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In the past decade considerable research in several disciplines has been oriented toward the design of optimal capacity expansion plans for water resource systems. The emphasis of most of these efforts has been directed toward minimization total cost outlays in project planning. This focus somewhat limits the full applicability of the optimal capacity expansion solutions since it is believed that the criteria of economic efficiency is not well addressed in this mode. This study explores the merits of scheduling water resource project facilities on the basis of anticipated economic benefits provided, an approach needed only infrequently in the systems engineering literature. Using the Umatilla River Basin in Northeast Oregon as a case study example, the facilities (and their alternatives) of a previously planned federal water resource development project in that area were carefully analyzed with respect to the magnitude and timing of anticipated benefits and costs. Irrigated agriculture and fishery development/enhancement benefits were the two principal purposes of the project considered. In addition, benefits arising

from flood prevention, municipal and industrial water supply, and erosion control were also integral to the original overall evaluation. The design of the research was to first implement a basic scheduling model in the context of the case study area and then to explore the ramifications of exchange-theoretic and distribution-theoretic criteria on the timing of facilities and the ultimate allocation of water among purposes. The model implemented was aimed at maximizing the present value of net benefits inherent in an optimally timed set of facilities subject to an annual budget constraint. Having designed the model along integer programming lines, three different solution techniques were explored in order to realize a desirable level of efficiency in basic model solution. It was found that reasonably efficient solutions could be obtained. By optimally timing the facilities it was found that the total present value of net benefits of the project could be significantly enhanced when compared to the original schedule proposed in the project planning documents. Of even greater interest is the issue of incorporating into the planning process (and specifically into the capacity expansion mode of planning) considerations of tradeoffs or exchanges between project beneficiaries. Such exchanges and other distributional criteria can affect and be affected by the selection and timing of project facilities within an overall project design. These interrelationships are explored paying particular attention to the way in which exchanges of water (via water rights transfers) could establish higher levels of benefits in future years. Noneconomic exchange processes such as the enforcement of extant property rights relating to water resources are another issue which complicated the process of water planning. Such distributional criteria are difficult to incorporate into the capacity expansion mode of planning analysis. However, ways are explored by which the basic model may be modified and used by decision makers in order to take account of more realistic problems in water resource planning for individual river basins.

Optimal Expansion of a Water Resource System and Issues of Water Allocation and Utilization: Umatilla River Basin, Oregon

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I. INTRODUCTION

An area of public concern that continues to attract considerable attention in nearly every nation is the issue of water resource allocation.[1] Although the literature on the subject is lengthy, the contributions of Eckstein (1961), Howe and Easter (1971), and Beattie et al. (1971) are representative of water allocation research pertaining to the western United States. As a consequence of rapid population and economic growth in certain locations in this region, demands for water can be observed to be increasing over time - water shortages during drought periods are certainly newsworthy items. In order to attempt to resolve these dilemmas (relatively few in number at present, but likely to increase in time), individual water users, their elected representatives, and the personnel of public sector bureaucracies have proceeded to promote significant investments in planning for water resource allocation and management. Even though the amounts of "new" water which can be developed (in the usual sense) are steadily diminishing, the planning activity continues.

Economic criteria have often been recommended as the most suitable means of directing the exploitation of water resources in a way

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[1] Throughout this thesis the term water allocation will be used to denote development activities (as commonly defined) as well as the more specific issues of reallocation and redistribution.

that the resultant net social benefits of the investment are maximized (Kelso, Martin, and Mack, 1973). The disclaimer to this statement is, of course, that if the opportunity exists to consider other criteria - social, political, cultural concerns, for example - then decisions must necessarily be based on all these concerns collectivley. Presuming that the economic criteria are important, the 1979 U.S. Water Resources Council Procedures for Evaluation of National Economic Development Benefits and Costs in Water Resources Planning lays out procedures to be followed when economic efficiency criteria are employed to select a desirable subset of projects. Maximization of total benefits is implied as the primary consideration in this selection procedure.

Many economists encourage the use of additional criteria from economics to aid in project selection. Chief among these is anticipated distribution of benefits among beneficiaries at least somewhat in proportion to the share of costs assumed. Willingness to pay for benefits from a project is closely related (and indeed is an underlying tenet) to the cost-sharing issue.

In addition to the distributional issue (a corollary to the principles of maximization of net benefits) in water resource planning, there is also a corollary concerning the optimum sequencing and sizing of projects in an overall plan of many economically feasible projects. Because of the interest cost of money, the time pattern over which benefits are generated by individual projects, and interdependencies among projects, there will be advantages to different sequences of projects. In striving to attain the maximum net benefits from a planning, the sequencing problem is not inconsequential. In fact, even within the confines of planning a single project, the sequencing of alternative facilities may make a difference in the overall evaluation of the project.

This thesis is aimed at exploring the practical, but more so economically relevant dimensions of sequencing a set of facilities for a single project. It will be seen that the economically relevant dimensions of project sequencing include not only the full consideration of benefit and cost measurements, but also the distributional issues just mentioned.

Background of the Study

One area of the Pacific Northwest where an emergency shortage of water supplies may lead to a need to examine all water allocation alternatives is within certain sub-basins of the Columbia River Basin. The Columbia Plateau region in Oregon is characterized by low rainfall amounts in the summer; this is especially true of the area near the Columbia River. Because of a high rate of water development (based on diversions from the Columbia River), this area has recently experienced changes in the local economy and requirements placed on the stock of water resources (viz, the Umatilla River) upon which the area has traditionally relied. The population growth has been significant, resulting in increased requirements for municipal and industrial (M & I) water as well as conversion of previously (older) irrigated farmland to rural residential property development. More important has been the recognition that any instream flow purposes such as fishery development and enhancement will be permanently jeopardized if significant offstream development (irrigation) continues.

As these issues emerge, two kinds of water development plans for the Umatilla River Basin have been suggested recently. The first envisions continued development of Columbia River but involving an integration of those facilities with existing facilities and systems which are part of older irrigation districts in the lower Umatilla River Basin. The recent Stanfield Westland Irrigation Development Plan (Vitro Engineering/Boyle Engineering, 1976) is an example of this development effort. More relevant to this thesis are river basin development plans which envision more or less complete allocation of the water resources of the Umatilla River by means of potentially feasible facilities and implementation of minimum streamflow levels. An example of this kind of plan is the U.S. Bureau of Reclamation (now U.S. Water and Power Resources Service) Feasibility Plan for the Umatilla River Basin Project. This plan, developed in 1970, is multiple purpose in nature but focuses primarily on the issues of irrigation and instream flow (fishery) benefits. While it is not a complete document delineated with respect to all possible water allocation alternatives, it is a convenient starting point for considering the practical and the economic relevance of project (facility) sequencing.

Economic Objectives in the Project Timing Problem[2]

The ultimate goal usually suggested by economists for natural resources management is the maximization of social welfare (McKean, 1958; Gardner, 1966). The Samuelson-Bergson social welfare function, though it is a useful device for conceptualizing social optima, has

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[2] In the literature of water resources capacity expansion and the text of this research, timing problem, sequencing problem and scheduling problem are used interchangeably to describe the task of sequencing a set of projects over time.

presented operational difficulties ranging from the possibility of indeterminacy to the overwhelming difficulty of empirical specification (Arrow, 1951).

There are several economic objectives instead often being considered by economists for water resources management: (1) economic efficiency, (2) greater equality of income redistribution, (3) economic growth of the nation or of a geographic area within the nation, and (4) stabilization of economic activity (Castle, 1964).

It is agreed that social welfare can be improved when economic efficiency and income redistribution effects are considered simultaneously, e.g., when Pareto-Safety criteria is employed (Randall, 1975). Unfortunately, up to now little consensus exists concerning how to handle the distributive consequences of water resources management.

When the problem of sequencing proposed projects is under consideration, the feasibility investigation of proposed projects should be available beforehand. Sequencing (timing) is to reach for a time table for the implementation of these proposed projects subject to various constraints (such as water requirements or budget constraints) in such a way that the total present value costs or the total present value net benefits of development are minimized or maximized. Therefore, sequencing techniques are tools used to guarantee the maximum economic efficiency of water resources development without disturbing the income distribution pattern. The timing problem is therefore consistent with the objective of social welfare maximization.

Objectives of the Thesis Research

The timing issue in water resource project implementation is here suggested to be essentially a corollary to the general issue of project evaluation and selection by means of benefit/cost analysis or some related technique. It was suggested above that when the timing issue has been studied, it has often been in a setting which focuses purely on cost minimization - avoiding the real essence of benefit/cost comparisons. In addition, it was pointed out that truly economic considerations concerning project evaluation do not stop with benefit/cost analysis, but should go on to deal with exchange possibilities and other distributional criteria. There is evidence that these latter issues will become increasingly more important in the field of water resource allocation.

In view of these observations, this thesis proposes to critically examine the timing issue as it has been applied to water resources planning - aiming, in particular, to add a more realistic (and relevant) economic dimension to the problem. The specific objectives are:

- to review the literature in the field of optimal capacity expansion of water resource systems
- to suggest a dynamic dimension to conventional benefit/cost analysis establishing a complete procedure for economic evaluation of a water resource allocation situation
- to identify and solve numerically a set of optimal capacity expansion problems for the Umatilla River Basin in Oregon
- to extend the results of the theoretical development and the

numerical excerises above by adding dimensions of economic exchange and distribtuion.

The end result, it is hoped, will add to the understanding about how complex decision-making situations can be somewhat simplified by the use of planning models which feature sound economic logic.

II. OPTIMAL CAPACITY EXPANSION OF WATER RESOURCE SYSTEMS: A REVIEW OF THE LITERATURE

In the past decade, a combination of rapid progress in computer technology, coupled with the development of refined computational procedures, has extended the study of optimal expansion of water resource capacity to the point where problems of increasing complexity can be solved more efficiently. Because the field of water resource capacity expansion is becoming increasingly diversified, a complete survey of the literature in this field is almost impossible and beyond the scope of this research. Instead, the literature review here is conducted in such a way that leads to the formulation of a general model which is valuable in solving a relatively common problem encountered in public water resource planning.

Historically, the emphasis of this voluminous literature in water resource capacity expansion has been placed almost exclusively on the cost aspect of the problem. The task of obtaining data on the expected benefits for water resources development may involve significant difficulties. This is especially true when non-market (or public) goods (such as recreation benefits) are the elements of the array of benefits. Simultaneous consideration of both cost and benefit aspects of proposed developments may be more desirable and, from an economist's perspective, more justifiable.

As just suggested, the literature in water resource capacity expansion can be classified into two categories. They are: (1) minimizing the present value of costs hereafter called the MPVC model and

(2) maximizing the present value of net benefits hereafter called the MPVNB model. The MPVC model has been well developed in the literature and is frequently employed in case studies. Although the MPVNB model has been almost totally ignored, its inherent appeal to economic logic should be deserving of an increasingly important role in the optimal capacity expansion area.

The literature review is organized in the following three stages. First, two commonly used solution techniques (i.e., dynamic programming and integer programming) are presented. This is a prerequisite for understanding the nature of the actual problems. Second, the minimizing present value cost model is addressed. Following the historical development of the MPVC model, a general MPVC model is formulated, followed by a summary of the applications of MPVC models that have been made. Last, the maximizing present value net benefit model, the basis of this thesis, is addressed. The need for a MPVNB model is first identified and followed by the discussion of the comparison between the MPVC model and the MPVNB model. The superiority of the MPVNB model over the MPVC model is then demonstrated. At the same time, it is suggested that a wider class of problems is solvable with the present state of art in MPVNB modeling.

Solution Techniques

There are two principle solution techniques that have been commonly used to solve the problems of water resource optimal capacity expansion. These techniques are discussed prior to the models in order to facilitate the latter discussions.

Dynamic Programming

Because the optimal expansion of a water resource system is typically a multi-stage decision problem (in which the decision for the present stage is affected by the decision made in the preceding stage), dynamic programming has been the most widely used problem-solving technique in this field. However, because of the usual dimensional difficulties[3] (Bellman and Dreyfus, 1962), the utilization of this versatile tool is usually limited to small problems, even though rapid progress in both computer technology and computational procedures has been made. Hence, the development and employment of efficient algorithms and computer codes are the principal concerns of most of the literature in this area (Morin and Escogbue, 1971).

In the so-called sequencing problem, Butcher, et al. (1969) solve their problem by employing Bellman's "The Principle of Optimality"[4] in dynamic programming. Although they claimed that the computational effort of the proposed method becomes relatively less imposing as the complexity of the problem increased, their statement is believed to be in conflict with the usual problems of dimensionality as pointed out by Morin and Escogbue. The latter authors attempted to eliminate some irrelevant project schedules from consideration. This is termed an application of the "imbedded state space approach" (called DP_2 by Morin and Escogbue). They were hopeful of reducing computational effort

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[3] That means, as the number of decision variables increases, the requirements for computational time and storage will soon go beyond the capacity of the computer.

[4] For example, an optimal policy has the property that whatever the initial state and initial decisions are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision.

but noted that improvements of the algorithm would still be needed to cope with yet more realistic water resource expansion problems.

Integer Programming (IP) and Mixed-Integer Progamming (MIP)

Recently, integer programming has been suggested as a viable optimization technique to deal with the problems of optimal capacity expansion of water resource systems. Integer programming is a special case of linear programming with two major distinctions. The values for all or part of the variables need to be integers for pure integer programming or mixed-integer programming, respectively. Corresponding problem-solving algorithms such as branch and bound, Gormory cut, and 0-1 implicit enumeration[5] have been developed particularly to search for integer solution. It is noted, for example, that Joeres, et al. (1974) Brill and Nakamura (1978) have employed branch and bound mixed-integer programming to the problems of waste-water treatment planning. On the other hand, the pioneering research done by Lauria (1972) used branch and bound mixed-integer programming to solve water resource capacity expansion problems. It deserves mention here because it is the only research which points out some of the important advantages of using mixed-integer (MIP) programming.

Lauria first recommends consideration of the concept that new projects should be implemented only when existing supply capacity is about exhausted. Therefore, only part, rather than all, of the planning horizon needs to be considered. When so-called "construction opportunity

[5] Discussion of these three techniques will be detailed in Chapter V..

periods" are substituted for complete enumeration of the whole planning horizon, the number of decision variables and hence the requirement for computational effort are reduced. However, the reduction of the number of decision variables depends upon how many combinations of the projects have their supply capacity falling into the same annual increment of the requirement function.[6] It is difficult to determine a priori how many decision variables can be eliminated for each specific problem without an actual calculation of construction opportunity periods.

Using mixed-integer programming with branch and bound algorithm developed by Shareshian (1969) to solve the problem illustrated by Butcher, et al., Lauria concludes that MIP is preferable to DP because the optimal solution (plus the sets of suboptimal solutions) can be identified by MIP. Although economic evaluation plays a predominant role in optimal expansion, it is not the only issue in project selection per se. A convincing and sound decision-making process can be achieved only by selecting an economically sound plan which is also acceptable with respect to social and political considerations. Therefore, a set of suboptimal solutions adds a useful dimension to decision-making, especially when the difference between optimal and suboptimal solutions is related to the preference of social and political considerations.

Another disadvantage to DP is the lack of standard DP algorithms such as the ones available for MIP and IP. Algorithms must be tailored to the individual problems (Major and Lenton, 1979). The availability

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[6] This observation can be better understood by looking at the numerical example in Chapter IV.

of commputer packages for employing MIP and IP therefore reduces the amount of time for programming which is regarded as part of computational effort in solving the problem. Even though Morin (1973) demonstrates that DP is more efficient than MIP in solving a specific problem, there is little consensus regarding the comparison of overall efficiency between these two solution techniques. Together with the fact that research in this diversified field can be conducted by researchers from different disciplines (such as economics, engineering, and management), selection of a proper technique seems to be determined by the nature of the problem to be investigated as well as by the interest, background, and resources (both of labor and computer times) of the researchers.

Because the mathematical expressions of MPVC and MPVNB models are more understandable when they are formulated according to MIP and IP, the following discussion of these two models will be presented in the forms that fit the modes of MIP and IP.

Minimizing Present Value Cost Model

Butcher, et al. (1969), in what appears to be one of the early such attempts, postulate a schedule of price-independent water requirements[7,8] that increases over a finite time horizon. To meet the water

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[7] The research in this field generally neglects the possibility of price sensitive demand relationships and instead forecasts the future use of water on a "requirement" basis.

[8] There is a wide class of applications in the field of water resource expansion. Hence, after Butcher's research water requirement function means a requirement function not only for water but also for various outputs that are produced by water resources projects, such as hydropower, treatment of waste-water, etc.

requirement, a set of water supply projects each having a different size and cost is defined, where the aggregate size (capacity) of the projects in the set are equal to the maximum level of requirements at the end of the planning horizon.

Since two major determining factors of present value costs, construction costs and interest rates, are assumed constant, the construction of these projects should be initiated as late as possible to minimize the total present value of construction costs (Figure 2-1). Analysis of a similar problem with the same model conducted by Erlenkotter (1967) reveals that construction of a project should ideally be delayed until the social losses due to unsatisfied requirements accrue at the same rate as the annual opportunity cost of capital invested in the project. Therefore, the planning problem is to determine the optimal sequence of the proposed projects subject to a water requirement function so as to minimizes the total present value of construction costs.

Development of the MPVC Model

The research done by Butcher, et al., is generally acknowledged as poineering in the field of water resource planning. However, in their over-simplified model there are several debatable assumptions which are discussed below:

1. The total supply capacities are equal to the level of requirements at the end of the planning horizon.
2. Projects are independent.
3. The benefit of each unit of supplied water is constant.
4. Operation costs are proportional to the benefits generated from supplied water.

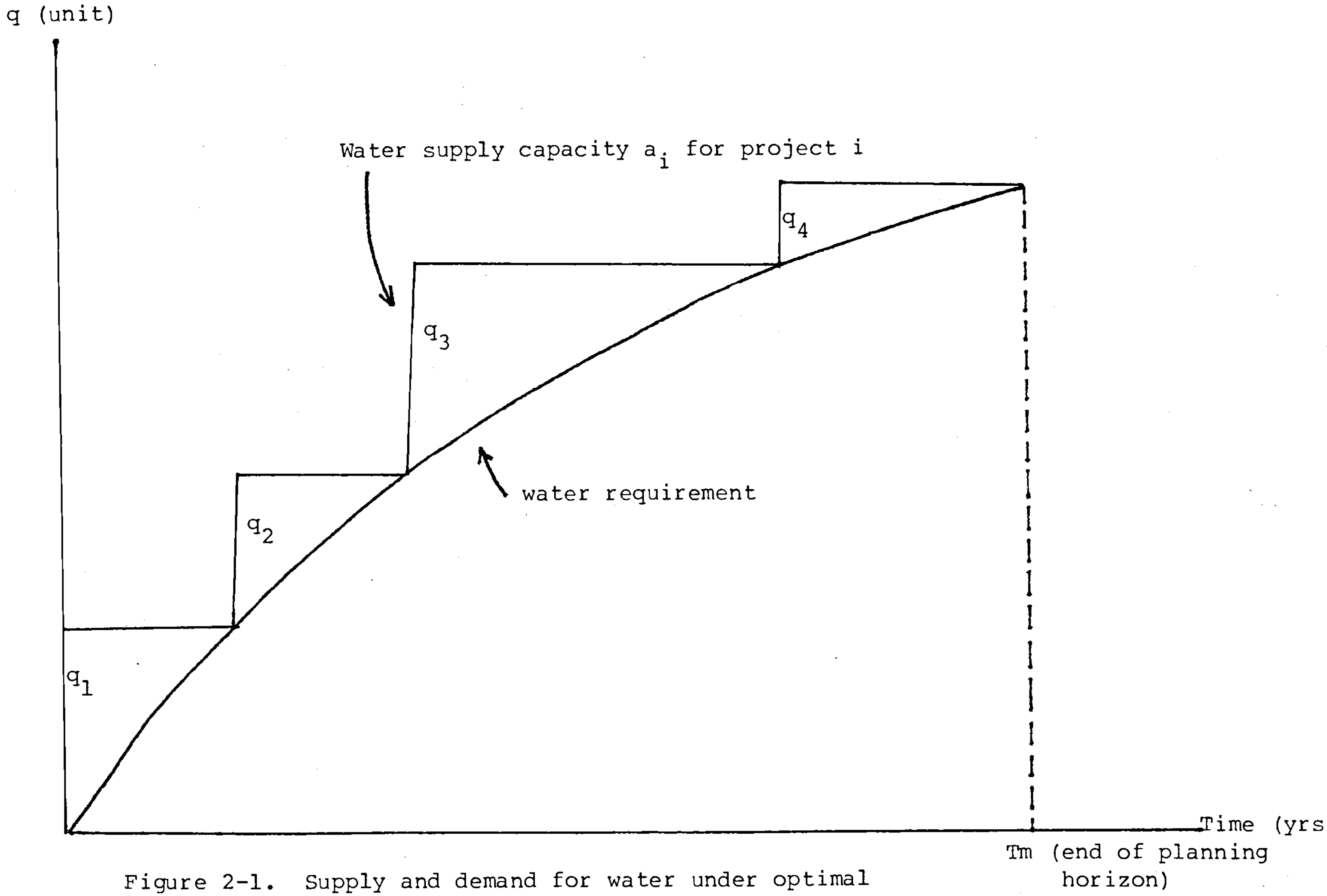

Figure 2-1. Supply and demand for water under optimal sequence of construction.

5. Social costs of an unsatisfied water requirement are infinite.

6. The scale for each project is fixed.

7. Water requirement function is deterministic and given.

The development of MPVC model has been centered on the first six assumptions while the discussion of the last assumption will stimulate the need for the development of the MPVNB model. Therefore, the discussion of the first six assumptions is presented as follows and the discussion of the last assumption will be elaborated later.

First, in what is termed a sequencing problem, the sum of supply capacity of projects postulated by Butcher, et al., is equal to the maximum requirement level at the end of the planning horizon. The optimal solution, hence, must include implementation of all proposed projects. This, however, is less common in the real life problems. Presenting a more general class of problems - scheduling problem - Morin and Escogbue (1971) consider a set of projects of which maximum supply capacity is much greater than the maximum level of requirements. The general scheduling problem thus becomes defined as selecting a subset of proposed projects and then sequencing their completion times.

The second assumption involves the phenomenon of interdependency among projects. In his analysis of optimal investment in a set of hydropower-generating projects, Erlenkotter (1973) incorporates this feature. Identification of these interdependencies among projects is essential to the problem formulation and hence in searching for the optimal sequence. Therefore, Erlenkotter was able to achieve greater reality in the MPVC model without causing any difficulties in problem formulation and solving.

Assumptions 3, 4, and 5 are concerned with the social costs of unsatisfied requirements. These costs are usually assumed to be infinite, making it essential that all requirements must be satisfied. With respect tot hese assumptions, different unit benefits and unit operation costs generally will be associated with different porjects,[9] even to the same project with different scales. These skeptical assumptions are noticed but sledom treated properly in recent literature.

In the United States, there is in effect a policy of providing abundant supplies of water to equal or exceed water requirements. This situation, however, cannot justify the assumption that unsatisfied water requirements would result in infinitely high social losses. Water requirements can often be satisfied by importation from a neighboring community (Beattie, _et al._, 1971) or other alternatives at finite prices. Such alternatives exist even in the case of sequencing a set of waste-water treatment plants. Although the enforcement of standard systems for effluent discharge encourages treatment capacity to always equal or exceed necessary capacity, it is seldom true that temporary failure in meeting required standards causes an infinitely high social cost.

A final point about assumptions 4, 5, and 6 concerns a finite social cost. If social losses of unsatisfied water requirements are made finite, the pricing of the social losses seems to be troublesome, especially in the case of multi-purpose development. To this end Lauria suggests that different price schemes be assigned to supply deficits thereby

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[9] Especially when multi-purpose is a major feature of water resources development.

leading to a kind of sensitivity analysis. However, a sensitivity analysis performed by use of some arbitrary prices may not generate any useful information to decision making. An economic analysis elaborating the resultant social losses of unsatisfied requirements, though some breaktroughs are needed, is essential if supply deficits are allowable. Further, the fact that primary social losses of the unsatisfied requirements may vary among different requirements (of multipurpose porject) adds complexity to the inherent difficulty and hence suggests the use of a MPVNB model instead of a MPVC model for optimal sequencing.

The sixth assumption alludes to a common situation in water planning. Instead of assuming a fixed scale for each project, it may be more realistic to examine the economies of scale which are possible in site-specific cases. Average costs of a project are believed to decrease with increasing size over a certain range. Therefore, one of the weaknesses of Butcher's model is the inability to completely consider comparative advantages among projects in sequencing exercises because project scale is assumed to be fixed. Consequently, the ocmparison of comparative advantages among and within projects, which are made possible by substituting variable scale for fixed scale, constitutes an important area of modification of the MPVC model.

There are two ways to relax this restrictive assumption. In what appears to be the first of such attempts, Lauria suggests a fixed construction cost and a unit cost for scale which are identified for each project. An upper limit on scale reflecting engineering feasibility is imposed on each project. Although a linear construction cost function does reflect the phenomenon of economies of scale, a concave construction function more realistically reflecting economies of scale is preferred. A separable (piece-wise) progrmaming is considered as a suitable technique in dealing with nonlinear cost functions when program formulation is preferred to be linear.

