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A SYSTEMATIC EXAMINATION OF ISSUES IN CONJUNCTIVE USE OF GROUND AND SURFACE WATERS

Stephen J. Burges
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Water Resources Series
Technical Report No. 44
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A SYSTEMATIC EXAMINATION OF ISSUES IN CONJUNCTIVE USE OF GROUND AND SURFACE WATERS

by

Stephen J. Burges and Reza Maknoon

Technical Report No. 44

September 1975

Project Completion Report: "Conjunctive Use of Ground and Surface Water"

Project Period: January 1, 1975 - September 30, 1975

Principal Investigator: Stephen J. Burges, Associate Professor of Civil Engineering, University of Washington

DOE Project Number: W-25

Allocation Number: 145-02-13A-3998-3026
(State of Washington Water Research Center)

Abstract

General characteristics of conjunctive ground-surface water use systems were examined in an attempt to develop a systematic procedure for examining such systems. Various types of conjunctive use problems were identified; weaknesses in existing approaches to problem solutions are principally caused by mismatched sophistication in representations of physical, legal and economic components of the problem. An extensive literature search yielded some thirteen articles representative of different conjunctive use problems and solution approaches. All approaches reviewed assume that the implementation of an optimal policy will be via a central agency. The limitations of this assumption are examined herein. In all conjunctive use analyses available to the authors limitations on data availability (and problems created by the dimensionality of the optimizing approaches taken) limited the utility of the analyses. It seems probable that low cost analyses of conjunctive use systems can only be used when considerable management latitude is available. Given the mismatch in modeling capabilities between physical and economic sectors and decoupling problems it is unlikely that enormous expenditures on extremely sophisticated modeling efforts will yield vastly improved management practices beyond those obtainable through moderate cost analyses.

Keywords: Groundwater Management, Systems Analysis, Optimization, Modeling, Water Resources Management.

ACKNOWLEDGEMENTS

The work upon which this report is based was supported by funds provided by the State of Washington Department of Ecology through the State of Washington Water Research Center. Helpful comments and advice were given by R. T. Milhous (Department of Ecology, Project Officer) during the project life. Constructive criticisms of an earlier draft by Dr. Jerry Ongerth, Washington State University, were most helpful. Discussions with R. A. Longenbaugh (Colorado State University) and T. A. Maddock III (USGS, National Center, Reston, VA) were beneficial to the authors. The manuscript was typed by Mrs. Yunja Yu.

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CHAPTER 1

INTRODUCTION

Whenever multiple sources of water with different characteristics, as is the case with ground water and surface water systems, are available, it may be possible to develop an operating strategy which exploits the different characteristics of the sources. This exploitive strategy has become known as the conjunctive management of ground water and surface water or "conjunctive use". The concept of conjunctive use of ground-surface water has been extended to the planning stage of water resources facilities where surface reservoirs are planned to be used conjunctively with nearby ground water aquifers.

Characteristics of surface water sources are generally well known. Surface waters are available seasonally with some degree of uncertainty with respect to time. It is possible to determine the size of surface storage facilities necessary to regulate supply for the desired output characteristics given the irregular inflow from the natural sources. A surface system is also characterized by floods which may not always be conveniently captured by the storage facility. Recreational potential of artificial lakes formed by storage reservoirs is a convenient byproduct of surface water management. Surface storages can be filled extremely rapidly depending upon inflow characteristics, but they are subject to losses due to evaporation and possible seepage. In contrast to stored surface water, ground water is generally available in large aquifers in large quantities and is available throughout the year. Compared with surface stream flows less uncertainly is involved in ground water availability.

It has been recognized by many authors that ultimately, optimum water development can only be obtained by conjunctive utilization of ground water and surface water, particularly as demand or use levels increase towards the mean available quantity.

The importance of the conjunctive use of ground waters and surface waters is well established in the literature (e.g. Banks, 1953; Chun, et al., 1964; Hall and Dracup, 1970; Morel-Seytoux, et al., 1973). While a considerable body of literature concerning conjunctive use of ground-surface water systems exists, much of it is analytical and area specific. Consequently, many of the significant papers in the field deal with mathematically tractable constraints and do not necessarily cover the set of problems faced by most regulatory or management agencies. Usually physical or direct constraints have been examined.

An overall "system analysis" of the conjunctive use of a ground-surface water system would be an essential step in understanding relevant problems and recognizing the important elements of the system. A review of representative literature is presented; for each article a brief summary, followed by its contributions and short-comings (from a systems viewpoint), is included. Other salient literature examined is listed in the bibliography.

The objective of this work is to systematically analyze major features of conjunctive use systems. The report includes a general description of conjunctive ground-surface water problems and relevant constraints that influence conjunctive use management. A general analysis approach for conjunctive use of ground-surface water systems is given. The general approach includes consideration of physical factors as well as social, legal, and economic aspects of conjunctive use systems which should be included in analyses of most categories of stream aquifer systems that could be conjunctively operated and managed.

CHAPTER 2

GENERAL DESCRIPTION OF CONJUNCTIVE GROUND-SURFACE WATER PROBLEMS

2.1 Introduction

It is convenient when examining conjunctive ground-surface water management problems to view the problem area under consideration via some systematic approach. Here we have found it convenient and instructive to separate issues of problem identification from those of problem analysis, decision making analysis, and implementation of planned policies. The material that follows is a summary of various elements involved in the conjunctive use of a ground-surface water system. These elements include: the nature (category) of the conjunctive use problem; scale of the problem; parameters and variables of interest; system management objective(s); detailed system modeling; consideration of analysis time scales; identification of principal interactions; implementation of optimal system policy; and, social aspects of the analysis.

2.2 Category of the Conjunctive Use Problem

Six principal physical problems have been identified which require careful management to overcome. These problems may occur singularly or in some combination in a specific instance. These problems are:

a) Ground Water Mining

This problem is encountered mostly in arid and semiarid areas. Mining results when recharge of ground water is less than withdrawal from the same system over a period of time. The consequences of the problem are higher pumping costs, possible shortage of water during future drought periods, and ultimately, depletion of the aquifer. Whenever surface water is available in an area conjunctive operation of surface water and ground water sources may reduce the impacts of the mining problem. Safe yield (or other measures of the long-term steady-state) is the rate at which water may be extracted without mining. There is, however, water in excess of this amount which may be "mined" (for brief periods) economically. Operation under a traditional safe yield approach might incur large opportunity costs because the water resources cannot be put to optimal or near optimal use. A conjunctive management analysis would illuminate the magnitudes of these costs (and inefficient resource use). Change from the traditional safe yield management strategy to more efficient resource use would be subject to social acceptance.

b) Salt Water Intrusion into an Aquifer[a]

Salt water intrusion is the shoreward movement of water from the sea or ocean into confined or unconfined aquifers (usually coastal) and the subsequent displacement of fresh water from these aquifers. This is the usual problem in coastal areas or in areas adjacent to salt water bodies where mismanagement of aquifer development can result in salt water intrusion to the aquifer. A conjunctive operation of ground water and surface water can mitigate the extent of intrusion. Optimal management in such situations might result from withdrawal and recharging regulations with respect to time and space for ground water and a temporal regulation for surface water allocation.

c) Low Flow Maintenance in a Stream Connected to an Aquifer

In a connected aquifer-surface water system, ground water withdrawal can influence the surface water quantity. A large withdrawal of ground water usually reduces the streamflow; flow time delay effects

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[a]For convenience we define an aquifer to be a body from which ground water can be extracted or recharged in economically useful quantities.

are important. This withdrawal usually occurs at the time where the small amount of surface water flow is of concern (dry periods). The consequences of such operation reduce the quantity of surface water and as a result may violate low flow criteria of the stream and/or jeopardize the rights of the surface water users downstream of the withdrawal area (prior right system). Conjunctive management of a surface water-ground water system will help in reducing the impacts of groundwater withdrawal upon stream-flow quantity and quality. Management would specify spatial and temporal schedules for groundwater withdrawal and surface water diversion.

d) Inter Aquifer Water Transfer

In some cases the diversion of surface water from a river system may result in shifting water from one aquifer to another aquifer system. The result is usually a continuous decrease in one aquifer storage (and/or water level) and increase in the storage of the other aquifer or nearby surface water system. Obviously optimal surface water transfer must be studied in conjunction with ground water movement.

e) Adverse Ground Water Quality (surface or surface/ground water supply)

Maintaining recommended standards for water quality for various purposes may require water treatment. As a means to reduce the cost of treatment facilities conjunctive utilization of surface water and ground water might be helpful. Conjunctive management, however, may be undertaken for both quality and quantity purposes.

f) Aquifer Recharge Using Treated Wastewater

Under special circumstances and subject to operational constraints and ultimate use of this water, the practice of recharging an aquifer using treated wastewater has been shown to be worthwhile (Parker, 1961; Fetter and Holzmacher, 1974; Brown, et al., 1974). The operation is useful in increasing fresh water storage, in developing a barrier against salt water intrusion, and as a method of receiving wastewater effluent. For each of these three applications conjunctive analysis of surface-ground water-treated wastewater interactions is necessary to understand the total system as well as for establishing new operational policy for future ground water extraction.

2.3 Scale or Level of the Problem under Examination

It is important to determine the hierarchy of an apparent management problem within a total water management structure. Thus the problem might necessitate examination at one or more of the system hierarchical boundaries. The level of the problem under examinations may include international, national, interstate—regional or major river basin, state, intrastate--river basin, county, and local boundaries and jurisdictions.

The level of the problem influences modeling of the system and also implementation of the optimal policy.

2.4 Parameters and Variables Involved in Studying and Managing Conjunctive Use Systems

Basically four categories of parameters and variables, viz., physical, legal (i.e. cumulative social and economic historical preference), economic, and general constraints, must be included in any conjunctive use issue. Availability of water in space and time for one reason or another obviously is a major system constraint. The variables of interest to any class of problem are given below.

2.4.1. Physical Variables

The characteristics and variation of surface water and ground water flow are important factors in a conjunctive use operation. The level[a] of data required for analysis depends on the objective(s) of the analysis and the purpose(s) of model building. If physical data are to be useful in system modeling, they must be compatible with the level of data of other parameters and variables (e.g. legal and economic).

a) Surface Water

The dominant sources of surface water are streams, reservoirs, lakes, springs, and snow packs. Availability of quantities of water from these sources in space and time is an important factor in design and/or allocation problems. These variables are used in models of complex conjunctive use systems. The stochastic nature of these variables (especially stream flow) is important in allocation problems; this characteristic should be explicitly considered in model building as well as in system operation. Three major areas of concern in use of surface water are: availability (stochastic nature), quality, and losses (evaporation opportunities).

b) Ground Water/Aquifer System

Aquifer capacity and characteristics are important elements in analyzing ground water flow where recharging systems of the aquifer are treated as an input to the ground water system. As a result temporal and spatial variation in the recharging system outputs are significant elements. Other factors such as water losses from the aquifer and the quality of ground water are important in various

[a]The "level" of required data refers to amount, type and space-time resolution.

cases. Four principal features of ground water/aquifer systems are listed below.

i) Type and characteristics of aquifer(s) in the system
The characteristics of an aquifer include storage capacity and hydraulic properties.

ii) Mechanisms for losses from aquifer
These mechanisms include: transfer of ground water to adjacent aquifers or streams, pumping, and evapotranspiration.

iii) Aquifer recharge mechanisms
Recharge mechanisms may involve precipitation (local and distant); seepage through streambeds, irrigation, and irrigation return flow; transfer of ground water either from another aquifer (horizontally or vertically) or through artificial recharge practice.

iv) Quality of ground water

2.4.2. Legal Constraints (Temporal Variability)

Legal constraints and variables consist of current laws and regulations governing the flow of water throughout the system. The variables of concern are related to surface water and ground water laws as well as administrative interpretations thereof. These variables are usually treated as constraints in a general conjunctive use model. Generally a conjunctive use problem can be examined under current laws, under anticipated laws, or from the point of view that major changes in the law might be made. Sensitivity analyses of the conjunctive system will clearly show the importance of any of these constraints and regulations. For a given situation it might be possible to employ a model to define the optimum forms and levels of legal and regulatory constraints on the conjunctive ground-surface water use system.

