t) dt \qquad [20]$$

or

$$z_{sb} = \frac{c_m}{2} k_s(o) Q_T^2 = \frac{c_m Q_T^2}{2\phi} \qquad [21]$$

(The subscript b refers to the strategy of pumping at beginning of season.) Q_T is now given by the constraint equation [16], namely:

$$X_T - W_T - E_T + Q_T + \int_o^T Q_T k_r(t) dt = 0$$

or

$$Q_T = \frac{E_T + E_T - X_T}{1 + \int_o^T k_r(t) dt} \qquad [22]$$

Since $k_r(\cdot)$ is a negative function Q_T in Eq. [22] exceeds the strict need $E_T + W_T - X_T$. The cost in this strategy of early pumping is larger than for the case of pumping at the last minute. Naturally pumping at the last minute is not a feasible strategy because the crop need e(t) must be satisfied at all times. Similarly the early pumping strategy is not feasible unless the water is stored and delivered as needed during the season.

Use of Groundwater After Exhaustion of Surface Water Supply (last resort)

Until the time t_o such that:

$$\int_{o}^{t_o} e(t)dt = X_T - W_T \tag{24}$$

then clearly (?) the optimal policy is (might be) to meet the crop need from the reservoir release and by diversion of surface water. Past time t_o one must pump from the aquifer but then again just to meet the need or in this case:

$$q(t) = e(t) \qquad \text{for} \qquad t_o \leq t \leq T \tag{25}$$

The minimum cost will be attained for a value:

$$z_{s1} = c_m \int_{t_o}^{T} \{\int_{t_o}^{t} k_s(t-\tau)\ e(\tau)d\tau\}\ e(t)dt \tag{26}$$

(The subscript 1 refers to fact that groundwater is used as last resort.) However, one constraint, Eq. [16] is not satisfied, because the last term introduces a lack of balance, namely the integral:

$$\int_{t_o}^{T} \{\int_{t_o}^{t} k_r(t-\tau)\ e(\tau)d\tau\}\ dt$$

Enough surface water is available to meet the downstream water right in the interval t_o to T but not to compensate for the seepage induced by pumping.

Pumping as Last Resort but with Continuous Satisfaction of Water Right

The water right function is actually usually defined as a rate $w(t)$. The continuous (permanent) satisfaction of the water right requires that:

$$x(t) - D(t) + q_r(t) = w(t)$$

A strategy that would meet irrigation need and water right without pumping until surface storage is exhausted will dry the river beyond that point. If drying of the river is not acceptable, which will now be assumed, pumping will have to occur before the seasonal surface storage availability is depleted. The time of initiation of pumping t_p is now an unknown. Until the time t_p the strategy is to release water to meet consumptive use and water right, that is:

$$x(t) = e(t) + w(t) \qquad o < t \leq t_p \tag{28}$$

Let the integrals of $x(\cdot)$, $e(\cdot)$ and $w(\cdot)$ up to that time t_p be denoted X_p, E_p and W_p. Beyond that time the reservoir release is used solely to meet the water right and to compensate for the seepage rate induced by pumping, that is:

$$x(t) = w(t) - q_r(t) \qquad t_p \leq t \leq T \tag{29}$$

whereas the pumping rate is determined by the consumptive use requirement, namely:

$$q(t) = e(t) \qquad t_p \leq t \leq T \tag{30}$$

The return flow $q_r(t)$ is related to the pumping rate, in this case $e(t)$, by the relation:

$$q_r(t) = \int_{t_p}^{t} k_r(t-\tau)e(\tau)d\tau \qquad [31]$$

Substitution in Eq. [29] yields the explicit constraint:

$$x(t) = w(t) - \int_{t_p}^{t} k_r(t-\tau)e(\tau)d\tau \qquad [32]$$

The objective function to be minimized is:

$$z_{sc} = c_m \int_{t_p}^{T} \{\int_{t_p}^{t} k_s(t-\tau)e(\tau)d\tau\} \; e(t)dt \qquad [33]$$

(The subscript c refers to the fact that water right is satisfied continuously.) The problem is reduced to one of minimization with respect to one unknown parameter t_p. Redefining the origin of time at the beginning of pumping and the pumping duration time $T-t_p$ as T_p, then Eq. [33] takes the slightly simpler form:

$$z_{sc} = c_m \int_{o}^{T_p} \{\int_{o}^{t} k_s(t-\tau)e(\tau)d\tau\} \; e(t)dt \qquad [34]$$

The minimization of Eq [34] for T_p is subject to the constraint over the irrigation season that:

$$X_T-W_T-E_T \; Q_T + \int_{o}^{T_p} \{\int_{o}^{t} k_r(t-\tau)e(\tau)\}dt = 0 \qquad [35]$$

Defining for convenience the excess need over seasonal storage water availability, namely $E_T+W_T-X_T$ as N_T, Eq. [35] takes the form:

$$\int_o^{T_p} \left[e(t) + \int_o^t k_r(t-\tau)e(\tau)d\tau \right] dt = N_T \qquad [36]$$

Actually Eq. [36] determines T_p since $k_r(\cdot)$, $e(\cdot)$ and N_T are given. Then once T_p is calculated from Eq. [36], substitution of the numerical value of T_p in Eq. [34] yields the value of pumping cost for the season. Prior to time $t_p = T-T_p$ the release rate is given by Eq. [28] and after t_p it is given by Eq. [32]. The diversion rate is e(t) before t_p and zero afterward.

<u>Pumping as Supplement to Surface Diversion with Continuous Satisfaction of Water Right</u>

In the previous strategy need was met solely by surface water up to initiation of pumping and thereafter solely by pumping. An alternative (more general) would initiate pumping while surface diversion continues. It is rather intuitively clear that such a strategy would induce seepage from river earlier and consequently require a larger fraction of X_T to meet downstream water rights. A smaller fraction of X_T would be used for irrigation and as a result a greater pumped volume would be required to meet the consumptive use. Altogether the strategy would cost more. Nevertheless it is instructive to consider this strategy. In this case the release rate is related to need, water right and pumping by the relation:

$$x(t) = e(t) + w(t) - q(t) - \int_o^t k_r(t-\tau)q(\tau)d\tau \qquad [37]$$

whereas the objective still is:

$$z_{ss} = c_m \int_0^T \{\int_0^t k_s(t-\tau)q(\tau)d\tau\}\ q(t)dt \qquad [38]$$

(The second subscript s refers to the fact that in this strategy groundwater is used as a supplement not entire replacement for surface water.) The global form of Eq. [37] for the irrigation season is written more generally:

$$\int_0^T q(t)dt + \int_0^T (\int_0^t k_r(t-\tau)q(\tau)d\tau)dt \geq N_T$$

This inequality expresses the fact that the downstream flow must meet or exceed the water right. The inequality may be rewritten in the form:

$$-\int_0^T q(t)dt - \int_0^T (\int_0^t k_r(t-\tau)q(\tau)d\tau)dt + N_T \leq 0 \qquad [39]$$

which is the standard form to express the constraint to write the Lagrangian function (for example to derive the Kuhn-Tucker theorem). In particular it is known that at the minimum the Lagrange multiplier λ is positive or zero.

Fundamentally the problem is to minimize the objective given by Eq. [38] for the unknown function q(t) subject to Eq. [39]. The Lagrangian function associated with the objective function in Eq. [38] is:

$$L = c_m \int_0^T \{\int_0^t k_s(t-\tau)q(\tau)d\tau\}\ q(t)dt$$

$$+ \lambda \left[-\int_0^T q(t)dt - \int_0^T \{\int_0^t k_r(t-\tau)q(\tau)d\tau\}\ dt + N_T\right] \qquad [40]$$

It remains to derive the Euler-Lagrange equation for this functional problem. The change in Lagrangian when q(t) changes to $q(t)+\varepsilon\eta(t)$, where $\varepsilon\eta(t)$ represents a variation in q(t), is:

$$\Delta L = c_m \varepsilon \int_o^T \left(\int_o^t k_s(t-\tau) q(\tau) d\tau\right) \eta(t) dt + c_m \varepsilon \int_o^T \left(\int_o^t k_s(t-\tau) \eta(\tau) d\tau\right) q(t) dt$$

$$- \lambda\varepsilon \int_o^T \eta(t) dt - \lambda\varepsilon \int_o^T \left(\int_o^t k_r(t-\tau)\eta(\tau) d\tau\right) dt + O(\varepsilon^2) \qquad [41]$$

If the function q(t) is to minimize L then the coefficient of ε must be zero for all arbitrary $\eta(t)$. After interchange of order of integration in the second and fourth integral in Eq. [41] one obtains.

$$\Delta L = c_m \varepsilon \int_o^T \left(\int_o^t k_s(t-\tau) q(\tau) d\tau\right) \eta(t) dt$$

$$+ c_m \int_o^T \left(\int_\tau^T k_s(t-\tau) q(t) dt\right) \eta(\tau) d\tau$$

$$- \lambda\varepsilon \int_o^T \eta(t) dt - \lambda\varepsilon \int_o^T \left(\int_\tau^T k_r(t-\tau) dt\right) \eta(\tau) d\tau + O(\varepsilon^2) \qquad [42]$$

Changing the name of the time variables in the second and fourth integral yields:

$$\Delta L = \varepsilon \int_o^T \{c_m \int_o^t k_s(t-\tau) q(\tau) d\tau + c_m \int_t^T k_s(\tau-t) q(\tau) d\tau$$

$$- \lambda - \lambda \int_t^T k_r(\tau-t) d\tau\} \; \eta(t) dt \qquad [43]$$

The Euler-Lagrange equation is thus:

$$c_m\left[\int_o^t k_s(t-\tau)q(\tau)d\tau + \int_t^T k_s(\tau-t)q(\tau)d\tau\right] = \lambda(1 + \int_t^T k_r(\tau-t)d\tau) \qquad [44]$$

It is an integral equation for the unknown function $q(\cdot)$. Eq. [44] can be expressed in a more standard form by defining a kernel:

$$k_s^*(u) = k_s(|u|) \qquad [45]$$

and by taking $T = \infty$ in the second irrigation (beyond the real irrigation season then $e(t) = 0$ and $q(t) = 0$). Eq. [44] takes the form:

$$c_m \int_o^\infty k_s^*(t-\tau)q(\tau)d\tau = \lambda\ (1+ \int_t^T k_r(\tau-t)d\tau) \qquad [46]$$

which is a linear integral equation of the first kind. The solution is a function of the (unknown) Lagrange multiplier λ. This multiplier is then found by substitution of the solution $q(t,\lambda)$ into the constraint Eq. [39], taken as an equality, which becomes an algebraic equation to be solved for λ. Once λ is obtained substitution of its value into the solution $q(t,\lambda)$ yields the optimal solution $q^*(t)$ to the problem.

However the solution so obtained is not valid if $q(t)$ is < 0 or $>$ $e(t)$, since clearly 0 and $e(t)$ are bounds for the pumping rate in the supplemental strategy.