Although a continuous scale approach makes the analysis of comparative advantage more complete, it may raise some difficulties in accurately estimating the unit cost over certain ranges. A set of discrete scales rather than one continuous scale may be a practical means of selecting the size of a project. In this regard, a second approach which tries to incorporate the comparison among and within projects without raisng any extra controversies to the model is employed by O'Laoghaire and Himmelblau (1974). Instead of using continuous scales, O'Laoghaire and Himmelblau consider three discrete scales and impose a mutually exclusive constraint to each project. One disheartening aspect of considering discrete scales is worthy of mention here. It can be estimated that computational time in solving the problem by employing dynamic programming or integer programming will increase rapidly as the number of decision variables (representing the number of projects and length of planning horizon) increases. Hence, limitations on the number of discrete scales is crucial to prevent an enormous need for computational time, especially when the number of projects being considered has already placed a strain on computational time.

General MPVC Model

Following from the preceding discussion, a MPVC model can be formulated first by making several basic assumptions. A general MPVC model then will be developed when modification of the model in light of various specific considerations are incorporated. The basic assumptions for the MPVC model are:

1. A non-decreasing water requirement function (or requirement function for project outputs) over time is deterministic and given (i.e., $Q_t = f(t)$, t=1 ... T, where Q_t is the quantity of requirement and T is the end of the planning horizon.
2. There are S different projects (X_i) with different scales (k_i) and different construction cost (C_i), i=1 ... S.
3. The resultant social losses from unsatisfied water requirements are P_t at year t.
4. Only one project can be built each year. With these four assumptions listed above, a MPVC model can be formulated as follows.

<u>Formulation of the MPVC Model</u>

Objective function:

$$\text{Minimize } Z = \sum_{i=1}^{S} \sum_{t=1}^{T} F_t C_{it} X_{it} + \sum_{t=1}^{T} F_t U_t P_t \qquad (1)$$

Subject to

Requirement constraints:

$$\sum_{j-1}^{t} \sum_{i-1}^{S} K_i X_{ij} + U_t \geq Q_t \qquad t=1...T \qquad (2)$$

Construction constraints:

Only one project can be constructed each year.

$$0 \leq \sum_{t=1}^{T} X_{it} \leq 1 \qquad i=1...S \tag{3}$$

Each project can be constructed at most once.

$$0 \leq \sum_{i=1}^{S} X_{it} \leq 1 \qquad t=1...T \tag{4}$$

Other constraints:

X_{it} is 0,1 integer variable

where F_t: Present value factor, $F_t = 1/(1 + i)^t$, i is discount rate.

X_{it}: Project i is constructed in year t when $X_{it} = 1$; otherwise $X_{it} = 0$.

U_t: Amount of unsatisfied requirement in year t, $U_t \geq 0$.

When additional data become available or some specific situations need to be considered, the MPVC model formulated above can be modified to incorporate any necessary considerations raised below. By so doing a set of general MPVC models is developed.

Formulation of General MPVC Models

(a) When the operating costs for each project over time can be estimated, the objective function can be modified to include total costs (both of construction and operating costs) while no modification for constraints has to be made.

$$Z = \sum_{t=1}^{T} \sum_{i-1}^{S} F_t C_{it} X_{it} + \sum_{t=1}^{T} F_t U_t P_t$$

$$+ \sum_{i=1}^{S} \sum_{t=1}^{T} \sum_{j\geq t}^{T} F_j O_{ij} X_{it} \quad (6)$$

where O_{ij} is the annual operating costs for project i operated since year t.

(b) When N_t number of projects can be built at same year t, then (3) becomes

$$0 \leq \sum_{i=1}^{S} X_{it} \leq N_t = 0, 1 \ldots S \quad (7)$$

(c) When interdependencies in water supply capacity exist between two or more projects, a set of non-linear requirement constraints are needed to replace (2). In this situation, dynamic programming and non-linear programming, rather than integer programming, are viable solution techniques. For example, if supply capacity of project 2 can be increased by 2 percent after implementation of project 3, then (2) becomes

$$\sum_{1=1}^{t} \sum_{i=1}^{S} K_i X_{i1} - .02k_2 \sum_{1-1}^{t} X_2 1 \ (1 - \sum_{1=1}^{t} X_{31}) + U_t \geq Q_t \quad (8)$$

where $K_2 = 1.02\ k_2$, k_2 is the supply capacity of X_2 without supplementary supply from X_3.

The preceding formulation is just an example of incorporating interdependencies into program formulation. Because interdependencies can exist in various ways, any consideration of interdependencies needs to be tailored into individual cases. It is impossible to determine in advance a standard formula which can be applied to all considerations of interdependencies.

(d) When continuous scales are substituted for fixed scales of candidate projects, some modifications are needed in both the objective function and the set of constraints. Under the assumption of a linear construction cost function, (1) and (2) become changed to (9) and (10), respectively.

$$Z = \sum_{t=1}^{T} \sum_{i=1}^{S} F_t (G_{it} X_{it} + W_{it} V_{it}) + \sum_{t=1}^{T} F_t U_t P_t \qquad (9)$$

$$\sum_{l=1}^{t} \sum_{i=1}^{S} V_{il} + U_t \geq Q_t \qquad (10)$$

where G_{it} is the set-up cost for project i built in year t.

W_{it} is the cost per unit of capacity including operating costs for project i built in year t.

V_{it} is the decision variable representing optimal scale for project i built in year t, $V_{it} \geq 0$.

In addition, a set of constraints is needed to guarantee consistency between X_{it} and V_{it}, i.e., when V_{it} is greater than zero, then X_{it} needs to be 1 at the same year; otherwise, $X_{it} = 0$.

$$X_{it} \geq 1/\bar{V}_i \; V_{it} \qquad (11)$$

where $\bar{V}_i$ is the upper limit on V_{it}.

When the construction cost function is non-linear, it is probably necessary to use separable (piece-wise) programming. For example, if the construction cost function for project 1 is concave as shown in Figure 2-2, and the construction cost functions for other projects are linear, then (9) is changed to (12) and a set of constraints (i.e., (13)) must be added to the original sets of constraints in order to perform separable programming.

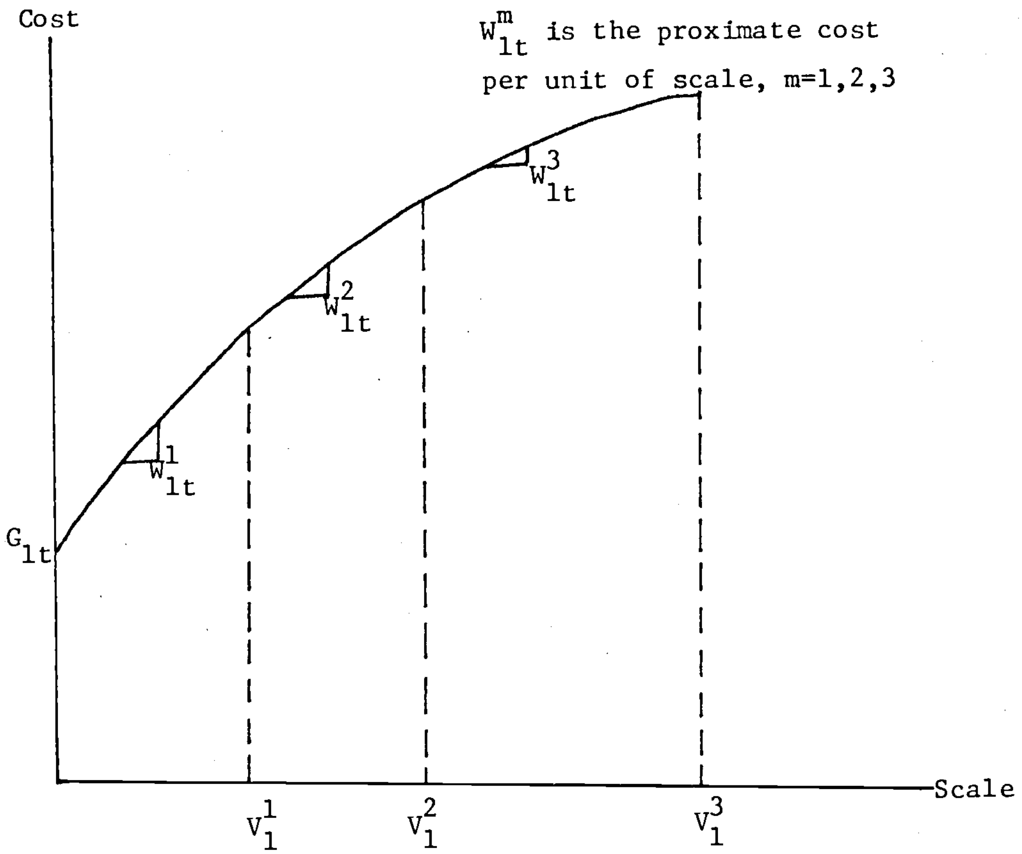

Figure 2-2. Concave construction cost function.

$$Z = \sum_{i-2}^{S} \sum_{t=1}^{T} F_t \, (G_{it} \, X_{it} + W_{it} V_{it}) + \sum_{m=1}^{3} \sum_{t=1}^{T} F_t \, (G_{it} \, \delta_1 + W^m_{ik} \, X^m_{ik}) + \sum_{t=1}^{T} F_t \, U_t \, P_t \qquad (12)$$

$$0 \leq X^1_{1t} \leq (0 \;\; V^1_1) \;\; \delta_1$$

$$X^1_{1t} \geq (0 \;\; V^1_1) \;\; \delta_2$$

$$X^2_{1t} \leq (V^1_1 \;\; V^2_1) \;\; \delta_2 \qquad (13)$$

$$X^2_{1t} \geq (V^1_1 \;\; V^2_1) \;\; \delta_3$$

$$X^3_{1t} \leq (V^2_1 \;\; \bar{V}_1) \;\; \delta_3$$

where δ_i is (0,1) binary variable.

(e) When the fixed scale assumption is replaced by a set of discrete scales, X_{it} needs to be expanded to include all possible scales for each project. A mutually exclusive constraint is also needed to guarantee that only one of the possible scale can be implemented at each project site. For example, if there are three discrete scales for each project, then the modifications to (6), (2), (4), are (14), (15), (16), respectively.

$$Z = \sum_{i=1}^{S} \sum_{t=1}^{T} \sum_{n-1}^{3} F_t C_{it}^n X_{it}^n + \sum_{i=1}^{S} \sum_{t=1}^{T} \sum_{j \geq t}^{T} \sum_{N=1}^{3} F_j O_{ij}^N X_{it}^N + \sum_{t=1}^{T} F_t U_t P_t \tag{14}$$

$$\sum_{i=1}^{S} \sum_{j-1}^{t} \sum_{N=1}^{3} K_i^N X_{ij}^N + U_t \geq Q_t \quad t=1 \ldots T \tag{15}$$

$$0 \leq \sum_{N=1}^{3} X_{it}^N \leq 1 \tag{16}$$

The formulation of the general MPVC models developed from (a) to (e) is an attempt to consider as many realities in the setting of water resource capacity expansion as possible. The discussion addressed in this section is an attempt to integrate the consideration of those realities, though they have been extensively discussed separately in the relevant literature.

With a basic understanding regarding the development of the MPVC model in water resource capacity expansion, the situations under which the MPVC model have been applied and the problems which can be solved by the MPVC model can be summarized as follows.

Applications of the MPVC Model

Even though it is net benefits rather than costs which are most interesting to the public the MPVC model has been employed frequently in recent research. However, there is a class of interesting problems which can be solved by applying the MPVC model. The common characteristics of this class of problems can be summarized as follows.

First, there are situations where it is practical and possible to predict the water (or project output) requirement function. If any formidable difficulties in predicting the requirement function emerge, it precludes the application of the MPVC model because necessary constraints can no longer be formulated.

Second, it is assumed that projects under consideration are single-purpose. Consideration of a set of multi-purpose projects will impose heavy restrictions on the identification of the optimal solution by necessitating the inclusion of too many constraints.

Third, the output of the water resource project must be transferable by inexpensive means from one source (supply) to different destinations (demands). Transferability from different sources to one or more than one destination should also be accomplished by inexpensive means.

Fourth, it may be difficult to price the output of the projects (such as waste-water treatment) or to estimate the benefit of the projects. This is a critical issue in determining if the MPVNB model should be used.

Any deviation from the first three conditions precludes the viability of the MPVC model in dealing with water resource capacity expansion. There are, however, several varieties of problems that can be solved by applying the MPVC model.

1. Sequence a set of electricity generating projects (Erlenkotter, 1973), (Rowse, 1978).
2. Sequence a set of water supply projects for municipal and/or industrial usages.
3. Sequence a set of waste-water treatment plants (Joeres, et al., 1974), (Brill and Nakamura, 1978).

Maximizing Present Value Net Benefit Model

Although the literature in water resource capacity expansion has been growing with continuing efforts toward improving both problem formulation and computational efficiency, little attention has been paid to justifying the model from an economic point of view. Failure in consolidating basic economic concepts to the model has perhaps misled researchers in such a direction that real applications based upon the developed model are limited and few. Correspondingly, there remains a wider class of meaningful problems which can be solved successfully with the present state of art. Moreover, some questions may be raised regarding how useful the information furnished by employing the MPVC model to the public investment decision making. Therefore, in the course of presenting the MPVNB model, the need and objectives are cited first which when combined with the comparison of the MPVC and MPVNB models would demonstrate why the MPVNB model deserves emphasis in this research.

Need and Objectives of Presenting a MPVNB Model

When the proposal of a single project development is broadened to include a set of projects, correct planning requires that all possible sequences of development be evaluated, and that the best alternative plans[10] be submitted for review (Eckstein, 1958; Marglin, 1962). Suppose that each proposed project needs to be justified first by cost-benefit analysis (i.e., the benefit/cost ratio needs to meet a preconditional level, usually 1.0). The implementation of all of the proposed projects should be initiated as soon as possible in order to maximize total present value net benefits of the system development. However, with two complicating factors this sequencing problem becomes nontrivial.

1. Construction activities should concentrate on one project in each time period, since benefits can be generated only after completion of construction.
2. A limited annual budget will be appropriated over the planning horizon, rather than one lump sum budget in the beginning.

O'Laoghaire and Himmelblau (1974) make, without demonstrating the reason for model selection, one of the first attempts in formulating a capital budgeting problem to deal with water resource system expansion. Their encouraging results, despite the commission of several errors, indicate a need for further development of the MPVNB model. Although efficient algorithms and modern computer systems have made exploration

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[10] This again implies that a set of suboptimal solutions rather than only the optimal plan identified by economic analysis should be submitted for the overall review.

of these complex problems less formidable, further improvements are still needed. The efforts made in the literature review of this research are considered twofold. They are:

1. To make an overall comparison between MPVC and MPVNB models. Hopefully, interest and efforts in developing more complicated yet efficient models can be presented afterward.
2. To postulate a less complex problem in water resource system expansion, which may be relatively common in the United States and especially in developing country situations.

The following sections attempt to elaborate on these two objectives.

The Superiority of the MPVNB Model

First and most important, investment decisions dictated by the cost minimizing approach may not fulfill the goal of investment in the public domain. It is also obvious that net benefits are the most important incentive perceived by the private sectors. Therefore, the sequencing problems coincide with capital budgeting problems when capacity expansion is considered by private firms. With this regard, Erlenkotter and Trippi (1976) have demonstrated that it is net benefits which are maximized in the optimal private investment. Even in the public domain, the use of benefit-cost analysis as the authorized criteria in evaluating the proposals of public projects confirms that benefits and costs should be considered simultaneously in the public investment.

Second, the use of a requirement function to pose constraints in the expansion problem has raised several controversial issues.

Rauser and Willis (1976) note that:

> "Much of the empirical work on water resources systems generally neglects the possibility of price sensitive demand relationships and instead forecasts 'demand' for water on a 'requirement' basis. In this context, the effect of water prices on future use is ignored. Surely, for this reason, available forecasts for future use should be questionable at best for use in actual policy decisions."

Although they urge the use of "demand" rather than "requirement" to bring price effect into consideration, the data difficulties and the sample size problems hamper their research and suggest future research is needed to overcome these practical difficulties.

Future requirements are derived based upon various factors (e.g., social, demographic, economic situations) and variations of these factors over time may be unpredictable, especially in the case of long-term projections. Therefore, the skepticism about the accuracy of the estimated water requirement function which is characterized by some degree of uncertainty perhaps has caused Butcher, et al., to make a dubious suggestion. They suggest that a new sequencing problem could be formulated and solved whenever construction of the next project in the optimal sequence is needed. This is a good suggestion in the sense that it adjsuts the construction sequence to avoid significant economic losses in light of the newly acquired information. However, this suggestion seems to deny that there is any value in solving a sequencing problem.

The optimal sequence which requires minimum total present value costs is the result from considering all possible sequences subject to the requirement function. The reasons why a project should be implemented in a certain order are the result of a simultaneous investigation of construction costs and supply capacity for each project, the discount rate, and the requirement function. Now, if the requirement function is predicted in a biased manner because of poor methods of prediction or wide fluctuations in the nature of requirement per se, the need for a second sequencing problem in order to correct the original sequence is then established. Under this situation, the new optimal sequence is expected to deviate somewhat from the original one. A real optimal sequence is, therefore, unlikely to be identified when based upon a biased requirement function. Consequently, it will be difficult to justify why a particular MPVC sequence is better than other simple sequencing criteria (such as sequencing the projects with respect to the least cost per unit of capacity).

A third point involves the case when a requirement function only represents the aggregate requirements over time for the entire projected area as a whole. Therefore a transferability of water or relevant output from one source to different destinations and from different sources to one destination by inexpensive means is a crucial point in sequencing a set of projects. If transferability cannot be achieved from economic/political standpoints, then the annual increments of requirements would require not only one but several projects to be implemented at once if the cost for unsatisfied requirements is assumed infinite. On the other hand, if supply deficitis are allowable (a more realistic case) the task of pricing unsatisfied requirements would call for some future research.

It is sometimes the implementation of a project which stimulates water requirements, not the increasing requirements for water initiating the construction of a project, (i.e., the water requirement function as shown in Figure 2-3. For example, it is possible that a dry land farming area, in which the actual water requirement is zero, can be converted to an irrigated area if an irrigation project (with surplus water) is implemented. Therefore, the conventional MPVC model is considered incapable of dealing with this special but relatively common case which can be solved without any difficulties by using the MPVNB model.

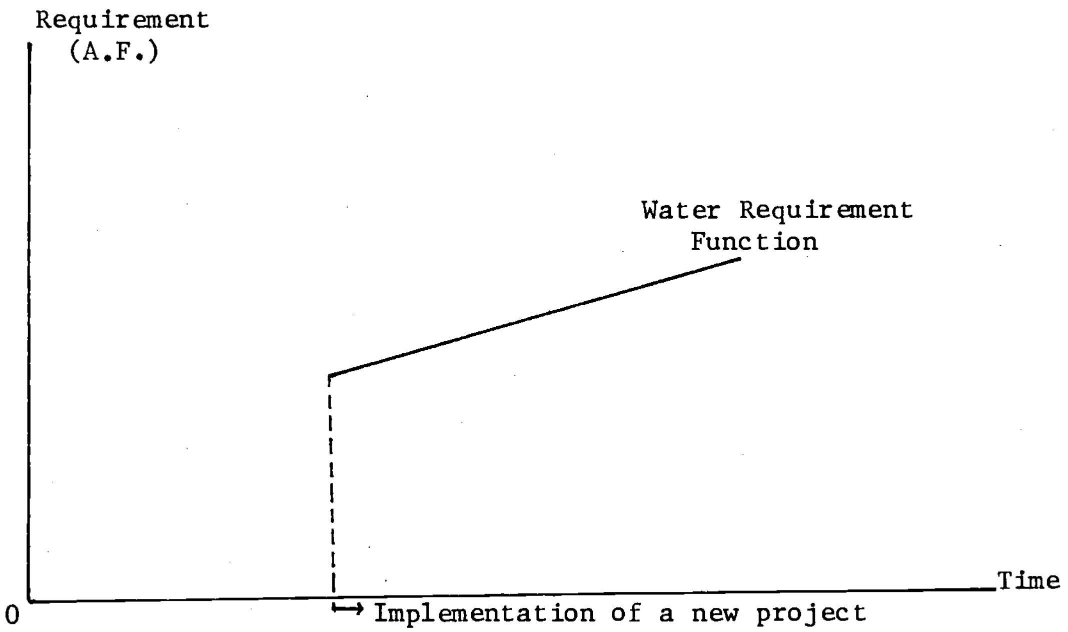

Figure 2-3. Discontinuous water requirement function.

It is implicitly assumed in a MPVC model that the requirements are invariant to the composition of benefits of the project outputs. In general, this assumption is debatable, especially in the case of multipurpose development. In the case of irrigation development, the requirements for water from different areas may need to be treated differently, because different soil types, technologies, weather, etc., for different areas would relfect different productivities with respect to water. An investment decision, therefore, should be made based upon knowledge of the composition of the benefits. A requirement function as used in the existing literature is too simple to incorporate the notion of productivity of water into the model. In the case of multi-purpose development, the simultaneous consideration of all types of requirements may cause the problem to become infeasible by necessitating the inclusion of too many constraints.

One possible approach to consolidating productivity into the model is to differentiate among requirements by weighting. However, because prices of outputs are the parallel indicators of productivities, benefits are the proper measure of the combined considerations of both quantity and productivity of requirements. Together with the fact that both benefits and costs should be considered simultaneously in the public investment, the MPVNB model is a better and more realistic model than the MPVC model.

Third, the information furnished by the MPVC model lies in the fact that the projects "should" be constructed in a specific order in specific years to minimize construction costs. However, without enough budget being appropriated the optimal sequence resulting from the MPVC model "could" no longer be feasible. It is then realized that annual budget appropriation may play a crucial role in bridging the gap between "could" and "should". Thus, the MPVC model is suffering from missing another practical dimension. To bring this dimension into consideration, a "budget appropriation" function is suggested as a replacement for the requirement function in the formulation of constraints in the MPVNB model.

Fourth, when a water resource project is under consideration, cost/benefit analysis is the conventional tool to evaluate absolute and relative cost and benefit values of the project. It is generally accepted that a favorable benefit/cost ration may justify the allocation of resources for a water resources project. Since estimation of costs and benefits for each proposed project is required by administrative procedures, there may be little basis for the use of a MPVC model. Only when the task of quantifying benefits encounters significant difficulties (such as in waste-water treatment planning) and when the budget can be appropriated consistently with respect to the suggested sequence, the MPVC model may become a viable approach.

In reviewing the previous literature of water resource capacity expansion, one may observe that there is no previous application of the MPVC model for sequencing a set of multi-purpose projects where the supply of irrigation water is the primary consideration. Following the previous discussion, one may conclude that it is the MPVNB model rather than the MPVC model which is the viable approach for sequencing a set of multi-purpose projects.

Formulation of a General MPVNB Model

Because the structure of a MPVNB model resembles with great similarity that of a MPVC model, only a brief illustration of the MPVNB model is presented here. Suppose a set of i projects each with j discrete scales needs to be scheduled subject to a budget appropriation function (M_T) over T years of planning horizon. Then the mathematical expression of a MPVNB model is as follows.

Objective function

$$\text{Maximize } Z = \sum_i \sum_j \sum_t F_t \left(\sum_{k \geq t}^{t+f} (B^j_{ik} - 0^j_{ik}) - C^j_{it} \right) X^j_{it}$$

where B^j_{ik} = the annual benefit for project i with scale j built at year t.

Other symbols have the same meanings as the ones used in the MPVC model. There are three sets of constraitns completing this model.

(1) Budget constraints

$$\sum_i \sum_j \sum_t C^j_{it} X^j_{it} \leq \sum_t M_t$$

(2) Mutually exclusive constraints

$$\sum_t \sum_i X^j_{it} \leq 1$$

(3) Integer constraitns

X^j_{it} is (0.1) binary variable.

Summary

The minimizing present value cost (MPVC) model and the maximizing present value net benefit (MPVNB) model have been suggested to identify the best alternatives in sequencing a set of water resources projects over a specific time horizon. Although the MPVC model has been frequently employed and well developed and the MPVNB model has been ignored in the literature, it is suggested in this chapter that the MPVNB model has some advantages over the MPVC model in dealing with a variety of water resource capacity expansion problems. Further development of employment of the MPVNB model will contribute to the literature in the following directions:

1. Elimination of the controversial issues with respect to the use of a requirement function in formulating constraints.
2. An influence of the literature in a direction where more economic concepts are consolidated and hence more applications can be included.

Therefore, it is concluded that the MPVNB model should be considered as the principal approach of this study.

In regard to problem-solving techniques (i.e., dynamic versus integer programming), there is no consensus documenting which technique per se has decisive advantages over the other one. However, because the MPVNB model later will be formulated as a pure integer programming problem, it is logical that integer programming will be the preferred technique in this study.

III. OPTIMAL TIMING OF A MULTI-PURPOSE MULTI-STAGE WATER PROJECT: A PROBLEM STATEMENT

The comparison between the minimizing present value cost (MPVC) and the maximizing present value net benefit (MPVNB) models made in the preceding chapter suggests that the literature of water resource capacity expansion can be improved and broadened by further development of the MPVNB model. The main objective of this chapter is then to identify a set of water resource problems which have been heretofore largely ignored and can be solved by employing the MPVNB model. The literature reviewed above reveals that advances have been made in the solution of complex and large-scale problems. Despite the levels of abstraction which are necessary, it is believed that the research does not alter significantly the essential situations.