The important laws and regulations governing surface water and ground water flow are usually separated into surface water and ground water categories and the interactions are not explicitly recognized. Specific laws are usually in force for the following aspects of surface water and ground water use.

a) Surface water

i) Low flow requirements (spatial and temporal variation)

ii) Interbasin surface water transfer (diversion "rights")

iii) Operation of reservoirs

iv) Navigation requirements

v) Allocation rights of users/diverters (intrabasin)

b) Ground water

i) Interaquifer water transfers

ii) Allocation rights of users

iii) Quality of recharge waters

iv) Land subsidence

2.4.3. Economic and Financial Variables

In any design or allocation problem economic aspects of the system have a great impact on the objective(s) of modeling and analysis activities. In conjunctive use problems, models are usually developed to allocate scarce water resources in an economically efficient way. The measure of effectiveness is usually taken to be the maximum return on the economic activities or satisfying a specific spatial or temporal set of demands at minimum cost.

Economic variables such as water demand and product return may be determined in advance and later used as parameters, or they might be considered as variables where their respective levels would be determined in a dynamic analysis. Four principal economic variables and constraints are briefly discussed.

a) Demand for Water

Demand for water can be categorized as consumptive and non consumptive uses. Spatial and temporal variation of demand is usually important in design and allocation problems. When demand variability is substantial, the variation must be considered through a probabilistic or stochastic approach. The demand vector for water use includes, agriculture, industry, municipal, hydroelectric, recreation, and water borne commerce.

b) Return on Economic Activities

There are two major situations where the "return on economic activities" is helpful in decision making. The first involves identifying which competitive users of water give rise to the maximum overall economic return for the area. The second situation involves allocation of water under shortage situations to those users where the return on economic activities is a function of both total amount and temporal distribution of supplied water, e.g. the output from irrigation land is a function of seasonally supplied water. In both cases a set of relationships can be developed for water supply-economic interactions. This necessitates identification of "direct" and "indirect" (or secondary) benefits. While separation of benefits into categories is controversial, value added by an economic activity can usually be estimated, at least for quasi static situations, from input-output analyses (Leontief, 1970).

c) Cost Functions (for technological activities)

The cost of transfering water from supply sources to demand sites (places of use) has to be determined. Transfers are effected through direct surface water diversion or through ground water pumping. These two types of transfer costs are briefly covered below.

i) Surface water transfer

Surface water transfer costs result from transporting water through canals or pipes. The capital cost of a transport element is usually a nonlinear function of flow rate, topography, geology, and distance. Operation costs are a function of head differences, flow rate, and distance; in some cases the operation cost can be assumed to be a linear function of the variables involved.

ii) Ground water transfer

The major capital costs associated with ground water development result from establishing and developing wells. Ground water transfer costs mainly result from pumping water from the aquifer. The cost of extracting groundwater is a function of the volume of extracted water, extraction rate, and the pumping head.

d) Project Financing (financial feasibility)

The authorities involved with planning will impose some restrictions and regulations, reflecting financial capability which constrain the economic activities and development in the area. These constraints must be realized in the planning stage and be treated as a part of the whole conjunctive use system.

2.5 General Constraints

Issues concerning physical, legal, and economic constraints and variables in conjunctive use problems were discussed in section 2.4. However, in a general conjunctive use system analysis, other factors, for instance data availability, time, and personnel available for analysis, etc., influence modeling and analysis of the conjunctive use system. Some of these constraints are important in the planning and analysis stage, while others are important at the implementation stage. Implementation constraints must be identified at the planning stage. The importance of availability of data, skilled personnel, and time as system constraints must not be overlooked.

a) Data Availability

A factor which usually dictates the level of analysis (i.e. the hierarchical scale at which the problem can be analyzed) is the available data for the particular problem. Complex conjunctive use problems necessitate use of a large variety of data. While many of the data may be available, different types, e.g. water levels, flow, economic measures, etc., may be in incompatible forms particularly with regard to space-time increments and scales. Nevertheless, available data sources should be utilized whenever possible to supplement well-thought-out acquisition of new data. In conjunctive problems, legal, physical, and economic data are required for analysis. In a well balanced total system model the resolutions of the various data must be comparable. In general, since the overall objective for managing a conjunctive use system is the optimal development of water and related land (in the context of multiple objectives) data collection should strongly emphasize those elements which affect water development and use both in economic and physical terms. It should additionally be recognized that the level and type of data required for management and operation of the system may differ from those data used in analysis of the system. Availability and/or convenience of obtaining these data became important factors in implementing operation policy.

For any optimal policy the level of data needed to implement the result must be determined and evaluated against the cost of obtaining, maintaining, and using such information.

b) Personnel

Number of, and skills of the personnel involved in both studying and implementing the optimal policy is a constraint which must be recognized and evaluated.

c) Time

Time is a factor which might be important in studying and implementing an optimal policy. Both physical system and management response times should be carefully determined to ensure appropriate constraints are used when seeking optimal management strategies.

2.6 System Management Objectives

Conjunctive use management objectives include identification of current problems as well as projection of future problems. A further objective involves determination of optimal or at least "satisficing"[a] solutions to the problems identified at different time horizons. Generally while there must be an economical justification for a specific policy, other factors such as equity among users, water quality conditions or some other social values will influence the solution to a given problem. As a result, most problems belong to the multiobjective domain. Major objective statements include (from highly specific to poorly defined):

a) Minimize total water cost to satisfy a set of demands

b) Maximize the total net benefits generated by economic activities that use the ground-surface water system.

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[a]The word satisfice was introduced by H. A. Simon (see H. A. Simon, Models of Man, John Wiley, New York, 1957) to represent "good" solutions to multiple value issues.

c) Maintain "acceptable" water quality

d) Achieve equity among water users

e) Enhancement of social well being

2.7 Issues in Detailed System Modeling

Only significant elements of the system need to be modeled. The system will need, however, to be modeled for different points in time. This means that different issues at different times (over a scale of 5 or 10 year increments of time) will require examination. Any modeling of the system is governed by the question(s) that need to be answered. Generally two types of models need to be considered.

a) Learning Models

A learning (or descriptive) model is constructed to describe some process or system processes in sufficient detail to yield information about actual system responses to various forcing functions (deLucia, et al., 1971). A detailed finite difference ground water quality model, for example, is of this type. Such models are best suited for exploring ranges of system responses and for determining model data needs and structural refinements or simplifications. These models are usually not suitable for operational decision making purposes.

b) Decision Making Models

A decision making (or prescriptive) model, is one intended for planning use because the prescriptive function of the model is aimed at deciding what should be done with the system to achieve the given objective(s). Since a prescriptive model provides only a means of testing possible designs and decisions it may not be necessary to model the actual fine scale interactions of the modeled system. Models can hardly be used, however, to prescribe if they are not also descriptive or else linked to complementary descriptive techniques. The descriptive function of the model is that of describing, to the degree of precision necessary, the way the system works. Types of conjunctive use problems for which different prescriptive models are used include:

i) System Design

The function of conjunctive use system engineering is to make available (in time, space, and quality) water resources of given properties. The question of determining the optimal dimensions of the various components of a conjunctive use system (i.e. surface water storage, well capacity, underground storage, etc.) has to be answered in the general context of comprehensive water resources planning. The question of what level of development should be chosen might be included in the system design phase. Mathematical models frequently presented and used for optimization of conjunctive use systems include simulation, and combinations of simulation, dynamic programming, and mathematical programming.

ii) Allocation Problem

In an existing ground-surface water situation, the allocation of water from various sources (stream, reservoir, ground water aquifer, etc.) to different users in an economical efficient way is a major objective of water resources planning. The allocation of water should be in space and time. Historically, mathematical programming, and dynamic programming models have been extensively used.

iii) Operational Policy

The optimal development of water resources is conditional on the establishment of an appropriate operating policy (Buras, 1972). In a conjunctive use situation, when no specific operational policy is in effect, operations research techniques might be employed to determine the optimal operational policy which yields more efficient use of available resources. The operating policy in a conjunctive use situation is usually a time schedule of release from reservoir(s), withdrawal from stream(s), pumpage from aquifers and/or reservoirs, and aquifer recharge operations. In cases where economic activity is a function of supplied water (e.g. agricultural yield is a function of supplied water over time) caution must be exercised in evaluating benefits and, particularly, uncertainty in economic returns. Operating procedures can be determined with the help of certain methods of applied mathematics, such as inventory theory, queuing theory, and dynamic programming. Forecasting techniques and simulation models should be integral parts of any optimization procedure used to obtain optimal operational policy.

In summary, no matter what model is used the model limitations should be explicitly stated. Limitations of theory may impose severe limitations in practice.

2.8 Modeling and Operational Time Increments

The time increment(s) to be used to cover the entire analysis or operation time horizon is an important constraint which must be determined at the detailed modeling stage. It is necessary to identify all the factors influencing time resolution in a conjunctive use system to determine optimum time increment(s) for analysis.

The analysis scope (or scale) of the problem (e.g. basin, county, state) will influence the overall time horizon and time increments used for analysis reflecting aggregation of total resources as the scope enlarges. For example, while a particular conjunctive use situation might need to be analyzed at monthly time increments, conjunctive management for an entire basin may only need to be examined in seasonal increments. Statewide it may be appropriate to consider economic benefits from conjunctive management in annual time increments. The nature of the problem (section 2.2) also influences the time resolution. For example, if an operational period of 50 years was being considered an annual time increment may be useful for answering broad scale questions. However, if interest was focussed upon changes in piezometric head during a single pumping season then it may be necessary to use time increments of weeks, days or hours depending upon needed precision in describing these variations. If a well is located very near a stream very fine time increments (or time scales) may be used to determine optimal pumping patterns to facilitate aquifer recharge. In these instances the localized problem needs to be decoupled from the overall system problem.

Demand levels in an area dictate conditions when over-year effects must be considered. With respect to variables of the system, the time increment used for analysis can become large as long as dominant interactions do not change significantly in a shorter time.

2.9 Identification of Significant System Elements

System elements will have differing importance in the overall understanding of the conjunctive management problem depending upon the nature of the problem and the level at which the problem is being analyzed. It is important to be able to identify variables and constraints that are of primary importance (as well as those that have lesser importance) to maximize the effectiveness of management activities. One approach to this problem is via interaction matrices (see, for example, Sulc, 1969) which indicate dynamic links that should be examined. If a dynamic simulation model which exploits these links is developed, variables that become spatially and temporally important can be identified and studied. This issue is examined in more detail in Chapter 4.