Suppose that the optimal solution was on the lower bound constraint at time t (thus $q(t)=0$). The only feasible variation is $\eta(t) > 0$. If indeed the objective is at a minimum then ΔL has to be positive for a positive variation $\eta(t)$. It follows that if $q=0$ is optimal in the interval $(0,t_p)$ the coefficient of $\varepsilon(t)$ in that range in Eq. [43] has to be positive namely:

$$\int_o^t k_s(t-\tau)q(\tau)d\tau + \int_t^T k_s(\tau-t)q(\tau)d\tau \geq \frac{\lambda}{c_m}\left(1+\int_t^T k_r(\tau-t)d\tau\right)$$

or more precisely since q is zero in interval $(0, t_p)$

$$\int_{t_p}^T k_s(\tau-t)q(\tau)d\tau \geq \frac{\lambda}{c_m}\left(1+\int_t^T k_r(\tau-t)d\tau\right) \quad \text{for } 0 \leq t \leq t_p \qquad [47]$$

Since λ is positive, this equation implies that q=0 up to time t_p can be optimal provided that beyond that time pumping is large enough and/or that t_p is small (i.e., pumping is initiated early) and/or that c_m is large. Similarly one may question whether or not $q(t) = e(t)$ can be an optimal policy. Suppose that the optimal solution was on the upper bound for times $t_e \leq t \leq T$. In that range the only feasible variation is $\eta(t) < 0$. The coefficient of $\eta(t)$ in that range of times has to be negative, thus:

$$\int_o^{t_e} k_s(t-\tau)q(\tau)d\tau + \int_{t_e}^t k_s(t-\tau)e(\tau)d\tau$$

$$+ \int_{t_e}^T k_s(\tau-t)e(\tau)d\tau \leq \frac{\lambda}{c_m}\left(1+\int_t^T k_r(\tau-t)d\tau\right) \quad \text{for } t_e \leq t \leq T \qquad [48]$$

Since λ is positive Eq. [48] implies that t_e cannot be too small and/or that prior to t_e $q(t)$ must be small and/or that c_m is small. Eqs. [47] and [48] imply that at early times a solution q=0 is optimal and that late times q=e is optimal. There remains a question about the possi ity of an optimal q in the range (0,e) during the interval (t_p, t_e) that case Eq. [44] must hold for $t_p \leq t \leq t_e$.

This discussion provides a basis to check whether the "bang-bang" solution that is q=0 up to t_p and q=e thereafter is indeed optimal. The solution for t_p in this strategy is given by Eq. [36] or more precisely by:

$$\int_{t_p}^{T} \left[e(t) + \int_{t_p}^{T} k_r(t-\tau)e(\tau)d\tau \right] dt = N_T \qquad [49]$$

Having determined t_p one would next verify that Eq. [47] holds, in this case:

$$\int_{t_p}^{T} k_s(\tau-t)e(\tau)d\tau \geq \frac{\lambda}{c_m}\,(1+\int_{t}^{T} k_r(\tau-t)d\tau)$$

$$\text{for} \qquad 0 \leq t \leq t_p \qquad [50]$$

The value of λ is determined from Eq. [46] for q(t) being a step function jumping from zero to $e(t_p)$ at $t=t_p$, namely:

$$\lambda = \frac{c_m \int_{t_p}^{T} k_s(\tau-t_p)e(\tau)d\tau}{1 + \int_{t_p}^{T} k_r(\tau-t_p)d\tau} \qquad [51]$$

One would also need to verify that Eq. [48] holds, in this case:

$$\int_{t_p}^{t} k_s(t-\tau)e(\tau)d\tau + \int_{t}^{T} k_s(\tau-t)e(\tau)d\tau \leq \frac{\lambda}{c_m}\,(1+\int_{t}^{T} k_r(\tau-t)d\tau \qquad [52]$$

From the value of λ in Eq. [51], Eq. [50] takes the more specific form:

$$\frac{\int_{t_p}^{T} k_s(\tau-t)e(\tau)d\tau}{1+\int_{t}^{T} k_r(\tau-t)d\tau} \geq \frac{\int_{t_p}^{T} k_s(\tau-t_p)e(\tau)d\tau}{1+\int_{t_p}^{T} k_r(\tau-t_p)d\tau}$$

$$\text{for} \quad 0 \leq t \leq t_p \qquad [53]$$

Similarly Eq. [52] takes the form:

$$\frac{\int_{t_p}^{t} k_s(t-\tau)e(\tau)d\tau + \int_{t}^{T} k_s(\tau-t)e(\tau)d\tau}{1+\int_{t}^{T} k_r(\tau-t)d\tau} \leq \frac{\int_{t_p}^{T} k_s(\tau-t_p)e(\tau)d\tau}{1+\int_{t_p}^{T} k_r(\tau-t_p)d\tau}$$

$$\text{for} \quad t_p \leq t \leq T \qquad [54]$$

It is not possible to state whether the "bang-bang" solution is the optimal one in all situations. The satisfaction of Eqs. [53] and [54] depends upon the shape of the kernels $k_s(\cdot)$ and $k_r(\cdot)$ and of the crop need $e(\cdot)$.

Consider the simpler case when the irrigation area extends far from the river. In that case the return flow kernel has the form:

$$k_r(t) = -\frac{1}{a}\sqrt{\frac{\gamma}{\pi}}\frac{1}{\sqrt{t}} \qquad [55]$$

In particular its integral with respect to time (the unit step kernel) is:

$$K_r(t) = -\frac{1}{a}\sqrt{\frac{\gamma}{\pi}}\int_{o}^{t}\frac{1}{\sqrt{\tau}}d\tau = -\frac{2}{a}\sqrt{\frac{\gamma}{\pi}}\sqrt{t}$$

Consequently:

$$\int_t^T k_r(\tau-t)d\tau = K_r\ (T-t) = -\frac{2}{a}\sqrt{\frac{\gamma}{\pi}}\ \sqrt{T-t}$$

whereas:

$$\int_{t_p}^T k_r(\tau-t_p)d\tau = K_r(T-t_p) = -\frac{2}{a}\sqrt{\frac{\gamma}{\pi}}\ \sqrt{T-t_p}$$

For $t \leq t_p$ then it follows that the denominator of the left-hand side of Eq. [53] is less than that on the right-hand side. Everything else the same, the larger the seepage flow (that is the better the hydraulic connection between stream and aquifer) the longer one waits to pump to operate optimally.

Similarly again for the case of an area extending far from the river the drawdown kernel has the form:

$$k_s(t) = \frac{1}{\phi}\ \mathrm{erf}\ \left(\frac{x}{2\sqrt{\gamma t}}\right) \qquad [56]$$

Supposing a constant consumptive use e(t) then the numerator on the left-hand side of Eq. [53] is proportional to:

$$\int_{t_p}^T \mathrm{erf}\left[\frac{x}{2\sqrt{\gamma(\tau-t)}}\right]d\tau = \frac{x^2}{2\gamma}\int_{\frac{x^2}{2\gamma(T-t)}}^{\frac{x^2}{2\gamma(t_p-t)}} \mathrm{erf}\ (u)\ \frac{du}{u^2}$$

whereas on the right-hand side the numerator is proportional to:

$$\int_{\frac{x^2}{2\gamma(T-t_p)}}^{\infty} \mathrm{erf}\ (u)\ \frac{du}{u^2}$$

The main contribution to these integrals comes from the lower limit. Thus for constant e the numerator on the left-hand side tends to be greater than the numerator on the right-hand side. The discussion tends to indicate that in many situations the bang-bang policy will be optimal but it is not sure.

General Procedure (for still the simple case)

One presumes that the "bang-bang" policy is optimal. The value of t_p is determined from Eq. [49]. One then checks that Eq. [53] is satisfied for $t \leq t_p$. One checks that Eq. [54] is satisfied for all $t > t_p$. If the checks are positive then the optimal solution was obtained. In the negative one must relax the assumption that at initiation of pumping pumping rate takes immediately the value of irrigation need. At this stage an iterative procedure becomes necessary. Selecting values of t_p and t_e a priori one solves Eq. [44] for values of t in the interval (t_p, t_e), more specifically:

$$c_m \left[\int_{t_p}^{t} k_s(t-\tau) q(\tau) d\tau + \int_{t}^{t_e} k_s(\tau-t) q(\tau) d\tau \right]$$
$$= - c_m \int_{t_e}^{T} k_s(\tau-t) e(\tau) d\tau + \lambda(1 - \int_{t}^{T} k_r(\tau-t) d\tau) \qquad [57]$$

The solution of this integral equation depends upon λ. Substitution of this solution for $q(t,\lambda)$ in Eq. [39] leads more specifically to the expression:

$$N_T - \int_{t_p}^{t_e} q(t,\lambda) dt - \int_{t_e}^{T} e(t) dt - \int_{t_p}^{T} (\int_{t_p}^{t} k_r(t-\tau) q(\tau,\lambda) d\tau) dt = 0 \qquad [58]$$

Once λ obtained one proceeds to Eqs. [47] and [48] for checks on optimality. If the tests are positive the solution has been found. In the negative one must reestimate t_p and t_e, etc.

CONCLUSIONS

The classical techniques for optimization of decision functions such as pumping rates, release rates, etc., are not powerful enough to find the optimal patterns as continuous functions of time as they really are. Instead the unknown functions are discretized over the time horizon. Often in addition to discretization, simplifications are made in the dependence of the objective function on the decision functions. In particular, as in Dynamic Programming, the instantaneous objective function cannot have a memory dependence on previous decisions. Yet this is precisely the case when there is interaction between stream and aquifer.

In this study it was decided to take a crack at the problem from a Functional Optimization point of view. Because of the intrinsic memory of the cost function on past decisions, not surprisingly the Euler-Lagrange equation turns out to be an integral equation rather than a differential equation (the classical case and only one discussed in the mathematical literature). In the simple case considered for which the Euler Lagrange equation was derived, the optimality condition has a clear economic meaning. Under optimal operations at any given time the marginal capitalized cost of future extra lifts due to additional unit of pumped water at that time equals the immediate marginal penalty cost for failing to meet the downstream legal right by one unit at the same time. Based on this optimality criterion optimal release and pumping decisions can be taken continuously throughout the season of operations. Unfortunately analytical solution of an integral equation, even a linear one, is not an easy task. In fact exact solutions are rare. However there are efficient numerical techniques of solution. Lack of time and other commitments did not permit to explore this new procedure in a quantitative manner for specific values of parameters for a reach of a river in hydraulic connection with an aquifer, at the present time. This will be done in the future. One must capitalize on a good idea when one encounters one!

REFERENCES

Illangasekare, T. H. and H. J. Morel-Seytoux, 1983a. "Design and Development of HYDROWAR South Platte Stream-Aquifer Simulation Model," HYDROWAR Program, Colorado State University, Fort Collins, Colorado, April 1983, 137 pages.

Illangasekare, T. H. and H. J. Morel-Seytoux, 1983b. "Evaluation of Strategies of Flow Augmentation by Pumped Groundwater and through Aquifer Recharge Using a Mathematical Model of the South Platte Stream-Aquifer System," HYDROWAR Program, Colorado State University, Fort Collins, Colorado, June 1983, 117 pages.

Morel-Seytoux, H. J. and T. H. Illangasekare, 1983. "Alternative Strategies of Surface and Groundwater Development for the Wadi Aquifer Systems of South Tihama Region in Saudi Arabia: a Case Study for Wadi Jizan," HYDROWAR Program, Colorado State University, Fort Collins, Colorado, March 1983, 72 pages.

Restrepo, J. I. 1984. "Optimal Capacity and Release Rules of an Upstream Reservoir Managed Conjunctively with the Downstream Aquifer Storage," Ph.D. dissertation (draft), Dept of Civil Engineering, Colorado State University, Fort Collins, Colorado, Spring 1984, 170 pages.

TABLE OF CONTENTS OF DISSERTATION
by Jorge Restrepo

Chapter | Page

ABSTRACT
LIST OF TABLES
LIST OF FIGURES
LIST OF SYMBOLS

I INTRODUCTION

II LITERATURE REVIEW
2.1 Conjunctive Use of Ground/Surface Water: Milestones
2.1.1 First Stage
2.1.2 Second Stage
2.1.3 Third Stage
2.2 Literature Review Conclusion

III GENERAL DEFINITION OF THE PROBLEM
3.1 Formulation of the Conjunctive Use Problem
3.1.1 General Statement of the Problem
3.1.2 Basic Assumptions of the Behavior of the System
3.1.3 Configuration of the Hypothetical System
3.2 Analysis of the Benefit Objective Function
3.2.1 The Gain Function
3.2.2 Cost Function
3.2.3 A Mathematical Statement of the Objective Function

IV CROP RESPONSE MODEL TO WATER SUPPLY
4.1 Crop Phenology and Evapotranspiration
4.1.1 Crop Phenology
4.1.2 Crop Evapotranspiration
4.2 A Crop Response Model to Limited Water Supply
4.2.1 Types of Crop Models
4.2.2 Review of the Existing Crop Yield Models
4.3 Adoption of the Growth Index and the Yield Model
4.3.1 Formulation of the Growth Yield Model
4.3.2 Simplifications of the Adopted Model

V WATER SUPPLY SYSTEM FOR IRRIGATION
5.1 Surface Storage for Irrigation Water Supply
5.1.1 Reservoir Storage Model for the Conjunctive Use System

Chapter		Page

5.2 Distribution of the Surface Water Supply . . . . . .
5.2.1 Diversion Canal from the Stream . . . .
5.2.2 On-Farm Irrigation System . . . .
5.2.3 Water Recharge Systems . . . .
5.2.4 Discussion of the System Water Loss . . . . .
5.2.5 Capacity of the Distribution System . . . . .
5.3 Water Rights in the Allocation Model . . . .