Introduction

Since the first arrival of settlers in the 1850s, residents of the Umatilla Basin have realized the importance of water resources to their economy. Now there are recognized needs not only for irrigation, but also for fish and wildlife enhancement, municipal and industrial water supply, and protection from flooding. Small-scale hydroelectric power generation is a remote possibility here as well. The accumulated experience with water shortage, flood damages, increasing demands for water in irrigation, and the competition among water users for limited supplies has stimluated the proposal of many (and the construction of some) water resource developments. Prior to the issuance of the 1970 feasibility investigation of the Umatilla Basin Project (U.S. Department of

Interior), a few water resources projects had been implemented. The major features among them are McKay Reservoir Dam (1927), Cold Springs Diversion Dam (1908), Westland Diversion Dam (1917), and other irrigation facilities. Those implemented features have had mixed success in developing the overall agricultural potential of the area. At the same time, the environment for the successful propagation of anadromous fish have been deteriorated because previous water resources developments have encroached upon streamflow levels and have imposed physical barriers to fish migration. Therefore, programs for reestablishing the anadromous fish have become a felt need in this area.

Responding to the multi-need for water resources, the Bureau of Reclamation completed a feasibility report on the Umatilla Basin Project (Figure 3-1) in 1970. Because this project includes several independent subprojects (described later), it represents an excellent opportunity to perform a timing problem. Because the overall project did not receive Congressional approval, this research is an attempt to schedule the array of project features as an exercise only. This is not an inconsiderable addition to the feasibility analysis since this research is considered to enhance the process of cost/benefit analysis.

First, it demonstrates that a type of water resource capacity expansion planning, which occurs sometimes in the United States and more often in the developing countries, could be better developed with the assistance of recent accomplishments in large-scale numerical optimization. Better planning in this case means that net social welfare would be augmented due to the increases in economic efficiency while original distribution patterns remain unchanged. Once this objective is accomplished

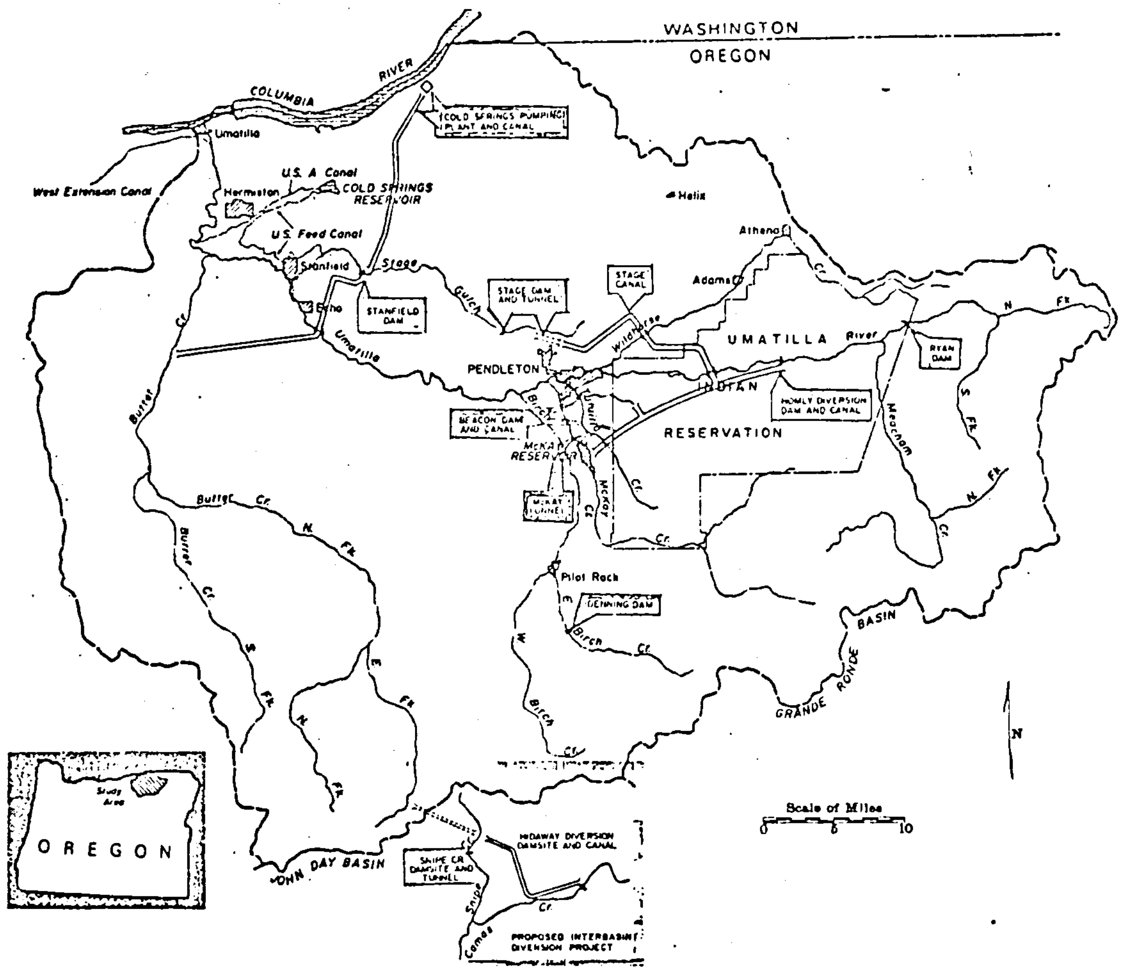

Figure 3.1 Umatilla Basin Project.

the literature of water resource capacity expansion becomes broadened to include more applications.

Second, this variation on planning makes a dynamic revision to the original static report on project feasibility. The revision to the construction plan of the Umatilla Basin Project suggested in this research could be regarded as guidelines for converting the conventional static cost/benefit analysis into a dynamic analysis for multi-facility planning problems.

Static Versus Dynamic Analysis in Planning

The feasibility report of the Umatilla Basin Project (1970) prepared by the Bureau of Reclamation reflects analysis by using conventional cost/benefit analysis. The expected benefits and costs and hence the viability[11] of the project development are estimated by assuming, the project has been operating since 1970. Therefore, the information reveals that the analysis in this report is static in nature. Both prices and quantities of the project outputs over time are explicitly considered, but the timing of construction is ignored. There are two different attempts which have been made in adding different dynamic considerations to the conventional cost/benefit analysis.

Marglin's Dynamic Rule

Marglin (1962) recommends the use of dynamic rules in project evaluation. Such rules involve prediction on the future prices of inputs

[11] By "viability" we mean the measure of merit (i.e., the present value of its benefit less its costs) assigned to a project. Usually, only construction outlays are treated as costs while operation, maintenance, and replacement costs are treated as negative benefits.

and the values of outputs of the project development in a cost/benefit analysis framework. Such rules would stipulate investment for each time period in terms of changes in measure of project viability (e.g., benefit/cost ratio) which are affected by undertaking projects sooner or later. Therefore, it is important to schedule the project at such a time to enhance the economic efficiency of the whole nation. As indicated by Marglin, the economic criteria for optimal timing is to delay construction until the period when the savings of delayed construction (i.e., the cost of interest) are just offset by the marginal benefits foregone. While Marglin's thesis is important for the theory of public investment decision making, a question may arise concerning the applicability of his thesis in actual public investment decision making. Perhaps it can be answered by two reasons.

First and most important, water resources development in existence can be considered to be the integration of politics and economics (Robbins, 1978). Thus, a project to be authorized and appropriated is likely to be not only required to satisfy the benefit/cost ratio criterion, but also required to win enough local support and hence local and national political representation. Robbins' historical review of the Willamette Valley Project of Oregon provides an excellent example of the integration of politics and economics in water resources development. The enhanced project viability resulting from postponement of the development as envisioned by Marglin may not be exclusively attributable to local economic effects, but would dispersed over the whole nation. Moreover, the postponement of the development may end up with withdrawal of federal investment due to some unexpected economic and political events.

It would seem that a local point of view would be unlikely to delay projects - a direct contradiction of Marglin's thesis.

Second, the future prices and output values are assumed to be deterministic in Marglin's framework. In fact, future prices cannot be predicted without some degree of uncertainty. The necessary consideration of a controversial factor - interest rate - would further complicate the estimation of future prices. It is possible that disagreements could emerge among different local groups (represented by their Congressmen) regarding future prices and output values as part of the competition for the appropriation of public investment. This addition of price-related controversies to the already complicated administrative procedures used in appropriating public investment funds for water resources projects may constitute another drawback in adopting the dynamic rule in conventional cost/benefit analysis.

Dynamic Consideration in the MPVNB Model

Although the MPVC model has been developed to identify the "ordering" and "timing" for implementing a set of projects, it fails to add a dynamic dimension to the cost/benefit analysis due to the exclusion of benefits in the analysis. Only a MPVNB model is capable of considering benefits and costs simultaneously and hence adding a dynamic dimension to the cost/benefit analysis. By "dynamic" we mean applying analytic economic tools to determine the "ordering" and "timing" of constructing a set of projects. The remainder of this chapter is devoted to developing a case study example demonstrating the merits of the MPVNB model. As indicated above, the case study is based in the Umatilla River Basin of northeast Oregon. The Umatilla Basin Project proposed by the Bureau of Reclamation provides the basis (the set of subprojects and the estimated costs and benefits) for analysis.

The economic value of the dynamic consideration in planning perhaps could be gauged by the difference of present value net benefits between the construction plan postulated by the Bureau of Reclamation in the feasibility report and the optimal construction sequence identified in this research. However, it should be kept in mind that construction plans postulated by the Bureau of Reclamation are believed to be made with respect to factors concerning mobilization of construction forces. The particular implementation plan designed in a feasibility report could be identical to the "optimal sequence" at best, but could also be the most undesirable sequence.

Summary of Cost and Benefit Statistics of the Umatilla Basin Project[12]

A maximizing present value net benefit model for scheduling a set of facilities within a project is thus a meaningful exercise not only for developing information for the planning area in question, but also would be desirable to consider advanced issues in capacity expansion modeling such as variable scales for each facility. The data base estimated by the Bureau of Reclamation only considers one scale for each subproject. Hence, the data limitations prohibit the development of a better model. This constraint, therefore, is indicative of a need for

[12] The statistical summary is quoted from "Umatilla Basin Project", Bureau of Reclamation - Region 1, April, 1970. Only the cost and benefit statistics relevant in formulating a timing problem are summarized here. Therefore, the data used in this research are secondary data.

a more detailed data estimation in contemporary water resource plannings. The data described here pertain to costs and benefits relevant to project development.

Cost Statistics

Basically, there are two types of costs associated with project implementation. They are construction costs and operating costs. Other costs such as losses of farmland and other "associated" costs necessary for constructing the project are generally taken into account by making appropriate deductions from the benefits.

Construction Costs. The total construction costs are estimated at $338 million. Major facilities and features required to achieve the project multi-purpose accomplishments include:

- six dams and reservoirs (hereafter called subprojects)
- four diversion dams
- 5-1/2 miles of tunnel, 98 miles of canal, and 334 miles of pipe laterals
- a drainage system
- a power grid system for project pumping and 17 relief pumping stations
- facilities for fish and wildlife enhancement and loss prevention
- recreation facilities
- project operating facilities.

These facilities and their respective construction costs are shown in Appendix A. The desirability of arranging these facilities into five subprojects for the scheduling exercise will be explained in the following chapter.

Operation, Maintenance and Replacement Cost (OM&R). The total annual costs of operation, maintenance, replacement and power for all functions are estimated at $1,369,000 as shown in Table III-1. Because these costs are summarized according to the project's purposes, necessary assumptions need to be made to disaggregate the OM&R costs into feature-by-feature level. Disaggregation will be detailed in the following chapter.

Benefit Statistics

The Umatilla Basin Project is a multi-purpose development. Irrigation development and fish and wildlife enhancement are the two major beneficial purposes. Municipal and industrial (M&I) water supply, flood control, and recreation constitute other significant benefits of the project.

Irrigation Benefits. Supply of irrigation water is the principal purpose of the project. The basic approach in determining irrigation benefits is to project agricultural production (including expenses and income) under long term conditions with and without project development. It was estimated that project irrigation service would result in total average annual benefits of $12,967,000, which represents the increase in net farm income, and indirect benefits[13] of $4,032,700, which constitutes profits for processing, handling, and marketing additional agricultural products. Those benefits are summarized in Table III-2. Necessary assumptions for disaggregating irrigation benefits into a feature-by-feature level will be discussed in the following chapter.

[13] Indirect benefits or secondary benefits are major concerns of local people. The inclusion of indirect benefits in the analysis is more appealing to local interest, although it is excluded from calculating the viability of the project.

TABLE III-1. Annual OM&R Costs

Purpose	Costs at 1969 Index		
Irrigation			$853,000
Cost associated with project pressure land		$609,000	
Power costs	$410,000		
Maintenance costs	134,000		
Replacement costs	65,000		
Fish and wildlife enhancement			374,300
Anadromous		115,800	
Resident		69,100	
Remaining joint cost		189,400	
Recreation			109,000
McKay		2,000	
Separable costs		48,700	
Joint costs		61,200	
Flood control			19,600
Municipal and industrial water			10,000

TABLE III-2. Irrigation Benefit Summary

ITEM	FULL SERVICE							SUPPLEMENTAL SERVICE					TOTAL
PROJECT SERVICE	PROJECT PRESSURE		FARM PRESSURE				GRAVITY	FARM PRESSURE					
Present Situation	Dryland 93,620 ac.	Wells b/ 2,380 ac.	Dryland 4,750 ac.		Wells b/ 250 ac.		Dryland 1,400 ac.	Surface Supply 17,110 ac.			Combination Surface Supply and Wells 1,090 ac. c/		
Service Area	Umatilla River a/	Umatilla River a/	Butter Creek	Birch Creek	Butter Creek	Birch Creek	Snipe Creek	Butter Creek	Birch Creek	Umatilla & McKay Btms.	Butter	Birch Cr.	120,600 ac.
	($)	($)	($)	($)	($)	($)	($)	($)	($)	($)	($)	($)	($)
Direct Benefits	11,604,600	189,800	237,000	296,900	6,900	7,100	31,500	548,200	124,000	422,500	33,300	24,900	13,526,700
Indirect Benefits	3,598,700	48,600	72,000	93,000	1,600	2,000	6,100	196,000	44,200	129,300	9,500	6,700	4,2[illegible]7,700
Total Benefits	15,203,300	238,400	309,000	389,900	8,500	9,100	37,600	744,200	168,200	551,800	42,800	31,600	17,734,400
Adjusted Total Benefits d/	14,519,100	237,200	295,100	372,400	8,500	9,100	35,900	736,000	166,300	545,700	42,800	31,600	16,[illegible],700
Per Acre	155	100	141	140	77	65	26	125	101	57	73	63	141
Adjusted Direct Benefits d/	11,082,400	189,800	226,300	283,500	6,900	7,100	30,100	542,200	122,600	417,900	33,300	24,900	12,967,000
Per Acre	118	80	108	107	63	51	22	92	74	44	56	50	108

a/ Includes all project service areas except Butter Creek Bottoms; Snipe Creek; Birch Creek Bottoms and Steward Bench; and Umatilla and McKay Creek Bottoms. This data will be disaggregated in the next chapter.

b/ Present supply to be abandoned in lieu of full service from project.

c/ Present supply from wells to be abandoned.

c/ Adjusted to reflect a development lag in realizing full irrigation benefits on project lands.

TABLE III-3. Projected Average Annual Commercial and Sport Fishery Without and With Project

Fishery	Without Project		With Project		Net Gain	
	Cml. (lbs)	Sport (angler-days)	Cml. (lbs)	Sport (angler-days)	Cml. (lbs)	Sport (angler-days)
Steelhead trout (stream)	21,000	61,000	47,400	133,700	26,400	72,400
Spring chinook (Beacon Res. rearing)	--	--	285,600	71,200	285,600	71,200
Spring chinook (stream)	--	--	186,150	40,000	186,150	40,000
Fall chinook (stream)	--	--	1,343,000	286,000	1,343,000	286,000
Coho (stream)	--	--	3,230	330	3,230	330
Rainbow trout[a/] (reservoir)	--	35,000	--	696,200	--	661,200
Rainbow trout[a/] (stream)	--	40,000	--	80,000	--	40,000
Spiny-rayed (reservoir)	--	18,000	--	18,000	--	--
Spiny-rayed (stream)	--	13,000	--	26,000	--	13,000

[a] Annual benefits for sport fishing at reservoirs were also estimated in feature-by-feature level and are shown in Table III-4.

Fish and Wildlife Enhancement. The enhancement of fish and wildlife is also a major purpose of this project. As indicated in the report, the siting of project storage features, the establishment of minimum reservoir pools, the maintenance of minimum streamflow, and fishery rearing and protecting facilities would provide a habitat which would permit reestablishment of salmon runs and enhance the steelhead trout and resident fisheries. This improved fishery was estimated to be of potential value (see Tables III-3 and III-4) to sport, commercial fishermen, and the Umatilla Indians.[14]

Because the effects of each proposed feature (in terms of value to anadromous and resident fisheries) are so independent, a feature-to-feature evaluation was not conducted by the Fish and Wildlife Service.

TABLE III-4. Annual Benefits for Sport Fishing at Facility-Specific Reservoirs

Reservoir	Average Angler Use (Over Project Life)	Initial Angler Use	Maximum Angler Use (Project Year 35)
	Angler Days		
Ryan	77,000	29,000	87,000
Beacon	78,700	29,700	89,100
Stage	117,300	44,000	133,000
Stanfield	33,100	12,500	37,500
Denning	26,500	10,000	30,000
Snipe	265,000	100,000	300,000
McKay	63,600	24,000	72,000
Total	661,200	249,200	748,600

Rather, the overall project was analyzed to provide a lump sum annual benefit. Therefore, necessary assumptions are needed (and will be made in

[14] The Umatilla Indian reservation is located on the Umatilla River three miles east of Pendleton, Oregon.

the following chapter) to disaggregate benefits for fish and wildlife enhancement.

Unit dollar values were assigned to project related recreational anadromous and resident fishing by the Fish and Wildlife Service using criteria in Supplement No. 1 to Senate Document 97 "Evaluation Standards for Pimary Outdoor Recreation Benefits."[15] Using these criteria the angler-day dollar values established for the sport fisheries by the agency were:

Anadromous Fish (all species)	$6.00
Rainbow Trout (stream)	$3.00
Rainbow Trout (reservoir)	$2.00
Spiny-rayed Fish	$1.50

Annual values assigned by the Fish and Wildlife Service to project related commercial fishing were:

Steelhead Trout (stream)	$ 8,000
Spring Chinook Salmon (Beacon Reservoir rearing program)	$160,000
Salmon, all species (stream)	$858,000

The project would contribute to wildlife enhancement in two ways. Increased acres of irrigated lands and the installation of the proposed reservoirs would result in the increase of upland game and waterfowl as a result of an improved habitat. Therefore, the hunting activities for these game wildlife are expected to be increased, and hence, will likely

[15] The evaluation principles and standards have been revised twice since then (U.S. Water Resources Council, 1973 and 1979).

result in increased benefits for wildlife enhancement activities. The Fish and Wildlife Service has assigned a value of $3.00 for each upland game hunter day and $4.00 for each waterfowl hunter day. Table III-5 summarizes projected upland game and waterfowl hunter use in the project with and without project development.

TABLE III-5. Average Annual Hunter Use in Project Area - Waterfowl and Upland Game

Wildlife Resource	Without Project	With Project	Net Gain
	------------ hunter days ---------		
Waterfowl	31,000	42,600	11,600
Upland Game	38,000	61,000	23,000
Total	69,000	103,600	34,600

Recreational Benefits. Recreation needs in the Umatilla Basin and immediate area and the project's recreation potential were studied by the Bureau of Outdoor Recreation (BOR). In their study BOR (1) analyzed recreation demand, supply, and need within the area; (2) determined initial and projected future recreation use associated with project development; (3) recommended a recreation plan; (4) evaluated recreation costs and benefits; and (5) discussed administration of the recreation function. The result of BOR's report which is relevant to this research is summarized below.

Using the guidelines provided in Senate Document 97, BOR assigned a value of $1.00 per visitor day for recreation activity at Beacon, Stage, Stanfield, Denning, and McKay Reservoirs and $1.10 at Ryan and

TABLE III-6. General Recreation Use[a]

Reservoir	Estimated Annual Recreation Days: Initial (1975)	Project Year 10 (1985)	Ultimate (2025 +)
Ryan	43,000	56,000	141,000
Beacon	104,000	137,000	345,000
Stage	34,000	41,000	117,000
Stanfield	29,000	37,000	95,000
Denning	16,000	21,000	54,000
Snipe	96,000	124,000	320,000
McKay	7,000	10,000	21,000
Total Project	329,000	426,000	1,093,000

[a] To identify recreation benefit alone, single-purpose angler use and present recreation use at McKay Reservoir were subtracted from total use figure.

Snipe Reservoirs.[15, 16] Applying these values to general recreation day estimates in Table III-6 would result in annual benefits as follows:

Reservoir	Initial (1975)	Project Year 10 (1988)	Ultimate (2025 +)
Ryan	$ 47,000	$ 62,000	$ 155,000
Beacon	104,000	137,000	345,000
Stage	34,000	41,000	117,000
Stanfield	29,000	37,000	95,000
Denning	16,000	21,000	54,000
Snipe	106,000	137,000	352,000
McKay	7,000	10,000	21,000
	$343,000	$445,000	$1,139,000

Flood Control Benefits. Project flood control benefits have been estimated by the Corps of Engineers; they represent reduction in losses

[15] Under the 1979 Water Resource Council Guidelines, the value per visitor day would depend on the characteristics of each reservoir.

[16] Benefits would not accrue to Homly Diversion Dam without Beacon and Stage or Stanfield Dams to store water. Homly benefit would be allocated 43 percent to Beacon and 57 percent to Stage.

to land and other private and public property and increases in net income from an increased or changed use of property resulting from reductions in flood hazards and damage. The average annual equivalent benefits were estimated at $374,500. A summary of the benefits by project feature is shown as follows:

Feature	Annual Equivalent Benefit
Ryan Dam and Reservoir	$115,320
Beacon Dam and Reservoir	2,700
Stanfield Dam and Reservoir	4,880
Denning Dam and Reservoir	43,180
McKay Dam and Reservoir	184,540
Homly Diversion Dam	23,890
Project Total	$374,510
Rounded	$374,500

Municipal and Industrial Water Uses. Early in the project planning, the cities of Pendleton, Hermiston, Umatilla, Stanfield, and Echo indicated an interest in the possibility of obtaining water supply from the project to meet future needs. In response to these requests, a comparative analysis was made to determine the justification from providing such water. The analysis demonstrated that all cities except Pendleton could develop a supplemental water supply more economically from a nonproject source.

Additional studies were made by the Bureau of Reclamation to more fully identify Pendleton's needs. The estimation of municipal and industrial water needed from the project and resultant profits are shown in Table III-7.

TABLE III-7. M & I Water Benefits

Year	Needed Water(A.F.)	Rate(A.F.)	Gross Revenue[a]
1985	2300	15.626	35,940
1995	5800	15.626	90,630
2005	8500	15.626	141,321
2015	9200	15.626	152,959
.	.	.	.
.	.	.	.
.	.	.	.
2085	9200	15.626	152,959

[a] Gross revenue is the product of needed water and rate.

Summary of Construction Plan

The construction plan postulated by the Bureau of Reclamation included six stages. Although only one of these six proposed dams will be implemented in each stage, the construction plan is contradictory to the basic rule of optimal sequencing - construction should concentrate on only one project at a time. In order to make the BOR's construction plan comparable with the optimal sequence, it is then necessary to make some modifications to the BOR's construction plan.

First, it is assumed that construction stages are physically independent. Only one of these six dams is included in each construction stage, and the following construction stage starts after the ending of the preceding stage.

Second, the annual construction budgets need to be explciitly specified. Because the Bureau's construction plan was formulated without consideration of annual construction budgets, completion times for these six construction stages need to be reassigned in light of a hypothetical annual construction budget for each year and the original construction sequence. The original construction sequence is as follows:

(1) Snipe Dam, (2) Ryan Dam, (3) Beacon Dam, (4) Stage Dam, (5) Cold Springs pumping plant and Stanfield Dam, and (6) Denning Dam.

Summary

This chapter was aimed at describing in some detail the study objective and the setting of the problem. The relevant data for formulating a timing problem were summarized. In the following two chapters the maximizing present value net benefit model is fully specified and solved for an optimal timing of the facilities of the Umatilla Basin Project.

IV. MODEL FORMULATION

There are, as described in Chapter II, two alternative models - the minimizing present value of cost (MPVC) model and the maximizing present value of net benefit (MPVN) model - have been suggested as a means of dealing with the project timing problem. Although the MPVC model has been frequently used in formulating timing problems, it is considered ill-suited for this study due to the following reasons.

First, a precise water (irrigation water) requirement function cannot be estimated. This is because the Umatilla Basin Project was not only projected to supply supplementary water for irrigated lands but was also intended to make full service irrigation possible for some dryland areas. The water requirement, therefore, was not only affected by time but also determined by whether the project would have been constructed or not.

Second, even if a water requirement function could be estimated, it has no practical value in formulating a timing problem for the Umatilla Basin Project. The water requirement function reflects aggregate requirements for the study area as a whole, but irrigation water, unlike electricity, cannot be transported costlessly within the basin. This means that in several instances more than one of the subprojects may have had to be built at the same time in order to meet the requirements from different areas. In this situation there is little need to find a solution to the timing problem.

A third point discussed in Chapter II concerns the available budget. Without sufficient construction funds being appropriated, the optimal sequence resulting from the MPVC model may no longer be feasible. The annual budget appropriation is thus seen to be playing a crucial economic role: it replaces the "should construct" arbitrariness of the requirements schedule with a "could construct" decision-making process based upon budget appropriation. Therefore, a limitation on the annual budget available for construction is a realistic constraint which should replace the water requirement function in formulating a timing problem.[17]

Fourth and above all, the cost minimizing approach cannot provide accurate economic information needed in making decisions on public investment.