2.10 Implementation of an Optimal System Policy

Numerous approaches have been suggested in the literature concerning issues that result in an optimal policy and the institutions needed to implement the policy. Both the agencies involved and the methods used are important to successful implementation of the policy. Agencies and methods for achieving optimal policies are summarized below:

2.10.1. Agencies Involved

In implementing an optimal policy for a conjunctive management problem various agencies might be involved depending upon the extent of the problem and the legal authority of the agencies. These agencies involve international, River Basin Commissions, Federal, State, and Local organizations.

2.10.2. Issues in Implementing an Optimal Policy

A number of ways have been suggested for implementing an optimal policy in ground water management systems. (Some of these alternatives were presented by Hirshleifer, et al. (1960)). These include centralized control of water supplies, taxation of withdrawals, and limitations (quotas) on withdrawal of water.

Centralized control of water supplies, necessitates monopoly control of a basin's water resources. Such control is usually required to effect policy implementation of policies resulting from optimal allocation models. The centralized control approach has been shown to be desirable (on narrow economic efficiency grounds) in a highly simplified setting (Young and Bredehoeft, 1972).

Taxation of withdrawals (to equate private and social costs) in spite of its appeal to economists, has been used only as a means to collect revenue, not as a resource allocation vehicle. Quotas, in effect rights to specified annual quantities of ground water, have been widely used for coping with allocation problems. The common approach has, however, been to limit the spacing of wells. Young and Bredehoeft (1972) discussed important inadequacies of taxation and quota approaches for remedying conjunctive use problems.

Some of the alternatives for water quality policy implementation include legislative constraints (i.e. quality of irrigation return flow), public education, recycling some irrigation water (through the aquifer), limiting irrigation practice, soil profile modification, and modifying irrigation techniques.

2.11 Sociological Factors

Any policy that is to be implemented must be socially acceptable. Acceptability is a dynamic function and is often overlooked by system analysts seeking to optimize a system. Social and environmental effects which emerge from application of a specific policy would determine the acceptability of the project. These changes include ecology (i.e. changes in landscape, and wildlife), economy (both public and private, relating to jobs, property values, tax, and insurance), community quality of life (e.g. recreational and aesthetic opportunities), social and political factors (such as new opportunities, and different demographic and political characteristics) (deNeufville and Marks, 1974).

Social acceptability of a conjunctive use issue can be examined by responses of the affected publics to their preferences for possible alternatives, the apparent optimal alternative, and the life span of the implementable alternative.

The considerable experience of planners as well as the extensive literature on public involvement in planning should not be overlooked (see, for example, Bishop, 1970, Wengert, 1971, Willeke, 1974).

CHAPTER 3

REPRESENTATIVE LITERATURE CONCERNING CONJUNCTIVE GROUND-SURFACE WATER USE

3.1 Introduction

Thirteen papers and reports were found to be representative of the current written state of understanding of conjunctive water management. These thirteen papers together with other reports on conjunctive use are listed in the bibliography. A feature of nearly all the literature is the assumption that one or several parameters or variables dominate the problem at hand.[a] These variables are then extensively modeled. What is lacking is a general approach to indicate what kind of problems are to be experienced in an area. Guidelines for the choice of model detail with respect to technological process representation in space and time for elements that should be included in a particular case are nonexistent. Each problem appears to have been approached on an *ad hoc* basis. The following discussion follows an approximate chronological order.

3.2 Review of Representative Literature

Buras (1963) used dynamic programming to determine design criteria for surface water facilities, the service area, and operating policies for combined reservoir releases and aquifer pumping for a conjunctively managed system. The third criterion (operating policies) was determined analytically while the surface facilities' design criteria and extent of service facilities were treated as parameters. An hypothetical situation consisting of an

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[a]This approach is consistent with traditional approaches to complexity; it is not clear that it is the best way to proceed.

hydraulically connected surface reservoir and an aquifer was analyzed. In the system examined, the aquifer was used as a reservoir to store water for dry season use. The primary variables were the amount of surface water diverted for irrigation, amount of water diverted for recharging ground water, and the amount of water diverted from the aquifer for irrigation. The surface water supply was assumed to be independent of the aquifer system.

Water supplied to the aquifer system was treated probabilistically; expected streamflow was used in computations. Two agricultural areas provided the system demand for irrigation water. These two areas were treated independently, one was irrigated exclusively from the surface supply and the other adjacent area from water withdrawn from the aquifer.

Return functions for both areas were derived from historical data. The scale of irrigation development was treated as a variable; optimal cropping patterns for each scale were developed. The results for different scales of irrigation development were simply compared to determine the optimal scale of development and related optimal allocation policy.

Surface water transport operation costs were assumed to be a part of the capital investment. A linear pumping cost with respect to the amount of water pumped and depth of pumping was assumed for simplicity. (This is an erroneous assumption, see for example, Maddock, 1974.) Optimization of the system was achieved by maximizing net present worth of the system over its economic life.

The major contribution of the paper results from introduction of dynamic programming to the problem of conjunctive management of ground and surface water. The physical assumptions used remove much of physical reality; the decoupling strategy employed reduces the problem to an allocation problem with supply from two different sources, each source supplying only one demand.

The economic part of the model is static, the two demand areas do not compete for each other's supply. Pumping was limited so that water could not be pumped when the piezometric head fell below a specified level. The other parts of the system did not influence this particular level. The approach was further limited because there were no penalties imposed when water shortage occurred. The delivery cost of irrigation water from the surface reservoir was assumed to be a part of the fixed cost of the dam.

The problem was generally treated as a relatively unconstrained allocation problem. Legal limitations per se were not considered in the problem.

Chun, et al. (1964) state as a basis for their paper that the full use of the extensive groundwater basins of California would be necessary to provide the future water requirements in all parts of the state. They commented that it seems essential that the operation of these ground water resources be coordinated with surface storage and distribution facilities to economically provide for local uses, long term cyclic storage, and short term terminal storage.

The paper is part of a general investigation of alternative plans to achieve the "optimum coordinated operation of surface and underground water supplies and facilities" conducted by the California Department of Water Resources and is limited to operational and economic consideration of conjunctive management. Water supply, water demand, alternative plans of operation, physical response of ground water basins and pipeline networks, and costs of facilities and operations were identified (stated) as important elements of conjunctive use systems. The investigators assumed in this work that legal obstacles to conjunctive management could be overcome and that in each situation the necessary management organization was available. To illustrate an approach to conjunctive management the coastal plain of Los

Angeles County was selected for investigations. In this case the management problem is caused by increasing costs of ground water extraction and sea-water intrusion into fresh water aquifers. The objective was to meet the growing water demand of the area by utilizing maximum water from local resources while correcting the undesirable effects of extraction.

A simulation model was used and various alternatives were examined in order to determine the most economical plan. Future supply and demand patterns were estimated in advance and were used as known inputs for each alternative plan. Each alternative operation plan was a combination of four variables, (the pattern of extraction, method of preventing sea-water intrusion, spreading schedule, and extraction schedule). A preliminary analysis of the ground water system was conducted to reduce the number of potential alternative plans of operation to a manageable number. No novel screening schemes were introduced. The physical limitations were: maximum artificial recharge; maximum amounts of imported water; and maximum delivery capacities for expanding networks of primary pipelines. For each alternative plan, various combinations of water resources were examined to determine the combination which met the maximum hourly water demand at a minimum cost.

In general, the approach used by the authors is useful in large scale problems and enables the engineer to understand the importance of conjunctive operation. However, for shorter time intervals and smaller scale problems, the physical model must adequately represent actual relationships between surface water and ground water. The costs were expressed in units of facilities such as well, boosting, and water storage units. For a small scale problem and for operational purposes, expressing the cost function in units of facilities is a gross assumption. For more detailed analyses, variables such as flow rate, depth of well and distances must be included directly in the cost functions.

Aron (1969) used a dynamic programming model to determine the optimum allocation of ground water and surface water in the Santa Clara Valley in California. The portion of the Santa Clara Valley north of Morgan Hill, California was chosen as a demonstration area for proposed methods of conjunctive water use optimization. The area is bounded by geographical divides; water demand is presently satisfied through extensive use of ground water and surface water sources and partly from water imported to the area. Also, throughout flood control and water conservation policy, ground water recharge is practiced.

In Aron's model a water distribution system consists of several sources and several demand areas. A fixed demand for water supply was established and the objective was to meet this demand at a minimum cost of supply over 8 years of operation. A three month interval for operational policy was arbitrarily defined. Costs of supplying water from different sources were obtained from historical operating data. These costs included surface supply, groundwater pumping, pipeline transportation, canal transportation, artificial recharge, land subsidence damage, and penalty functions for drawing down the water level in recreational areas.

The total system was divided into several subsystems some of which were optimized independently of the total system. Subsystem optimizations included:

1. Determining the most economical pipe sizes for the major water conveyance routes as a function of expected maximum flow.
2. Scheduling surface storage distribution among the major reservoirs to result in minimum expected flood damage and evaporation losses.
3. Scheduling relative pumping activity levels in the forebay and pressure zone areas to minimize the total costs resulting from pumping, conveyance and land subsidence.

Since wells already existed the issue of determining the most efficient spacing and pattern of well networks was omitted in the subsystem optimization analysis.

After the subsystem optimization a three state variable dynamic programming model for conjunctive system operation was developed. The state variables were the confined aquifer in Coyote Basin, the combined and unconfined aquifers in the San Jose basin, and seven major surface storage reservoirs in the system. Twelve decision variables were defined which affected the state variables. These decision variables were:

Coyote Basin

1.[a] Ground water pumping

2. Surface water use for agriculture

3,4. Ground water supply to San Jose forebay for industrial and municipal or agricultural use respectively

San Jose Basin

5,6. Ground water pumping rates in forebay and pressure zone respectively

7,8. Surface water supply for industrial and municipal and agricultural use respectively.

External

9,10. Importing water from South Bay and Pacheco Pass, respectively

11,12. Recharge of local or imported surface water in San Jose Forebay or Coyote Basin respectively.

An eight-year period in 3-month intervals was used for the operation period analysis. A probabilistic representation of surface flow was used in

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[a]Decision variables reference number.

conjunction with time-dependent constraints. Several dynamic programming runs were made assuming zero residual water value. The results showed strong preferences towards mining the ground water resources towards the end of the test period. (This could imply an improperly constrained formulation of the actual problem.)

It was assumed that a central authorative administrative organization would implement the optimal operating policy and all legal problems and constraints would be overcome. The feasibility of dynamic programming as a satisfactory mathematical tool for handling conjunctive use problems was illustrated. However, the scale of the problem and the limitation on the number of state variables as well as the required computer time would limit the use of dynamic programming in conjunctive management problems.

Milligan (1969) developed a mathematical model for studying conjunctive operation of ground water-surface water systems. A linear programming technique was used for allocation of surface water, ground water, and imported sources of water to irrigation and for recharging the groundwater aquifer.

Mathematical models were formulated for two different general cases:

1. A two-season year broken into a wet season and a dry season, and
2. A single season model in which all surface flows were probabilistic.

Sets of historical data were used to define deterministic and/or probabilistic characteristics of inflows. The overall objective was to maximize the net return of agricultural activities over a period of time. For each individual case a benefit value for agricultural activity was estimated (dollar per acre foot of water applied). Cost functions for the following activities were estimated from historical data:

1. Water diversion through surface distribution
2. Artificial recharge cost

3. Ground water pumpage

4. Shortage in actual irrigation deliveries

5. Shortage of surface water

A linear programming model was developed and applied to Little Lost River Basin in Idaho and San Pete Basin in Utah. The results for both two season and a single season years were presented. The importance of recharging the ground water aquifer in order to achieve the optimum policy was demonstrated.