VI STREAM-AQUIFER SYSTEM . . . .
6.1 Groundwater System . . . .
6.1.1 Governed Equation and Fundamental Solution . .
6.1.2 Hydrological Model of the Groundwater System .
6.2 Stream-Aquifer System . . . .
6.2.1 Return Flow from Non-fully Penetrating Stream . . . .
6.2.2 Return Flow from Fully Penetrating Stream . .

VII GENERAL MATHEMATICAL FORMULATION OF THE PROBLEM . . . . .
7.1 Full Mathematical Statement of the Objective Function . . . .
7.2 Analysis of the Set of Constraints . . . .
7.3 General Analysis of the Formulated Problem . . . . .

VIII CONJUNCTIVE USE SYSTEM: CONTINUOUS TIME APPROACH . . . .
8.1 Modified Formulation of the Continuous Time Approach . . . .
8.1.1 Main Assumptions of the General Formulation .
8.1.2 Continuous Time Approach Assumptions . . . . .
8.1.3 Updating the Continuous Time Formulation with the Physical System Description . . . . .
8.2 Lagrange Function of the Continuous Time Approach . .
8.3 Euler-Lagrange Equations for the Conjunctive Use System . . . .
8.4 Analysis of the Euler-Lagrange Equation . . . .

IX CONJUNCTIVE USE SYSTEM: DISCRETE TIME APPROACH . . . . . .
9.1 Formulation of the Discrete Time Approach . . . . . .
9.1.1 Main Assumptions for the Discrete Approach . .
9.1.2 Mathematical Formulation for the Discrete Time Approach . . . .
9.2 Analysis of the Formulated Problem Using Quadratic Programming . . . .
9.3 Condensed Formulation of the Quadratic Programming .

X CASE STUDY: SOUTH PLATTE RIVER BASIN . . . .
Part 1: South Platte River Basin Project . . . .
10.1 Illustrative Configuration of the Case Study . . . .
10.1.1 Description of the Physical System . . . .
10.1.2 Hydrological Description . . . . .
10.1.3 Description of the Irrigation System . . . .

Chapter | Page

10.1.4 Economical Characteristics of the System . . . .
Part 2: Application of the Discrete Time Approach . . . . .

XI CONCLUSIONS AND RECOMMENDATIONS . . . .

REFERENCES . . . .

APPENDIX
A NON-EXPLICITLY SOLUTION OF THE RETURN FLOW INTEGRAL (EQUATION 6.17) BY THE LAPLACE TRANSFORM TECHNIQUE . . . .

B APPROXIMATE NON-EXPLICITLY SOLUTION OF THE RETURN FLOW INTEGRAL (EQUATION 6.17) BY THE LAPLACE TRANSFORM TECHNIQUE . . . .

C FULLY PENETRATING RIVER RETURN FLOW KERNEL (EQUATION 6.26) . . . .

D EQUIVALENT KERNEL FOR THE DRAWDOWN RETURN FLOW COMPONENT IN EQUATION (6.30) . . . .

E DEVELOPMENT OF THE OBJECTIVE FUNCTION (EQUATION 9.23) AND THE SET OF CONSTRAINTS (EQUATION 9.24) . . . .

COLORADO WATER RESOURCES RESEARCH INSTITUTE

Revised Price List
May 1, 1984

LIST OF PUBLICATIONS

AVAILABLE FROM: BULLETIN ROOM
171 AYLESWORTH HALL
COLORADO STATE UNIVERSITY
FORT COLLINS, CO 80523

PLEASE ENCLOSE PAYMENT & POSTAGE FOR ORDERS OF $25.00 OR LESS.

Amount of Order	Postage
Up to 99c	75c
$1.00 to $4.99	$1.00
$5.00 to $9.99	$1.50
$10.00 and over	$2.00

PROBLEM-AREA GUIDE TO PUBLICATIONS

A. WATER SUPPLY MANAGEMENT

1. PHYSICAL PROCESSES
   a. Atmospheric
   b. Hydrologic
   c. Hydraulic
   d. Geomorphic
   e. Geochemical
2. PLANNING/EVALUATION METHODOLOGY
   a. Valuation
   b. System Simulation
   c. Analytical Models
   d. Planning Procedures
3. DEMAND REDUCTION
4. SUPPLY AUGMENTATION
5. MANAGEMENT OF HYDROLOGIC EXTREMES
6. RECREATION

B. WATER QUALITY

1. IDENTIFY AND CONTROL ENTERING POLLUTANTS
2. EFFECTS OF POLLUTANTS
3. TREATMENT AND DISPOSAL OF WASTES

C. ECONOMIC IMPACTS

D. ECOSYSTEM ISSUES

E. SOCIAL-INSTITUTIONAL-POLICY

1. INSTITUTIONS
2. PROCESSES

F. WATER CONVEYANCE AND CONTROL WORKS

G. WATER DATA, PROJECTIONS, GENERAL INFORMATION

A. WATER SUPPLY MANAGEMENT

1. PHYSICAL PROCESSES

a. Atmospheric

Report No.	Title	Authors	Date	Price
CR 24	STUDIES OF THE ATMOSPHERIC WATER BALANCE	Rasmussen	8/71	$ 6.00
CR 57	SNOW-AIR INTERACTIONS AND MANAGEMENT OF MOUNTAIN WATERSHED SNOWPACK	Meiman, Grant	6/74	4.00
CR 63	ANALYSIS OF COLORADO PRECIPITATION	Kuo, Cox	6/75	3.00

b. Hydrologic

Report No.	Title	Authors	Date	Price
CR 4	RUNOFF FROM FOREST AND AGRICULTURAL WATERSHEDS	Holland	6/69	4.00
CR 16	EXPERIMENTAL INVESTIGATION OF SMALL WATERSHED FLOODS	Smith, Yevjevich, Holland	6/68	3.00
CR 18	EXPERIMENTAL INVESTIGATION OF SMALL WATERSHED FLOODS	Schulz, Yevjevich	6/70	6.00
CR 23	A SYSTEMATIC TREATMENT OF THE PROBLEM OF INFILTRATION	Morel-Seytoux	6/71	4.00
CR 25	EVAPORATION OF WATER AS RELATED TO WIND BARRIERS	Verma, Cermak	6/71	6.00
CR 26	WATER TEMPERATURE AS A QUALITY FACTOR IN THE USE OF STREAMS AND RESERVOIRS	Ward, J.	12/71	4.00
CR 30	GEOHYDRAULICS AT THE UNCONFORMITY BETWEEN BEDROCK AND ALLUVIAL AQUIFERS	Waltz, Sunada	6/72	6.00
CR 32	BACTERIAL MOVEMENT THROUGH FRACTURED BEDROCK	Morrison, Allen	7/72	6.00
CR 35	AN APPLICATION OF MULTI-VARIATE ANALYSIS IN HYDROLOGY	Yevjevich, Dynr-Neilsen, Schulz	8/72	6.00
CR 40	SELECTION OF TEST VARIABLE FOR MINIMAL TIME DETECTION OF BASIN RESPONSE TO NATURAL OR INDUCED CHANGES	Morel-Seytoux	12/72	4.00
CR 41	GROUNDWATER RECHARGE AS AFFECTED BY SURFACE VEGETATION AND MANAGEMENT	Klute, Danielson, Linden, Hamaker	12/72	6.00
CR 42	THEORY AND EXPERIMENTS IN THE PREDICTION OF SMALL WATERSHED RESPONSE	Yevjevich, Schulz	12/72	6.00
CR 43	EXPERIMENTS IN SMALL WATERSHED RESPONSE	Schulz, Yevjevich	12/72	6.00
CR 50	SYSTEMATIC TREATMENT OF INFILTRATION WITH APPLICATIONS	Morel-Seytoux	6/73	6.00
CR 51	AN EXPERIMENTAL STUDY OF SOIL WATER FLOW SYSTEMS INVOLVING HYSTERESIS	Klute, Gillham	8/73	8.00
CR 54	GEOLOGIC FACTORS IN THE EVALUATION OF WATER POLLUTION POTENTIAL AT MOUNTAIN DWELLING SITES	Burns, McCrumb, Morrison	12/73	11.00
CR 59	A SYSTEM FOR GEOLOGIC EVALUATION OF POLLUTION AT MOUNTAIN DWELLING SITES	Waltz	1/75	4.50
CR 64	COMPUTER ESTIMATES OF NATURAL RECHARGE FROM SOIL MOISTURE DATA - HIGH PLAINS OF COLORADO	Longenbaugh	7/75	5.00
CR 69	ENGINEERING AND ECOLOGICAL EVALUATION OF ANTITRANSPIRANTS FOR INCREASING RUNOFF IN COLORADO WATERSHEDS	Kreith	9/75	3.50
CR 76	DETERMINATION OF SNOW DEPTH AND WATER EQUIVALENT BY REMOTE SENSING	Steinhoff, Barnes	6/76	3.00
CR 92	HYDRAULIC CONDUCTIVITY OF MOUNTAIN SOILS	Williams, Ponce, Meiman, Spearnak	9/78	4.00
CR 97	WATER REQUIREMENTS FOR URBAN LAWNS IN COLORADO	Danielson, Hart Feldhake, Haw	8/80	4.00
CR 99	APPLICATIONS OF REMOTE SENSING IN HYDROLOGY	Striffler, Fitz	9/80	4.00
CR 106	URBAN LAWN IRRIGATION AND MANAGEMENT PRACTICES FOR WATER SAVING WITH MINIMUM EFFECT ON LAWN QUALITY	Danielson, Feldhake	5/81	7.00