In regards to the preceding, the MPVNB model is considered to be a more advantageous approach for formulating a timing problem for a river basin such as the Umatilla Basin. In the following sections the necessary considerations for formulating a timing problem will be discussed followed by a description of four versions of the MPVNB model.

Characteristics of the Umatilla Basin Project Related to the Model Formulation

First, it was decided in the previous chapter that the Umatilla Basin Project could be decomposed into six independent subprojects or facilities. However, it becomes necessary to limit the number of subprojects to five in order to avoid excessive dimensionality in problem

[17] In an operations research sense, however, it could be claimed that the two approaches are equally arbitrary. Nevertheless, it must be remembered that one of the objectives in this thesis is to bring more dimensions of economic reality to this kind of timing problem.

solving with the algorithms selected. The Snipe Creek and Denning Dams are combined as a subproject, because they are close to each other, cost relatively less, and store water from local tributaries (Birch and Butter Creeks, respectively) which flow into the Umatilla River.

Second, as planned, the planning horizon for the project is roughly about 20 years.

Third, the project life is 100 years, an approximation of the expected physical longevity of the facilities.

Assumptions Made for the Model Formulation

Because the Umatilla Basin Project was planned as a whole by the Bureau of Reclamation, some assumptions are needed to disaggregate the cost and benefit data into a feature-by-feature presentation. Additional assumptions are also required in order to calculate the anticipated present value of net benefits for each subproject. Those assumptions are summarized as follows.

First, as shown in Figure 3.1, Homly Diversion Dam and Homly Canal (hereafter, called the common facility) are the common facilities to divert water from the Umatilla River to Beacon and Stage Dams. The involvement of the common facility necessitates the development of different versions for the model formulation. A more detailed discussion regarding this assumption will be made later.

Second, as shown in Table III-2, the irrigation benefits for the North and South Reservation, Lower and Upper Paradise, Cold Spring, Despain, Teel and Stanfield service areas must be disaggregated. The irrigation acreages, land classification, and the estimated payment capacity[18] for each land class are the weights used to disaggregate benefits. A summary of these weights is tabulated in Table IV-1.

Third, the most troublesome item in accomplishing a disaggregation task is the data on the Umatilla River fishery. It was realized during project planning by the Fish and Wildlife Service that the effects of proposed subprojects are so interdependent that fishery benefits could not be easily decomposed into feature-by-feature levels. Therefore, some arbitrary assumptions are needed to reflect this aspect in model formulation. In this regard, different versions of the model have been developed for formulating the timing problem. The discussion in a later section details the differences among the four versions of the MPVNB model with respect to the assumptions.

Fourth, the operation, maintenance, and replacement (OM&R) costs for irrigation include power and general costs. They are amortized in the following ways. Power costs are amortized according to the average annual power (MW-hrs) requirements for each subproject. General costs are amortized proportionally to the benefits accruing to each subproject. Some of the OM&R costs for fish and wildlife and flood control purposes were already assigned to each subproject; however, the general OM&R costs for these purposes need to be disaggregated. They are amortized according to the same procedure which is applied to the amortization of the general OM&R costs of irrigation.

Fifth, the benefits for wildlife were predicted by the Bureau of Reclamation to increase as a result of an increase of hunter days for

[18] For more detail on the definition and estimation of the payment capacity see Umatilla Basin Project (USDI, 1970, pp. 42-44).

waterfowl and upland game. Benefits resulting from waterfowl hunting are disaggregated to a feature-by-feature level according to the acreages for each subproject.

Sixth, for simplicity, the rate of inflation and rate of interest (discount) are assumed to be invariant over the planning horizon. Therefore, the present value net benefits for each subproject can be calculated based upon the data on costs, benefits, and the interest (discount) rate relevant to one single year. The cost and benefit statistics used in this research are stated in terms of 1969 price levels.

With respect to the discount rate applicable to the Umatilla River Project plan of 1970, the President's Water Resources Council (1962) established the procedures to calculate the discount rate to be used in plan formulation and evaluations for water resources projects. Accordingly, the interest rate of 1969 used in this research is the federal rate of 3-3/4 percent.

Lastly, the annual budget for construction is assumed fixed for each year of planning horizon. It is set equal to the total cost of construction for all facilities divided by the number of years in the planning horizon. Because appropriation of budget is actually decided by legislative procedures, the actual budget in each year over planning horizon is felt to be more or less a random process.

Major Differences Among the Four Versions of the MPVNB Model

As stated previously, there are two assumptions regarding the common facility and the fishery data which necessitate the development of different versions of the MPVNB model. With two alternative considerations for each assumption, there are four versions (i.e., versions I to IV) need to be specified.

Alternative Considerations for the Common Facility

As shown in Figure IV-1, the Homly Diversion Dam and Canal are the common facilities for the function of the Stage and Beacon Dams. The capacity for the Homly, Stage, and Beacon Canals are 1400, 800, 600 c.f.s., respectively. Two alternatives regarding the implementation of the common facility are made in this thesis.

In versions I and III of the MPVNB model, the common facility is assumed to be implementable in two stages. Based upon the capacity for each canal, 6/14 and 8/14 of the common facility are attached to the Beacon and Stage Dams, respectively. This means that 6/14 of the common facility and the Beacon Dam are combined as a subproject which is symbolized by X_{2t} (the identification of decision variables will be explained in the following section); while 8/14 of the common facility combined with the Stage Dam are symbolized by X_{3t}.

In versions II and IV of the MPVNB model, the common facility is assumed to be constructed in one stage. Therefore, if Beacon Dam is selected for implementation earlier than Stage Dam in the optimal sequence, Becon Dam and the common facility will be built at the same time; otherwise, if Stage Dam is scheduled earlier, the common facility will be built with it. In these two versions, the decision variables X_{2t} and X_{3t} denote Beacon Dam with the common facility and Stage Dam with the common facility, respectively; while Y_{2t} and Y_{3t} represent Beacon Dam and Stage Dam, respectively.

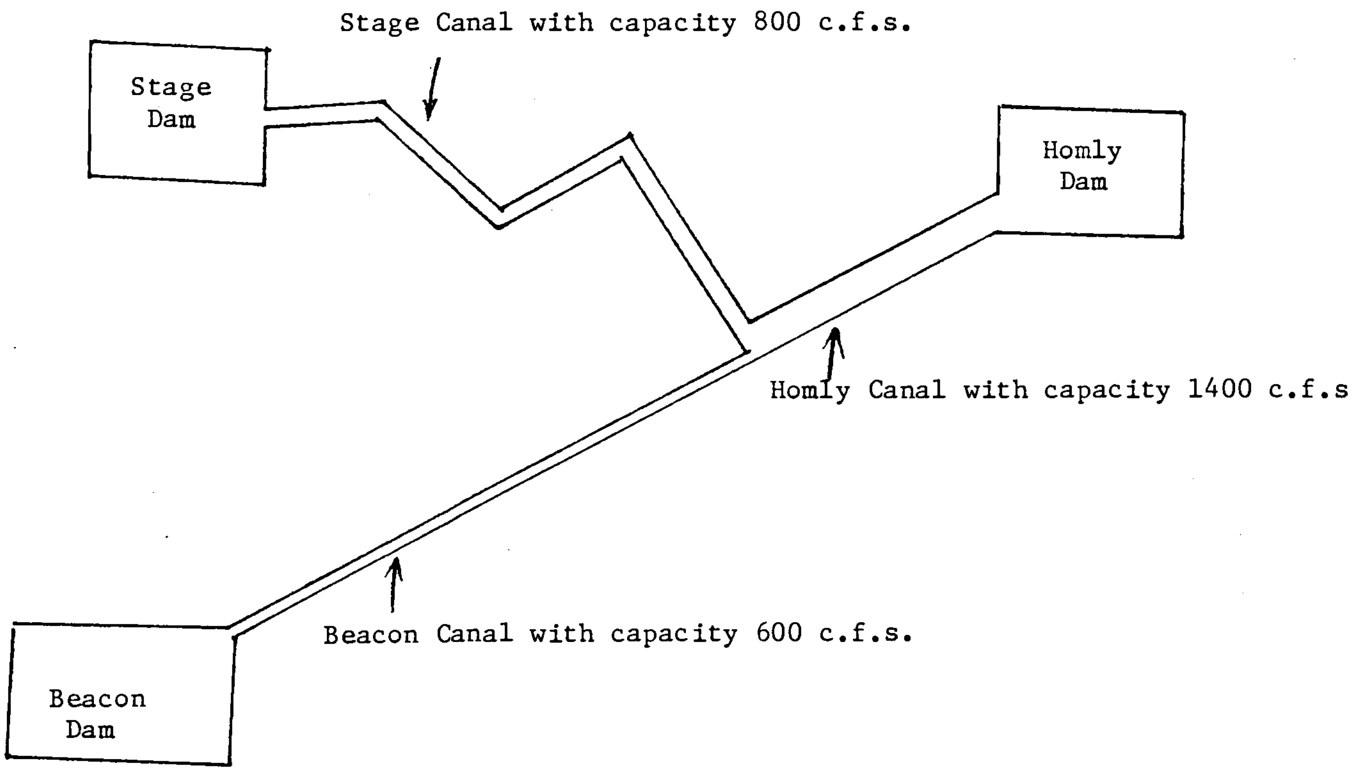

Figure 4-1. The common facility for Stage and Beacon Dams.

TABLE IV-1. The Weights for Disaggregation of Irrigation Benefits

Service Areas	Land Class	Acreages	Payment Capacity Per Acre
North Reservation	1	10490	25.94
	2	1740	24.24
	3	570	18.54
South Reservation and Upper Paradise	1	8710	27.12
	2	5130	25.12
	3	5160	19.12
Stanfield	2	7850	28.65
	3	1750	22.65
Lower Paradise, Cold Spring, Despain & Teel	1	18550	30.64
	2	21160	28.65
	3	14890	22.65

Alternative Considerations for the Fishery Costs and Benefits

Arbitrary assumptions need to be made for disaggregating fishery data, since the effects of fishery enhancement programs are interdependent. For the four versions of the MPVNB model, fishery data are disaggregated according to the levels of streamflow released below each relevant subproject (i.e., Ryan, Beacon, and Snipe Dams) in versions I and II; while in versions III and IV Ryan Dam is assumed a single-purpose subproject which is exclusively responsible for fishery enhancement. Consequently, in versions III and IV the irrigation areas served originally by Ryan Dam will be served by Stanfield Dam and pumping plant subproject. Meanwhile, irrigation benefits for Beacon Dam are assumed to increase by 50 percent because more stored water in this dam can be used for irrigation. In this regard, the annual cost and benefit data for these four versions can be summarized as shown in Tables IV-2 and IV-3. A summary of the major differences among these four versions of the MPVNB model is tabulated in Table IV-13.

Description of Decision Variables

Four versions of the MPVNB model have been formulated and solved in the course of this research. Each version uses a different set of decision variables. Because all the decision variables are symbolized by either X or Y with different subscripts, it is convenient to have a general description of variables prior to model formulation.

Decision Variables

A general decision variable in the timing problem is Γ_{it} when

Γ_{it} = 1 if subproject i is constructed at time period t,

Γ_{it} = 0 otherwise

TABLE IV-2. Costs and Benefits Data for Versions I and II

$ Subproject	Construction Costs	Annual O M & R Costs				Annual Benefits			
		Irrigation	Recreation	Fish & Wildlife	Flood Control	Irrigation	Recreation	Fish & Wildlife	Flood Control
Ryan Dam	68,418,783	110,766	15,093	299,200	6,035	2,054,698	99,562	3,639,067	115,320
Beacon Dam	40,956,846	58,501	35,398	55,875	9,802	1,046,133	236,059	933,088	187,240
Common Facility	8,227,328	--	--	--	1,248	--	--	--	23,890
Stage Dam	70,548,695	138,513	10,919	--	--	3,515,263	65,840	246,023	--
Stanfield Pumping Plant	112,856,211	497,692	9,313	--	255	8,685,907	59,416	87,817	4,880
Snipe & Denning	36,755,136	47,729	39,178	19,225	2,260	1,697,700	253,723	891,211	43,180

TABLE IV-3. Costs and Benefits Data for Versions III and IV

$ Subproject	Construction Costs	Annual O M & R Costs				Annual Benefits			
		Irrigation	Recreation	Fish & Wildlife	Flood Control	Irrigation	Recreation	Fish & Wildlife	Flood Control
Ryan Dam	56,851,038	--	15,093	373,700	6,035	--	99,562	3,957,780	115,320
Beacon	40,610,755	87,751	35,398	--	10,337	1,569,199	236,059	329,226	197,513
Common Facility	8,227,328	--	--	--	1,248	--	--	--	23,890
Stage	70,548,695	138,513	10,919	--	--	3,515,263	65,840	246,023	--
Stanfield Pumping Plant	124,784,831	1,605,458	9,313	--	255	10,740,605	59,416	87,817	4,880
Snipe & Denning	36,637,741	47,729	39,178	--	2,260	1,697,700	253,723	743,257	43,180

Two types of decision variables (X and Y) are employed in the model: X is the primary variable used to denote whether a subproject will be constructed; however, the assumption of inseparable common facility necessitates an additional set of variables (Y) to differentiate whether Stage Dam or Beacon Dam is built with the common facility in version II and IV. The following is a list of decision variables and the facilities to which they pertain: X_{1t} denotes Ryan Dam in version I to IV; X_{2t} denotes Beacon Dam with 6/14 of the common facility in versions I and III or Beacon Dam with the inseparable common facility in version II and IV; X_{3t} denotes Stage Dam with 8/14 of the common facility in versions I and III or Stage Dam with the inseparable common facility in versions II and IV; X_{4t} denotes Stanfield Dam and the pumping plant in all versions; X_{5t} denotes Snipe and Denning Dams in all versions; Y_{2t} and Y_{3t} are used in versions II and IV only, they represent the Beacon and Stage Dams, respectively.

Cumulative Construction Budget Over the Planning Horizon

It is assumed that the annual construction budget is constant and equal to total construction costs divided by the planning horizon (that is, 20 years). Later, in solving the MPVNB model version II the introduction of an inseparable common facility causes an exponential increase of computation time due to the increase in the number of decision variables (expressed by Y_{jt}). As will be explained later, in order to avoid excessive amount of computation time in solution, a decomposition of the problem was accomplished and a different set of construction budget called residual cumulative construction budget was needed. Table IV-4

TABLE IV-4. Cumulative Construction Budget ($1,000)

		R.C.C.B. when the following subproject built first				
T	C.C.B.	1	2	3	4	5
1	16,889	--	--	--	--	--
2	33,778	--	--	--	--	--
3	50,667	--	1,483	--	--	31,923
4	67,556	--	18,372	--	--	30,801
5	84,445	16,026	35,261	5,669	--	47,690
6	101,334	32,915	52,150	22,558	--	64,579
7	118,223	49,804	69,039	39,447	5,367	81,468
8	135,112	66,693	85,928	56,336	22,256	98,357
9	152,001	83,582	102,817	73,225	39,145	115,246
10	168,890	100,471	119,706	90,114	56,034	132,135
11	185,779	117,360	136,595	107,003	72,923	149,024
12	202,668	134,249	153,484	123,892	89,812	165,913
13	219,557	151,138	170,373	140,781	106,701	182,802
14	236,446	168,027	187,262	157,670	123,590	199,691
15	253,335	184,916	204,151	174,559	140,479	216,580
16	270,224	201,805	221,040	191,448	157,368	233,469
17	287,113	218,694	237,929	208,337	174,257	250,358
18	304,002	235,583	254,818	225,226	191,146	267,247
19	320,891	252,472	271,707	242,115	208,035	284,136
20	337,780	269,361	288,596	259,004	224,924	301,025

shows the cumulative construction budget (C.C.B.) and the residual cumulative construction budget (R.C.C.B.) when one of subprojects is determined to be built first.

Model Formulation

Four versions of the MPVNB model will be specified in this section. The procedures for determining decision variables and the structure for each version will be explained in detail. The computer programs for each version, however, are listed in Appendix B.

MPVNB Model Version I

Lauria (1972) demonstrated that, in formulating a MPVC model, it is necessary to examine only certain years (construction completion periods) instead of the whole planning horizon in order to define the decision variables. Those years correspond to years in which existing supply capacity is exhausted by increasing demands. Because the facilities in this study are assumed to begin generating benefits only after the completion of construction, Lauria's idea can also be applied to formulate the MPVNB model. Only the years in which enough budget is accumulated to complete any subproject or subprojects are necessary for selecting decision variables. These years are called construction completion years (C.C.Y.) in this study. The construction completion years for version I are shown in Table IV-5.

With construction costs for subprojects and corresponding C.C.Y., decision variables for this version can be identified and are shown in Table IV-6. For example, subproject 2 can be completed with three-year budget, therefore, X_{203} is a necessary decision variable but X_{201} and

TABLE IV-5. Construction Completion Years (version I)

Number of Subprojects	Combination of Subprojects					Corresponding C.C.Y.				
1	(1)[a]	(2)	(3)	(4)	(5)	5	3	5	7	3
2	(1,2)	(1,3)	(1,4)	(1,5)	(2,3)	7	9	11	7	8
	(2,4)	(2,5)	(3,4)	(3,5)	(4,5)	10	5	12	7	9
3	(1,2,3)	(1,2,4)	(1,2,5)	(1,3,4)	(1,3,5)	12	14	9	16	11
	(1,4,5)	(2,3,4)	(2,3,5)	(2,4,5)	(3,4,5)	13	14	10	12	14
4	(1,2,3,4)	(1,2,3,5)	(1,2,4,5)	(1,3,4,5)	(2,3,4,5)	18	14	16	18	16
5			(1,2,3,4,5)					20		

a/ The numbers inside parentheses are presenting the subprojects.

TABLE IV-6. Decision Variables (version I)

C.C.y \ D.V.	X_{1t}	X_{2t}	X_{3t}	X_{4t}	X_{5t}
3	--	X_{203}	--	--	X_{503}
5	X_{105}	X_{205}	X_{305}	--	X_{505}
7	X_{107}	X_{207}	X_{307}	X_{407}	X_{507}
8	--	X_{208}	X_{308}	--	--
9	X_{109}	X_{209}	X_{309}	X_{409}	X_{509}
10	--	X_{210}	X_{310}	X_{410}	X_{510}
11	X_{111}	--	X_{311}	X_{411}	X_{511}
12	X_{112}	X_{212}	X_{312}	X_{412}	X_{512}
13	X_{113}	--	--	X_{413}	X_{513}
14	X_{114}	X_{214}	X_{314}	X_{414}	X_{514}
16	X_{116}	X_{216}	X_{316}	X_{416}	X_{516}
18	X_{118}	X_{218}	X_{318}	X_{418}	X_{518}
20	X_{120}	X_{220}	X_{320}	X_{420}	X_{520}

X_{202} are not. Therefore, the number of decision variables for version I totals 54 while 100 decision variables would be required without employing the idea of construction completion years. The present value of net benefits data used for designating the coefficients of the objective function are summarized in Table IV-7.

Structure of MPVNB Model Version I[19]

In this version the objective function and the constraints are formulated as follows:

Objective Function:

$$\text{Maximize } Z = \sum_i \sum_t NB_{it} * X_{it}$$

where:

NB_{it} = the total present value of net benefits for subproject i built in year t.

X_{it} = decision variables.

Subject to:

(a) Construction constraints: each subproject can be built only once.

$$\sum_i X_{it} \leq 1$$

(b) Budgetary constraints:

$$\sum_{j=1}^{t} \sum_i C_i X_{ij} \leq CCB_t$$

where:

C_i = the construction costs for subproject i

CCB_t = the cumulative construction budget for year t

(c) X_{it} is 0 or 1 integer.

19 The computer program for version I is listed in Appendix B-1.

TABLE IV-7. Present Value Net Benefit for Subproject Built in Year t

T	Subproject NB_{1t}	NB_{2t}	NB_{3t}	NB_{4t}	NB_{5t}
3	68,719,566	13,705,828	18,554,478	96,340,799	34,027,109
5	63,841,664	12,836,046	17,237,431	89,502,267	31,611,772
7	59,310,008	12,028,004	16,013,871	83,149,152	29,367,882
8	57,166,273	11,645,753	15,435,057	80,143,761	28,306,392
9	55,100,022	11,277,318	14,877,163	77,246,998	27,283,270
10	53,108,455	10,922,201	14,339,434	74,454,938	26,297,127
11	51,188,872	10,579,919	13,821,141	71,763,796	25,346,629
12	49,338,672	10,250,009	13,321,582	69,169,924	24,430,486
13	47,555,347	9,932,023	12,840,079	66,669,806	23,547,456
14	45,836,479	9,625,530	12,375,980	64,260,054	22,696,343
16	42,582,881	9,045,379	11,497,499	59,698,700	21,085,295
18	39,560,232	8,478,143	10,681,375	55,461,124	19,588,603
20	36,752,138	7,951,170	9,923,182	51,524,342	18,198,151

MPVNB Model Version II

The construction completion years for version II are tabulated in Table IV-8. Using the calculated construction completion years, the decision variables for version II can be determined as shown in Table IV-9. Because the major difference between versions I and II is whether the common facility can be built in two stages, only the present value net benefit data for Beacon and Stage Dams are different (see Table IV-10) in these two versions.

Structure of the MPVNB Model Version II[20]

In this version the objective function and the constraints are formulated as follows:

Objective Function:

$$\text{Maximize} \quad Z = \sum_i \sum_t NB_{it} * X_{it} + \sum_j \sum_t NBY_{jt} * Y_{jt}$$

where:

NBY = the present value of net benefits for making the decision variable Y_{it} equal to one.

Y_{jt} = decision variables

Subject to:

(a) Construction Constraints:

$$\sum_t X_{it} \leq 1 \qquad \text{for } i = 1, 4, 5$$

$$\sum_t (X_{it} + Y_{it}) \leq 1 \qquad \text{for } i = 2,3$$

(b) Common facility constraints: a common facility is required to be built whenever either Beacon or Stage Dam is first scheduled for construction.

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20 The computer program is listed in Appendix B-2.

TABLE IV-8. Construction Completion Years (version II)

Number of Subprojects	Combination of Subprojects					Corresponding C.C.Y.				
1	(1)	(2)	(3)	(4)	(5)	5	3	5	7	3
2	(1,2)	(1,3)	(1,4)	(1,5)	(2,3)[a]	7	9	11	7	8
	(2,4)	(2,5)	(3,4)	(3,5)	(4,5)	10	6	12	7	9
3	(1,2,3)	(1,2,4)	(1,2,5)	(1,3,4)	(1,3,5)	12	14	10	16	11
	(1,4,5)	(2,3,4)	(2,3,5)	(2,4,5)	(3,4,5)	13	14	10	12	14
4	(1,2,3,4)	(1,2,3,5)	(1,2,4,5)	(1,3,4,5)	(2,3,4,5)	18	14	16	18	16
5			(1,2,3,4,5)					20		

[a] Whenever the combination of subprojects includes Beacon and Stage dams, the construction costs for this combination should include construction costs for common facility only once. And Beacon and Stage dams are presented by Y_{2t} and Y_{3t} while X_{2t} or X_{3t} stand for Beacon dam and common facility or Stage dam and common facility.

TABLE IV-9. Decision Variables (version II)

C.C.Y. \ D.V.	X_{1t}	X_{2t}	Y_{2t}	X_{3t}	Y_{3t}	X_{4t}	X_{5t}
3	--	X_{203}	--	--	--	--	X_{503}
5	X_{105}	--	--	X_{305}	--	--	--
6	--	X_{206}	--	--	--	--	X_{506}
7	X_{107}	X_{207}	--	X_{307}	--	X_{407}	X_{507}
8	--	--	Y_{208}	--	Y_{308}	--	--
9	X_{109}	--	--	X_{309}	--	X_{409}	X_{509}
10	X_{110}	X_{210}	Y_{210}	--	Y_{310}	X_{410}	X_{510}
11	X_{111}	--	--	X_{311}	--	X_{411}	X_{511}
12	X_{112}	X_{212}	Y_{212}	X_{312}	Y_{312}	X_{412}	X_{512}
13	X_{113}	--	--	--	--	X_{413}	X_{513}
14	X_{114}	X_{214}	Y_{214}	X_{314}	Y_{314}	X_{414}	X_{514}
16	X_{116}	X_{216}	Y_{216}	X_{316}	Y_{316}	X_{416}	X_{516}
18	X_{118}	--	Y_{218}	X_{318}	Y_{318}	X_{418}	X_{518}
20	X_{120}	--	Y_{220}	--	Y_{320}	X_{420}	X_{520}

TABLE IV-10. Present Value Net Benefit for Subproject Built in Year t (version I & II)

DVNB T	NB_{2t}	NBY_{2t}	NB_{3t}	NBY_{3t}
3	8,674,071	17,479,634	14,780,676	23,586,239
5	8,161,457	16,341,977	13,731,503	21,912,023
6	7,918,961	15,803,800	13,235,184	21,120,022
7	7,685,230	15,285,074	12,756,804	20,356,648
8	7,459,947	14,785,098	12,295,714	19,620,866
9	7,242,807	14,303,193	11,851,291	18,911,678
10	7,033,515	13,838,707	11,422,931	18,228,123
11	6,831,788	13,391,009	11,010,054	17,569,275
12	6,637,352	12,959,493	10,612,100	16,934,241
13	6,449,944	12,543,574	10,228,530	16,322,160
14	6,269,310	12,142,688	9,858,824	15,732,203
16	5,927,393	11,383,862	9,159,018	14,615,488
18	5,581,479	10,650,634	8,508,886	13,578,041
20	5,260,119	9,969,452	7,904,902	12,614,235

$$\sum_i \sum_t Y_{it} \leq 1$$

This is a constraint which requires the common facility needs to be built only once.

$$X_{305} - Y_{208} \geq 0$$

$$X_{305} + X_{307} - Y_{210} \geq 0$$

$$X_{305} + X_{309} - Y_{212} \geq 0$$

$$X_{305} + X_{307} + X_{309} + X_{311} + X_{312} - Y_{214} \geq 0$$

$$X_{305} + X_{307} + X_{312} + X_{314} - Y_{216} \geq 0$$

$$X_{305} + X_{309} + X_{312} + X_{316} - Y_{218} \geq 0$$

$$X_{203} - Y_{308} \geq 0$$

$$X_{203} + X_{206} - Y_{310} \geq 0$$

$$X_{203} + X_{207} - Y_{312} \geq 0$$

$$X_{203} + X_{206} + X_{207} + X_{210} - Y_{314} \geq 0$$

$$X_{203} + X_{206} + X_{210} + X_{212} - Y_{316} \geq 0$$

$$X_{203} + X_{207} + X_{210} + X_{214} - Y_{318} \geq 0$$

The above constraints require that the common facility needs to be built whenever it is decided to build the Beacon or Stage Dam.