The model did not consider any legal and administrative constraints or limitations in applying the optimal policy. For example, in the San Pete Basin, forty-six different agencies were involved in water supply operation and distribution. In this illustrative case, it is unlikely that an optimal policy would be adopted by all agencies. The physical and economical assumptions made are not strictly representative of the actual system. Such a model might, however, be useful as a first attempt to identify dominant interactions and the most likely broad alternatives for optimal allocation of water from a conjunctively operated system.

<u>Cochran and Butcher (1970)</u> studied the application of conjunctive management of groundwater and surface water to the Las Vegas Valley, Nevada area. In the Las Vegas area, like many other semi-arid basins, rapid growth in demand for water caused unplanned,increased,extraction of ground water and as a result the ground water table had substantially lowered. The decline in ground water table level increased the cost of pumping and also created a water shortage during peak demand. The principal demand for water was for municipal and industrial uses. The sources of water consisted of a ground water aquifer and two different surface water basins, each one having its own unique set of physical, legal, and economic constraints.

A dynamic programming model was developed in order to determine the optimal allocation of existing water with possible augmentation from imported water. It was assumed that a central administrative organization would implement the optimal policy determined from the model.

A set of legal restrictions and regulations covering ground water extraction had been imposed to mitigate the effect of further ground water mining. These legal constraints which comprised specification of categories of preferred water users via temporary and revokable permits to appropriate water were incorporated into the basic model structure. To limit considerations to only those made by the central administration (district), a groundwater reservoir response function was derived for the major cone of depression at the well field. For the two surface water resources, two different kinds of cost functions were employed depending upon the nature of the contract between the water district and the agencies.

A set of operating rules was established (rather than determined by the model) for supplying the demand areas from surface water and ground water. These regulations mainly dealt with who would receive the surface water first; the complement was to be made up from ground water. As a result the decision variable considered in the problem was the allocation of ground water by the regulatory agency.

The overall planning/operating objective was to satisfy a set of demands at a minimum cost of operation over a period of time. All aspects of the problem were considered to be deterministic. For the stated problem an analysis life time of fifty years and a time interval of one month were used. Three different management alternatives were examined. The first used the existing regulations and laws concerning ground water withdrawal. In the second and third alternatives, it was assumed that all temporary permits for ground water uses could be revoked, then under each alternative, a new group of users was allowed to extract groundwater.

The model represents allocation of water from various independent sources to a demand side; the optimal policy is a set of operating rules for the 50 years of operation which minimizes the delivery cost of supplying water. To implement the optimal policy a central administrative office is required.

Due to the deterministic assumptions concerning interacting variables the operational policy determined might substantially differ from reality. However, the model is useful in understanding the general allocation pattern of an optimal policy and the areas where further detailed study must be directed. For more detailed analyses and operational policies, it is advisable to consider uncertainty of both future supply and demand.

Cochran (1971) expanded his earlier study (Cochran and Butcher, 1970) to include the Las Vegas and Eldorado Valleys and to consider wastewater recharge. A review of the past studies of the ground water systems in the area was presented. The review discussed a direct electrical analog model of the extensive Las Vegas Valley aquifer system which was used to simulate and compare the effects of alternative long-range ground water development policies on water levels. The main part of this report covered a study which was conducted to determine the feasibility of recharging wastewater to the aquifer. This involved developing a simulation model of the aquifer systems and also a fluid analog (Hele-Shaw) (Clark, 1967) model for a small portion of the valley. The economics of wastewater reclamation were evaluated by a linear programming algorithm.

The study area covers the Las Vegas and Eldorado Valleys. The general objective of the study was to develop, through an interdisciplinary approach, system analysis techniques to produce an efficient overall scheme to manage and develop a ground water and surface water supply for urban use. The specific objective of the model was to satisfy all projected water requirements (over 50 years) at a minimum supply cost. The area had two available sources of water: (1) Nevada's share from the Colorado River (which can be delivered through three separate pipeline systems) would be based on cost-sharing for each participating agency, and (2) ground water procured through a diversified set of collection wells.

A monthly time interval was used for the 50 year study period. Factors including monthly fluctuation in water demand, water distribution costs as a function of source of water, and peak energy requirements (which might change within a month) which were identified in a preliminary analysis were given special attention in the analysis.

For ground water flow modeling purposes, the groundwater basin as a whole was assumed to respond to storage withdrawals as a large open reservoir according to a relationship derived from pumpage and water level records (a linear relationship was used). Interference effects between individual wells within a well field were not considered. (Maddock (1974) has shown this latter issue to be important.) The cost of surface water was assumed to be a function of the source of water, distribution of population, and water requirements. Ground water production costs were calculated for water delivered at the well-head. These costs were a function of well characteristics (pumping rate, pumping lift, "wire-to-water" efficiency) and energy contracts. A dynamic programming algorithm was used to optimize the sequential decision making process of resource utilization by minimizing the present value of operating costs over the fifty-year planning horizon. The decision variable used in the model was the total monthly production of ground water from the Las Vegas Valley. Preliminary versions of the model used two state variables, average depth to the static water level surface, and percent of annual permitted ground water volume used in a given month. The state variables were used to examine some of the effects of legal constraints placed on the annual production of ground water in terms of maximum volume and rate or production.

The model allocates water resources from different sources to various demand areas. It was developed for a particular situation (Las Vegas area); only the general concept may be used in other situations. The dynamic programming algorithm is useful for allocation over numerous time periods when sufficient knowledge of resource and demand variations is available. However, for situations where a long-term commitment by the agencies is required, the difference between a "common sense" approach and an optimization approach is of great importance in acceptance of an optimally derived policy which necessarily responds to model and data errors.

Butcher (1971) addressed general issues of conjunctive use of ground water and surface water in urban areas. The question of supplying enough water to meet the demands of urban areas was investigated. Statistics for 1962 showed that only fourteen cities of the one hundred largest cities in the United States used surface water in conjunctive with ground water as the sources of water supply. The ratio of cities using conjunctive surface-ground water management is larger for smaller communities. He suggested that ground water be used as a supplement to overall supply, as a reservoir, as a distribution system, and as a means for wastewater utilization. The salient points of his general arguments are summarized below. Butcher points out that conjunctive use of water supply sources for a city with more than one source of available water is possible and economies can often be obtained by conjunctive operation. Where the multiple sources have different space-time and quality characteristics as in the case with groundwater and surface water, it is possible to develop an operating policy which exploits their different characteristics. In general groundwater may be used as a supplement to the overall supply of the area. Surface reservoirs are built at a great cost in order to regulate the surface water in the area whereas in many cases large underground reservoirs could be used to achieve this end. The characteristics of underground reservoirs are different from those of surface water reservoirs but their ability to conveniently and economically store water is one feature that may be very valuable. Ground water reservoirs are usually large and losses from evaporation and surface outflow are quite low. Another valuable feature of the storage aquifer is its ability to act as a distribution system. When a ground water aquifer is recharged at one point, this may make possible withdrawal of water from many points throughout the same aquifer. The management of a groundwater system can have an important influence on the energy needs in pumping water from it. From an energy point of view it is logical to have the groundwater reservoir filled to as high a level as is possible. This will affect the economics of operating the ground water facility. As a result a general policy for spatial and temporal ground water extraction must be established to minimize the overall cost of pumping.

A useful feature of ground water aquifers is the ability of the soil, through which recharge water may pass, to be an effective barrier to pathogens as well as absorbing nitrates and phosphates. This characteristic of the soil opens up the possibility of using wastewaters for ground water recharge.

Butcher also pointed out the importance of the fact that data, their availability and reliability might be more of an issue with respect to actual development of a solution, than how to go about solving the problem. Another problem confronting potential conjunctive management (as well as other complex water systems) is the question of the management objective. Typically a minimum cost objective is used. This approach can lead to inequities among users. Butcher suggested criteria such as maximum equity among users and the best water quality for the area as being conceptually appealing as objective effectiveness measures.

Butcher suggested the application of optimization techniques as a tool for illuminating issues and to study alternatives which can then be examined for their political, social, and institutional viability. In summary, this work is an excellent discussion of issues in conjunctive use management.

Danielson and Qazi (1972) discussed problems concerning conjunctive operation of surface water and ground water under conditions of natural and pump induced flow. They examined part of the South Platte Valley of Colorado where heavy groundwater withdrawal results in decreased surface water flow in a stream jeopardizing the rights of senior surface appropriators. An analysis of a segment of the South Platte Valley on an inflow-outflow basis was conducted to determine if the amounts of stream depletion caused by pumping of irrigation wells could be quantified on a seasonal basis. The amount of water withheld from the stream reflects direct damage to the surface water rights during the irrigation season.

A general mass balance equation, developed for the study area, included the following factors:

1) $R - D = S - Cu_s - E_R - E_D + P - C_{up} - E_P$ (Pre-well conditions)

2) $R - D = S - Cu_s - E_R - E_D + P - C_{up} - C_{uw} - E_P$ (Post-well conditions)

where

R = Return flow to river as ground water

D = Direct stream depletion

S = Surface diversion from the stream

Cu_s = Consumptive use of surface diverted water

E_R = Surface evaporation from reservoirs

E_D = Surface evaporation from ditches

P = Annual precipitation on the study area

C_{up} = Consumptive use of precipitation

E_P = Phreatrophytic consumptive use

C_{uw} = Consumptive use of well water

The term R - D presents the net gain or loss to the river from ground water accretion. The mass balance equation is valid for any time period. Comparing equations 1 and 2 it is obvious that the difference in net river accretion, between a purely surface diversion system and a "surface-well diversion" system, is the C_{uw} term. C_{uw} can be estimated by pre-well and post-well data analysis. After defining the C_{uw} term it is possible to estimate the net seasonal effect of well pumping on the surface water in the stream.

Quantities in equations 1 and 2 were estimated and the flow records and diversions from surface water and ground water were obtained from regulatory agencies. The results showed that in the period 1940 to 1970 stream depletion was equal to the consumptive use of well water for irrigation purposes.

The model is very helpful in analyzing a conjunctive use system and in understanding the water movement in the system. Specifically,it is applicable for cases where existence of a problem must be verified. It must be realized that the model is not constructed to be used for decision making purposes. In using the model one point should be clarified, viz.,the time interval of the study must be long enough to overcome groundwater dynamics. In this study a yearly time interval was used to determine the impact of well extraction on stream flow over several years. Results must be carefully interpreted because of possible changes of water uses over the period of study. Any water use changes which influence parameters such as consumptive use should be included specifically in the analysis. It is also important to accommodate error propagation in studies of this kind when quantities of interest may be of the same order of magnitude as uncertainty estimates for each (or some) of the variables.

Young and Bredehoeft (1972) developed a basin-planning simulation model that incorporated the temporal and spatial relationships of a stream-aquifer system, the stochastic properties of surface flows, and the response of individual water users to hydrologic, economic, and institutional conditions.

The South Platte River Valley in Colorado was modeled. Background information about the hydrology, economics, and institutional characteristics of the area were presented. In the South Platte River Valley surface waters are distributed by a series of user-owned ditch companies that divert water from various points along the river to the farms. Colorado's constitution contains the doctrine of prior appropriation. At this time, rights exceed expected flows, so that the ditches located in the lower valley are actually using return flow. In the 1950's after a period of insufficient water supply, some irrigators began to drill wells to provide supplemental water. This practice has extended to the point that part of the return flow to the river is being intercepted by irrigation wells, and downstream holders of junior surface water rights find themselves with inadequate water even in a year of average runoff.