Report No.	Title	Authors	Date	Price
CR 108	WATERLOGGING CONTROL FOR IMPROVED WATER AND LAND USE EFFICIENCIES: A SYSTEMATIC ANALYSIS	Simpson, Morel-Seytoux, Young	12/80	$ 6.00
CR 123	ARTIFICIAL GROUNDWATER RECHARGE, SAN LUIS VALLEY, COLORADO	Sunada	5/83	7.00
CR 127	MATHEMATICAL MODELS FOR PREDICTION OF SOIL MOISTURE PROFILES	Morel-Seytoux	7/83	4.00
TR 13	IMPACT OF IRRIGATION EFFICIENCY IMPROVEMENTS ON WATER AVAILABILITY IN THE SOUTH PLATTE RIVER BASIN	Bittinger, Danielson, Evans, Hart, Morel-Seytoux, Skinner	1/79	6.00
TR 15	WEEKLY CROP CONSUMPTIVE USE AND PRECIPITATION IN THE LOWER SOUTH PLATTE RIVER BASIN (Fort Morgan, Sterling, and Julesburg) 1947-1975		2/79	Free

c. Hydraulic

Report No.	Title	Authors	Date	Price
CR 6	STABILIZATION OF ALLUVIAL CHANNELS	Bhowmik, Simons	6/69	4.00
CR 7	STABILITY OF SLOPES WITH SEEPAGE	Muir, Simons	6/69	4.00
CR 117	DYNAMIC WATER ROUTING USING A PREDICTOR-CORRECTOR METHOD WITH SEDIMENT ROUTING	Simons, Li, Garbrecht, Simons	9/82	6.00
IS 50	POSSIBLE CAPTURE OF THE MISSISSIPPI BY THE ATCHAFALAYA RIVER	Higby	8/83	5.00
SR 1	DESIGN OF WATER AND WASTEWATER SYSTEMS FOR RAPID GROWTH AREAS - (BOOM TOWNS, MOUNTAIN RESORTS)	Flack	7/76	5.00
S-522S	WEED SEED AND TRASH SCREENS FOR IRRIGATION WATER		1966	.35
S-TB61	PARSHALL MEASURING FLUMES OF SMALL SIZES		1957	.25
S-TB120	SELECTION AND INSTALLATION OF CUTTHROAT FLUMES FOR MEASURING IRRIGATION AND DRAINAGE WATER		1976	3.50
S-TB126	A SHUNT-LINE METERING SYSTEM FOR IRRIGATION WELLS		1977	.75
X-426A	PARSHALL FLUMES OF LARGE SIZE		1961	.50

d. Geomorphic

Report No.	Title	Authors	Date	Price
CR 69	ENGINEERING AND ECOLOGICAL EVALUATION OF ANTITRANSPIRANTS FOR INCREASING RUNOFF IN COLORADO WATERSHEDS	Kreith	9/75	$ 3.50
CR 93	APPLICATION OF GEOMORPHIC PRINCIPLES TO ENVIRONMENTAL MANAGEMENT IN SEMIARID REGIONS	Schumm, Bradley, Begin	2/80	4.00
CR 107	ROLE OF SEDIMENT IN NON-POINT SOURCE SALT LOADING WITHIN THE UPPER COLORADO RIVER BASIN	Shen, Laronne, Enck, Sunday, Tanji, Whittig, Biggar	8/81	9.00
CR 110	GEOMORPHIC AND LITHOLOGIC CONTROLS OF DIFFUSE-SOURCE SALINITY, GRAND VALLEY, WESTERN COLORADO	Johnson, Schumm	4/82	6.00

e. Geochemical

CR 14	HYDROGEOLOGY AND WATER QUALITY STUDIES IN THE CACHE LA POUDRE BASIN, COLORADO	Waltz	6/69	6.00
CR 67	TOXIC HEAVY METALS IN GROUNDWATER OF A PORTION OF THE FRONT RANGE MINERAL BELT (Partial Report)	Edwards, Klusman	6/75	4.00
CR 71	SALT TRANSPORT IN SOIL PROFILES WITH APPLICATION TO IRRIGATION RETURN FLOW	Glas, McWhorter	1/76	6.00
CR 72	TOXIC HEAVY METALS IN GROUNDWATER OF A PORTION OF THE FRONT RANGE MINERAL BELT (Final Report)	Klusman, Edwards	6/76	5.00
CR 79	EVALUATION OF THE STORAGE OF DIFFUSE SOURCES OF SALINITY IN THE UPPER COLORADO RIVER BASIN	Laronne, Schumm	9/77	5.00

2. PLANNING/EVALUATION METHODOLOGY

a. Valuation

CR 56	EVALUATION AND IMPLEMENTATION OF URBAN DRAINAGE AND FLOOD CONTROL PROJECTS	Grigg, Rice, Bothan, Shoemaker	6/74	9.00
CR 70	AN ECONOMIC ANALYSIS OF WATER USE IN COLORADO'S ECONOMY	Gray	12/75	6.00
CR 81	ACHIEVING URBAN WATER CONSERVATION: TESTING COMMUNITY ACCEPTANCE	Snodgrass, Hill	9/77	6.00
CR 91	ECONOMIC BENEFITS FROM INSTREAM FLOW IN A COLORADO MOUNTAIN STREAM	Daubert, Young, Gray	6/79	6.00
CR 101	AN EMPIRICAL APPLICATION OF A MODEL FOR ESTIMATING THE RECREATION VALUE OF INSTREAM FLOW	Walsh, Ericson, Arosteguy, Hansen	10/80	4.00
CR 102	MEASURING BENEFITS AND THE ECONOMIC VALUE OF WATER IN RECREATION ON HIGH COUNTRY RESERVOIRS	Walsh, Aukerman, Milton	9/80	4.00
CR 103	EMPIRICAL APPLICATION OF A MODEL FOR ESTIMATING THE RECREATION VALUE OF WATER IN RESERVOIRS COMPARED TO INSTREAM FLOW	Walsh	12/80	4.00
IS 19	THE ENVIRONMENTAL QUALITY OBJECTIVE OF PRINCIPLES AND STANDARDS FOR PLANNING	McGinnis, Plott, Swanson	8/75	8.00

Report No.	Title	Author	Date	Price
TR 14	ECONOMIC VALUE OF BENEFITS FROM RECREATION AT HIGH MOUNTAIN RESERVOIRS	Walsh, Aukerman, Rud	12/78	$ 4.00
TR 24	THE SURVEY-BASED INPUT-OUTPUT MODEL AS A RESOURCE PLANNING TOOL	McKean	1/81	4.00
TR 44	DIRECT AND INDIRECT ECONOMIC EFFECTS OF HUNTING AND FISHING IN COLORADO - 1981	McKean, Nobe	1/84	5.00

b. System Simulation

CR 2	COMPUTER SIMULATION OF WASTE TRANSPORT IN GROUNDWATER AQUIFERS	Redell, Sunada	6/69	3.00
CR 53	SYSTEMATIC DESIGN OF LEGAL REGULATIONS FOR OPTIMAL SURFACE-GROUNDWATER USAGE - PHASE I	Morel-Seytoux, Young, Radosevich		
CR 62	FEASIBILITY AND POTENTIAL OF ENHANCING WATER RECREATION OPPORTUNITIES ON HIGH COUNTRY RESERVOIRS	Aukerman	6/75	5.00
CR 68	SYSTEMATIC DESIGN OF LEGAL REGULATIONS FOR OPTIMAL SURFACE-GROUNDWATER USAGE, PHASE 2	Morel-Seytoux	9/75	13.00
CR 82	DEVELOPMENT OF A SUBSURFACE HYDROLOGIC MODEL AND USE FOR INTEGRATED MANAGEMENT OF SURFACE AND SUBSURFACE WATER RESOURCES	Morel-Seytoux	12/77	4.00
CR 87	DEVELOPMENT OF A STREAM-AQUIFER MODEL SUITED FOR DEVELOPMENT	Morel-Seytoux	8/78	4.00
CR 89	SYNTHESIS AND CALIBRATION OF A RIVER BASIN WATER MANAGEMENT MODEL	Shafer, Labadie	10/78	4.00
CR 108	WATERLOGGING CONTROL FOR IMPROVED WATER AND LAND USE EFFICIENCIES: A SYSTEMATIC ANALYSIS	Simpson, Morel-Seytoux, Young	12/80	6.00
CR 112	DAILY OPERATIONAL TOOL FOR MAXIMUM BENEFICIAL USE MANAGEMENT OF SURFACE AND GROUNDWATERS IN A BASIN	Morel-Seytoux, Verdin, Illangasekare	3/82	4.00
CR 125	A RIVER BASIN NETWORK MODEL FOR CONJUNCTIVE USE OF SURFACE AND GROUNDWATER: PROGRAM CONSIM	Labadie, Phamwon, Lazaro	6/83	8.00
IS 33	THE IMPACTS OF IMPROVING EFFICIENCY OF IRRIGATION SYSTEMS ON WATER AVAILABILITY IN THE LOWER SOUTH PLATTE RIVER BASIN	Morel-Seytoux, Illangasekare, Bittinger, Evans	1/79	Free
TR 16	WATER MANAGEMENT MODEL FOR FRONT RANGE RIVER BASINS	Labadie, Shafer	4/79	6.00
TR 18	AN INTERACTIVE RIVER BASIN WATER MANAGEMENT MODEL: SYNTHESIS AND APPLICATION	Shafer	8/79	5.00
S-TB127	A SIMULATION MODEL FOR ANALYZING TIMBER-WATER JOINT PRODUCTION IN THE COLORADO ROCKIES		1975	1.25

c. Analytical Models

Report No.	Title	Author	Date	Price
CR 13	ECONOMICS OF GROUNDWATER DEVELOPMENT IN THE HIGH PLAINS OF COLORADO	Rohdy	6/69	$ 2.50
CR 29	IDENTIFICATION OF URBAN WATERSHED UNITS USING REMOTE SPECTRAL SENSING	Root, Miller	6/71	6.00
CR 40	SELECTION OF TEST VARIABLE FOR MINIMAL TIME DETECTION OF BASIN RESPONSE TO NATURAL OR INDUCED CHANGES	Morel-Seytoux	12/72	4.00
CR 45	MATHEMATICAL MODELING OF WATER MANAGEMENT STRATEGIES IN URBANIZING RIVER BASINS	Walker, Skogerboe	6/73	8.50
CR 83	MODELLING THE DYNAMIC RESPONSE OF FLOODPLAINS TO URBANIZATION IN EASTERN NEW ENGLAND	Doehring, Smith	1/78	7.50
CR 90	MODELS FOR SYSTEM WATER PLANNING WITH SPECIAL REFERENCE TO WATER REUSE	Hendricks, Morel-Seytoux	6/78	6.00
CR 101	AN EMPIRICAL APPLICATION OF A MODEL FOR ESTIMATING THE RECREATION VALUE OF INSTREAM FLOW	Walsh, Ericson, Arosteguy, Hansen	10/80	4.00
CR 103	EMPIRICAL APPLICATION OF A MODEL FOR ESTIMATING THE RECREATION VALUE OF WATER IN RESERVOIRS COMPARED TO INSTREAM FLOW	Walsh	12/80	4.00
CR 108	WATERLOGGING CONTROL FOR IMPROVED WATER AND LAND USE EFFICIENCIES: A SYSTEMATIC ANALYSIS	Simpson, Morel-Seytoux, Young	12/80	6.00
CR 111	INVESTIGATION OF OBJECTIVE FUNCTIONS AND OPERATION RULES FOR STORAGE RESERVOIRS	Yevjevich, Hall, Salas	9/81	4.00
CR 114	PLANNING WATER REUSE: DEVELOPMENT OF REUSE THEORY AND THE INPUT-OUTPUT MODEL, VOL. I: FUNDAMENTALS	Turner, Hendricks	9/80	13.00
CR 115	PLANNING WATER REUSE: DEVELOPMENT OF REUSE THEORY AND THE INPUT-OUTPUT MODEL, VOL. II: APPLICATION	Klooz, Hendricks	9/80	6.00
CR 127	MATHEMATICAL MODELS FOR PREDICTION OF SOIL MOISTURE PROFILES	Morel-Seytoux	7/83	4.00
IS 37	WATER FOR THE SOUTH PLATTE BASIN	Hendricks, Morel-Seytoux, Turner	3/79	Free
IS 40	PROCEEDINGS OF THE WORKSHOP ON INSTREAM FLOW HABITAT CRITERIA	Smith	12/79	6.00
IS 41	EXPLORING WAYS OF INCREASING THE USE OF SOUTH PLATTE WATER	Labadie, Shafer		Free
TR 8	MODELS DESIGNED TO EFFICIENTLY ALLOCATÉ IRRIGATION WATER USE BASED ON CROP RESPONSE TO SOIL MOISTURE STRESS	Anderson, Yaron, Young	5/77	5.00
TR 14	ECONOMIC VALUE OF BENEFITS FROM RECREATION AT HIGH MOUNTAIN RESERVOIRS	Aukerman, Rud	12/78	4.00
TR 20	DEVELOPMENT OF METHODOLOGIES FOR DETERMINING OPTIMAL WATER STORAGE STRATEGIES	Labadie, Fontane	9/80	3.00
TR 24	THE SURVEY-BASED INPUT-OUTPUT MODEL AS A RESOURCE PLANNING TOOL	McKean	1/81	4.00
TR 26	AN INPUT-OUTPUT ANALYSIS OF SPORTSMAN EXPENDITURES IN COLORADO	McKean	1/81	5.00
TR 34	ENERGY AND WATER SCARCITY AND THE IRRIGATED AGRICULTURAL ECONOMY OF THE COLORADO HIGH PLAINS: DIRECT ECONOMIC-HYDROLOGIC IMPACT FORECASTS (1979-2020)	Young, Conklin, Longenbaugh, Gardner	2/82	8.00
TR 44	DIRECT AND INDIRECT ECONOMIC EFFECTS OF HUNTING AND FISHING IN COLORADO	McKean, Nobe	1/84	5.00

d. Planning Procedure

Report No.	Title	Author	Date	Price
TR 7	MANUAL FOR TRAINING IN THE APPLICATION OF PRINCIPLES AND STANDARDS (Water Resources Council)	Caulfield	12/74	$11.00