(c) Budgetary Constraints:

$$\sum_{j=1}^{t} \sum_i (C_i X_{ij} + CY_i Y_{ij}) \leq CCB_t$$

where:

$CY_i = C_i - 8227328$, is the construction cost for Beacon Dam (CY_2) or Stage Dam (CY_3)

(d) X_{it} and Y_{it} are 0 or 1 integers.

Five Subprograms for Version II

As explained earlier, these problems are formulated in a form suitable for solution by integer programming. One drawback of integer programming, however, is that the computation time increases exponentially as the number of decision variables increase. Because version II of the model includes seven more decision variables than version I, the excessive amount of computation time likely to be required provides an incentive to develop a strategy for making this problem less costly to solve.

The timing problem is formulated to reach the optimal construction sequence which maximizes the benefits of constructing a set of projects. With five projects (or subprojects) the number of possible sequences to be examined is 120 (i.e., the permutation of 5). When a subprogram is formulated by assigning one of these five projects to be built first, the number of possible sequences for each subprogram is reduced to 24 (i.e., the permutation of 4). Therefore, both the numbers of decision variables needed and sequences to be examined are reduced significantly. Together with the nature of integer programming, the advantage of developing subprograms with respect to computation time is obvious. Since all of these 120 sequences are examined in these five subprograms, the best solution for these five subprograms is identical to the optimal solution.

Although the subprogram approach can save computation time, it is not without disadvantage. There is certainly more effort required in formulating the five programs instead of one is the principal disadvantage to the approach. The trade-off between computation time and program formulating time will be more attractive as the size (especially the planning horizon) of the problem is enlarged. Whether subprograms should be developed is a matter which is determined by the size of the problem and the researcher's preference and resources.

Because these five subprograms in this case are subsets of the original program and because formulation of subprograms follows the same procedure, only one subprogram formulation will be illustrated below. Computer programs for these five subprograms are listed in Appendix B-3.

Subprogram No. 1. In this subprogram Ryan Dam is assigned to be built first. Therefore, the timing problem is formulated to reach the optimal sequence of constructing the rest of four subprojects. Since subprograms are the subsets of the original program, the construction completion years and the decision variable for each subprogram can be determined directly from the original problem. For subprogram No. 1, only the combinations which include Ryan Dam (No. 1) in Table IV-8 are relevant in calculating the construction completion years (see Table IV-11) for subprogram No. 1. The same procedures also apply to the formulation of the other subprograms.

Because the structure for subprogram No. 1 is identical to the structure for the original program (see page 68), only the constraints for the common facility are worth mentioning here. They are:

$$Y_{212} + Y_{214} + Y_{218} + Y_{220} + Y_{312} + Y_{314} + Y_{318} + Y_{320} \leq 1$$

$$X_{309} - Y_{212} \geq 0$$

$$X_{309} + X_{311} - Y_{214} \geq 0$$

$$X_{309} + X_{316} - Y_{218} \geq 0$$

$$X_{207} - Y_{212} \geq 0$$

$$X_{207} + X_{210} - Y_{214} \geq 0$$

$$X_{207} + X_{214} - Y_{218} \geq 0$$

TABLE IV-11. Construction Completion Years (subprogram 1)

Number of Subprojects	Combination of Subprojects	Corresponding C.C.Y
2	(1,2), (1,3), (1,4), (1,5)	7, 9, 11, 7
3	(1,2,3), (1,2,4), (1,2,5), (1,3,4), (1,3,5), (1,4,5)	12, 14, 10, 16, 11, 13
4	(1,2,3,4), (1,2,3,5), (1,2,4,5), (1,3,4,5)	18, 14, 16, 18
5	(1,2,3,4,5)	20

TABLE IV-12. Decision Variables (subprogram 1)

D.V. C.C.Y.	X_{2t}	Y_{2t}	X_{3t}	Y_{3t}	X_{4t}	X_{5t}
7	X_{207}	--	--	--	--	X_{507}
9	--	--	X_{309}	--	--	--
10	X_{210}	--	--	--	--	X_{510}
11	--	--	X_{311}	--	X_{411}	X_{511}
12	--	Y_{212}	--	Y_{312}	--	--
13	--	--	--	--	X_{413}	X_{513}
14	X_{214}	Y_{214}	--	Y_{314}	X_{414}	X_{514}
16	X_{216}	--	X_{316}	--	X_{416}	X_{516}
18	--	Y_{218}	X_{318}	Y_{318}	X_{418}	X_{518}
20	--	Y_{220}	--	Y_{320}	X_{420}	X_{520}

The discussion above has illustrated in detail how versions I and II of the model are constructed. Because the structure of version III and IV follows the same patterns and procedures, only a brief discussion regarding the two later versions will be made in the remainder of this chapter.

MPVNB Model Versions III and IV

As indicated before, a major distinction of the versions III and IV to version I and II is the consideration given to fishery establishment and enhancement in the Umatilla River is assigned exclusively to Ryan Dam. Consequently, the Stanfield irrigation service areas are served by Stanfield Dam and pumping plant subproject. Furthermore, the irrigation benefits that accrue to Beacon Dam are increased by 50 percent resulting from the increased deliveries of irrigation water. The only difference between version III and IV concerns whether or not the common facility can be built in two stages. In summary, the differences among these four versions are shown in Table IV-13.

TABLE IV-13. The Differences Among the Four Versions of the MPVNB Model

Version	Common Facility	Fishery Enhancement in the Umatilla River are considered to be provided by
I	Separable	Beacon and Ryan Dams
II	Inseparable	Beacon and Ryan Dams
III	Separable	Ryan Dam exclusively
IV	Inseparable	Ryan Dam exclusively

Because the assumption regarding fishery data will affect only the calculation of the present value of net benefits for each subproject, the structure for version III is identical to the structure of version I and the structure for version IV is identical to the structure of version II; however, the decision variables and the present value of net benefits for these four versions are different. In this regard, only the tables summarizing the decision variables and benefit data will be presented in the following text.

For version III, the construction completion years are calculated as shown in Table IV-14 and can be used to determine the necessary decision variables presented in Table IV-15. The present value of net benefit values which are used to formulate the objective function are summarized in Table IV-16.

For version IV, the construction completion years and the decision variables are summarized in Tables IV-17 and IV-18, respectively. Table IV-19 includes additional benefit data for completing the objective function.

Computer programs for versions III and IV are listed in Appendix B-4 and B-5.

Summary

In this chapter four models for optimally expanding water resource facilities in the Umatilla River Basin were formulated. The data basis for formulating the models was the 1970 Umatilla Basin Project Feasibility Report. The following chapter emphasizes the issue of problem solution techniques and the presentation of results.

TABLE IV-14. Construction Completion Years (version III)

Number of Subprojects	Combination of Subprojects					Correspo-ding C.C.Y.				
1	(1)	(2)	(3)	(4)	(5)	4	3	5	8	3
2	(1,2)	(1,3)	(1,4)	(1,5)	(2,3)	6	8	11	6	8
	(2,4)	(2,5)	(3,4)	(3,5)	(4,5)	11	5	12	7	11
3	(1,2,3)	(1,2,4)	(1,2,5)	(1,3,4)	(1,3,5)	11	14	9	16	10
	(1,4,5)	(2,3,4)	(2,3,5)	(2,4,5)	(3,4,5)	13	15	10	13	15
4	(1,2,3,4)	(1,2,3,5)	(1,2,4,5)	(1,3,4,5)	(2,3,4,5)	18	13	16	18	17
5			(1,2,3,4,5)					20		

TABLE IV-15. Decision Variables (version III)

C.C.Y. \ D.V.	X_{1t}	X_{2t}	X_{3t}	X_{4t}	X_{5t}
3	--	X_{203}	--	--	X_{503}
4	X_{104}	--	--	--	--
5	--	X_{205}	X_{305}	--	X_{505}
6	X_{106}	X_{206}	--	--	X_{506}
7	--	--	X_{307}	--	X_{507}
8	X_{108}	X_{208}	X_{308}	X_{408}	--
9	X_{109}	X_{209}	--	--	X_{509}
10	X_{110}	X_{210}	X_{310}	--	X_{510}
11	X_{111}	X_{211}	X_{311}	X_{411}	--
12	--	--	X_{312}	X_{412}	--
13	X_{113}	X_{213}	X_{313}	X_{413}	X_{513}
14	X_{114}	X_{214}	--	X_{414}	--
15	--	X_{215}	X_{315}	X_{415}	X_{515}
16	X_{116}	X_{216}	X_{316}	X_{416}	X_{516}
17	--	X_{217}	X_{317}	X_{417}	X_{517}
18	X_{118}	X_{218}	X_{318}	X_{418}	X_{518}
20	X_{120}	X_{220}	X_{320}	X_{420}	X_{520}

TABLE IV-16. Present Value Net Benefit for Subprojects Built in Year T (versions III and IV)

T \ PVNB	NB_{1t}	NB_{2t}	NB_{3t}	NB_{4t}	NB_{5t}
3	39,239,441	12,978,871	18,554,478	107,280,347	31,033,725
4	38,239,259	12,574,761	17,883,835	102,971,590	29,916,194
5	37,275,229	12,185,257	17,237,431	98,818,570	28,839,057
6	36,346,043	11,809,832	16,614,391	94,815,659	27,800,853
7	35,450,441	11,447,976	16,013,871	90,957,432	26,800,173
8	34,587,211	11,099,199	15,435,057	87,238,660	25,835,663
9	33,755,182	10,763,029	14,877,163	83,654,299	24,906,015
10	32,953,226	10,439,010	14,339,434	80,199,495	24,009,968
11	32,180,257	10,126,702	13,821,141	76,869,564	23,146,309
12	31,435,227	9,825,682	13,321,582	73,659,991	22,313,869
13	30,717,125	9,535,183	12,840,079	70,566,427	12,511,512
14	30,024,979	9,255,890	12,375,980	67,584,980	20,738,158
15	29,357,850	8,986,346	11,928,655	64,710,703	19,992,757
16	28,714,834	8,726,543	11,497,499	61,940,607	19,274,299
17	28,095,059	8,461,739	11,081,927	59,270,635	18,581,808
18	27,497,687	8,206,506	10,681,375	56,697,168	17,914,347
20	26,366,936	7,723,381	9,923,182	51,825,923	16,650,929

TABLE IV-17. Construction Completion Years (version IV)

Number of Subprojects	Combination of Subprojects					Corresponding C.C.Y.				
1	(1)	(2)	(3)	(4)	(5)	4	3	5	8	3
2	(1,2)	(1,3)	(1,4)	(1,5)	(2,3)	7	9	11	6	8
	(2,4)	(2,5)	(3,4)	(3,5)	(4,5)	11	6	13	7	11
3	(1,2,3)	(1,2,4)	(1,2,5)	(1,3,4)	(1,3,5)	11	14	9	16	11
	(1,4,5)	(2,3,4)	(2,3,5)	(2,4,5)	(3,4,5)	13	15	10	13	15
4	(1,2,3,4)	(1,2,3,5)	(1,2,4,5)	(1,3,4,5)	(2,3,4,5)	18	13	16	18	17
5			(1,2,3,4,5)					20		

TABLE IV-18. Decision Variables (version IV)

D.V. / C.C.Y.	X_{1t}	X_{2t}	Y_{2t}	X_{3t}	Y_{3t}	X_{4t}	X_{5t}
3	--	X_{203}	--	--	--	--	X_{503}
4	X_{104}	--	--	--	--	--	--
5	--	--	--	X_{305}	--	--	--
6	X_{106}	X_{206}	--	--	--	--	X_{506}
7	X_{107}	X_{207}	--	X_{307}	--	--	X_{507}
8	--	--	Y_{208}	--	Y_{308}	X_{408}	--
9	X_{109}	X_{209}	--	X_{309}	--	--	X_{509}
10	--	--	Y_{210}	--	Y_{310}	--	X_{510}
11	X_{111}	X_{211}	Y_{211}	X_{311}	Y_{311}	X_{411}	X_{511}
13	X_{113}	X_{213}	Y_{213}	X_{313}	Y_{313}	X_{413}	X_{513}
14	X_{114}	X_{214}	--	--	--	X_{414}	--
15	--	--	Y_{215}	X_{315}	Y_{315}	X_{415}	X_{515}
16	X_{116}	X_{216}	--	X_{316}	--	X_{416}	X_{516}
17	--	--	Y_{217}	--	Y_{317}	X_{417}	X_{517}
18	X_{118}	--	Y_{218}	X_{318}	Y_{318}	X_{418}	X_{518}
20	X_{120}	--	Y_{220}	--	Y_{320}	X_{420}	X_{520}

TABLE IV-19. Present Value Net Benefit for Subprojects 2 and 3 Built in Year T (version III & IV)

PVNB / T	NB_{2t}	NBY_{2t}	NB_{3t}	NBY_{3t}
3	7,947,114	16,752,677	14,780,676	23,586,239
4	7,724,875	16,212,164	14,246,435	22,733,724
5	7,510,668	15,691,188	13,731,503	21,912,023
6	7,304,204	15,189,043	13,235,184	21,120.022
7	7,105,202	14,705,046	12,756,804	20,356,648
8	6,913,393	14,238,544	12,295,714	19,620,866
9	6,728,518	13,788,904	11,851,291	18,911,678
10	6,550,324	13,355,516	11,422,931	18,228,123
11	6,378,571	12,937,792	11,010,054	17,569,275
13	6,053,104	12,146,734	10,228,530	16,322,160
14	6,899,670	11,773,048	9,858,824	15,723,203
15	5,752,435	11,412,522	9,502,481	15,163,569
16	5,608,557	11,065,026	9,159,018	14,615,488
17	5,456,451	10,715,699	8,827,969	14,087,217
18	5,309,842	10,378,997	8,508,886	13,087,268
20	5,032,330	9,741,663	7,904,902	12,614,235

V. METHODOLOGY AND RESULT

As discussed in Chapter II, dynamic programming and integer programming are two promising techniques for solving the problems of water resource capacity expansion. Because the objectives of this research emphasized (1) model formulation, (2) problem formulation, and (3) economic implications of the research, it was considered unnecessary to pursue the modeling by application of both techniques. However, one should be aware of the reason why integer programming rather than dynamic programming is employed in this research. The availability of readily available coded algorithms for integer programming[21] was a distinct advantage over the dynamic programming codes which must be individually programmed for each application.

In the following section, the three algorithms (Gomory cut, branch and bound, and zero-one implicit enumeration) developed for identifying solutions to integer programming problems will be discussed.[22] Next, the results from solving the problems formulated in Chapter IV will be summarized. Following that the merits of performing a timing problem will be illustrated.

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[21] The availability of the Multi-Purpose Optimization System (MPOS, Northwestern University, 1978) at Oregon State University was an important factor in selecting a technique.

[22] Part of the text is quoted from the class notes given by Dr. Jeffrey Arthur for his course "Advanced Topics in Mathematical Programming" offered at OSU in 1980. I am indebted to Dr. Arthur for permission to quote from these notes.

The Gomory Cutting Plane Algorithm

Pure integer programming (Pure IP) problems are a typical class of integer programming (IP) problems in which all variables need to be integers for any feasible solutions. Gomory's cutting plane algorithm (Gomory, 1963) was developed particularly for solving pure IP problems.

In the course of searching for the optimal integer solution, an optimal solution will be identified first by solving the continuous linear progrmaming (LP) problem with relaxation of the integer constraints. The idea of the cutting plane is then to change the feasible region by adding new constraints while two conditions need to be satisfied.

- Fractional (non-integer) LP optimal solution must become infeasible.
- All integer feasible solutions must remain feasible with the new constraints.

Therefore, the introduction of new constraints will progressively eliminate the infeasible regions to the IP problem until an integer solution becomes identified. Because the feasible region is shrinking, the value of the objective function is likely to become decreasing as new constraints are introduced, the first integer solution should therefore be the optimal solution.

The procedures to generate Gomory's cut are briefly summarized below. For a complete description of the method, see Dakin (1975) and Garfinkel and Nemhauser (1972).

The Procedures to Generate Gomory's Cut. For a pure IP problem such as

Maximum $Z = CX$

Subject to $AX \leq b$

$X_j \geq 0$ and integer for all j

where Z represents the value of the objective function

C is a vector consisting of the coefficients for the variables in the objective function

A is a matrix consisting of the coefficients for the variables in the constraints

b is a vector consisting of the values for the right-hand side of the constraints

Step 1. Solve the LP problem with relaxation of integer constraints.

Let X_B represent a set of the basic variables $\overline{b}_i$ of the optimal tableau.

X_N represent a set of the nonbasic variables of the optimal tableau.

Step 2. If all the $\overline{b}_i$ are integer, then the IP problem is solved. However, if $\overline{b}_i$ is fractional, the ith row of the LP optimal tableau is used to generate the Gomory cutting plane.

Let $\overline{b}_i = \overline{I}_i + \overline{f}_i$

$Y_{ij} = I_{ij} + f_{ij}$

where $\overline{I}_i$: largest integer $\leq \overline{b}_i$

$\overline{f}_i$: fractional part of $\overline{b}_i$ and $0 \leq f_i \leq 1$

Y_{ij} : all the coefficients of the nonbasic variables in the ith row

I_{ij} : largest integer $\leq Y_{ij}$

f_{ij} : fractional part of Y_{ij} and $0 \leq f_{ij} \leq 1$

Step 3. Gomory's cut: $- \sum_{j \in N} f_{ij} X_j + S = -\bar{f}_i$

where $S \geq 0$ and integer is a slack variable

Step 4. Adding the cut to the present tableau and performing the dual-simplex pivot to identify the next optimal solution. Then, go back to Step 2.

Rule of Cutting Plane Algorithm. When more than one $\bar{b}_i$ variables are fractional, it is desirable to select a $\bar{b}_i$ with the largest $\bar{f}_i$ among the candidate variables to form a deeper cut so as to reduce computation time.

Drawbacks of the Cutting Plane Algorithm. There are two drawbacks of the cutting plane algorithm which have been noted.

- Even though the algorithm has been proven theoretically to converge in a "finite" number of steps, in many practical problems it does not reach the optimum in a reasonable time.
- None of the intermediate solutions are feasible until the problem is completely solved.

The Branch and Bound Algorithm

The Branch and Bound Mixed-Integer Programming (BBMIP) algorithm of MPOS employs a branch and bound algorithm developed by Shareshian (1967). It is based upon the Land and Doig (1960) method to solve mixed-integer programming (MIP) problems of limited size. It may also be used to solve LP problems as well as pure IP problems.

As with Gomory's cutting plane method, the MIP problem is first solved without regard to integer constraints (i.e., relaxing MIP to LP). If the values of some basic variables of the optimal solution are, but should not be fractionals, two major functions - branching and bounding - of BBMIP are performed to reach the optimum. Rounding and truncating are the rules based upon to do branching. A dual-simplex LP algorithm is used as a bound-establishing mechanism immediately after each better integer solution is reached. The following are the procedures to solve a mixed-integer problem by using branch and bound algorithm. For a complete description of this algorithm, Geoffrion and Marsten (1972) and Garfinkel and Nemhauser (1972) are recommended.

The Procedures of Doing Branch and Bound. Consider one of the branch and bound MIP problems such as

Maximum $Z_k = CX$ (1)

Subject to $AX \leq b$ (2)

$X_j \geq 0$ and integer for a subset (X_t) of X_j (3)

$X_j \leq U_{jk}$ (4)

$X_j \geq L_{jk}$ (5)

$Z_k \geq LB_k$ (6)

$Z_k \leq UB_k$ (7)

where

Z_k is the value of the objective function at the kth branch and bound iteration

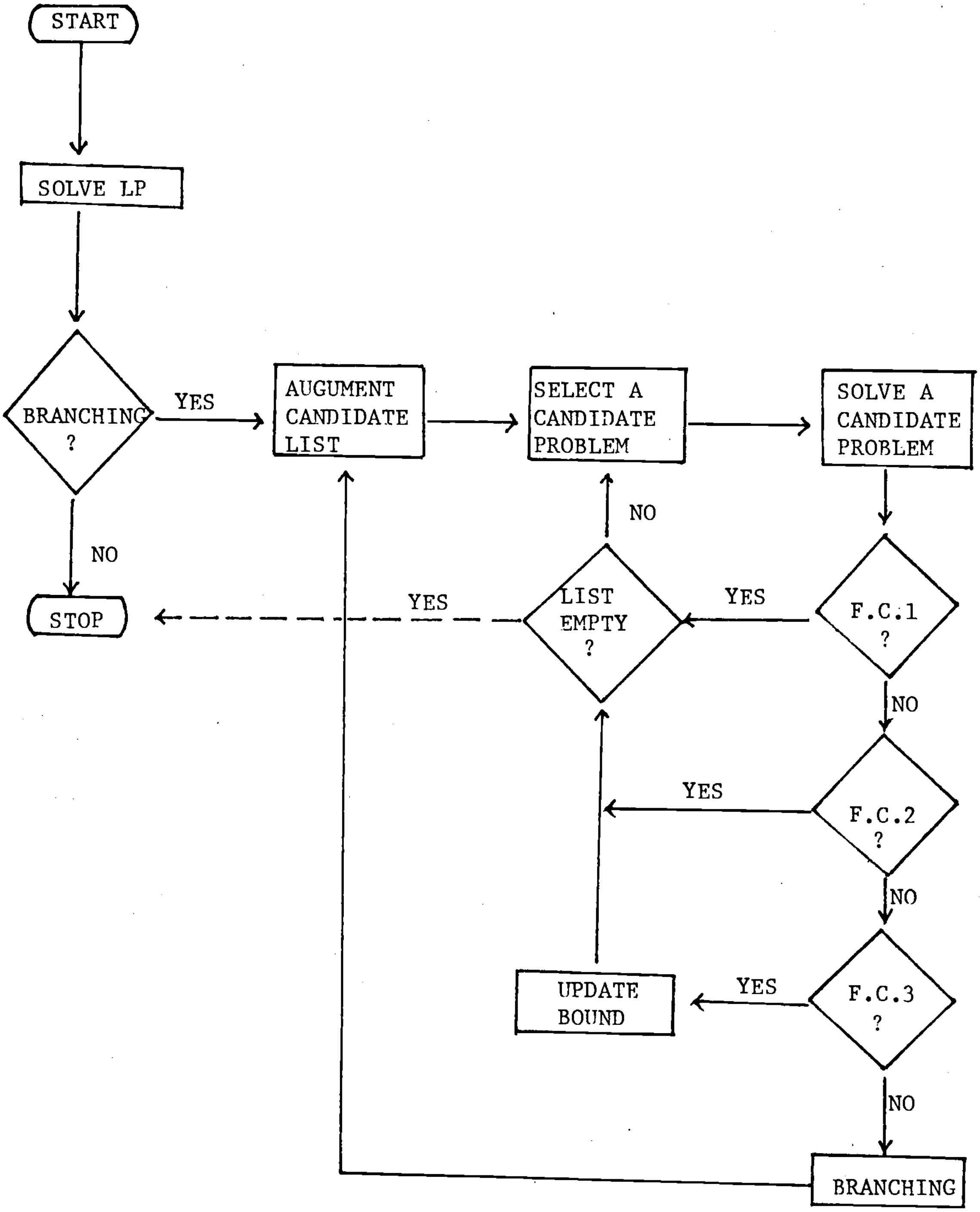

Figure 5-1. Flowchart for the general procedures.

U_{jk} is the upper bound on the jth variable at the kth iteration

L_{jk} is the lower bound on the jth variable at the kth iteration

LB_k is the lower bound on the integer objective function at the kth iteration

UB_k is the upper bound on the solution at the kth iteration

If initially all U_{jk} are set to positive infinity, all L_{jk} to zero, UB_k to positive infinity and LB_k to negative infinity; then we have a continuous LP problem with trivial constraints (4) - (7).

A solution which satisfies all conditions but (3) will be referred to as a noninteger solution. From every noninteger solution two new restrictive integer programs (branching) are generated. These integer programs differ from the parent program only through the interjection of tighter solution bounds (4) and (5). The following are general procedures to perform the branch and bound algorithm. A flowchart summarizing these procedures is given in Figure 5-1.

Step 1. Set up an LP problem with relaxation of integer constraints.

Step 2. Solve the LP program. If the problem is infeasible then it is terminated. If the problem is feasible and satisfies (3) then the problem is terminated with an optimal solution.