An institutional structure, adopted for study purposes, involved a basin wide organization which supplied and controlled water distribution according to the present appropriative rights system. The components of the system were sources of water (stream-aquifer) and demand for water (crop irrigation); the key decision variable was "capacity and spatial distribution of the wells in the system". Other important variables were treated by specifying some operational rules in advance.

The general model consisted of two submodels, an hydrologic model and an economic model. A groundwater simulation model, which was the heart of the hydrologic model, was used to solve the nonlinear partial differential equations governing the flow of groundwater. A spatial finite difference approximation to the governing equation was used. The economic model,which was based on micro economic theory of the firm,[a] represented a decision maker who is seeking the allocation of resources that maximizes profit within a set of technical and resource constraints.

The economic model was employed in two stages. In the first stage (planning stage), which was at the beginning of the season, each farmer determined the optimum level of agricultural activities for the next season based on the following knowledge which was given to him in advance:

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[a]The response of the water-using firm to alternative supply and cost conditions depends on its production possibilities and on the revenues and costs associated with those conditions.

1. The constraints including expected surface water for each month of the irrigation season, well capacity, limitations on total land and land available for specific crops,
2. The production response relationships, particularly crop response to alternative water applications, and
3. Product and input prices, including charges for water from either groundwater or surface water sources.

A linear programming model was used (for the planning stage) at the beginning of each irrigation season to identify the optimum level of land usage for irrigation. In the second stage (monthly operational model), the decision was made to allocate water to each crop by maximizing incremental net revenues within the constraints of water supply and planted acres. This model was solved sequentially for each of the months of the irrigation season by using water resource data from the hydrologic model and parameters representing productivity, prices, and costs; a small (relatively few variables and constraints) linear programming model is used for each subarea. A penalty cost term was added to the objective function for failure to meet downstream delivery requirements.

The overall objective was to maximize the average annual net economic yield. Alternative institutional and developmental solutions to the problem were ranked according to the average annual net economic yield. Two cases studied were reported.

The model is the earliest work we have encountered which considers most of the components of a general ground-surface water system. However, there are some limitations to using this approach; simulation models do not provide an optimal solution to a problem. The decision maker using model outputs should be made aware of the important variables and by use of a set of logical alternatives define the best one. Furthermore, the model was applied to a reach rather than the entire length of the river-aquifer system. Results of model usage must therefore be regarded as an approximation of the true optimum. (The issue of system disaggregation was not specifically addressed.) The short-comings of the economic model were discussed in detail by Morel-Seytoux, et al. (1973). The economic model assumed that the water-user's attitude is rational and that he plans various crop acreages at the beginning of the irrigation season based on an estimate of the availability of surface water within the priority system.

It was indirectly assumed that farmers make their decisions based on expected value (or flow prediction) and they are not overly worried by the possibility that actual flow may be lower than expected. This attitude might be true when other constraints and uncertainty such as well capacity, taxation of groundwater, or quotas on groundwater withdrawals are removed or at least are weakened. Experience of loss might cause farmers to be risk averse in the future. A further limitation of the model is that penalties incurred for not meeting downstream rights were not charged to the upstream users. Consequently, with low well capacity the farmer would probably guard against risk by anticipating only some fraction of the expected values; the first stage water allocation and farmer attitudes are definitely related and need to be modeled.

Perez, et al. (1972) proposed a mathematical model to predict water quality in a surface-groundwater system. The model was applied to Lake Apopka in Florida. Three submodels were considered for surface flow, unsaturated flow, and groundwater flow. Water quantity aspects were considered first, followed by water quality considerations. Since Lake Apopka is located in an agricultural area, nitrogen and phosphorus were used to parameterize pollutants.

Three kinds of models, two for flow from land areas and one for receiving water, were used to represent surface water flow. For flat areas a computer program developed by the University of Florida was used. This model computed inflows into the canals; flow rates in the canals were computed basically from Manning's equation. For other land areas, consideration was given to the use of the Stanford Watershed Model (Crawford and Linsley, 1966). The receiving water model contains water quality routines which consider advection and chemical reactions. These routines utilized flow velocity information which was generated by the surface flow model. For unsaturated flow a numerical solution of the differential equations for flow in unsaturated porous media was used. Due to the geographical situation, only vertical flow was considered. In the quality aspects of the unsaturated model numerous simplifying assumptions involving reactions among substances and between substances and the soil were established. A steady state, two dimensional model was used for the groundwater subsystem. A quality model which utilizes velocity vectors from the groundwater model computes concentrations of various substances as they move away from their sources. Molecular diffusion was neglected being small relative to hydrodynamic dispersion.

The general model assembled several existing models, and in itself is a relatively complicated system. Before employing such an extensive model, however, a simple mass balance model is necessary in order to define the main sources and sinks of pollutants and the linkage between them. Also it must be borne in mind that if Perez's model was to be used as a submodel in a general conjunctive ground-surface water system its demands upon computer facilities may be prohibitive. Due to lack of information it may not be necessary (or practical) to develop such an extensive water quality model for studying conjunctive management.

Maddock (1974) introduced a mathematical model for operation of a stream-aquiver system under stochastic demand and supply. The sources in the system were stream flow and groundwater between which there was an hydraulic interaction.

The system modeled consisted of a stream and a connected aquifer, the stream was assumed to provide a constant head for the aquifer. There was a demand area which could use water from groundwater or surface water, the return flow had to be treated and returned either to the stream or to be used for recharging the aquifer.

The assumptions in the physical model were:

- There is sufficient knowledge concerning the interactive flow behavior between the stream and the aquifer to produce a distributed parameter model of the flow system.
- There is sufficient flow in the stream at all times so that withdrawals directly from the stream or losses from the stream to the aquifer do not affect the head levels in the stream.
- The saturated thickness of the aquifer is always large compared to that of any drawdown, hence, transmissivity is independent of head.

A "linear" groundwater model was applied where the impact of pumping in one location upon any other location was determined in advance (response matrix). (This procedure dramatically reduces computer time.) A response matrix was also developed to determine the effect of pumping in any location on the stream-aquifer coupled flow. Demand for water supply was considered to be stochastic. Two methods for modeling demand were considered. In one approach demands were represented by a Markov Process (mean, variance, lag-1 serial correlation are the only statistics needed). In the second approach certain demands were taken to be serially independent. For both cases the effects of demand variance on pumping and drawdown statistics were determined.

Economic, legal and adminstrative consideration included:

- A central agency, which has the power to control the location and withdrawals of groundwater, location and quantities of water spread for recharge, available surface water, and return flow to the stream, was assumed to apply the optimum policy. The quality criterion for treated water was assumed to be an external decision independent of modeling.

- The water rights of the demand area were considered as junior either to some other water right downstream or to a low-flow requirement ("instream user").

- The hypothetical agency's objective was assumed to be the minimization of the discounted expected value of costs.

The groundwater pumping cost was modeled as a quadratic function of the total lift (drawdown plus initial lift) and the quantity of water pumped. The cost of stream withdrawals, return flow to the stream, and spreading were all linear functions of the quantity of water moved.

The four (4) decision variables at each time period were:

1. Fraction of the demand to be supplied by stream diversion
2. Fraction of the demand to be supplied by each well
3. Fraction of water available after consumptive use that is spread during each period
4. Fraction of water available after consumptive use that is returned to the river during each period.

The result for an hypothetical situation was presented. A sensitivity analysis recognizing uncertainty in a few parameters was conducted. This latter analysis showed the great sensitivity of operational policy to stochastic demand.

The following suggestions were made for further study.

1. The assumed constant head of stream should be modified to handle varying head.
2. A noise term might be needed in the stochastic demand sequence.
3. More complicated generating processes for demands could be used.

4. The minimization objective may be replaced by maximization of some benefit function.

5. A senior right may be allowed to be violated on rare occasions by assigning a penalty cost.

6. More extensive sensitivity analysis may help in understanding the important elements of the system.

7. A possible modification could be to construct operating rules that would allow shortages (with penalties) to occur.

Considering the author's suggestions, the model might be useful for a detailed analysis of a conjunctive use problem at a local level. The calculation difficulty and complexity rapidly grows by increasing the size of the problem. The amount of information needed in analysis makes it difficult to apply the model in many situations. In all cases a simpler model could be used to identify the general problem and the need for conjunctive operation of groundwater-surfacewater before attempting to use Maddock's model. Maddock's model is, relative to other approaches, quite appealing particularly for the clever modeling of "drawdown influence". This approach avoids many costly computer simulation runs.

Chaudhry, et al. (1974) developed a model for optimal conjunctive use of water for the Indus Basin in Pakistan.

The principal management problems in the Indus Basin were stated as:

1. The Indus Basin irrigation system depends mainly on the run-of-the river water supply. Thus the irrigation supply is uncertain which inhibits investments in agricultural inputs,

2. Shortages of water during sowing and maturing of crops results in limitations on cultivation intensity and yield per acre, respectively, and

3. The "use-when-available" system of using water creates serious water use inefficiencies.

The paper presents an optimization model for a limited part of the large-scale conjunctive use problem in the Indus Basin.

A decomposition and multilevel optimization technique was introduced. The subsystems were chosen in a way to minimize the impacts of links between them. Since the emphasis was on design, a deterministic approach was taken to study the problem. The following assumptions and criteria were used in the modeling effort.

1. Water was allocated to subsystems on an historical basis. It was assumed that the average historical river water diversions to canal systems reflects government and local priority rules for water supply. As a result, in months of small surface water supply, the water is distributed in proportion to average historical uses and in other periods the canals receive surplus water again proportional to their average historical uses.

2. Allocation of surface storage

   It was assumed that the surface storage facilities were common to all areas; it was further assumed that a part of the storage space in the common surface reservoirs would be reserved for the model area. The model area would be charged pro rata cost for such reservation. This assumption enabled the model area to be decoupled from other areas with respect to surface storage facilities.

3. Allocation of ground water

   Subsurface water was assumed to be available for the area's exclusive use. Subsurface inflow into the area was always assumed to equal subsurface outflow. This assumption dictates complete subsurface flow independence between subareas.

4. Monthly irrigation water demands were determined on the basis of assumed cropping patterns and irrigation intensity. A specific irrigation pattern was selected from a particular study.

The submodel was designed to minimize the cost of supplying water for meeting the given irrigation water requirements. Cost functions were separated into design costs and operational costs, furthermore, all functions were assumed to be linear except for items expressed as a function of canal capacity or as a function of pumping capacity.

The major concern in the area was the optimal sizing of surface storage facilities, canal capacities, and pumping capacities. The optimization was carried out by selecting various design combinations, optimizing the operation of the subsystem under each alternative, and determining the design that minimizes a cost criterion. A direct solution of the outer problem by standard dynamic programming required several hours of computer time. To overcome this problem, a systematic search algorithm was developed to reduce the computer time needed to obtain the optimal policy. The results showed that the aquifer provided the least cost alternative for development and management of the water resources of the area. Efficient use of the aquifer allows generation of additional usable water by employing the aquifer as a recycling facility.

In cases when the assumptions of this model are relevant to the problem area the model might be used (with obvious caution) to define the approximate optimal policy in a large scale system. However, the limitations on physical and legal assumption must be realized and not be overlooked when applying this type of model to a complicated system.