3. DEMAND REDUCTION

CR 8	IMPROVING EFFICIENCY IN AGRICULTURAL WATER USE	Kemper, Danielson	6/69	2.00
CR 15	HYDRAULIC OPERATING CHARACTERISTICS OF LOW GRADIENT BORDER CHECKS IN THE MANAGEMENT OF IRRIGATION WATER	Heermann, Evans	6/68	4.00
CR 19	HYDRAULICS OF LOW GRADIENT BORDER IRRIGATION SYSTEMS	Evans, Heermann, Howe, Kincaid	6/70	4.00
CR 20	IMPROVING EFFICIENCY IN AGRICULTURAL WATER USE	Kemper	7/70	4.00
CR 25	EVAPORATION OF WATER AS RELATED TO WIND BARRIERS	Verma, Cermak	6/71	6.00
CR 41	GROUNDWATER RECHARGE AS AFFECTED BY SURFACE VEGETATION AND MANAGEMENT	Klute, Danielson, Linden, Hamaker	12/72	6.00
CR 49	IMPROVEMENTS IN MOVING SPRINKLER IRRIGATION SYSTEMS FOR CONSERVATION OF WATER	Miles	6/73	8.50
CR 52	CONSOLIDATION OF IRRIGATION SYSTEMS: PHASE I - ENGINEERING, LEGAL, AND SOCIOLOGICAL CONSTRAINTS AND/OR FACILITATORS	Skogerboe, Radosevich, Vlachos	6/73	25.00
CR 69	ENGINEERING AND ECOLOGICAL EVALUATION OF ANTITRANSPIRANTS FOR INCREASING RUNOFF IN COLORADO WATERSHEDS	Kreith	9/75	3.50
CR 80	ACHIEVING URBAN WATER CONSERVATION, A HANDBOOK	Flack, Weakley, Hill	9/77	7.00
CR 81	ACHIEVING URBAN WATER CONSERVATION: TESTING COMMUNITY ACCEPTANCE	Snodgrass, Hill	9/77	6.00
CR 94	CONSOLIDATION OF IRRIGATION SYSTEMS: PHASE II - ENGINEERING, ECONOMIC, LEGAL AND SOCIOLOGICAL REQUIREMENTS	Vlachos, Huszar, Radosevich, Skogerboe	5/80	9.00
CR 105	MUNICIPAL WATER USE IN NORTHERN COLORADO: DEVELOPMENT OF EFFICIENCY-OF-USE CRITERION	White, DiNatale, Greenberg, Flack	9/80	5.00
CR 106	URBAN LAWN IRRIGATION AND MANAGEMENT PRACTICES FOR WATER SAVING WITH MINIMUM EFFECT ON LAWN QUALITY	Danielson, Feldhake	5/81	6.00
CR 109	SALT- AND DROUGHT-TOLERANT CROP PLANTS FOR WATER CONSERVATION	Nabors	10/81	6.00
CR 120	THE EFFECTS OF WATER CONSERVATION ON NEW WATER SUPPLY FOR URBAN COLORADO UTILITIES	Ellinghouse, McCoy	12/82	9.00

IS 16	ANNOTATED BIBLIOGRAPHY ON TRICKLE IRRIGATION	Smith, Walker	6/75	Free
IS 26	WATER USE AND MANAGEMENT IN AN ARID REGION (Fort Collins, Colorado and Vicinity)	Anderson, DeRemer, Hall	9/77	6.00
IS 36	CUTTING CITY WATER DEMAND	Flack	5/79	Free

TR 8	MODELS DESIGNED TO EFFICIENTLY ALLOCATE IRRIGATION WATER USE BASED ON CROP RESPONSE TO SOIL MOISTURE STRESS	Anderson, Yaron, Young	5/77	5.00
TR 13	IMPACT OF IRRIGATION EFFICIENCY IMPROVEMENTS ON WATER AVAILABILITY IN THE SOUTH PLATTE RIVER BASIN	Bittinger, Danielson, Evans, Hart, Morel-Seytoux, Skinner	1/79	6.00
TR 28	AN ASSESSMENT OF WATER USE AND POLICIES IN NORTHERN COLORADO CITIES	DiNatale	3/81	6.00
S-TR 12B	EVALUATING WATER DISTRIBUTIONS OF SPRINKLER IRRIGATION SYSTEMS		1976	.85

Report No.	Title	Author	Date	Price
CR 3	SNOW ACCUMULATION IN RELATION TO FOREST CANOPY	Meiman, Froehlich, Dils	6/69	$ 2.50
CR 9	CONTROLLED ACCUMULATION OF BLOWING SNOW	Rasmussen	6/69	3.50
CR 24	STUDIES OF THE ATMOSPHERIC WATER BALANCE	Rasmussen	8/71	6.00
CR 57	SNOW-AIR INTERACTIONS AND MANAGEMENT OF MOUNTAIN WATERSHED SNOWPACK	Meiman, Grant	6/74	4.00
CR 108	WATERLOGGING CONTROL FOR IMPROVED WATER AND LAND USE EFFICIENCIES: A SYSTEMATIC ANALYSIS	Simpson, Morel-Seytoux, Young	12/80	6.00
CR 114	PLANNING WATER REUSE: DEVELOPMENT OF REUSE THEORY AND THE INPUT-OUTPUT MODEL, VOL. I: FUNDAMENTALS	Turner, Hendricks	9/80	13.00
CR 115	PLANNING WATER REUSE: DEVELOPMENT OF REUSE THEORY AND THE INPUT-OUTPUT MODEL, VOL. II: APPLICATION	Klooz, Hendricks	9/80	6.00
CR 123	ARTIFICIAL GROUNDWATER RECHARGE, SAN LUIS VALLEY, COLORADO	Sunada	5/83	7.00
IS 32	SNOWPACK AUGMENTATION BY CLOUD SEEDING IN COLORADO AND UTAH	Chisholm, Grimes	8/79	5.00
IS 33	THE IMPACTS OF IMPROVING EFFICIENCY OF IRRIGATION SYSTEMS ON WATER AVAILABILITY IN THE LOWER SOUTH PLATTE RIVER BASIN	Morel-Seytoux, Illangasekare, Bittinger, Evans	1/79	Free

5. MANAGEMENT OF HYDROLOGIC EXTREMES

CR 10	ECONOMICS AND ADMINISTRATION OF WATER RESOURCES	Flack	6/69	3.50
CR 16	EXPERIMENTAL INVESTIGATION OF SMALL WATERSHED FLOODS	Smith, Yevjevich, Holland	6/68	3.00
CR 18	EXPERIMENTAL INVESTIGATION OF SMALL WATERSHED FLOODS	Schulz, Yevjevich	6/70	6.00
CR 56	EVALUATION AND IMPLEMENTATION OF URBAN DRAINAGE AND FLOOD CONTROL PROJECTS	Grigg, Rice, Bothan, Shoemaker	6/74	9.00
CR 65	URBAN DRAINAGE AND FLOOD CONTROL PROJECTS: ECONOMIC, LEGAL, AND FINANCIAL ASPECTS	Grigg, Tucker, Rice, Shoemaker	7/75	11.00
CR 85	DEVELOPMENT OF A DRAINAGE AND FLOOD CONTROL MANAGEMENT PROGRAM FOR URBANIZING COMMUNITIES - PART I	Riordan, Grigg, Hiller	9/78	3.00
CR 86	DEVELOPMENT OF A DRAINAGE AND FLOOD CONTROL MANAGEMENT PROGRAM FOR URBANIZING COMMUNITIES - PART II	Riordan, Grigg, Hiller	9/78	8.00
CR 95	DROUGHT-INDUCED PROBLEMS AND RESPONSES OF SMALL TOWNS AND RURAL WATER ENTITIES IN COLORADO: THE 1976-78 DROUGHT	Howe	6/80	5.00
CR 126	INCREASING THE ECONOMIC EFFICIENCY AND AFFORDABILITY OF STORM DRAINAGE PROJECTS	Cochrane, Huszar	9/83	4.00
IS 13	FLOOD PLAIN MANAGEMENT OF THE CACHE LA POUDRE RIVER NEAR FORT COLLINS, COLORADO	Combs, McDonald, Martens, Rowe	8/74	3.75
IS 17	CACHE LA POUDRE RIVER NEAR FORT COLLINS, COLORADO - FLOOD MANAGEMENT ALTERNATIVES - RELOCATIONS AND LEVIES	Koirtyohann, Miller, Pope, Stein	8/75	6.00
IS 24	FACTORS AFFECTING PUBLIC ACCEPTANCE OF FLOOD INSURANCE IN LARIMER AND WELD COUNTIES, COLORADO	James, Kreger. Barrineau	9/77	4.00
IS 27	PROCEEDINGS, COLORADO DROUGHT WORKSHOPS		11/77	Free
IS 44	THE NATIONAL FLOOD INSURANCE PROGRAM IN LARIMER COUNTY, COLORADO AREA	Shoudy	8/80	4.00
S-GS856	RESEARCH DATA ASSEMBLY FOR SMALL WATERSHED FLOODS, PART II		1967	.50

Report No.	Title	Author	Date	Price
CR 62	FEASIBILITY AND POTENTIAL OF ENHANCING WATER RECREATION OPPORTUNITIES ON HIGH COUNTRY RESERVOIRS	Aukerman	6/75	$ 5.00
CR 78	SELECTING AND PLANNING HIGH COUNTRY RESERVOIRS FOR RECREATION WITHIN A MULTIPURPOSE MANAGEMENT FRAMEWORK	Aukerman, Carlson, Hiller, Labadie	7/77	7.00
CR 103	EMPIRICAL APPLICATION OF A MODEL FOR ESTIMATING THE RECREATION VALUE OF WATER IN RESERVOIRS COMPARED TO INSTREAM FLOW	Walsh	12/80	4.00
CR 124	EFFECTS OF WILDERNESS LEGISLATION ON WATER-PROJECT DEVELOPMENT IN COLORADO	Weaver	5/83	8.00
TR 3	IMPLEMENTATION OF THE FEDERAL WATER PROJECT RECREATION ACT IN COLORADO	Spence	6/74	Free
TR 11	FEDERAL WATER RECREATION IN COLORADO: COMPREHENSIVE VIEW AND ANALYSIS	Stefanec	5/78	6.00
TR 12	RECREATION BENEFITS OF WATER QUALITY: ROCKY MOUNTAIN NATIONAL PARK, SOUTH PLATTE RIVER BASIN, COLORADO	Walsh, Ericson, McKean, Young	5/78	5.00