Step 3. When the problem has a noninteger feasible solution, select a variable which should be an integer but is not. Using the rule of rounding and truncating, two problems with each of the following two constraints are generated.

$$X_t \leq U_{t1} = [\bar{B}_t] \quad (8)$$

$$X_t \geq L_{t1} = [\bar{b}_t] + 1 \quad (9)$$

where $[\bar{b}_t]$ is a notation symbolizing the maximum integer which is less than $\bar{b}_t$ - the solution value of the X_t in the parent problem. These two problems constitute the initial list of candidate problems.

Step 4. Select one of the problems from this candidate list. Stop if the candidate list is empty. In this situation if there exists a LB then it must be optimal in MIP, otherwise MIP has no feasible solutions. If the candidate list is not empty, select one of the problems and go to Step 5.

Step 5. Solve the problem with dual-simplex method.

Step 6. Fathoming Criteria 1.[23] If the outcome of Step 5 reveals that the problem has no better feasible solution than the present lower bound, backtrack to Step 4.

Step 7. Fathoming Criteria 2. If the outcome of Step 5 reveals that the problem has no better feasible solution than the present lower bound, backtrack to Step 4.

Step 8. Fathoming Criteria 3. If the outcome of Step 3 reveals an integer optimal solution, reset the lower bound by the new objective function. Then, backtrack to Step 4.

Step 9. If the problem is not fathomed by Criteria 1 through 3, it indicates further branching is needed. Therefore, go to Step 3.

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[23] Fathoming criteria are established to determine whether the present problem needs to be pursued further. When the solution of the present problem meets these criteria, the problem is terminated.

Rules in Selecting a Variable on Which to Branch. Many strategies may be employed when carrying out the branching process. The number of problems solved depends greatly upon the variables which are chosen. Consequently, the choice of the branching variable is a nontrivial task meriting the mention of the following rules.

- Choose the integer variable which has the maximum fractional value among the integer variables.
- Choose the variable which has the maximum original coefficient in the objective function.
- Choose a variable according to a user specified priority ordering.

Guidelines for Formulating MIP Problems. The requirement of computational time for solving a MIP problem is a major concern to the researchers. It is realized that the requirement of computational time depends upon the sizes (number of variables) of the problem, and is also sensitive to the formulation of the problem. Therefore, Arthur has summarized the following guidelines for formulating the MIP problem so the computational time can be reduced.

- If the lower bound on an integer variable is big, say 20, then it is desirable to declare it as a continuous variable and round off its solution.
- Try to get realistic and tighten lower and upper bounds on all the variables as far as possible.
- Increasing the number of variables, especially integer variables, will increase the complexity of the problem and hence the computational effort.

- Unlike the simplex method, whose computational effort increases proportionally to the number of constraints, an increase in the number of constraints generally reduces the computational effort for MIP problems.
- The sequence in which the integer variables are selected does affect the solution time. Therefore, it is desirable to use a priority rule based on the importance of the integer variables. Importance may be determine by:
  - (i) representation of an important decision
  - (ii) the coefficients in the objective function.

Up to now, the BBMIP algorithm has been widely used to solve both IP and MIP problems, because of its flexibility in dealing with both IP and MIP problems and its relative efficiency in solving the problem when compared with other algorithms. Therefore, it is considered a good algorithm for this research.

The Zero-One Implicit Enumeration

A special class of IP problems, such as timing problems, can be treated with 0-1 mathematical programming. Within this class of problems all variables are required to be either 0 or 1. Additionally, the use of zero or one variables also occurs in different modeling situaations. In particular, separable programming problems such as the one suggested in the discussion in Figure 3-2 are often solved in this manner.

For the 0-1 IP problem with n variables, a complete investigation of all possible answers ignoring constraints accounts for 2^n enumeration.

A complete search is only possible for small problems, but even with high-speed computers one may not handle problems with more than 20 variables which require 2^{20} or 1048567 enumerations. Therefore, many algorithms for 0-1 IP rely on partial or implicit enumeration of the whole set of solutions; the algorithms exclude large numbers of solutions from consideration but do not cause a possible optimal solution to be ignored.

In order to achieve this, Balas (1965) first demonstrated that any 0-1 problem can be converted to satisfy:

- all coefficients in the objective function can be made non-negative,
- the objective function is to minimize,
- all constraints are $\geq$ inequalities.

With the first two points, Balas concluded that some enumerations become trivial to reach the optimum and therefore can be ignored.

The general procedures in doing 0-1 programming are summarized below. For a review and examination of 0-1 algorithms see Gue, *et al.* (1968); for a tutorial on enumeration techniques, see Haverly (1972).

The Procedures for 0-1 IP . For a 0-1 IP problem such as

$$\text{Maximum} \qquad Z = \sum_{j=1}^{n} C_j X_j + W$$

$$\text{Subject to} \qquad \sum_{j=i}^{n} A_{ij} X_j \leq b_i$$

$$X_j: \; 0, 1 \text{ integer variable}$$

$$\text{where} \qquad Z \geq LB$$

Step 1. Convert the problem into the form demonstrated by Balas:

(1) Change the objective function as:

$$\text{Min. } -Z = -\sum_{j=1}^{n} C_j X_j$$

If $-C_i$ is negative, replace X_i by $(1-Y_i)$ where Y_i is binary variable.

(2) In the course of changing the objective function, the constraints become $b_i - \sum_{j=1}^{n} A_{ij} X_j \geq 0$, and $-Z \leq UB$

Step 2. Start out with a partial solution where all the variables are free (i.e., can be either 0 or 1). Try the zero completion to see whether it is feasible. If it is feasible go to Step 6.

Step 3. Find the set of violated constraints, i.e., where $\sum_{j=1}^{n} A_{ij} X_j - b_i \geq 0$. If there are no violated constraints, go to Step 6.

Step 4. For each violated constraint find free variables with negative coefficients.

Step 5. For those variables which are considered in Step 4, form the sum of the $\sum_{i=1}^{m} A_{ij}$ for each variable where m is the number of violated contraints. Choose the variable with the least sum whose objective function coefficient does not cause a violation of the upper bound. Fix this variable at one: Set $Z = Z + C_j$. Go to Step 3.

Step 6. A feasible integer solution has been found. Reset the solution upper bound to this objective function value minus a tolerance. Initiate a backtrack (i.e., Step 7).

Step 7. Take the last variable fixed at one and change it to zero. If there are variables to be fixed, go to Step 3.

Step 8. The last integer solution found, if any, is optimal. Terminate.

Summary

Because the MPVNB model formulated in the chapter of the model formulation is a pure 0-1 integer programming problem, all of these three algorithms - Gomory's cut, branch and bound, and 0-1 implicit enumeration are capable of reaching the optimum for this research. However, in running a sample problem, the Gomory cutting plane algorithm reveals one of its major drawbacks - inefficiency - when compared with the other two algorithms. Only the branch and bound and 0-1 implicit enumeration algorithms are employed in this study. Later, when the results of the MPVNB model are presented, a brief comparison is made between branch and bound and 0-1 implicit enumeration with regard to computational efficiency.

Summary of Results

The empirical results of this study consist of two parts. First, the experience of doing integer programming will be briefly described. Second, the optimal timing for constructing the Umatilla Basin Project will be illustrated. Last, a comparison of the optimal timing solution with other timing criteria is also included.

Experience of Doing Integer Programming

Branch and bound mixed-integer programming (BBMIP) and 0-1 implicit enumeration (DSZ1IP) algorithms have been employed to solve the problems formulated in Chapter IV. The problem of "dimensionality" has been encountered, especially for the DSZ1IP algorithm. For example, in the MPVNB model version II (see Table IV-14) it is assumed that the common facility is inseparable leading to an increase in the number of decision variables and therfore the need for formulating solution subprograms.

In this regard, five mutually exclusive subprograms were formulated for the original program. The advantage in so doing was clear since computation time was significantly reduced. A comparison of the BBMIP and the DSZ1IP algorithms can also be demonstrated in solving version II of the model. Because the BBMIP is found more efficient than the DSZ1IP in solving version II, it was decided to use the BBMIP to solve the other versions. The computation times for solving these versions are summarized in Table V-1.

Optimal Timing for the Umatilla Basin Project

In addition to the optimal timing for the problems formulated in Chapter IV, there are other criteria determining the construction timing. In the feasibility report of the Umatilla Basin Project, the Bureau of Reclamation designed a brief plan for the construction. Other simple criteria such as constructing the subprojects according to an ordering of the benefit/cost ratios may be suggested. A comparison of these timing criteria in terms of the present value of net benefits is summarized in Table V-2. The merits of formulating a timing problem for the Umatilla Basin Project are therefore able to be demonstrated.

As shown in Table V-2, the differences in terms of present value of net benefits between the optimal sequence and the Bureau's construction plan are significant. Therefore, the need to perform a facility timing problem for the Umatilla Basin Project is justified. Although

TABLE V-1. Computation Time

	BBMIP Time (seconds)		DSZ1IP Time (seconds)	
Version I		19.287		
Version II				
Original program		57.781		1,200[a]
Subprograms				
total		19.279		92.456
1	4.498		20.783	
2	2.865		15.369	
3	3.369		15.891	
4	3.819		16.432	
5	4.729		24.041	
Version III		47.545		
Version IV		62.943		

[a] The computation time was 1,149.05 seconds without reaching the optimal solution in a computer run. It is estimated that more than 1,200 seconds of computation time are needed to reach the optimal solution.

TABLE V-2. Empirical Result for the Four Versions of the MPVNB Models

	PVNB of Opt.Seq.[a] (a)	PVNB of B.O.R.[b] (b)	PVNB of B/C Ratio[c] (c)	(a)-(b)	(a)-(c)
Version I	179,177,125	169,519,435	178,847,913	9,657,690	329,212
(sequence)	X_{503} X_{107} X_{413} X_{216} X_{320}	d	X_{105} X_{507} X_{413} X_{216} X_{320}		
Version II	178,548,551	168,967,005	178,357,690	9,581,546	190,861
(sequence)	X_{503} X_{107} X_{413} X_{216} Y_{320}	d	X_{105} X_{507} X_{413} X_{318} Y_{220}		
Version III	160,615,478	140,004,747	160,150,070	20,610,731	465,408
(sequence)	X_{408} X_{510} X_{113} X_{216} X_{320}	e	X_{503} X_{410} X_{113} X_{216} X_{320}		
Version IV	160,216,302	139,007,273	160,199,894	21,209,029	16,408
(sequence)	X_{408} X_{510} X_{113} X_{318} Y_{220}	e	X_{503} X_{410} X_{113} X_{318} Y_{220}		

[a] The present value net benefit for the optimal sequence (timing).

[b] The present value net benefit for the construction plan designed by the Bureau of Reclamation.

[c] The present value net benefit for the construction plan decided by the benefit/cost ratio.

[d] Snipe, Ryan, Beacon, Stage, Pumping Plant & Stanfield, and Denning Dams are constructed in year 2, 6, 9, 13, 20, 20, respectively.

[e] Snipe, Ryan, Beacon, Stage, Pumping Plant & Stanfield, and Denning Dams are constructed in year 2, 6, 8, 12, 20, 20, respectively.

the differences in terms of present value of net benefits between the optimal sequence and the sequence based upon the benefit/cost ratio criteria are relatively small for this case study, the differences may become significant for other cases. A major advantage of performing a timing problem over other simple sequencing criteria is that the optimal sequence can be identified by incorporating all relevant economic factors to the model.

Summary

It is concluded that the minimizing present value cost model is an inadequate means of formulating a problem of water resource facility expansion as exemplified by the Umatilla Basin Project. In order to further enhance the analysis of the vaiability of a water resource project, it is often recommended that optimization techniques be employed. When this is the case, the techniques must be supplemented with insights relevant to the economic issues in water resources planning. Therefore, the maximizing present value net benefit model as defined earlier is seen to play a more important role in the formulation of capacity expansion problems. Since the problem of capacity expansion is believed to be still relevant to the United States but increasingly more common in developing country situations, the further improvement of the MPVNB model to cope with more complex situations is warranted.

With respect to the Umatilla Basin Project, it (in 1980) had not been and seems unlikely to be authorized for implementation. This is not an indication, however, that the issues of water allocation have become diminished in importance in this area. Subsequent development plans such as the Stanfield-Westland Irrigation District proposal appear to be attempting to address the issues of water allocation along with the conventional plans.[24] Consequently, one relevant question to this research is whether the framework of optimal capacity expansion can be developed to incorporate water allocation issues. It is desirable, then, to examine the nature of water allocation issues which may be relevant to the optimization modeling. The following chapter thus is incorporated here to discuss the water allocation issues as they might affect the Umatilla River Basin. An approach which perhaps can consolidate the water allocation issues in the framework of optimal capacity expansion will be suggested.

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[24] This proposal, for example, considers a few means of supplementing streamflow levels in the Umatilla River during summer months in order to satisfy salmonid fishery enhancement requirements.

VI. ISSUES OF WATER ALLOCATION AND UTILIZATION RELEVANT TO CAPACITY EXPANSION MODELING

The preparation of the Umatilla Basin Project feasibility plan and subsequent water development plans for that area suggest that there is a bona fide interest among local residents in developing and using their water resources wisely. At the same time, it has also been revealed that there is anticipated competition among water users in sharing those limited resources. The project planned by the U.S. Bureau of Reclamation may have contributed to resolving the argument over the disposition of limited resources, but there are other issues which may need to be further examined. The discussion in the preceding chapters was directed toward an analysis of that water resource development plan without regard to the allocative issues that are inherent in it. In this chapter, it is asked whether optimal plans (in this case, optimal capacity expansion plans) can be developed to incorporate the issues of allocation of scarce resources.

The competition for Umatilla River water may emerge in several ways. There is, of course, competition among holders of water rights on the Umatilla. But, as intimated previously in this study, the chief competitive arena will involve instream uses of water (fisheries) and offstream uses (irrigation). It is noted that the Umatilla Indians and the irrigators, respectively, are the likely active economic interests corresponding to these uses. There are three aspects of the fishery-irrigation competition for water.

The first issue concerns the proponents of fishery development and enhancement. While sports fishermen acting through their organized interest groups will certainly be expressive of their point of view, it is believed that primary impetus will come from the Umatilla Indians.[25] Believing that their treaty rights have been abridged by the long history of irrigation development in the lower Umatilla River Basin, the Indians may in the future elect to exercise the option of clarifying those rights as they apply to the waters of the Umatilla River. Based on legal precedents established in the Winters' Doctrine,[26] the recent Boldt decision,[27] and similiar litigation in Washington,[28] they may receive recognition of claims for water rights with a very early priority date of 1867. What used to be an economic issue therefore becomes multifarious because of the complications of legal judgments and cultural/religious considerations.

Second, because the Umatilla Basin Project had not been approved and is unlikely to receive Congressional approval in the present form, farmers in the area have tried at various times to re-propose part of the irrigation features of the project. Although their developments

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[25] Technically, the Confederated Tribes of the Umatilla Indian Reservation. This Reservation was established in 1867 under a treaty with the U.S. Government which among other things contains language which implies that the Indians and their descendants may continue to use waters on their Reservation and fish in common water with non-Indians in usual and accustomed places.

[26] Winters V. United States (207 U.S. 564) see Merrill, p. 57-64 for a summary of this issue.

[27] See the Anadromous Fish Law Memo, Issue 2 for a discussion of fisheries-related litigation in the Columbia River Basin.

[28] See Dellwo and Anadromous Fish Law Memo, Issue 3, for further details.

have been confined to pumping from the Columbia River, there is interest in developments which would further encroach on the Umatilla River to the detriment of instream uses in this area. Since the estimation of irrigation benefits is a relatively straightforward task, an evaluator of alternatives will always have more information about the benefits of using water offstream rather than instream.

Last, the utilization of the whole river system so as to benefit the local economy at large is assumed to be the ultimate goal of the local residents. In theory, the water allocation alternatives which have the greatest appeal should at least be the ones which identify the current level of community benefits. The alternatives should help to clearly focus the issues implied in allocative decision making. Those considerations have been largely ignored in the preceding discussions of optimal capacity expansion. This is due in part to (1) the difficulties in reliably estimating benefits of fishery reestablishment. Perhaps more relevant is (2) the lack of information on how the primary benefit categories would generate local responding effects (secondary benefits) and (3) external environmental effects. In order to tackle the allocation-related issues taking account of these three kinds of difficulties, different economic analyses can be performed to <u>assist but not to prescribe</u> the formulation of decisions. Because irrigation and fishery enhancement are two major competing water uses, the analysis of this chapter will focus on these two aspects.

Although the neoclassical economic framework is incapable of completely resolving an allocation problem of these dimensions, the application of economic constructs to this issue may reveal some insights which are helpful for arriving at a sound decision. It is believed in planning for long-term water utilization, the capacity expansion framework can reflect the economic consequences of different considerations and therefore furnish useful information to the decision-making process. In the preceding four chapters, the overview of the literature of water capacity expansion and the formulation of a timing problem have focused on the issues of supply and economic efficiency. Those efforts constitute the main part of this research. Similarly, the issues of water allocation are analyzed from the economic efficiency point of view in the beginning of this chapter. Later, as the consideration of property rights is incorporated, economic efficiency is considered no longer to be the sole economic criterion for water allocation. Specifically, the objective of this chapter is threefold.

First, the nature of these issues is discussed and analyzed by employing suitable economic constructs.

Second, the disputes and questions which may arise in estimating fishery benefits are discussed.

Last, an approach is suggested which perhaps can be employed to examine the economic consequences of different alternatives of long-term water utilization. The framework of optimal capacity expansion can possibly be developed to reflect the various considerations regarding water allocation.

Economic Criteria for the Allocation of Water Resources

In this section an attempt is made to review the basic criteria which underlie the contemporary wisdom as well as formally articulated rules[29] for allocation of water resources. The allocation issues raised in this research are admittedly complex and the details may obscure the means by which economic criteria may be applied. In order to simplify the issues, it may be desirable to consider just two uses (irrigation and fishery enhancement) which exemplify competing uses in a watershed Many authors have referred to this case as the general instream vs. off-stream conflict in water resource allocation (e.g., Daubert and Young, 1979).

Economic Efficiency Criterion for Water Allocation

To develop the criteria, assume that economic efficiency is the goal being pursued. Also assume that production functions[30] for irrigated agricutlure and fishery can be estimated. With these two assumptions, economic constructs can be employed to prescribe the water allocation decision. Now suppose these two production functions are:

$$A = g\ (W_a, X_1, X_2, \ldots X_n) \quad (1)$$

$$F = h\ (W_f, \text{Others}) \quad (2)$$

where

A and F represent the agricultural product and fish; W_a and W_f are the water allocated to agricultural production and streamflow and X_i denotes the ith input for agricultural production.

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29 Although the recent U.S. Water Resource Council's Procedures for Evaluation of National Economic Development Benefits does not address the allocation issue per se, the message is clear that the economic efficiency crtierion is of prime consideration in the broad definition of allocation.

30 For simplicity, the agricultural production function is assumed to be an aggregated function.

Basic Conditions. In order to maximize the profit from irrigated farming, farmers should employ the inputs in such a way[31] that

$$\frac{P_a \, \partial A}{\partial W_a} = P_w, \quad \frac{P_a \, \partial A}{\partial X_i} = P_{x_i} \qquad i = 1, \ldots n \tag{3}$$

Where P_a, P_w and P_{x_i} are the prices for agricultural product, irrigation water, and agricultural input X_i, respectively.

With respect to different levels of streamflow, the Indians can derive their marginal net benefits[32] of fishing as $\frac{P_f . C . \partial F}{\partial W_f}$. In which P_f is the economic value of fish to the Indians; C is the coefficient measuring the relationship between the resultant increase of Indians' catch from the increase of fish runs.[33]

Economists have named $\frac{P_a \, \partial A}{\partial W_a}$ and $\frac{P_f . C . \partial F}{\partial W_f}$ as the marginal value of productivities of water for F and A and are denoted as MVP_a and MVP_f, respectively. Let us recall that the economic issue meriting the preceding discussion is to reach a water allocation alternative which maximizes the economic efficiency of utilizing the limited water. Economic efficiency of water utilization can be maximized when $MVP_a = MVP_f$. Because if MVP_a is greater than MVP_f, then economic efficiency can be improved by diverting more water for irrigation from streamflow; otherwise, streamflow needs to be augmented to maximize economy efficiency.

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[31] For detail, see Henderson and Quandt, 1971, p. 68.

[32] For convenience, the Indians are assumed to be the primary beneficiaries of the fishery enhancement. However, the cultural/religious values of fish to the Indians are temporarily ignored here.

[33] Water reallocation is usually a local matter in nature, therefore, only the local economic impacts are under consideration.

The preceding are the economic criteria which dictate the optimal water allocation. These criteria when employed to a graphical approach, solutions to the water reallocation issues could be suggested.

Because the law of diminishing marginal productivity has commonly existed in the production functions, MVP_a and MVP_f are monotonically decreasing functions with respect to water. Several situations may exist illustrating the relationships between the MVP_a and MVP_f.

Misallocation Situations. Suppose at certain times, the discharge record is OS^* which OS_o and S_oS^* amounts of water have been allocated for instream and irrigation uses individually as shown in Figure 6-1. In order to illustrate the improvement of economic efficiency of water reallocation, it is convenient to draw the figure in a way that the movement along the horizontal axis has opposite implications to the Indians and irrigators. Thus, moving rightward along the axis means more water for the Indians but less for the irrigators. Therefore, the MVP curves decrease monotonically as more water becomes available.

The situation as illustrated in Figure 6-1 is considered most likely to occur when the development of irrigation has created a so-called "critical period" to the fish, such as the low-flow summer months in the Umatilla River. The Indians have the right and also are willing to pay to increase the streamflow at least to OS_1 level. This means that at most only S_1S^* of water should be diverted for irrigation to attain the optimal allocation.

The economic efficiency will be increased by the area Δabc and is maximized when streamflow is augumented from OS_o to OS_1. There are two alternatives to reach an optimum. First, a mandatory reallocation

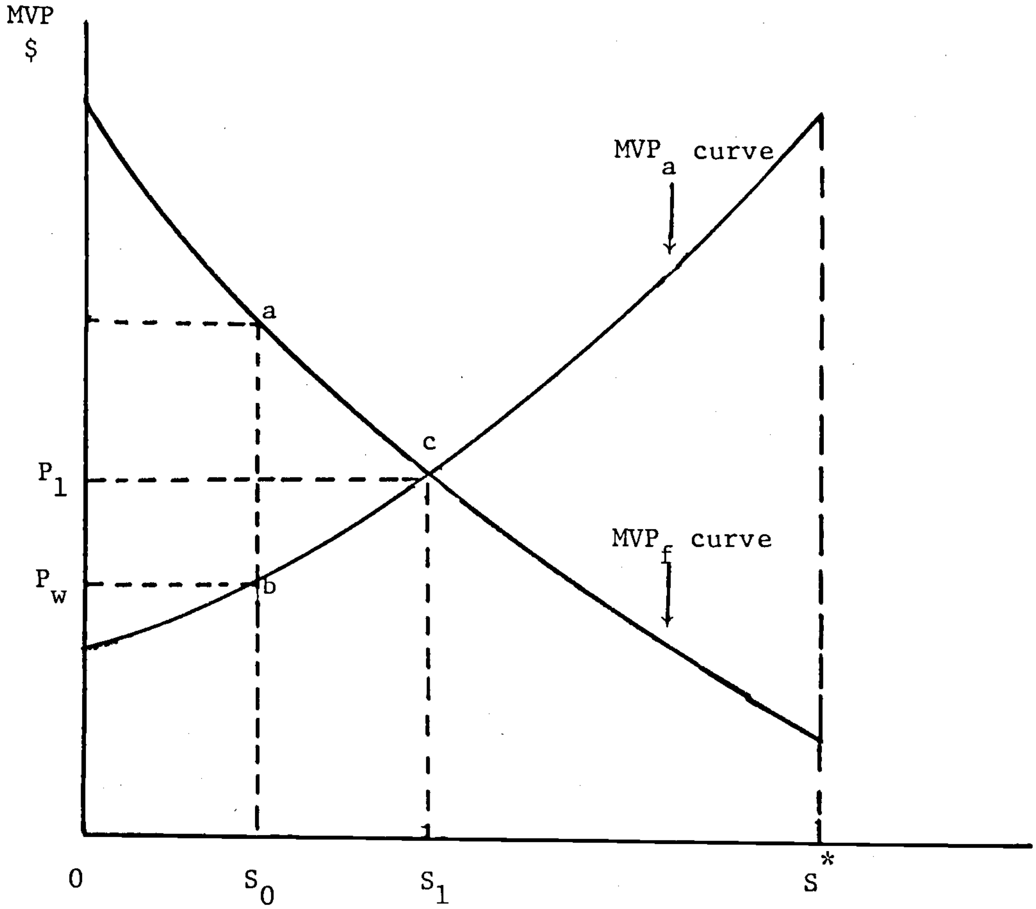

Figure 6-1. Water misallocation situation.

could be enforced. But this alternative would also force farmers out of equilibrium in a state of profit maximization in the short run, because the new MVP_a is forced to increase and exceed P_w. In the long run the plan of future irrigation development will be abandoned.

The other alternative is to price out the inefficient irrigation. If the water rate is raised to P_1, the optimal allocation can be reached automatically via market forces. Because some economists have been critical about the practice of the preferential water rate for irrigation (Hirshleifer, 1970), this alternative is of especial relevance.

Now, with the conclusion of this economic analysis, one may pose other noneconomic questions such as by how much the Indians should be compensated and what are the additional values incremental to the MVP_f when Indians' cultural/religious values are considered. Because the political system may be more adept at considering the importance of noneconomic factors (such as the definition of a yet to be declared water right), these questions are beyond the context of economic analysis.