Yu and Haimes (1974) applied a general systems analysis approach to conjunctive use of ground water and surface water. They considered an hypothetical region to be served by both surface water and pumped water from an underlying ground water basin. All the water supply activities for the region are assumed to be administrated by several local water agencies, who are responsible for water supply to a sector of the region (subregion). Each local water agency is assigned exclusive rights for developing and controling all water resources in its operation area except for some activities that are centrally controlled by the regional authority. A decomposition and hierarchical multilevel approach to the general system was proposed. The overall regional problem was decomposed into two levels, subproblems for each local agency at the first level, and coordination of the subproblem solutions by the regional authority at the second level. The regional water authority was assumed to have the following responsibilities.

1. It is responsible for all the activities that will enhance the public interests but are too big for any local agency to deal with, such as artificial recharge, importing water, sea water intrusion, and regulation of water quality.

2. Revenues for the activities of the regional authority will be provided by taxing local agencies.

3. The major task of the regional authority is to make equitable apportionment of pumping rights among local water agencies.

At the first level, each local agency optimizes its own regional resource allocation independent from the other agencies. The regional authority, by changing common variables among the subregions, then tries to optimize the regional problem. These common variables are intersubregional boundary water levels, pumping tax rates, and the artificial recharge rates. The responses of local agencies are cross intersubregional boundary water flows, pumping plan, and water supply cost. It was assumed that the regional authority does not know the cost functions of the local agencies. The overall regional objective was to satisfy a fixed demand at a minimum cost.

Each subregion of the hydrologic system was divided into polygonal zones with a representative node used for the purpose of analysis and for representing hydrological characteristics. The polygonal zones and nodes were based on geohydrological considerations; for example, the number of nodes was increased in areas where water level elevations changed rapidly.

At the local level, the individual subregional mathematical models had nonlinear objective functions and nonlinear constraints. Each subregional model was solved by a penalty function approach (by including all constraints, as penalties, in the objective function). A hill climbing technique was used to search for the optimal local activities and their levels. A hypothetical region was modeled using a yearly time interval as an illustrative example. Results from this model included the optimum pumping plant in each polygonal zone for each subregion.

The authors concluded that the aquifer is the key element that should be controlled for the optimal conjunctive use of groundwater and surface water resources. For this reason the model was established basically to control the common pool through a regional authority which levies the pumping tax to provide the revenue for artificial recharge of the aquifer basin. The hypothetical example showed that heaviest pumping is done in areas where artificial recharge is practiced. Most of the municipal and industrial demands were satisfied through groundwater extraction while almost all of the agricultural use was provided by imported surface water.

The model contains a detailed hydrologic component (monthly groundwater movement); less emphasis was placed on economic and legal parts of the system. The regional water authority was, however, given the power to modify any of the laws and regulations to achieve optimal allocation for the whole system. The required computer facilities for solving the mathematical model would limit application of the model to small scale conjunctive use systems.

3.3 Summary Observations

Tables 3.1 to 3.3 summarize the 13 articles reviewed. Table 3.1 presents general characteristics of the articles, the way each problem was identified and modeled, and the effectiveness of the modeling. Table 3.2 shows the actual techniques developed and generally deals with handling of inputs and variables that were modeled. Table 3.3 summarizes the data used and the detail and extent of information needed in developing the various submodels.

In reviewing the representative conjunctive use articles it was recognized that most of the articles addressed themselves to a particular aspect of a conjunctive use system. Usually mathematical models and optimization techniques were employed to determine the most economically efficient system of operation and/or design.

It appears that a general approach to the conjunctive use problem is necessary to evaluate large scale problems, determine important variables and constraints of the system, develop and test a model for validity, and determine how to implement the results of the overall analysis.

The summarized articles represent a broad sampling of quantitative approaches taken toward managing ground-surface water systems. Ongoing research, particularly at Colorado State University and at the USGS National Center, Reston, Virginia, is directing attention to model resolution needed for decision making purposes. Current researchers recognize the need to spend less time refining groundwater hydrology models and to spend more time and effort improving the economic and legal aspects of system models. From analysis of the foregoing articles, it appears that there is room for much work to be done with these latter items to bring comparable levels of resolution to all the interrelated aspects of ground-surface water system modeling.

Table 3.1 Summary of Issues Covered in Representative Conjunctive Use Literature

Item \ Article	1 Buras 1963	2 Chun 1964	3 Aron 1969	4 Milligan 1969	5 Cochran 1970	6 Cochran 1971	7 Butcher 1971	8 Danielson 1972	9 Young 1972	10 Perez 1972	11 Maddock 1974	12 Chaudhry 1974	13 Yu 1974
1. Did the article cover real or hypothetical (hypo) situation?	Hypo	Real	Real	Real	Real	Real	Hypo	Real	Real	Real	Real	Real	Hypo
2. Did the formulation adequately cover the total problem?	Not applicable	Not completely	Not completely	Not completely	Not completely	Not completely	Not applicable	Yes	Yes	No	Not applicable	Yes	Not applicable
3. What was the identified problem?	Not applicable	Groundwater mining and salt water intrusion	Ground water mining	Rapid demand growth	Rapid demand growth	Rapid demand growth	Not applicable	Decrease in surface water due to nearby ground water pumping	Decrease in surface water due to nearby ground water pumping	Not applicable	Not applicable	Rapid growth	Not applicable
4. How was the problem modeled?	Set of DP's[(a)]	Simulation	DP and subsystem optimization	LP[(b)]	Set of DP's	Set of DP's	Not applicable	Mass balance	Simulation + LP	Simulation	Quadratic programming	Decomposition and multi-level optimization technique	
5. What limited the suggested approach?	Inc.[(c)]	Inc. and required computer time	Inc. and required computer time	Inc.	Inc.	Inc.	Inc.	Inc.	Specific conditions of the studied area	Inc. and required computer time	Inc. and required computer time	Technique	Required computer time
6. Is the approach readily extendable to other conjunctive use system?	No	No	No	No	No	No	No	No	No	No	No	No	No

[(a)] DP - Dynamic Programming [(b)] LP - Linear Programming [(c)] Inc. - Incomplete representation of the conjunctive use system

Table 3.2 Summary of Features of the Conjunctive Use Problems Examined and Modeling Procedures and Techniques Used

Issue \ Article	1 Buras 1963	2 Chun 1964	3 Aron 1969	4 Milligan 1969	5 Cochran 1970	6 Cochran 1970	7 Butcher 1971	8 Danielson 1972	9 Young 1972	10 Perez 1972	11 Maddok 1974	12 Chaudhry 1974	13 Yu 1974
1. Was a mathematical model involved?	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
2. Was this an everyear allocation problem?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes
3. Was this a design problem?	Yes	Yes	No	No	No	No	Yes	No	No	No	No	Yes	No
4. What was the objective (or objective function)?	Max[a]	Min[b]	Min	Max	Min	Min	Not applicable	Identifying the effect of pumpage on stream flow	Max	Predicting water quality	Min	Min	Min
5. Was this a static model?	Yes	Yes	Yes	Yes	Yes	Yes	Not applicable	Yes	No	Yes	Yes	Yes	No
6. How were the water supplies modeled?	Probabilistically	Deterministically	Probabilistically	Deter. and prob.	Deterministically	Deterministically	Not applicable	Deterministically	Deterministically	Deterministically	Stochastically	Deterministically	Deterministically
7. How were the demands for water modeled?	Unlimited	Deterministically	Deterministically	Unlimited	Deterministically	Deterministically	Not applicable	Not applicable	Response[c]	Not applicable	Stochastically	Deterministically	Deterministically
8. How was ground water hydrology modeled?	Deterministic flow	Simulation	Deterministic flow	Deterministic flow	Deterministic flow	Deterministic flow	Not applicable	Deterministic flow	GN[d]	GN	GN	Deterministic flow	GN
9. How were the economic aspects of the system modeled?	Return func. for agricultural activities	Fixed demand	Fixed demand	Water value was defined	Fixed demand	Fixed demand	Not applicable	Not applicable	Micro-economic approach	Not applicale	Stochastically	Fixed demand	Fixed demand
10. How were the legal issues handled in the model?	Not included	Not included	Not included	Not included	Existing law	Existing law	Not applicable	Not applicable	Not included	Not applicable	Not applicable	Traditional water supply used as law	Administrative system was proposed

(a) Max - Maximize net present worth of returns from system operation

(b) Min - Minimize the cost of supplying a fixed demand

(c) Response - Responses of farmers (users of water) throughout a dynamic system of responses

(d) GN - General differential equation of ground water movement

Table 3.3 Summary of Data Needs for the Techniques of Table 3.2

Data Item Number \ Article	1 Buras 1963	2 Chun 1964	3 Aron 1969	4 Milligan 1969	5 Cochran 1970	6 Cochran 1971	7 Butcher 1971	8 Danielson 1971	9 Young 1972	10 Perez 1972	11 Maddock 1974	12 Chaudhry 1974	13 Yu 1974
1. Form of stream flow data used.	Deterministic characteristics of historical data		Prob. charac. of historical data	Det. and prob. charac. of historical data	Deterministic characteristics of historical data		Not applicable	Deter. charac. of historical data	Deter. charac. of historical data	Deter. charac. of historical data	Stochastic charac. of historical data	Deterministic characteristics of historical data	
2. Form of ground water flow data used.	Deter. value from historical data	Charac. of ground water	Deterministic values were obtained from historical values				Not applicable	Deter. value from historical data	General characteristics of ground water			Deter. value from historical data	Charac. of ground water
3. Were additional data necessary for ground water surface water modeling?	No	No	No	No	No	No	Not applicable	Yes	Yes	Yes	Yes	No	Yes
4. What temporal and spatial data were required for the economic model?	Return function for agric. act. from historical data	Demands were estimated from historical data		Fixed return for each unit of water	Demands were estimated from historical data		Not applicable	Not applicable	Forecast the responses of water users	Not applicable	Stochastic charac. of historical data	Demands were estimated from historical data	
5. Which of these data have to be updated?	2,[a] 4	1,2,4	1,2,4	1,2,4	1,2,4	1,2,4	-	-	1,2,3,4	1,2,3	1,2,3,4	1,2,4	1,2,3,4
6. What type of data were necessary for accommodating legal issues?	Not applicable	Not applicable	Not applicable	Not applicable	Existing law	Existing law	Not applicable	Not applicable	Existing law	Not applicable	Not applicable	Not applicable	Not applicable

[a] Refers to data item number.

CHAPTER 4

A GENERAL APPROACH TO CONJUNCTIVE USE ANALYSIS

4.1 Introduction

In addition to physical factors, social, legal, and economic aspects of conjunctive ground-surface water systems need to be included in analyses of these systems. The relative importance of the interacting parts of the total system gives rise to differing complexity in different systems. Of all the interacting parts of a system the physical characteristics may be relatively well understood; other parts of the system are usually less well understood. Maddock (1974) showed the importance of treating the stochastic nature of the supply-demand elements of a conjunctive use system. In some instances where only the overall level of physical interactions needs to be understood a simple deterministic analysis of the aquifer system may be adequate for decision making purposes.

The legal characteristics of the system have usually been applied as a set of constraints. The major difficulty lies in transfering laws and regulations into quantitative measures. In some cases legal problems and restrictions may overwhelm the other characteristics of the system and simply dicatate the policy for conjunctive use operation. However, system sensitivity to legal constraints may be studied to determine their impact on the overall operation of a system and the cost of having such legal constraints.