B. WATER QUALITY

1. IDENTIFY AND CONTROL ENTERING POLLUTANTS

CR 14	HYDROGEOLOGY AND WATER QUALITY STUDIES IN THE CACHE LA POUDRE BASIN, COLORADO	Waltz	6/69	6.00
CR 21	WATERFOWL-WATER TEMPERATURE RELATIONS IN WINTER	Ryder	6/70	6.00
CR 54	GEOLOGIC FACTORS IN THE EVALUATION OF WATER POLLUTION POTENTIAL AT MOUNTAIN DWELLING SITES	Burns, McCrumb, Morrison	12/73	11.00
CR 60	RESEARCH NEEDS AS RELATED TO THE DEVELOPMENT OF SEDIMENT STANDARDS IN RIVERS	Gessler	3/75	4.00
CR 67	TOXIC HEAVY METALS IN GROUNDWATER OF A PORTION OF THE FRONT RANGE MINERAL BELT	Edwards, Klusman	6/75	4.00
CR 71	SALT TRANSPORT IN SOIL PROFILES WITH APPLICATION TO IRRIGATION RETURN FLOW	Glas, McWhorter	1/76	6.00
CR 72	TOXIC HEAVY METALS IN GROUNDWATER OF A PORTION OF THE FRONT RANGE MINERAL BELT	Klusman, Edwards	6/76	5.00
CR 79	EVALUATION OF THE STORAGE OF DIFFUSE SOURCES OF SALINITY IN THE UPPER COLORADO RIVER BASIN	Laronne, Schumm	9/77	5.00
CR 84	POLLUTIONAL CHARACTERISTICS OF STORMWATER RUNOFF	Bennett, Linstedt	9/78	8.00
CR 104	DETECTION OF WATER QUALITY CHANGES THROUGH OPTIMAL TESTS AND RELIABILITY OF TESTS	Koch, Sanders, Morel-Seytoux	9/80	5.00
CR 107	ROLE OF SEDIMENT IN NON-POINT SOURCE SALT LOADING WITHIN THE UPPER COLORADO RIVER BASIN	Shen, Laronne, Enck, Sunday, Tanji, Whittig, Biggar	8/81	9.00
IS 25	SURVEILLANCE DATA, PLAINS SEGMENT OF THE CACHE LA POUDRE RIVER, COLORADO, 1970-1977	Morrison	1/78	6.00

Report No.	Title	Author	Date	Price
TR 38	PUBLIC PARTICIPATION PRACTICES OF THE U.S. ARMY CORPS OF ENGINEERS	Crist, Lanier	7/79	$ 4.00
S-GS870	CHEMICAL QUALITY OF GROUNDWATER IN THE PROSPECT VALLEY AREA, COLORADO		1968	.25

2. EFFECTS OF POLLUTANTS

Report No.	Title	Author	Date	Price
CR 26	WATER TEMPERATURE AS A QUALITY FACTOR IN THE USE OF STREAMS AND RESERVOIRS	Ward, J.	12/71	4.00
CR 31	SEDIMENTATION AND CONTAMINANT CRITERIA FOR WATERSHED PLANNING AND MANAGEMENT	Shen	6/72	6.00
CR 73	PRODUCTION OF MUTANT PLANTS CONDUCIVE TO SALT TOLERANCE	Nabors	7/76	5.00
CR 96	THE PRODUCTION OF AGRICULTURALLY USEFUL MUTANT PLANTS WITH CHARACTERISTICS CONDUCIVE TO SALT TOLERANCE AND EFFICIENT WATER UTILIZATION	Nabors	10/79	4.00
CR 98	THE EFFECT OF ALGAL INHIBITORS ON HIGHER PLANT TISSUES	Kugrens	7/80	3.50
CR 116	EFFECTS OF RELEASES OF SEDIMENT FROM RESERVOIRS ON STREAM BIOTA	Ward, J.	9/82	4.00

3. TREATMENT AND DISPOSAL OF WASTES

Report No.	Title	Author	Date	Price
CR 1	BACTERIAL RESPONSE TO THE SOIL ENVIRONMENT	Boyd, Yoshida, Vereen, Cada, Morrison	6/69	4.50
CR 2	COMPUTER SIMULATION OF WASTE TRANSPORT IN GROUNDWATER AQUIFERS	Reddell, Sunada	6/69	3.00
CR 28	COMBINED COOLING AND BIO-TREATMENT OF BEET SUGAR FACTORY CONDENSER WATER EFFLUENT	Lof	6/71	6.00
CR 32	BACTERIAL MOVEMENT THROUGH FRACTURED BEDROCK	Morrison, Allen	7/72	6.00
CR 33	THE MECHANISM OF WASTE TREATMENT AT LOW TEMPERATURE, PART A: MICROBIOLOGY	Morrison, Newton, Boone, Martin	8/72	6.00
CR 34	THE MECHANISM OF WASTE TREATMENT AT LOW TEMPERATURE, PART B: SANITARY ENGINEERING	Ward, J., Hunter, Johansen	8/72	6.00
CR 59	A SYSTEM FOR GEOLOGIC EVALUATION OF POLLUTION AT MOUNTAIN DWELLING SITES	Waltz	1/75	4.50
CR 66	INDIVIDUAL HOME WASTEWATER CHARACTERIZATION AND TREATMENT	Bennett, Linstedt	7/75	9.00
CR 77	EVAPORATION OF WASTEWATER FROM MOUNTAIN CABINS	Ward, J.	3/77	9.00
CR 113	A WATER HANDBOOK FOR METAL MINING OPERATIONS	Wildeman	11/81	6.00
CR 121	SOLAR HEATING OF WASTEWATER STABILIZATION PONDS	Klemetson	3/83	5.00
IS 4	PROCEEDINGS, WORKSHOP ON HOME SEWAGE DISPOSAL IN COLORADO	Ward, R.	6/72	Free
IS 9	PROCEEDINGS OF THE SYMPOSIUM ON LAND TREATMENT AND SECONDARY EFFLUENT		11/73	4.00
IS 20	PROCEEDINGS, SECOND WORKSHOP ON HOME SEWAGE DISPOSAL IN COLORADO	Ward, R.	9/75	4.00
IS 29	PROCEEDINGS, THIRD WORKSHOP ON HOME SEWAGE DISPOSAL IN COLORADO - COMMUNITY MANAGEMENT	Ward, R.	7/78	5.00

Report No.	Title	Author	Date	Price
CR 45	PROCEEDINGS, FOURTH WORKSHOP ON HOME SEWAGE DISPOSAL IN COLORADO - STATE/COUNTY COOPERATION IN MANAGING SMALL WASTEWATER FLOWS	Ward, R.	8/81	$ 5.00
CR 49	PROCEEDINGS, FIFTH WORKSHOP ON HOME SEWAGE DISPOSAL IN COLORADO: OPERATION AND MAINTENANCE OF ON-SITE WASTEWATER TREATMENT SYSTEMS	Ward, R.	6/83	5.00
TR 10	EFFICIENCY OF WASTEWATER DISPOSAL IN MOUNTAIN AREAS	Walsh, Soper, Prato	1/78	6.00
TR 17	LAND TREATMENT OF MUNICIPAL SEWAGE EFFLUENT AT HAYDEN, COLORADO	Barbarick, Sabey, Evans	10/77	4.00

C. ECONOMIC IMPACTS

CR 10	ECONOMICS AND ADMINISTRATION OF WATER RESOURCES	Flack	6/69	3.50
CR 12	ECONOMICS AND ADMINISTRATION OF WATER RESOURCES	Nobe	6/69	4.00
CR 13	ECONOMICS OF GROUNDWATER DEVELOPMENT IN THE HIGH PLAINS OF COLORADO	Rohdy	6/69	2.50
CR 58	PRIMARY DATA ON ECONOMIC ACTIVITY AND WATER USE IN PROTO-TYPE OIL SHALE DEVELOPMENT AREAS OF COLORADO: AN INITIAL INQUIRY	Gray	6/74	3.00
CR 65	URBAN DRAINAGE AND FLOOD CONTROL PROJECTS: ECONOMIC, LEGAL AND FINANCIAL ASPECTS	Grigg, Tucker, Rice, Shoemaker	7/75	11.00
CR 70	AN ECONOMIC ANALYSIS OF WATER USE IN COLORADO'S ECONOMY	Gray	12/75	6.00
CR 75	PHYSICAL AND ECONOMIC EFFECTS ON THE LOCAL AGRICULTURAL ECONOMY OF WATER TRANSFER TO CITIES	Anderson, Wengert, Heil	10/76	4.00
CR 91	ECONOMIC BENEFITS FROM INSTREAM FLOW IN A COLORADO MOUNTAIN STREAM	Daubert, Young, Gray	6/79	6.00
CR 101	AN EMPIRICAL APPLICATION OF A MODEL FOR ESTIMATING THE RECREATION VALUE OF INSTREAM FLOW	Walsh, Erickson, Arosteguy, Hansen	10/80	4.00
CR 102	MEASURING BENEFITS AND THE ECONOMIC VALUE OF WATER IN RECREATION ON HIGH COUNTRY RESERVOIRS	Walsh, Aukerman, Milton	9/80	4.00
CR 118	ECONOMIC ASPECTS OF COST-SHARING ARRANGEMENTS FOR FEDERAL IRRIGATION PROJECTS: A CASE STUDY	Keleta, Young, Sparling	12/82	4.00
CR 122	ECONOMIC IMPACTS OF TRANSFERRING WATER FROM AGRICULTURE TO ALTERNATIVE USES IN COLORADO	Young	4/83	6.00
CR 126	INCREASING THE ECONOMIC EFFICIENCY AND AFFORDABILITY OF STORM DRAINAGE PROJECTS	Cochrane, Huszar	9/83	4.00
IS 2	ECONOMICS OF WATER QUALITY--SALINITY POLLUTION, Abridged Bibliography	Miller	6/71	12.00
IS 43	AN EVALUATION OF THE CACHE LA POUDRE WILD AND SCENIC RIVER DRAFT ENVIRONMENTAL IMPACT STATEMENT AND STUDY REPORT	Eubanks	8/80	6.00

Report No.	Title	Author	Date	Price
TR 14	ECONOMIC VALUE OF BENEFITS FROM RECREATION AT HIGH MOUNTAIN RESERVOIRS	Walsh, Aukerman, Rud	12/78	$ 4.00
TR 19	AN ECONOMIC EVALUATION OF THE GENERAL MANAGEMENT FOR YOSEMITE NATIONAL PARK	Walsh	3/80	5.00
TR 24	THE SURVEY-BASED INPUT-OUTPUT MODEL AS A RESOURCE PLANNING TOOL	McKean	1/81	4.00
TR 34	ENERGY AND WATER SCARCITY AND THE IRRIGATED AGRICULTURAL ECONOMY OF THE COLORADO HIGH PLAINS: DIRECT ECONOMIC-HYDROLOGIC IMPACT FORECASTS (1979-2020)	Young, Conklin, Longenbaugh, Gardner	2/82	8.00
TR 44	DIRECT AND INDIRECT ECONOMIC EFFECTS OF HUNTING AND FISHING IN COLORADO - 1981	McKean, Nobe	1/84	5.00
S-545S	SECONDARY ECONOMIC EFFECTS OF IRRIGATION ON THE COLORADO HIGH PLAINS		1971	.80