Adequate Allocation Situations. When the situation is as shown in Figure 6-2, the Indians may have institutional and moral rights but lack of economic support to increase streamflow. Since the Indians have the promise of an old water right which, if declared valid, would augument streamflow, economists have defined the MVP_a curve as the "bribe function"[34] of the farmers. It follows that farmers are induced by the legal system to bribe the Indians. Since the economic efficiency is decreased as the irrigational water is reallocated to streamflow, a wise legal system should compensate the Indians monetarily but not with water. This situation may become common when streamflow is relatively high or the fishery environment is barely encroached.

The preceding discussion has illustrated the most common water reallocation situations which may occur in the Umatilla River Basin. Presumably, variations of these two situations may exist. Because economic analyses for these variations are believed to follow the same procedure, it is unnecessary to repeat similar discussions.

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[34] Bribe function is defined as the maximum willingness to pay of the acting party (farmer) to buy the right of producing externalities.

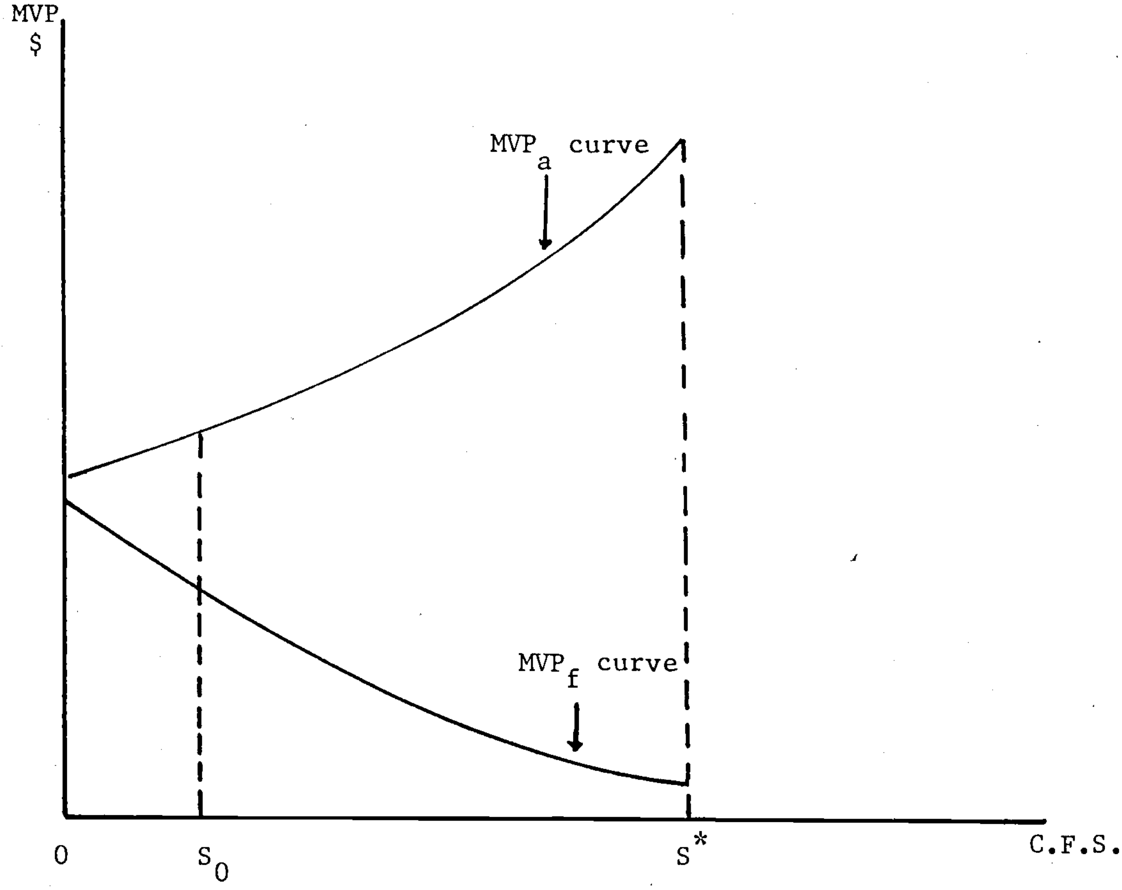

Figure 6-2. Adequate water allocation situation.

Opportunity Cost Issues in New Irrigation Development

The allocation issue may also be examined in the context of opportunity costs inherent in autonomous decisions to implement new irrigated farming activity in the Umatilla Basin. Such opportunity cost issues have become well known to the residents of the Umatilla area as a result of the irrigation-hydropower tradeoff analysis developed by Whittlesey and Gibbs (1978) among others.

Consider a specific example from the proposed Umatilla Basin Project. Suppose the farmers in the Stage Dam service area try to build the Stage Dam individually for supplying irrigational water. If the construction of Stage Dam will affect streamflow then the associated fishery losses need to be explicitly considered in the cost-benefit analysis. What, then, is the role of water allocation decision making in this situation?

Referring to the model introduced above, assume that the curves in Figure 6-3 reflect the situation facing the irrigators before constructing Stage Dam. If irrigation in this area already diverts more than S_1S^* of water, the Stage Dam proposal should be rejected. If irrigation in this area diverts less than S_1S^*, say S_0S^*, of water, then the economic efficiency of water utilization can be improved by building Stage Dam.

If the Indians are endowed with a well defined water right, some amount of "bribe" based upon economic analysis can make both irrigators and Indians better off. MVP_f now represents the minimum amount the Indians will accept to allow further diminishment of the streamflow. They will be better off if the irrigators can offer them more than

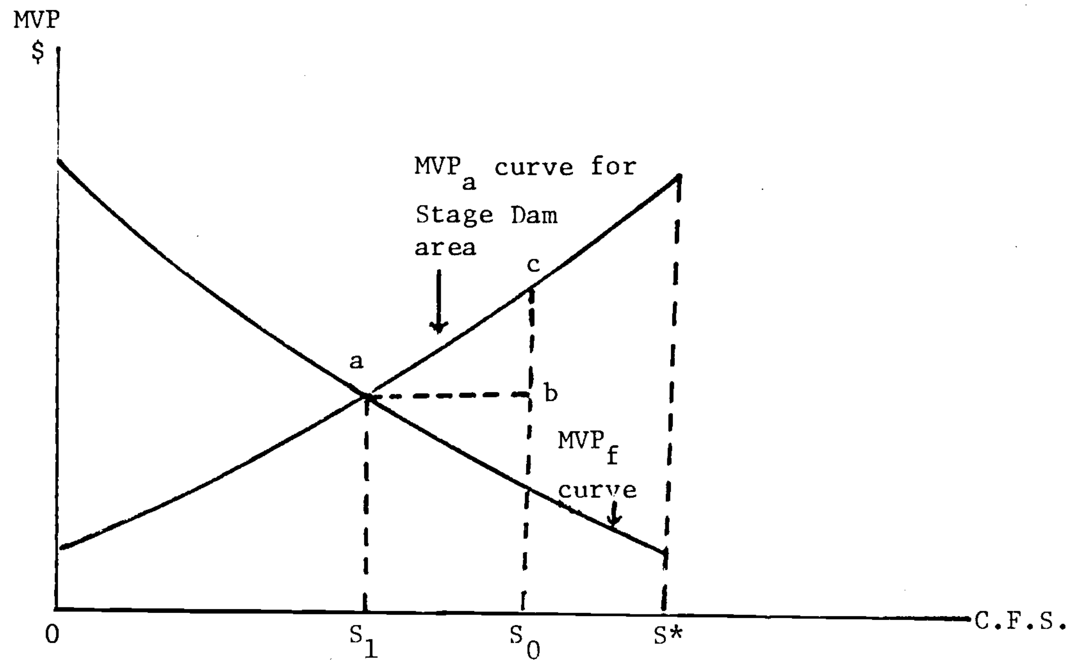

Figure 6-3. Water allocation for new irrigation project.

the MVP_f. If the irrigators can offer the amount of money which is equal to the area aS_1S_0b to exchange S_0S_1 of water, they are also better off because they earn an extra amount of money which is equal to the area abc from this venture.

In summary, the depletion of streamflow is a cost associated with irrigation development. But the relevant cost is the area under MVP_f, not the actual payment made by the irrigators. The capacity for the Stage Dam should be S_0S_1, if the maximization of economic efficiency of water utilization is concerned.

In summarizing the preceding discussion, there is a need to admit that the discussion is incomplete with several heroic assumptions, not the least of which is knowledge of the production function for fish. In addition, more efforts are needed to examine the details of the relevant agricultural production function; especially, the necessary treatment of several different agricultural processes at the same time. Moreover, the discussion is static and is ignoring the time effect on water availability and crop response. Nevertheless, the neoclassical model can be valuable in at least two ways. First, the nature of the issues related to water allocation in the study area is demonstrated to be able to be examined in the confines of an economic model. Second, the suitable economic criteria can be applied to determine allocations first without and then with institutional constraints.

Estimatation of Instream Benefits

As just pointed out, perhaps the most significant obstacle to applying a formal model to water resource allocation problems is the specification of an instream flow benefit production relationship. While economists are somewhat handicapped in estimating the multidimension function that would be required (i.e., water quality, recreation, and other fishery-related outputs to streamflow), they have attempted to examine various issues surrounding this fundamental problem.

Problems in Estimating Fishery Benefits

As indicated in Chapter II, the estimate of fishery benefits in the proposed Umatilla Basin Project was undertaken by two procedures. First, the physical increase in levels of recreational use (angler days per year) and commercial catch (pounds per year) were estimated by the U.S. Fish and Wildlife Service when the evaluation of anadromous fishery enhancement features was completed. Then the monetary benefits were derived by using the criteria established in the "Evaluation Standards for the Primary Outdoor Recreeation Benefits."[35] These consist of unit values which when multiplied by the physical quantity projections yield an estimate of total annual benefits. Although this estimate was conducted by an agency assumed to represent the best knowledge about such issues in project development, several quesitons may emerge in regard to the accuracy of the estimate and therefore stimulate the need of future research of multi-disciplines. These questions can be divided into two categories - production and pricing aspects.

Production Aspects of Fishery Benefits. The estimation of the production relationship between the physical increase of fishery benefits and the means of fishery enhancement including low streamflow mitigation may involve difficulties related to biological and other factors. Fishery biologists may be more or less confident in estimating the increase of salmon and steelhead runs results from the enhancement activities, but difficulties may arise in estimating the increase of sport fishing activities attracted by the increase of fish. It is true that the increase of fish runs will correspondingly improve the success of fishing and, hence, attract more fishing-related recreation to the area; however, these relationships may not be estimated easily for an area where sport fishing has been severly hampered in the recent past. Moreover, the problem of accessibility (trespass) and fishing characteristics (probability of success and trespass) of nearby streams are other significant factors which complicate the task of estimation.

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[35] For details, see the Umatilla Basin Project (USDI, 1970).

In order to obtain an easy answer to the problem, one may suggest the use of observed fishing activities in a nearby stream with similar fishing situations as an approximation; however, it is a mistake to ignore the substitution effects among neighboring streams. The increase of fishing activity for an area resulting from fishery enhancement may consist of net increase and switch from (decrease of) nearby areas. Thus, it is necessary to estimate the net increase rather than the whole impact for the calculation of benefit-cost ratio. Although it is true that the total increase figure rather than the net increase figure is appealing to the local residents, especially for solving the water allocation problem which is a local matter in nature.

With respect to commercial catch, the controversial and variable regulations, the dynamic fishery biology, and fishing effort complicate the task of estimation. Nevertheless, planners tend to assume that these issues do not affect outcomes and proceed to estimate the production function directly. Meanwhile, one may observe that the increase of commercial catch may be claimed by both Indians and non-Indians (for example, the ocean fishermen). Although the figure is "right" from the evaluation point of view, it is, of course, opposed by the irrigators of the area. As mentioned in Chapter II, local interest and support are important factors in developing water resources, local impacts therefore, should receive more emphasis in the evaluation process when the differences between local and national impacts are significant. These are the realized difficulties in solving a water allocation problem.

Pricing Problems in Deriving Fishery Benefits. The fish production function characteristics of a watershed may be viewed as separate from any valuation characteristics (i.e., they are pure physical production functions). However, it has already been intimated that output of a fishery depends critically on the effort applied to exploiting it and that, in turn, effort expended depends upon valuation. As one might expect, the evaluation issue is different for commercial fish catches than it is for sports fisheries.

Because of the common property characteristic of the fishery, difficulties emerge in the evaluation of the commercial catch. Unlimited entry allows additional men and boats to enter the fishery, coupled with the rapid progress of fishing technologies and the limited renewable capacity of the fishery, thereby reducing the catch per boat to the point where the cost of harvest approaches the ex-vessel value of the catch (Gordon, 1954; Crutchfield, 1962).

Because of the common property problem the net economic value of the fishery tends toward zero from the standpoint of the fisherman. Thus, economists have discarded using the net economic value of the catch as a measure of the benefits. Instead, Crutchfield recommended that a "potential" net economic value, 90 percent of the gross value to the fisherman, based upon an assumed efficiency harvest of the fish could be used.

Brown, et al., not being satisfied with this method, attempted to estimate the demand function for the fish first. Theoretically, the demand function can be used to compute the prices consumers would be willing to pay for certain quantities of fish and the corresponding consumer surplus associated with increased production.

Similarly, a demand function for sport fishing was also estimated to compute the value of each angler day. Although the research conducted by Brown, et al., was hampered by data limitations, their approach is believed to be a promising approach to price commercial catch and evaluate sport fishing from economic standpoints.

It was estimated by Brown, et al., that the value for salmon-steelhead sport fishing was at $22.00 per day in 1974 price level and the consumer saving was $0.73 per pound of increased production in 1972 price level. When adjusted to the 1970 price level by using consumer price index, the values were $17.80 and $0.70, individually, which were significantly higher than the values (i.e., $6.00 and $0.56) used by the U.S. Fish and Wildlife Service as cited in the Umatilla Basin Project Plan (p. 57). These differences therefore imply the difficulties in estimating fishery benefits from the aspect of price.

Regarding to the local fishery benefits, very little research on the value of fish to the Indian fishermen in the Northwest has been performed. From the Indians' point of view, the valuation question is irrelevant since the essential amenities are of a cultural and religious nature. Certainly, some finite quantity of fish falls into this category. But beyond a certain catch level (sufficient to cover cultural-religious and subsistence needs), there is a good chance that Indians turn to selling fish in the local market. Obviously further research is needed to ascertain the quantities of fish involved.

Given these initial disparate data on the realistic valuation of the fishery resources which could be expected to be developed in the

Umatilla, it may be that the residents of the area will have to undertake river basin planning with a number contingencies in mind. Designing long-term plans with considerable scope for changes may well be the same as no planning, but at least some candidate framework will have been selected in which to analyze issues. The concluding part of this chapter turns to the design of such long-term plans.

Planning for Long Term Water Utilization in the Umatilla River Basin

One necessary assumption of a long term water resource allocation (in the broad sense) plan is that the residents of the area perceive some decided advantages in developing such a plan. The Umatilla River resource allocation issue may not be the most unifying task for the area because of the large number of resource development possibilities which exist there. Nevertheless, the assumption made here is that the interest is high and that there are divergent points of view on water allocation.

Economic as well as noneconomic considerations are of course represented in these points of view. Since the optimal capacity expansion framework developed in the preceding chapters is devoid of such controversies, it is conjectured that inclusion of such features is necessary to make the MPVNB model more creditable. A summary of the different points of view in long term river basin development will be addressed below. Afterward, several alternatives of development plannings will be suggested.

Considerations in the Long Term Development Plans

Three representative controversies are briefly considered here although this is by no means meant to be an exclusive list. However, one should realize that these three controversies are the most relevant issues to the area and therefore, should be consolidated in the analytic model.

Low Streamflow Level Mitigation. The Oregon State Game Commission (1973) completed the report of "Environmental Investigations" for the Umatilla River Basin. In this report, the minimum streamflow as well as the optimum streamflow for fish enhancement expressed in cubic feet per second (c.f.s.) for different locations at different times were recommended. One may ask which recommendation should be adapted and what are the economic consequences of different decisions. These questions will be further complicated when the difficulties of estimating fishery benefits emerge.

Locally Relevant Benefits. In conducting a cost-benefit analysis, the secondary (or local) benefits are only allowed to be displayed but not to be included in the calculation of benefit-cost ratio (U.S. Water Resources Council, 1973; 1979). But in determining the construction timing may emphasize the magnitude of locally-relevant benefits (i.e., external benefits in fishery and irrigation). Therefore, it is necessary to clearly define what are the relevant data for deciding construction timing. If the residents are embued with the power to determine the construction timing, secondary benefits (or so-called "stemming from" or "induced by" benefits) would be emphasized. A well defined policy is needed to be established in this regard.

Priorities Implementing Alternatives. In a long term development planning such as the Umatilla Project, all of the water uses will be satisfied subject to constraints on availability; however, the subject ation, the Indians have requested streamflow mitigation by reducing off-stream water uses. Accordingly, in a long-term development, they may claim that fishery reestablishment has first priority since the fishery environment has been deteriorated by past irrigation development and probably will be further encroached if irrigation features are invested first.

On the other hand, the irrigators may oppose the plans favoring the Indians if they are based upon the questionable fishery benefits. Therefore, noneconomic arguments as well as economic arguments have emerged in the problem of construction timing.

If improvement of estimating methods for fishery benefits can be achieved, several development alternatives in light of the Indians' claim could be developed. The economic consequences of the development alternative may be helpful to the residents to reach a decision by examining the problem of tradeoff between the economic efficiency and institutional considerations. Unfortunately, a situation exists in which improvement of estimating methods are badly needed.

Alternatives in Planning Long Term Allocation

In planning facilities for water resources allocation, one relevant question is the sizing problem, especially when there are several independent features such as analyzed in Chapter IV. When several discrete scales for each of the proposed facilities are made possible, the optimal capacity expansion framework is capable of determining both the sizes of the features and the optimal timing by comparing the comparative advantages among and within the features. Therefore, additional investigations are warranted in order to make better decisions.

As suggested above, there are difficulties in accurately estimating fishery enhancement benefits. Thus, the allocation alternatives will be discussed here by assuming that the fishery reestablishment is an institutional obligation to all plans. While the direct benefits are real enough, they will have to be considered an unknown. It is noted that the concept of "opportunity cost" has been widely used in theory by economists as a preferred measure of benefits. With respect to the issue of water allocation, the irrigation net benefits foregone when reallocation is enforced are the opportunity costs for low stream level mitigation. These costs need to be explicitly considered in deciding whether reallocation proposals should be exercised.

Suppose there are two alternatives in utilizing the Umatilla water, one is completely dedicated to irrigation allocations, while the other one is dedicated to streamflow maintenance necessary to support a fishery (with no direct fishery benefits assigned). The difference of the economic consequences of these two alternatives is a measure of the opportunity cost for low streamflow level mitigation. A comparison between the opportunity costs and the estimated fishery benefits by the U.S. Fish and Wildlife Service agents may provide the relevant information of the decision makers.

In light of the preceding discussion, several alternatives of development can be specified.

All Irrigation Development Alternative (A.1). Irrigation development is the main purpose in this development alternative. The resultant irrigation net benefits for each different scale of each feature must be estimated. The timing problem for this alternative is to reach the optimal sequence of constructing the proposed features. Although this alternative is unlikely to be accepted by the local residents, in particular the native Umatilla Indians, it is a necessary option to examine the opportunity costs of low streamflow level mitigation.

Irrigation Development Priority Alternative (A.2). In this alternative, low streamflow level mitigation is an obliged under the development. Since there are no direct benefits assigned to the fishery enhancement, it is necessary to add a constraint to the timing problem to enforce the construction of fishery enhancement features. The differences between the economic consequences of A.1 and A.2 are the minimum of opportunity costs of streamflow mitigation. One may ask what role does the concept of opportunity costs assume in this situation? If the opportunity costs are relatively high when compared wtih the directly estimated local fishery benefits, it indicates that A.2 is an alternative which is most beneficial to the local economy; otherwise other alternatives may be more desirable.

Low Streamflow Level Mitigation Priority Alternative (A.3). In this alternative, the features having the purpose of streamflow maintenance are constructed first. The timing problem for this alternative is to sequence the irrigation features. The differences between the economic consequences of A.1 and A.3 are the maximum of opportunity costs of streamflow mitigation. This figure together with the local fishery benefits constitutes the information which is helpful to the local people to understand the economic implications of different institutional considerations.

Other Alternatives (A.4). It may be suggested that irrigation development has a priority for investment up until the irrigation developments reach a certain acreage level where low streamflow levels need to be protected. This is an alternative between A.2 and A.3 and many variations of this alternative can be posed. In any event, the resultant opportunity costs would be somewhere between the opportunity costs of A.2 and A.3.

Opportunity Costs vs. Strength of Water Rights. The alternative which aims at protecting the level of streamflow can be interpreted as the consequence of the Indians possibly having clarified the issue of prior water rights. This prior water right, if granted to the Indians, is the kind of noneconomic force to require that low streamflow level mitigation have first priority. Following this interpretation, the strength of the Indians' water right becomes progressively weakened in the order of alternatives A.3, A.4, A.2, and finally A.1. It is also noted that the magnitude of opportunity costs is progressively decreasing in the same order. Different levels of low streamflow level mitigation attained (e.g., minimum and optimum levels) are believed to affect the magnitude of opportunity costs differently. The opportunity costs for low streamflow level mitigation will be higher when the optimal streamflow level rather than the minimum streamflow level is selected in the plan. In summary, these relationships can be expressed in Figure 6-4.

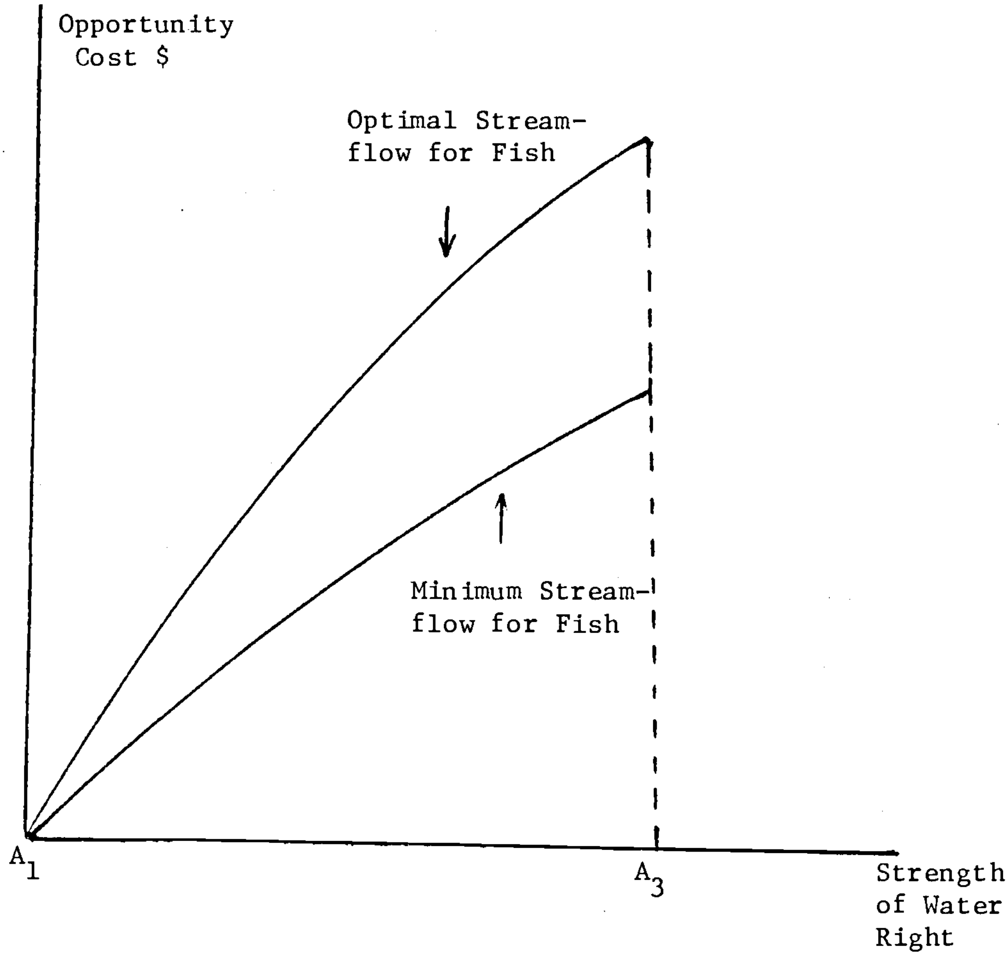

Figure 6-4. Opportunity costs vs. strength of water right.

The stronger the Indians' Water Right[36] is, the sooner the streamflow is to be protected and hence, the greater the irrigation benefits are to be foregone; the more the streamflow needs to be protected the more the irrigation benefits need to be considered as opportunity costs.

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[36] The strength of a water right may vary. One absolute senior right granted to Indians for a large quantity of water would be very strong. A set of incremental rights which are less senior and are for small quantities of water would be diminished in strength.

Summary

The relevant issues of water allocation and utilizaiton in the Umatilla River Basin have been discussed conceptually in this Chapter with the hope of suggesting revisions to a capacity expansion model developed earlier. In order to examine numerically those issues, multi-dimensional forms are needed. In particular, economic and biological research is sorely needed to estimate accurate fishery benefits. Meanwhile, a more complex model which is more realistic will certainly require more (costly) computation time and computer capacity. Therefore, improvements in problem-solving algorithms are desirable.