Economic characteristics and behavior of the system are major constraints in constructing any mathematical representation of a conjunctive use system. Normally a measure of effectiveness, for instance, the maximum return on economic activities or minimum cost of supplying a set of demands, is used as an objective function. In systems where various economic activities are not highly interrelated (i.e. secondary relationship can be neglected) the conjunctive use system may be disaggregated into an allocation of resources over time and/or space problem under a set of physical and legal constraints. These later constraints are used as the system couplings. When activities are highly related, prediction of economic activities is an essential part of the modeling activity. This considerably increases the complexity of the system representation and provides additional sources of uncertainty. Checking the validity of economic prediction is a formidable task. In most cases ability to model physical aspects of the system is mismatched with ability to model economic and legal aspects of the system.

4.2 Complexity

It is important to recognize that in a complex system the relative influence of various elements is a primary factor in developing a mathematical model. For instance there is no advantage in building or using a model of a conjunctive ground-surface water system that includes considerable hydrologic detail but neglects to adequately represent legal and economic nuances. Output from such a model is essentially worthless from the viewpoint of obtaining an optimal, "satisficing," (or good), total system operation policy.

Where practical, it is important to consider using a relatively simple model of the total system as a learning model. Such a model might only perform relatively crude water balances and greatly simplify legal and economic aspects. It may give misleading results but its principal use would be to identify dominant variables and to indicate which parts of the system need to be modeled in greater detail. This type of model can be used in a "what if" mode provided the physical features are adequately represented for the scenarios examined. Principal use of such a model would be in problem identification; such models would be unsuitable for system operation decision making purposes.

The complexity of the conjunctive management issue becomes apparent in Table 4.1. Here eleven issues associated with management of conjunctive use systems have been included in an interaction matrix. The rows represent the affectors (causative factors) and the columns the affectees (items influenced by the affectors). Only symbolic interactions are shown; strengths and levels of interactions are not included. The notes (a) through (g) in Table 4.1 are included to add a third dimension where appropriate. Several conclusions can be immediately drawn from Table 4.1. The interaction matrix is not sparse, therefore, dynamic coupling presents a serious problem to be considered by the analysts. The item "Data" could have been disaggregated into several categories, e.g. data for problem identification, data for model building, data for model verification, data needed for implementing and managing the optimal policy, and data needed for updated modeling/management activities. In the interaction matrix the respective data needed, resultant model requirements, etc., are not given. The matrix is included to indicate items that the analyst must address. The matrix is valid for both very crude as well as sophisticated data intensive analyses. With these interactions in mind (many subdivisions of activities are possible) it is appropriate to consider a systematic approach for analyzing conjunctive use problems.

4.3 Systematic Analysis

4.3.1 General

Basically four major activities are involved in conjunctive use studies:

1. Define the problem[a]

   This requires determing

   a) the nature of the problem, and

   b) the level of the problem.

[a]See Chapter 2 for greater detail.

Table 4.1 Interaction of Elements of General Conjunctive Use Systems

Affectee / Affector	Level of the problem	Nature of the problem	Physical system	Legal system	Economic system	Object-ive(s)	Data	System dynamics modeled	Optimal policy	Social criteria	Optimal policy implemen-tation
Level of the problem			X	X	X	X	X	X	X	X	X
Nature of the problem	a		b	X	X	X	X	X	X		X
Physical system		X				X	X	X	X		X
Legal system	a				c	X	X	X	X		X
Economic system		d				X	X	X	X		
Objective(s)						X	X	e			X
Data		f	f	f	f	f	f	X			f
System dynamics modeled							X	X	X		
Optimal policy					g	X	X				X
Social criteria	X					X	X	X	X		X
Optimal policy implementation						X	X	X	X		

Notes:
- a) Determines agencies and publics that are involved.
- b) Determines what parts of the physical system are of interest
- c) Interpret as constraints on water transfer
- d) Economic demand may contribute significantly to the physical problem
- e) The overall objectives define the type(s) of model(s) to be used.
- f) Data availability or collectability can be overriding constraints
- g) The optimal policy may cause a significant change in economic activities.

2. Analyze the problem

   This requires determining:

   a) the objective of the analysis

   b) the significant variables and interactions

   c) all parameters involved

   d) data availability

   e) constraints, and

   f) preliminary screening of alternative solutions

3. Perform Detailed System Modeling

   a) Model development

      Mathematical and analog models

      i) learning models

      ii) decision making models

   b) Model verification

      Specific data will be required for this task.

   c) Determination of "optimal" policy

      i) yearly and seasonal

      ii) short term operational

4. Implement Optimal Policy

   a) Set up management structure

   b) Set up feedback mechanisms

   c) Set up information system and data gathering networks for needed data.

These major activities are shown schematically in Figure 4.1 which only outlines necessary activities; general feedback paths are shown but logical branching steps are omitted. It is important to provide supplemental information addressing the issues of how to perform an actual analysis. The first major issue is to identify the conjunctive use issue for the area. This can

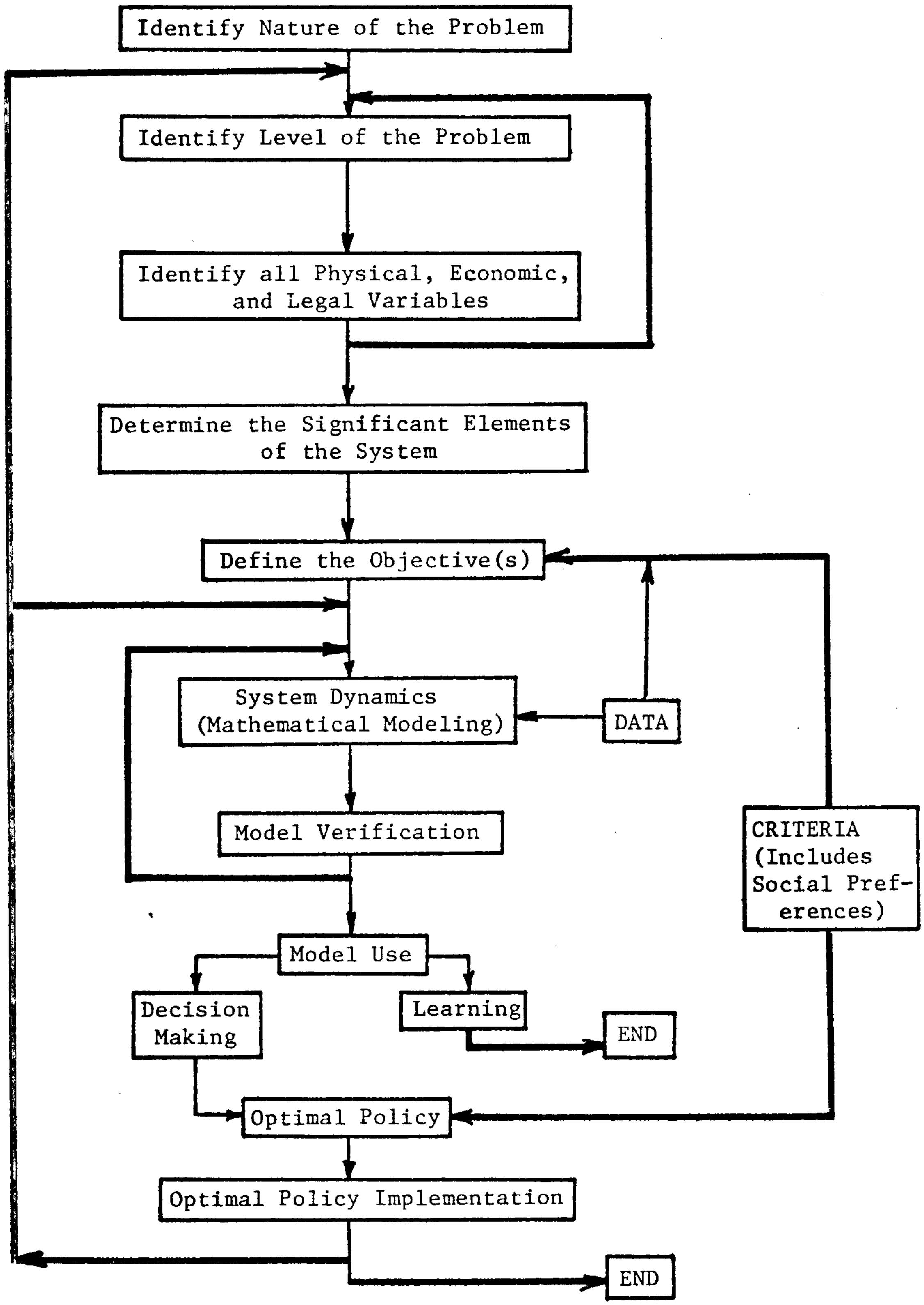

Figure 4.1. Schematic Representation of a Systematic Approach for Studying Conjunctive Use Problems

be done by following the series of questions/actions given in Table 4.2. It is most important to recognize that there are many levels at which the question of Table 4.2 can be answered. For convenience three levels have been identified here. Level I corresponds to low levels of information use, few personnel and small time commitments. Level III is more demanding of information, personnel and time commitments. The categorization into three levels follows the approach taken by Lettenmaier and Burges (1975).

The interactions shown in Table 4.1 indicate, for example, that the nature of the problem (Table 4.2 can be used to help define this) influences the level of the problem (i.e. geographical and political boundaries), the study objective(s), the physical system to be examined, data needs, economic disaggregation, legal hierarchy, and obviously the optimal policy. Therefore, steps such as those listed in Table 4.2 should be thoughtfully considered (as well as others where appropriate) to avoid analyzing the wrong problem(s) for an area.

The items of Table 4.2 only relate to current or past problems. If future levels of water use are likely to increase, conjunctive systems that have not been a problem in the past could become problems for changed future demands. Therefore, problem systems as well as apparent trouble free systems must be analyzed by the relevant "agency" with respect to planned or anticipated future demand scenarios. This hierarchical approach will permit allocation of personnel and other resources to study the most important regional problems first. An approximate rule of thumb would be that as demand levels and pollutant loads increase on surface supplies, problems of conjunctive management will occur first in watersheds exhibiting higher variability and skew in the distribution of natural streamflow data. Demands can be controlled to some extent through issuance of water right permits.

Table 4.2 Identification of Conjunctive Use Issues for an Area

Activity or Question	Level	Data Needs*	Uncertainty	Personnel Needs
Has there been an increase or decrease in piezometric head with time?	I III	Minimal Extensive	high moderate	U, S, F S, M
Identify claims of surface and groundwater diversion violations	I	Minimal to extensive	small	U, F
What adverse groundwater or surface water quality observations are available?	I II	Minimal Moderate	high high	U, F U, M
Has salinity of groundwater increased (coastal)?	I III	Minimal Moderate	moderate moderate	U, F U, F
Is it possible to recharge one or more aquifers with fresh water or treated wastewaters?	I III	Modeling Needed	high high (moderate)	S, F S, M
Examine historical data for water supply and demand to determine if conjunctive management might be of some benefit	I III	Minimal Extensive	moderate/ high moderate	S, F S, M
Conduct a mass balance of water movement for the area and identify any unexplained "leaks" or interaquifer transfers**	I III	Moderate to extensive Extensive	high moderate/ high	S, M S, M

* Minimal (e.g. newspaper account)
Moderate: available records
Extensive: Available records; verification of records; additional observations

F Few personnel
M Moderate numbers of personnel
S Skilled personnel
U Unskilled "technical" assistants
** This analysis can be extremely expensive and unreliable particularly if the quantities of interest are of the same order as the errors in measured flow quantities. Error propagation analysis is essential.

4.3.2 Scale of Problem

The scale of a problem can be determined by performing the following four tasks.