D. ECOSYSTEM ISSUES

Report No.	Title	Author	Date	Price
CR 5	SOIL MOVEMENT IN AN ALPINE AREA	Striffler	6/69	2.00
CR 69	ENGINEERING AND ECOLOGICAL EVALUATION OF ANTITRANSPIRANTS FOR INCREASING RUNOFF IN COLORADO WATERSHEDS	Kreith	9/75	3.50
CR 93	APPLICATION OF GEOMORPHIC PRINCIPLES TO ENVIRONMENTAL MANAGEMENT IN SEMIARID REGIONS	Schumm, Bradley, Begin	2/80	4.00
CR 98	THE EFFECT OF ALGAL INHIBITORS ON HIGHER PLANT TISSUES	Kugrens	7/80	3.50
CR 116	EFFECTS OF RELEASES OF SEDIMENT FROM RESERVOIRS ON STREAM BIOTA	Ward, J.V.	9/82	4.00
IS 7	WILDLIFE AND THE ENVIRONMENT, PROCEEDINGS OF THE GOVERNOR'S CONFERENCE, MARCH 1973 (Out of print--available through interlibrary loan)	Swanson	3/73	
IS 10	PROCEEDINGS, WORKSHOP ON REVEGETATION OF HIGH-ALTITUDE DISTURBED LANDS	Berg, Brown, Cuany	7/74	6.00
IS 11	SURFACE REHABILITATION OF LAND DISTURBANCES RESULTING FROM OIL SHALE DEVELOPMENT (Executive Summary)	Cook	6/74	Free
IS 14	BIBLIOGRAPHY PERTINENT TO DISTURBANCE AND REHABILITATION OF ALPINE AND SUBALPINE LANDS IN THE SOUTHERN ROCKY MOUNTAINS	Steen, Berg	2/75	4.00
IS 18	MINIMUM STREAM FLOWS AND LAKE LEVELS IN COLORADO	Rhinehart	8/75	9.00
IS 21	PROCEEDINGS, HIGH ALTITUDE REVEGETATION WORKSHOP NO. 2	Zuck, Brown	8/76	6.00
IS 28	PROCEEDINGS, HIGH ALTITUDE REVEGETATION WORKSHOP NO. 3	Kenny	6/78	6.00
IS 40	PROCEEDINGS OF THE WORKSHOP ON INSTREAM FLOW HABITAT CRITERIA	Smith	12/79	6.00
IS 42	PROCEEDINGS, HIGH ALTITUDE REVEGETATION WORKSHOP NO. 4	Jackson, Schuster	6/80	6.00
IS 48	PROCEEDINGS, HIGH ALTITUDE REVEGETATION WORKSHOP NO. 5	Cuany, Etra	12/82	6.00

D. ECOSYSTEM ISSUES (cont'd)

Report No.	Title	Author	Date	Price
TR 1	SURFACE REHABILITATION OF LAND DISTURBANCES RESULTING FROM OIL SHALE DEVELOPMENT	Cook	6/74	$11.00
TR 4	VEGETATIVE STABILIZATION OF SPENT OIL SHALE	Harbert, Berg	12/74	4.00
TR 5	REVEGETATION OF DISTURBED SURFACE SOILS IN VARIOUS VEGETATION ECOSYSTEMS OF THE PICEANCE BASIN	Sims, Redente	12/74	5.25
TR 39	SPORTSMEN EXPENDITURES FOR HUNTING AND FISHING IN COLORADO, 1981	McKean, Nobe	1/83	5.00
TR 44	DIRECT AND INDIRECT ECONOMIC EFFECTS OF HUNTING AND FISHING IN COLORADO - 1981	McKean, Nobe	1/84	5.00
SR 2	ENVIRONMENT AND COLORADO - A HANDBOOK		1973	5.00

E. SOCIAL-INSTITUTIONAL-POLICY

1. INSTITUTIONS

Report No.	Title	Author	Date	Price
CR 10	ECONOMICS AND ADMINISTRATION OF WATER RESOURCES	Flack	6/69	3.50
CR 12	ECONOMICS AND ADMINISTRATION OF WATER RESOURCES	Nobe	6/69	4.00
CR 36	URBAN-METROPOLITAN INSTITUTIONS FOR WATER PLANNING DEVELOPMENT AND MANAGEMENT: AN ANALYSIS OF USAGES OF THE TERM "INSTITUTIONS"	Wengert	9/72	6.00
CR 37	SEARCHING THE SOCIAL SCIENCE LITERATURE ON WATER: A GUIDE TO SELECTED INFORMATION STORAGE AND RETRIEVAL SYSTEMS - PRELIMINARY VERSION	Hogge, Wengert	9/72	6.00
CR 39	INSTITUTIONS FOR URBAN-METROPOLITAN WATER MANAGEMENT: ESSAYS IN SOCIAL THEORY	Wengert	11/72	6.00
CR 44	ECONOMIC, POLITICAL, AND LEGAL ASPECTS OF COLORADO WATER LAW	Radosevich, Nobe, Meek, Flack	2/73	6.00
CR 46	EVALUATION OF URBAN WATER MANAGEMENT POLICIES IN THE DENVER METROPOLITAN AREA	Walker, Ward, R. Skogerboe	6/73	8.50
CR 47	COORDINATION OF AGRICULTURAL AND URBAN WATER QUALITY MANAGEMENT IN THE UTAH LAKE DRAINAGE AREA	Walker, Huntzinger, Skogerboe	6/73	8.50
CR 48	INSTITUTIONAL REQUIREMENTS FOR OPTIMAL WATER QUALITY MANAGEMENT IN ARID URBAN AREAS	Walker, Skogerboe, Ward, R., Huntzinger	6/73	4.00
CR 52	CONSOLIDATION OF IRRIGATION SYSTEMS: PHASE I - ENGINEERING, LEGAL, AND SOCIOLOGICAL CONSTRAINTS AND/OR FACILITATORS	Skogerboe, Radosevich, Vlachos	6/73	25.00
CR 53	SYSTEMATIC DESIGN OF LEGAL REGULATIONS FOR OPTIMAL SURFACE-GROUNDWATER USAGE - PHASE I	Morel-Seytoux, Young, Radosevich	8/73	8.00
CR 55	WATER LAW IN RELATION TO ENVIRONMENTAL QUALITY	Allardice, Radosevich, Kobel, Swanson	3/74	30.00
CR 61	ECONOMIC AND INSTITUTIONAL ANALYSIS OF COLORADO WATER QUALITY MANAGEMENT	Young, Radosevich, Gray, Leathers	3/75	6.00
CR 65	URBAN DRAINAGE AND FLOOD CONTROL PROJECTS: ECONOMIC, LEGAL AND FINANCIAL ASPECTS	Grigg, Tucker, Rice, Shoemaker	7/75	11.00
CR 75	PHYSICAL AND ECONOMIC EFFECTS ON THE LOCAL AGRICULTURAL ECONOMY OF WATER TRANSFER TO CITIES	Anderson, Wengert, Heil	10/76	4.00
CR 85	DEVELOPMENT OF A DRAINAGE AND FLOOD CONTROL MANAGEMENT PROGRAM FOR URBANIZING COMMUNITIES - PART I	Riordan, Grigg, Hiller	9/78	3.00

Report No.	Title	Author	Date	Price
CR 86	DEVELOPMENT OF A DRAINAGE AND FLOOD CONTROL MANAGEMENT PROGRAM FOR URBANIZING COMMUNITIES - PART II	Riordan, Grigg, Hiller	9/78	$ 8.00
CR 88	INSTITUTIONAL ARRANGEMENTS FOR EFFECTIVE WATER MANAGEMENT IN COLORADO	Foss	11/78	5.00
CR 94	CONSOLIDATION OF IRRIGATION SYSTEMS: PHASE II, ENGINEERING, ECONOMIC, LEGAL AND SOCIOLOGICAL REQUIREMENTS	Vlachos, Huszar, Radosevich, Skogerboe	5/80	9.00
CR 118	ECONOMIC ASPECTS OF COST-SHARING ARRANGEMENTS FOR FEDERAL IRRIGATION PROJECTS: A CASE STUDY	Keleta, Young, Sparling	12/82	4.00
CR 124	EFFECTS OF WILDERNESS LEGISLATION ON WATER-PROJECT DEVELOPMENT IN COLORADO	Weaver	5/83	8.00
IS 6	WATER LAW AND ITS RELATIONSHIP TO ENVIRONMENTAL QUALITY: A BIBLIOGRAPHY OF SOURCE MATERIAL	Radosevich, Allardice, Swanson, Koebel	1/73	8.00
IS 12	WATER QUALITY CONTROL AND ADMINISTRATION LAWS AND REGULATIONS	Radosevich, Allen	1974	16.00
IS 15	PROCEEDINGS OF THE SYMPOSIUM ON WATER POLICIES ON U.S. IRRIGATED AGRICULTURE: ARE INCREASED ACREAGES NEEDED TO MEET DOMESTIC OR WORLD NEEDS?	Koelzer	3/75	5.00
IS 18	MINIMUM STREAM FLOWS AND LAKE LEVELS IN COLORADO	Rhinehart	8/75	9.00
IS 29	PROCEEDINGS, THIRD WORKSHOP ON HOME SEWAGE DISPOSAL IN COLORADO - COMMUNITY MANAGEMENT	Ward, R.	7/78	5.00
IS 34	SAN LUIS VALLEY WATER PROBLEMS: A LEGAL PERSPECTIVE	Radosevich, Rutz	1/79	5.00
IS 35	FEDERAL WATER STORAGE PROJECTS: PLUSES AND MINUSES	Howe	6/79	Free
IS 39	ADMINISTRATION OF THE SMALL WATERSHED PROGRAM, 1955-1978, AN ANALYSIS	Fontenot	8/79	4.00
IS 45	PROCEEDINGS, FOURTH WORKSHOP ON HOME SEWAGE DISPOSAL IN COLORADO - STATE/COUNTY COOPERATION IN MANAGING SMALL WASTEWATER FLOWS	Ward, R.	8/81	5.00
IS 46	THE DECLINING ROLE OF THE U.S. ARMY CORPS OF ENGINEERS IN THE DEVELOPMENT OF THE NATION'S WATER RESOURCES	Yoe	8/81	8.00
IS 49	PROCEEDINGS, FIFTH WORKSHOP ON HOME SEWAGE DISPOSAL IN COLORADO - OPERATION AND MAINTENANCE OF ON-SITE WASTEWATER TREATMENT SYSTEMS	Ward, R.	6/83	5.00
TR 3	IMPLEMENTATION OF THE FEDERAL WATER PROJECT RECREATION ACT IN COLORADO	Spence	6/74	Free
TR 9	THE 1972 FEDERAL WATER POLLUTION CONTROL ACT'S AREA-WIDE PLANNING PROVISION: HAS EXECUTIVE IMPLEMENTATION MET CONGRESSIONAL INTENT?	Stark	11/77	6.00
TR 11	FEDERAL WATER RECREATION IN COLORADO: COMPREHENSIVE VIEW AND ANALYSIS	Stefanec	5/78	6.00
TR 31	COMMUNITY AND SOCIO-ECONOMIC ANALYSIS OF COLORADO'S HIGH PLAINS REGION	Burns	2/82	8.00
TR 38	GROUNDWATER QUALITY REGULATION IN COLORADO	Looft	12/82	5.00

2. PROCESSES

Report No.	Title	Author	Date	Price
CR 11	ORGANIZATIONAL ADAPTATION TO CHANGE IN PUBLIC OBJECTIVES FOR WATER MANAGEMENT OF CACHE LA POUDRE RIVER SYSTEM	Hill, Foss, Meek	6/69	$ 4.00
CR 17	AN EXPLORATION OF COMPONENTS AFFECTING AND LIMITING POLICYMAKING OPTIONS IN LOCAL WATER AGENCIES	Hill, Garrison, Foss	11/68	6.00
CR 22	AN EXPLORATION OF COMPONENTS AFFECTING AND LIMITING POLICYMAKING OPTIONS IN LOCAL WATER AGENCIES	Hill, Meek	6/70	4.00
CR 27	LOCAL WATER AGENCIES, COMMUNICATION PATTERNS, AND THE PLANNING PROCESS	Hill, Meek	9/71	6.00
CR 38	WATER QUALITY MANAGEMENT DECISIONS IN COLORADO	Nichols, Skogerboe, Ward, R.	6/72	6.00
CR 52	CONSOLIDATION OF IRRIGATION SYSTEMS: PHASE I - ENGINEERING, LEGAL, AND SOCIOLOGICAL CONSTRAINTS AND/OR FACILITATORS	Skogerboe, Radosevich, Vlachos	6/73	25.00
CR 65	URBAN DRAINAGE AND FLOOD CONTROL PROJECTS: ECONOMIC, LEGAL AND FINANCIAL ASPECTS	Grigg, Tucker, Rice, Shoemaker	7/75	11.00
CR 74	THE RELEVANCE OF TECHNOLOGICAL CHANGE IN LONG-TERM WATER RESOURCES PLANNING	Kraynick, Howe	10/76	4.50
CR 81	ACHIEVING URBAN WATER CONSERVATION: TESTING COMMUNITY ACCEPTANCE	Snodgrass, Hill	9/77	6.00
CR 94	CONSOLIDATION OF IRRIGATION SYSTEMS: PHASE II - ENGINEERING, LEGAL, AND SOCIOLOGICAL REQUIREMENTS	Vlachos, Huszar, Radosevich, Skogerboe	5/80	9.00
CR 95	DROUGHT-INDUCED PROBLEMS AND RESPONSES OF SMALL TOWNS AND RURAL WATER ENTITIES IN COLORADO: THE 1976-78 DROUGHT	Howe	6/80	5.00
CR 119	ECONOMIC ISSUES IN RESOLVING CONFLICTS IN WATER USE	Gray, Young	2/83	4.00

IS 22	IMPLEMENTATION OF THE NATIONAL FLOOD INSURANCE PROGRAM IN LARIMER COUNTY, COLORADO	Landenberger, Whittington	9/76	5.00
IS 24	FACTORS AFFECTING PUBLIC ACCEPTANCE OF FLOOD INSURANCE IN LARIMER AND WELD COUNTIES, COLORADO	James, Kreger, Barrineau	9/77	4.00
IS 27	PROCEEDINGS, COLORADO DROUGHT WORKSHOPS		11/77	Free
IS 38	PUBLIC PARTICIPATION PRACTICES OF THE U.S. ARMY CORPS OF ENGINEERS	Crist, Lanier	7/79	4.00
IS 44	THE NATIONAL FLOOD INSURANCE PROGRAM IN THE LARIMER COUNTY, COLORADO AREA	Shoudy	8/80	4.00
IS 47	SECTION 404 OF THE CLEAN WATER ACT - AN EVALUATION OF THE ISSUES AND PERMIT PROGRAM IMPLEMENTATION IN WESTERN COLORADO	Barnett	8/82	6.00

F. WATER CONVEYANCE AND CONTROL WORKS

CR 6	STABILIZATION OF ALLUVIAL CHANNELS	Bhowmik, Simons	6/69	4.00
CR 7	STABILITY OF SLOPES WITH SEEPAGE	Muir, Simons	6/69	4.00
CR 111	INVESTIGATION OF OBJECTIVE FUNCTIONS AND OPERATION RULES FOR STORAGE RESERVOIRS	Yevjevich, Hall, Salas	9/81	4.00

IS 50	POSSIBLE CAPTURE OF THE MISSISSIPPI BY THE ATCHAFALAYA RIVER	Higby	8/83	5.00

SR [illegible]	DESIGN OF WATER AND WASTEWATER SYSTEMS FOR RAPID GROWTH AREAS [illegible] MOUNTAIN RESORTS)	Flack	7/76	5.00

Report No.	Title	Author	Date	Price
S-496S	FARM IRRIGATION STRUCTURES		1966	$ .50
S-522S	WEED SEED AND TRASH SCREENS FOR IRRIGATION WATER		1966	.35
S-TB61	PARSHALL MEASURING FLUMES OF SMALL SIZES		1957	.25
S-TB120	SELECTION AND INSTALLATION OF CUTTHROAT FLUMES FOR MEASURING IRRIGATION AND DRAINAGE WATER		1976	3.50
S-TB126	A SHUNT-LINE METERING SYSTEM FOR IRRIGATION WELLS		1977	.75
X-426A	PARSHALL FLUMES OF LARGE SIZE		1961	.50

G. WATER DATA, PROJECTIONS, GENERAL INFORMATION

Report No.	Title	Author	Date	Price
CR 37	SEARCHING THE SOCIAL SCIENCE LITERATURE ON WATER: A GUIDE TO SELECTED INFORMATION STORAGE AND RETRIEVAL SYSTEMS - PRELIMINARY VERSION	Hogge, Wengert	9/72	6.00
CR 46	EVALUATION OF URBAN WATER MANAGEMENT POLICIES IN THE DENVER METROPOLITAN AREA	Walker, Ward, R., Skogerboe	6/73	8.50
CR 60	RESEARCH NEEDS AS RELATED TO THE DEVELOPMENT OF SEDIMENT STANDARDS IN RIVERS	Gessler	3/75	4.00
CR 63	ANALYSIS OF COLORADO PRECIPITATION	Kuo., Cox	6/75	3.00
CR 100	A WATERSHED INFORMATION SYSTEM	Thomsen, Striffler	9/80	5.00
CR 113	A WATER HANDBOOK FOR METAL MINING OPERATIONS	Wildeman	11/81	6.00
IS 1	AN INVENTORY OF ENVIRONMENTAL RESOURCES RESEARCH IN PROGRESS		1/71	Free
IS 2	ECONOMICS OF WATER QUALITY - SALINITY POLLUTION, Abridged Bibliography	Miller	6/71	11.00
IS 3	AN INVENTORY OF ENVIRONMENTAL RESOURCES RESEARCH IN PROGRESS		7/72	Free
IS 5	DIRECTORY OF ENVIRONMENTAL RESEARCH FACULTY, CSU		12/72	Free
IS 8	INVENTORY OF CURRENT WATER RESOURCES RESEARCH AT CSU		7/73	Free
IS 23	INVENTORY OF COLORADO'S FRONT RANGE MOUNTAIN RESERVOIRS	Aukerman, Springer, Judge	5/77	6.00
IS 25	SURVEILLANCE DATA, PLAINS SEGMENT OF THE CACHE LA POUDRE RIVER, COLORADO	Morrison	1/78	6.00
IS 30	THE LARIMER-WELD COUNCIL OF GOVERNMENTS 208 WATER QUALITY PLAN: AN ASSESSMENT AND SUGGESTIONS FOR FUTURE DIRECTIONS	Bryniarski, Carter, Danley, Gurule	8/78	3.00
IS 31	THE DENVER BASIN: ITS BEDROCK AQUIFERS	Bittinger	1/79	Free
IS 34	SAN LUIS VALLEY WATER PROBLEMS: A LEGAL PERSPECTIVE	Radosevich, Rutz	1/79	5.00
IS 35	FEDERAL WATER STORAGE PROJECTS: PLUSES AND MINUSES	Howe	6/79	Free
IS 36	THE DECLINING ROLE OF THE U.S. ARMY CORPS OF ENGINEERS IN THE DEVELOPMENT OF THE NATION'S WATER RESOURCES	Yoe	8/81	8.00
IS 50	POSSIBLE CAPTURE OF THE MISSISSIPPI BY THE ATCHAFALAYA RIVER	Higby	8/83	5.00
TR 2	ESTIMATED AVERAGE ANNUAL WATER BALANCE FOR PICEANCE AND YELLOW CREEK WATERSHEDS	Wymore	8/74	Free
TR 6	COLORADO ENVIRONMENTAL DATA SYSTEMS (Abridged)	Whaley, Dyer	10/72	6.00
TR 12	RECREATION BENEFITS OF WATER QUALITY: ROCKY MOUNTAIN NATIONAL PARK, SOUTH PLATTE RIVER BASIN, COLORADO	Walsh, Ericson, McKean, Young	5/78	5.00
TR 21	THE ECONOMY OF ALBANY, CARBON, AND SWEETWATER COUNTIES, WYOMING - DESCRIPTION AND ANALYSIS	McKean, Weber	1/81	4.00
R 22	AN INPUT-OUTPUT STUDY OF THE UPPER COLORADO MAIN STEM REGION OF WESTERN COLORADO	McKean, Weber	1/81	5.00

Report No.	Title	Author	Date	Price
TR 26	AN INPUT-OUTPUT ANALYSIS OF SPORTSMAN EXPENDITURES IN COLORADO	McKean	1/81	$ 5.00
TR 27	AN INPUT-OUTPUT STUDY OF THE KREMMLING REGION OF WESTERN COLORADO	McKean, Weber	3/81	4.00
TR 29	AN ECONOMIC INPUT-OUTPUT STUDY OF THE HIGH PLAINS REGION OF EASTERN COLORADO	McKean, Ericson, Weber	2/82	5.00
TR 30	ENERGY PRODUCTION AND USE IN COLORADO'S HIGH PLAINS REGION	McBroom	2/82	8.00
TR 31	COMMUNITY AND SOCIO-ECONOMIC ANALYSIS OF COLORADO'S HIGH PLAINS REGION	Burns	2/82	8.00
TR 34	ENERGY AND WATER SCARCITY AND THE IRRIGATED AGRICULTURAL ECONOMY OF THE COLORADO HIGH PLAINS: DIRECT ECONOMIC-HYDROLOGIC IMPACT FORECASTS (1979-2020)	Young, Conklin, Longenbaugh, Gardner	2/82	8.00
TR 35	THE ECONOMIES OF MESA COUNTY AND GARFIELD, MOFFAT, RIO BLANCO, AND ROUTT COUNTIES, COLORADO	McKean, Weber, Ericson	4/81	5.00
TR 36	THE ECONOMY OF THE POWDER RIVER BASIN REGION OF EASTERN WYOMING: DESCRIPTION AND ANALYSIS	McKean, Weber, Ericson	1/81	4.00
TR 37	AN INTERINDUSTRY ANALYSIS OF THREE FRONT RANGE FOOTHILLS COMMUNITIES: ESTES PARK, GILPIN COUNTY, AND WOODLAND PARK, COLORADO	McKean, Trock, Senf	7/82	6.00
TR 39	SPORTSMEN EXPENDITURES FOR HUNTING AND FISHING IN COLORADO, 1981	McKean, Nobe	1/83	5.00
TR 40	THE ECONOMY OF LINCOLN, SUBLETTE, SWEETWATER AND UINTA COUNTIES, WYOMING, ROCK SPRINGS BLM DISTRICT	McKean, Weber	5/83	5.00
TR 41	THE ECONOMY OF ALBANY, CARBON AND FREMONT COUNTIES, WYOMING, RAWLINS BLM DISTRICT	McKean, Weber	5/83	5.00
TR 42	THE ECONOMY OF BIG HORN, HOT SPRINGS, PARK, AND WASHAKIE COUNTIES, WYOMING, WORLAND BLM DISTRICT	McKean, Weber	5/83	5.00
TR 43	THE ECONOMY OF EASTERN WYOMING, CASPER BLM DISTRICT	McKean, Weber	5/83	5.00
SR 1	DESIGN OF WATER AND WASTEWATER SYSTEMS FOR RAPID GROWTH AREAS (BOOM TOWNS, MOUNTAIN RESORTS)	Flack	7/76	5.00
SR 3	IRRIGATION DEVELOPMENT POTENTIAL IN COLORADO	Whittlesey		5.00
SR 4	PICEANCE BASIN INVENTORY		12/71	11.00
SR 5	A GUIDE TO COLORADO WATER LAW	Fischer, Ray, Rask, Wyatt	9/78	3.50
S-GS870	CHEMICAL QUALITY OF GROUNDWATER IN THE PROSPECT VALLEY AREA, COLORADO		1968	.25
S-GS953	ECONOMIC ANALYSIS OF WATER USE IN BOULDER, LARIMER AND WELD COUNTIES, WITH PROJECTIONS TO 1980		1976	1.00
S-GS757	PUBLIC WATER SUPPLIES OF COLORADO 1959-1960		1961	1.25
S-504S	COLORADO'S GROUNDWATER PROBLEMS		1967	.35
S-512S	GROUNDWATER IN THE BIJOU VALLEY		1961	.25
S-543S	PUMP IRRIGATION ON THE COLORADO HIGH PLAINS		1970	.65
X-470A	GROUNDWATER MANAGEMENT DISTRICT DIRECTOR'S HANDBOOK		1970	.25