1) Define physical aquifer and watershed boundaries of interest
2) Determine political boundaries and identify all "agencies" involved (both public and private)
3) Determine the level of economic activities
   i) local (output from economic activities is used in local area)
   ii) interstate
   iii) national
   iv) international
4) Specify undefined users of water
   i) downstream users' rights
   ii) low flow requirement in stream
   iii) intra-aquifer water transfer

4.3.3 Variables

In identifying the variables involved in a conjunctive use system, it is necessary to analyze physical, legal, and economic aspects of the system. Tables 4.3 to 4.5 show the variables which should be considered in the analysis. After defining all the variables it might be necessary to redefine the level of the problem in order to include all relevant variables, particularly legal criteria.

At this point in the analysis a means should be developed to screen the unimportant variables and reduce the alternative management/operation scenarios. The screening function is extremely important: such an analysis necessitates inclusion of sufficient detail of the many interacting variables to ensure that valid modeling and review of alternatives takes place. It is not clear how, in general, this activity should be pursued. Whatever is done, the

Table 4.3 System Physical Variables

1. Surface Water
   a. Availability (stochastic nature)
   b. Quality
   c. Losses especially from surface reservoir
   d. Possible surface water transfer
2. Groundwater Aquifer
   a. Type of aquifer
   b. Storage capacity and aquifer hydraulic characteristics
   c. Losses from aquifer
      i. Transfer to adjacent aquifer or stream
      ii. Pumping facilities
      iii. Evapotranspiration
   d. Recharge features
      i. Precipitation (local and distant)
      ii. Streams
      iii. Other aquifer
      iv. Irrigation
      v. Irrigation return flows
      vi. Artificial recharge
   e. Quality of groundwater

Table 4.4 List of Legal Constraints/Variables

1. Surface Water
   a. Low flow requirements (spatial and temporal variation)
   b. Surface water transfer
   c. Operation of reservoirs
   d. Navigation requirements
   e. Allocation rights of users/diverters
2. Groundwater
   a. Interaquifer water transfer
   b. Allocation rights of users
   c. Quality of recharge waters
   d. Land subsidence

Table 4.5 Economic and Financial Variables

1. Demand for Water
    a. Agriculture
    b. Industry
    c. Municipal
    d. Hydroelectric
    e. Recreation
    f. Water Borne Commerce
2. Return on Economic Activities
3. Cost Functions (for technological activities)
    a. Surface water transfer
    b. Groundwater transfer
4. Project Financing
    a. Financial feasibility
    b. Constraints on available policies

representations of economic, physical, and legal aspects of the system must be equally matched. The total system model resolution needed for screening purposes is not clear to the authors at this point in time. One possible approach to follow for system modeling is given below.

4.3.4 Modeling

It may be possible to approach identified issues in an hierarchical manner. Objectives at high level hierarchies may be reached via broad policy actions. Objectives at much lower hierarchies may require extensive analyses to examine possible solutions. No matter what hierarchy is involved, however, it is always necessary to clearly define the objectives that models must explore.

In defining system modeling objectives there are usually two steps involved:

1) determining the intention of modeling (e.g, decision making, understanding flow physics, etc.), and
2) obtaining evaluative criteria or measures of effectiveness particularly for economic activities.

The measure(s) of effectiveness for various planning or operational alternatives to meet the objective(s) has usually been taken to be one or more of the following:

1. Minimize the system cost to satisfy a set of demands
2. Maximize total net benefits
3. Maintain water quality (to some specified standards)
4. Achieve equity among users
5. Enhance social well being.

Measures 1 through 3 can be quantified; 4 and 5 fit the fuzzy domain (Zadeh, 1965). Measures 1 and 2 are satisfactory provided all benefits and costs are fully expressed in terms of a single numeric. Unfortunately it is not known how to handle this problem at this time so a less than satisfactory multiobjective approach for several dominant measures might be pursued. Some work in the multiobjective domain has been reported by Cohen and Marks (1973, 1975) and Haimes and Hall (1974).

It was shown in Table 4.1 that the nature of the problem and the objective of the modeling defines the type of the model needed to incorporate physical, economical, and legal features either through use of constraints or via direct modeling. A further limitation on modeling is imposed by the method used to implement the optimal alternative. A very important factor which has seldom been directly considered is the availability of data for all variables. In many cases the model cannot be verified or be applied due to a lack of necessary data. The purpose of the modeling is the criterion which governs the type of model to be used. Basically two types of models, decision making, and learning models, are appropriate. Useful learning models fit more into a category of "general information learning" rather than "scientific update" learning models.

Now that variables constraints and objectives have been covered the remainder of the chapter covers different types of models of use in conjunctive use analyses.

For general purpose information and overall understanding of the physical system, simple mass balance or flow simulation models have been used to trace water movement through conjunctive systems. Some of the articles reviewed employed these techniques either to identify a problem or to determine the anticipated future state of groundwater (Danielson and Qazi, 1972, Perez, et al., 1972). Such models were not intended for use in decision making concerning allocation. For decision making purposes several well known operations research techniques have been used. Whenever they are used simplifying assumptions about the flow physics do, however, need to be made. Five basic techniques, linear programming, quadratic programming, dynamic programming, simulation, and multilevel optimization techniques, appear to be most useful in the overall decision making context. It should be noted, however, that all representations require large numbers of variables/parameters and considerable data. Specific suggestions covering these techniques follow.

Linear Programming

In cases where relationships and cost functions for variables can be explained in linear forms, linear programming approaches have been used. Factors which cannot be directly incorporated into the modeling are treated as constraints. This usually requires legal issues to be treated as constraints. The sensitivity information from the LP output is of considerable use in assessing the importance of different constraints. However, LP formulations are unlikely to adequately determine the "optimal" legal policy because of difficulties in representing stochastic supply and demand for the system. Efforts to linearize nonlinear relationships contribute to problems of dimensionality. High dimensionality caused by the number of variables and constraint equations can rapidly use up digital computer capacity.

Quadratic Programming

This approach has the advantages and disadvantages of the LP approach. The major positive feature is the ability to accommodate certain forms of nonlinear relationships. Maddock (1974) has demonstrated the utility of the approach for a relatively small area. This approach coupled with his "linear pumping influence" representation appears to have significant utility.

Dynamic Programming

The principal advantages of state incremental dynamic programming for conjunctive use studies result from the convenience with which the approach handles nonlinearities. A major disadvantage, however, is that no sensitivity information is available with the optimal result. The methods is further limited by the number of state and decision variables that can be accommodated. For systems where only two or three decision variables are involved, dynamic programming should be seriously considered for determining optimal policies.

Simulation

Simulation *per se* cannot yield an optimal solution. All system nonlinearities can be included to whatever level of detail is practical or desired. The approach will yield a set of outputs for a given set of inputs. Many such simulations are needed to cover the range of possibilities. The best of these outcomes can be determined from a search procedure, hence a satisficing solution can be obtained. There is no sensitivity information associated with this result. Simulation is most useful in a learning sense but has limited utility in decision making settings. Performance of an adequate analysis of a highly interacting system can rapidly become prohibitively expensive in terms of time and resources.

Multilevel Optimization

Yu and Haimes (1974) have used this approach in a conjunctive use problem; one or more of the techniques may show promise in future work. Basically the approach provides a means for system decomposition with respect to optimization. This permits choice of different geographical zoning and political decision making levels which reflect the nature of subproblems of the major regional problem. One or more optimization technique is used to optimize each sub-level. Some criterion is used to lump these optimized sub-level outcomes to obtain an overall policy. The technique is still undergoing development.

4.3.5 Policy Implementation

One of the important factors which is usually neglected, or has been simplified by a statement assuming some "all powerful agency will implement policy," is the implementation of the optimal policy. Almost all the articles reviewed expressed in one way or another that "a central administrative authority exists and will implement the optimal policy" (Young and Bredehoft, 1972; Maddock, 1974).

Clearly the acceptance of the optimal policy by the numerous affected publics[a] is a major issue for without public interest the optimal policy may never be implemented. Social criteria and methods for implementing an optimal policy influence the optimal policy and a part of the model or the whole system model might need to be redefined to accommodate these realities. For example, the "equity" of the optimal policy, the water quality criteria, and social well-being may be evaluated at this point. This may necessitate redefinition of a part of the system to include new criteria.

4.4 Summary

In a general sense, issues that must be considered in conjunctive use analyses have been identified and discussed. These issues have been distilled from the work of many authors who have examined numerous conjunctive systems. The systematic approach does not offer an immediate solution. Nor does it provide an all inclusive checklist. It is hoped that the reader

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[a] See Bishop (1970) for a discussion of the publics involved in water resource issues.

will approach conjunctive use problems with a mental attitude conditioned by the approach outlined herein.

Two very useful steps which should always be taken include constructing an approach to determine the nature of the problem to be studied, and determining the interactions of importance. Constructing interaction flows such as Figure 4.1 and Table 4.1 reduce the risk of the analyst prematurely deciding what dominant interactions should be modeled.

We are unable to offer concrete guidelines as to what types of models should be used where. All models have advantages and disadvantages and all are data demanding. Before attempting any modeling, determination of the level of the problem must be carefully addressed. In data limited situations the data scarcity or cost to obtain data may well dictate the use of coarser spatial and temporal scales than the analyst would prefer. This in turn means that the policy to be implemented will be conservative, reflecting the lack of knowledge of flow movement and system dynamics. The economic value of data will dictate future levels of problem investigation.

CHAPTER 5

SUMMARY

This report covers many dimensions of the conjunctive ground-surface water use problem. The numerous possible types of problems reported in Chapter 2 resulted from a distillation of the writings from numerous authors as well as from anticipating some effects resulting from increased usage levels in the future. Considerable detail concerning the disaggregation of variables is given to emphasize the importance of complexity in this type of management situation.

A large body of literature covering the conjunctive use issue is listed in the bibliography. Thirteen of these papers which represent the basic approaches that have been taken to date are discussed in some detail in Chapter 3. It is clear that the dimensionality of the problem has forced all investigators to make simplifying assumptions whose validity usually cannot be checked. It is also clear from the literature that in most cases the physical part of the system has been much more thoroughly modeled than have the economic and legal components. Major efforts are needed to equalize the sophistication of representation of all parts of conjunctive use modeling.

Chapter 4 is an attempt to show a systematic approach to analyzing conjunctive use problems. Emphasis is placed on correctly identifying the problem to be solved. No panaceas are offered; rather a mental attitude approach to the problem is suggested. What must be definitely recognized is the influence of dynamic feedback in these systems. This feature makes system couplings an important issue when choosing sub system modeling boundaries.

The analysis method presented here is only a framework for conducting analyses. The approach needs to be tested and further studied to determine its utility. It appears that there are three areas that need to be given particular attention:

1. Models need to be developed that can be conveniently used to identify conjunctive use problems both for the present and future,
2. Simple models which incorporate physical, legal and economic components of the system need to be developed to facilitate determining the most important interactions, and
3. The developed models need to be applied to several different well known conjunctive use problems to test their utility.

A major problem confronting the analyst is still to be found in the choice of a detailed system modeling approach. Simulation most faithfully represents the system but does not yield an optimal policy. An important direction for research effort would be to examine the general nature of "response surfaces" for conjunctive use problems. If they turn out to be relatively flat then it may be possible to use the simulation approach rather than direct optimization procedures. This would overcome many of the problems of dimensionality which limit the use of optimization models.

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APPENDIX A - BIBLIOGRAPHY

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