The development of the maximizing present value net benefit model in the previous chapters aims to modify the goal of optimal capacity expansion to be consistent with the criterion of economic efficiency. It is believed that the improvement of the MPVNB model should be encouraged; therefore, this chapter aims to incorporate other relevant criteria (such as distributional considerations and property right issues) in order to develop a complete model. Despite the fact that economists still need to apply themselves to these problematic issues the message of this chapter is not to deny the usefulness of the model developed previously. However, an attempt has been made to suggest several approaches which may be employed by those seeking to develop realistic yet economically relevant plans for water resource allocation.

VII. SUMMARY AND CONCLUSIONS

Objectives of the Research

The major objectives of this study were (1) to critically review the literature of optimal water resource system expansion in the hope of adding more economic content to the planning techniques, and (2) to identify and solve a facility scheduling problem commonly encountered when a water system development is planned. By way of accomplishing these two objectives, a dynamic consideration can be added to the conventional benefit/cost analysis for a water resource system development which includes several independent facilities in the plan. It was also desirable to discuss and analyze the issues of water allocation which have received increasing concerns in the study area and elsewhere. Finally, this research attempted to present a procedure to examine how the alternatives of long term water planning can be enhanced by optimal capacity expansion modelling. This chapter summarizes the accomplishments of the research related to these objectives.

Accomplishments of the Research

The objective of a critical literature review was accomplished in Chapter II. It was observed that the emphasis of the literature in optimal water resource system development has been on the cost aspect of the problem. Consequently, the goal of water resource capacity expansion specified in the literature sometimes is inconsistent with the concept of economic efficiency; therefore, it was concluded that simultaneous consideration of both cost and benefit aspects of the development should be treated as the economic criteria for the study in the optimal expansion of water resource systems. As an immediate result of incorporating more relevant economic concepts in the model, the applicability of the model is broadened.

The Umatilla Basin Project provides an excellent example to examine the problem of optimal water resource system development, since it includes several major features in the plan. In Chapter III and Chapter IV, the entire project was decomposed into five facilities in order to state a formal scheduling problem. This problem was formulated along integer programming lines solving for the maximum present value of net benefits schedule of facilities. A common phenomenon -- interdependency among facilities -- in the water resource planning was incorporated in the public formulation. It was concluded in these two chapters that the maximizing present value net benefit model may become an important element in planning water resources capacity expansion, since the multi-purpose nature prevails in the present water resources plannings. The timing problem was successfully formulated and solved in Chapters IV and V, respectively. It was then suggested that a dynamic dimension can be easily added to the conventional benefit/cost analysis. The empirical results of Chapter V suggested that integer programming is a suitable technique to solve the facility timing problem. The merits of applying optimization techniques to expand water systems are found to be significant, especially when compared with the construction plan designed by the U.S. Bureau of

Reclamation. Savings in costs and additional benefits would have been realized by implementation of the optimal plan.

In addition to the long term development, there are two related short term issues -- reallocation and water rights -- related to water allocation in the study area. These issues were discussed and analyzed in Chapter VI. In light of these issues, several long term development alternatives were suggested to local residents to make a decision regarding an overall development of their water resources. The framework of optimal capacity expansion was also employed to discuss the economic consequences of the development alternatives.

Conclusions

As a consequence of rapid population and economic growth in certain locations in the western United States, demands for water can be observed to be increasing over time. Thus the issues of water allocation continue to attract considerable attention in this region. In order to resolve these issues, individual water users, their elected representatives, and the personnel of public sector bureaucracies have proceeded to promote significant investments in planning for water resource allocation and management. Even though the amounts of "new" water which can be developed (in the usual sense) are steadily diminishing, the planning activity continues.

Economic criteria have often been recommended as the most suitable means of directing the exploitation of water resources in a way that the relevant net social benefits of the investment are maximized.

Although the benefit/cost analysis has been a widely used tool to evaluate water resources developments, it is ill-suited to determine the optimum sequencing and sizing of projects in an overall plan of many economically feasible projects. It is believed that both economic criteria and optimization techniques need to be employed to decide the best sequences of projects.

In light of this need, a maximizing present value net benefit model focusing on economic efficiency was developed and employed successfully to solve the facility-timing problem in the Umatilla River Basin. Although more relevant economic concepts are incorporated in the model, one should realize that there are other realities which when incorporated would improve the usefulness of the model developed in this study. For example, the variations of water availability at different locations and times may need to be incorporated to formulate a complete model.

Although economic efficiency is an important factor in affecting social well-being, there are other considerations which still need to be incorporated. The discussion of the issues related to water allocation introduced, for example, the distribution considerations implied in property rights. When other considerations such as property rights emerge in the decision-making process, it is to be expected that the economic efficiency criterion will become relaxed. Therefore, a discussion of these relevant issues is believed to be an important ingredient in incorporating a higher degree of reality into the framework of optimal capacity expansion. It was admitted that this study is still far from incorporating all relevant considerations in a single model. Therefore, improving the MPVNB model to include distributional and institutional characteristics of water resources systems is the recommended future research of this study.

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APPENDICES

APPENDIX A

CONSTRUCTION COSTS FOR THE UMATILLA BASIN PROJECT

BASIC ESTIMATE DC-I SUMMARY

OFFICE PREPARED BY: Upper Columbia Development Office, Spokane, Wash.

PROJECT: UMATILLA BASIN
Date of Estimate: December 1951 to October 1968
Prices as of: July 1969 (indexed)
Sheet 1 of 2 sheets

DESCRIPTION	DC-1 SHEET NUMBERS	LABOR AND MATERIALS BY CONTRACTOR Cost	LABOR AND MATERIALS BY GOVERNMENT Cost	FIELD COST Plant Account	TOTAL FIELD COST Identified Property	OTHER COSTS Identified Property	TOTAL COST Identified Property	TOTAL COST Property Class
2	3	4	5	6	7	8	9	10
RESERVOIRS AND DAMS								123,875,000
RYAN DAM AND RESERVOIR					42,940,000	10,860,000	53,800,000	
BEACON DAM AND RESERVOIR					16,033,000	4,007,000	20,040,000	
STAGE DAM AND RESERVOIR					15,071,000	3,762,000	18,512,000	
STANFIELD DAM AND RESERVOIR					9,723,000	2,427,000	12,150,000	
DENNING DAM AND RESERVOIR					10,680,000	2,660,000	13,340,000	
SNIPE DAM AND RESERVOIR					3,709,000	921,000	4,630,000	
McKAY SPILLWAY REHABILITATION					860,000	215,000	1,075,000	
DIVERSION WORKS								3,895,000
HOMLY DIVERSION DAM					2,182,000	618,000	2,800,000	
STEWART DIVERSION DAM					235,000	85,000	320,000	
HIDAWAY DIVERSION DAM					497,000	198,000	685,000	
OWIPE DIVERSION DAM					64,000	26,000	90,000	
PUMPING PLANTS								9,220,000
COLD SPRINGS PUMPING PLANT					7,008,000	2,212,000	9,220,000	
CANALS AND CONDUITS								66,245,000
COLD SPRINGS DISCHARGE CANAL					1,008,000	322,000	1,330,000	
COLD SPRINGS RELIFT PUMPING PLANT					7,402,000	1,888,000	9,290,000	
HOMLY CANAL					4,445,000	935,000	5,380,000	
BEACON CANAL					3,359,000	726,000	4,085,000	
McKAY-BEACON TUNNEL					1,184,000	251,000	1,435,000	
STAGE CANAL					12,697,000	2,663,000	15,360,000	
COLD SPRINGS CANAL					6,453,000	1,352,000	7,805,000	
PARADISE-TEEL CANAL					6,848,000	1,437,000	8,285,000	
STEWART CANAL					995,000	285,000	1,280,000	
HIDAWAY CANAL					4,385,000	925,000	5,310,000	
EAST OWIPE CANAL					517,000	168,000	685,000	
WEST OWIPE CANAL					387,000	128,000	515,000	
SNIPE TUNNEL					4,531,000	954,000	5,485,000	
LATERALS								85,330,000
SOUTH RESERVATION DISTRIBUTION SYSTEM								
SOUTH RESERVATION A					824,000	196,000	1,020,000	
SOUTH RESERVATION B					3,729,000	942,000	4,670,000	
SOUTH RESERVATION C					1,340,000	350,000	1,690,000	
NORTH RESERVATION DISTRIBUTION SYSTEM								
NORTH RESERVATION A					6,464,000	1,606,000	8,070,000	
NORTH RESERVATION B					2,871,000	719,000	3,590,000	
NORTH RESERVATION C					313,000	77,000	390,000	
UPPER PARADISE DISTRIBUTION SYSTEM					11,187,000	2,573,000	13,760,000	
COLD SPRINGS DISTRIBUTION SYSTEM								
COLD SPRINGS A					2,206,000	574,000	2,780,000	
COLD SPRINGS B					2,115,000	560,000	2,675,000	
COLD SPRINGS C					3,072,000	788,000	3,860,000	
COLD SPRINGS D					3,009,000	776,000	3,785,000	
DESPAIN DISTRIBUTION SYSTEM								
DESPAIN A					2,570,000	660,000	3,230,000	
DESPAIN B					1,589,000	421,000	2,010,000	
LOWER PARADISE DISTRIBUTION SYSTEM								
LOWER PARADISE A					2,405,000	625,000	3,030,000	
LOWER PARADISE B					2,776,000	714,000	3,490,000	
TEEL DISTRIBUTION SYSTEM								
TEEL A					3,668,000	927,000	4,595,000	
TEEL B					3,820,000	970,000	4,790,000	
TEEL C					4,716,000	1,204,000	5,920,000	
TEEL D					3,532,000	903,000	4,435,000	
STANFIELD EXTENSION DISTRIBUTION SYSTEM					6,033,000	1,507,000	7,540,000	
DRAINS								35,150,000
SOUTH RESERVATION					2,664,000	601,000	3,265,000	
NORTH RESERVATION					5,195,000	1,094,000	6,290,000	
UPPER PARADISE					2,582,000	573,000	3,155,000	
COLD SPRINGS					3,939,000	841,000	4,730,000	
DESPAIN					1,144,000	301,000	1,445,000	
LOWER PARADISE					2,543,000	582,000	3,125,000	
TEEL					5,189,000	1,091,000	6,280,000	
STANFIELD EXTENSION					1,482,000	368,000	1,850,000	
STEWART BENCH					87,000	33,000	120,000	
SNIPE					70,000	25,000	95,000	
UMATILLA BOTTOMS					2,005,000	464,000	2,470,000	
BIRCH CREEK BOTTOMS					442,000	143,000	585,000	
BUTTER CREEK BOTTOMS					1,349,000	341,000	1,690,000	
CHANNELS								2,840,000
STAGE GULCH					432,000	143,000	575,000	
BUTTER CREEK					1,835,000	430,000	2,265,000	
TRANSMISSION LINES, SWITCHYARDS AND SUBSTATIONS								3,905,000
COLD SPRINGS TERMINAL					250,000	75,000	325,000	
COLD SPRINGS TRANSMISSION LINE					127,000	39,000	165,000	
COLD SPRINGS PUMPING PLANT SUBSTATION					286,000	89,000	375,000	
COLD SPRINGS RELIFT PUMPING PLANT SUBSTATION					388,000	122,000	510,000	
SPRINGS-TEEL TRANSMISSION LINE					583,000	187,000	770,000	
COLD SPRINGS SUBSTATIONS					191,000	84,000	275,000	
DESPAIN SUBSTATIONS					84,000	41,000	125,000	
STANFIELD SUBSTATION					64,000	31,000	95,000	
LOWER PARADISE SUBSTATIONS					101,000	44,000	145,000	
TEEL SUBSTATIONS					212,000	88,000	300,000	
ROUND-UP TERMINAL					250,000	100,000	350,000	
RESERVATION TRANSMISSION LINE					127,000	58,000	185,000	
SOUTH RESERVATION SUBSTATION					85,000	40,000	125,000	
NORTH RESERVATION SUBSTATION					111,000	49,000	160,000	
GENERAL PROPERTY								7,540,000
PENDLETON PROJECT OFFICE					1,305,000	321,000	1,626,000	
STANFIELD FIELD OFFICE					160,000	45,000	205,000	
PROJECT HOUSING					90,000	22,000	112,000	
RYAN RESERVOIR RECREATION FACILITIES					400,000	121,000	521,000	
BEACON RESERVOIR RECREATION FACILITIES					272,000	88,000	360,000	
STAGE RESERVOIR RECREATION FACILITIES					175,000	53,000	228,000	
STANFIELD RESERVOIR RECREATION FACILITIES					182,500	54,500	237,000	
DENNING RESERVOIR RECREATION FACILITIES					62,500	18,500	81,000	
SNIPE RESERVOIR RECREATION FACILITIES					647,000	193,000	840,000	
McKAY RESERVOIR RECREATION FACILITIES					15,000	5,000	23,000	
RYAN BIG GAME MANAGEMENT AREA					195,000	55,000	250,000	
HIDAWAY CANAL BIG GAME FACILITIES					10,000	3,000	13,000	
NONGAME FISH TREATMENT					15,000	5,000	20,000	
RESIDENT FISH HATCHERY					500,000	100,000	600,000	
ANADROMOUS FISH HATCHERY					1,000,000	200,000	1,200,000	
BEACON RESERVOIR PASSAGE FACILITY					620,000	130,000	750,000	
UMATILLA RIVER CHANNELIZATION					236,000	48,000	284,000	
FISH PASSAGE FACILITIES, EXISTING DIVERSION DAMS					75,000	15,000	90,000	
FISH SCREENS, EXISTING DIVERSION DAMS					80,000	20,000	100,000	

APPENDIX B-1

COMPUTER PROGRAM FOR VERSION I

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BBMIP
TITLE
    UMATILLA BASIN PROJECT MPVNB MODEL VERSION I
INTEGER
    X105 X107 X109 X111 X112 X113 X114 X116 X118 X120
    X203 X205 X207 X208 X209 X210 X212 X214 X216 X218 X220
    X305 X307 X308 X309 X310 X311 X312 X314 X316 X318 X320
    X407 X409 X410 X411 X412 X413 X414 X416 X418 X420
    X503 X505 X507 X509 X510 X511 X512 X513 X514 X516 X518 X520
MAXIMIZE
  63841664X105+  59310008X107+  55100022X109+  51188872X111+  49338672X112+
  47555347X113+  45836479X114+  42582881X116+  39560232X118+  36752138X120+
  13705828X203+  12836046X205+  12028004X207+  11645753X208+  11277318X209+
  10922201X210+  10250009X212+   9625530X214+   9045379X216+   8478143X218+
   7951170X220+  17237431X305+  16013871X307+  15435057X308+  14877163X309+
  14339434X310+  13821141X311+  13321582X312+  12375980X314+  11497499X316+
  10681375X318+   9923182X320+  83149152X407+  77246998X409+  74454938X410+
  71763796X411+  69169924X412+  66669806X413+  64260054X414+  59698700X416+
  55461124X418+  51524342X420+  34027109X503+  31611772X505+  29367882X507+
  27283270X509+  26297127X510+  25346629X511+  24430486X512+  23547456X513+
  22696343X514+  21085295X516+  19588603X518+  18198151X520
CONSTRAINTS
   44483X203+ 36755X503 .LE. 50667
   44483X203+ 36755X503+ 68419X105+ 44483X205+ 74844X305+ 36755X505
     .LE. 8445
   44483X203+ 36755X503+ 68419X105+ 44483X205+ 74844X305+ 36755X505+
   68419X107+ 44483X207+ 74844X307+112856X407+ 36755X507 .LE. 118223
   44483X203+ 36755X503+ 68419X105+ 44483X205+ 74844X305+ 36755X505+
   68419X107+ 44483X207+ 74844X307+112856X407+ 36755X507+ 44483X208+
   74844X308 .LE. 135112
   44483X203+ 36755X503+ 68419X105+ 44483X205+ 74844X305+ 36755X505+
   68419X107+ 44483X207+ 74844X307+112856X407+ 36755X507+ 44483X208+
   74844X308+ 68419X109+ 44483X209+ 74844X309+112856X409+ 36755X509
     .LE. 152001
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   68419X107+ 44483X207+ 74844X307+112856X407+ 36755X507+ 44483X208+
   74844X308+ 68419X109+ 44483X209+ 74844X309+112856X409+ 36755X509+
   44483X210+ 74844X310+112856X410+ 36755X510 .LE. 168890
   44483X203+ 36755X503+ 68419X105+ 44483X205+ 74844X305+ 36755X505+
   68419X107+ 44483X207+ 74844X307+112856X407+ 36755X507+ 44483X208+
   74844X308+ 68419X109+ 44483X209+ 74844X309+112856X409+ 36755X509+
   44483X210+ 74844X310+112856X410+ 36755X510+ 68419X111+ 74844X311+
  112856X411+ 36755X511 .LE. 185779
   44483X203+ 36755X503+ 68419X105+ 44483X205+ 74844X305+ 36755X505+
   68419X107+ 44483X207+ 74844X307+112856X407+ 36755X507+ 44483X208+
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   44483X210+ 74844X310+112856X410+ 36755X510+ 68419X111+ 74844X311+
  112856X411+ 36755X511+ 68419X112+ 44483X212+ 74844X312+112856X412+
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 74844X314+112856X414+ 36755X514+ 68419X116+ 44483X216+ 74844X316+
112856X416+ 36755X516 .LE. 270224
 44483X203+ 36755X503+ 68419X105+ 44483X205+ 74844X305+ 36755X505+
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 36755X512+ 68419X113+112856X413+ 36755X513+ 68419X114+ 44483X214+
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112856X416+ 36755X516+ 68419X118+ 44483X218+ 74844X318+112856X418+
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 68419X107+ 44483X207+ 74844X307+112856X407+ 36755X507+ 44483X208+
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 44483X210+ 74844X310+112856X410+ 36755X510+ 68419X111+ 74844X311+
112856X411+ 36755X511+ 68419X112+ 44483X212+ 74844X312+112856X412+
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 X203+X205+X207+X208+X209+X210+X212+X214+X216+X218+X220 .LE. 1
 X305+X307+X308+X309+X310+X311+X312+X314+X316+X318+X320 .LE. 1
 X407+X409+X410+X411+X412+X413+X414+X416+X418+X420 .LE. 1
 X503+X505+X507+X509+X510+X511+X512+X513+X514+X516+X518+X520 .LE. 1
BNDINT 1
PRINT 1
LIMIT 15000
OPTIMIZE
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APPENDIX B-2

COMPUTER PROGRAM FOR VERSION II

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BBMIP
TITLE
     UMATILLA BASIN PROJECT MPVNB MODEL VERSION II
INTEGER
    X305 X307 X309 X311 X312 X314 X316 X318 Y308 Y310 Y312 Y314 Y316 Y318
    X203 X206 X207 X210 X212 X214 X216 Y208 Y210 Y212 Y214 Y216 Y218 Y220
    X407 X409 X410 X411 X412 X413 X414 X416 X418 X420 Y320
    X105 X107 X109 X110 X111 X112 X113 X114 X116 X118 X120
    X503 X506 X507 X509 X510 X511 X512 X513 X514 X516 X518 X520
MAXIMIZE
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   12756804X307+  11851291X309+  11010054X311+  10612100X312+   9858824X314+
    9159018X316+   8508886X318+  19620866Y308+  18228123Y310+  16934241Y312+
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  83149152X407+
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  36752138X120+  34027109X503+
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   18198151X520
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    X305+X309-Y212 .GE. 0
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    X305+X309+X312+X316-Y218 .GE. 0
    X203-Y308 .GE. 0
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    X203+X207+X210+X214-Y318 .GE. 0
    Y208+Y210+Y212+Y214+Y216+Y218+Y220+Y308+Y310+Y312+Y314+Y316+Y318+Y320
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    49184X203+ 36755X503+ 68419X105+ 78776X305+ 49184X206+ 36755X506
     .LE. 101334
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    68419X107+ 49184X207+ 78776X307+112856X407+ 36755X507+ 40957Y208+
    70549Y308 .LE. 135112
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70549Y308+ 68419X109+ 78776X309+112856X409+ 36755X509 .LE. 152001
49184X203+ 36755X503+ 68419X105+ 78776X305+ 49184X206+ 36755X506+
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70549Y308+ 68419X109+ 78776X309+112856X409+ 36755X509+ 68419X110+
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68419X107+ 49184X207+ 78776X307+112856X407+ 36755X507+ 40957Y208+
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78776X311+112856X411+ 36755X511 .LE. 185779
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78776X311+112856X411+ 36755X511+ 68419X112+ 49184X212+ 40957Y212+
78776X312+ 70549Y312+112856X412+ 36755X512 .LE. 202668
49184X203+ 36755X503+ 68419X105+ 78776X305+ 49184X206+ 36755X506+
68419X107+ 49184X207+ 78776X307+112856X407+ 36755X507+ 40957Y208+
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78776X312+ 70549Y312+112856X412+ 36755X512+ 68419X113+112856X413+
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49184X203+ 36755X503+ 68419X105+ 78776X305+ 49184X206+ 36755X506+
68419X107+ 49184X207+ 78776X307+112856X407+ 36755X507+ 40957Y208+
70549Y308+ 68419X109+ 78776X309+112856X409+ 36755X509+ 68419X110+
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78776X312+ 70549Y312+112856X412+ 36755X512+ 68419X113+112856X413+
36755X513+ 68419X114+ 49184X214+ 40957Y214+ 78776X314+ 70549Y314+
112856X414+ 36755X514 .LE. 236446
49184X203+ 36755X503+ 68419X105+ 78776X305+ 49184X206+ 36755X506+
68419X107+ 49184X207+ 78776X307+112856X407+ 36755X507+ 40957Y208+
70549Y308+ 68419X109+ 78776X309+112856X409+ 36755X509+ 68419X110+
49184X210+ 40957Y210+ 70549Y310+112856X410+ 36755X510+ 68419X111+
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78776X312+ 70549Y312+112856X412+ 36755X512+ 68419X113+112856X413+
36755X513+ 68419X114+ 49184X214+ 40957Y214+ 78776X314+ 70549Y314+
112856X414+ 36755X514+ 68419X116+ 49184X216+ 40957Y216+ 78776X316+
70549Y316+112856X416+ 36755X516 .LE. 270224
```

```
    49184X203+ 36755X503+ 68419X105+ 78776X305+ 49184X206+ 36755X506+
    68419X107+ 49184X207+ 78776X307+112856X407+ 36755X507+ 40957Y208+
    70549Y308+ 68419X109+ 78776X309+112856X409+ 36755X509+ 68419X110+
    49184X210+ 40957Y210+ 70549Y310+112856X410+ 36755X510+ 68419X111+
    78776X311+112856X411+ 36755X511+ 68419X112+ 49184X212+ 40957Y212+
    78776X312+ 70549Y312+112856X412+ 36755X512+ 68419X113+112856X413+
    36755X513+ 68419X114+ 49184X214+ 40957Y214+ 78776X314+ 70549Y314+
   112856X414+ 36755X514+ 68419X116+ 49184X216+ 40957Y216+ 78776X316+
    70549Y316+112856X416+ 36755X516+ 68419X118+ 40957Y218+ 78776X318+
    70549Y318+112856X418+ 36755X518 .LE. 304002
    49184X203+ 36755X503+ 68419X105+ 78776X305+ 49184X206+ 36755X506+
    68419X107+ 49184X207+ 78776X307+112856X407+ 36755X507+ 40957Y208+
    70549Y308+ 68419X109+ 78776X309+112856X409+ 36755X509+ 68419X110+
    49184X210+ 40957Y210+ 70549Y310+112856X410+ 36755X510+ 68419X111+
    78776X311+112856X411+ 36755X511+ 68419X112+ 49184X212+ 40957Y212+
    78776X312+ 70549Y312+112856X412+ 36755X512+ 68419X113+112856X413+
    36755X513+ 68419X114+ 49184X214+ 40957Y214+ 78776X314+ 70549Y314+
   112856X414+ 36755X514+ 68419X116+ 49184X216+ 40957Y216+ 78776X316+
    70549Y316+112856X416+ 36755X516+ 68419X118+ 40957Y218+ 78776X318+
    70549Y318+112856X418+ 36755X518+ 68419X120+ 40957Y220+ 70549Y320+
   112856X420+ 36755X520 .LE. 337780
    X105+X107+X109+X110+X111+X112+X113+X114+X116+X118+X120 .LE. 1
    X305+X307+X309+X311+X312+X314+X316+X318+Y308+Y310+Y312+Y314+Y316
    +Y318+Y320 .LE. 1
    X203+X206+X207+X210+X212+X214+X216+Y208+Y210+Y212+Y214+Y216+Y218
    +Y220 .LE. 1
    X407+X409+X410+X411+X412+X413+X414+X416+X418+X420 .LE. 1
    X105+X107+X109+X110+X111+X112+X113+X114+X116+X118+X120 .LE. 1
    X503+X506+X507+X509+X510+X511+X512+X513+X514+X516+X518+X520 .LE. 1
PRINT
LIMIT 100000
OPTIMIZE
```

APPENDIX B-3

COMPUTER PROGRAMS FOR SUBPROGRAMS

```
BBMIP
TITLE
    UMATILLA BASIN PROJECT SEQUENCING EXERCISE BUILD RYAN DAM FIRST
INTEGER
    X207 X210 Y212 X214 Y214 X216 Y218 Y220
    X309 X311 Y312 Y314 X316 X318 Y318 Y320
    X411 X413 X414 X416 X418 X420
    X507 X510 X511 X513 X514 X516 X518 X520
MAXIMIZE
  7685230X207+   7033515X210+  12959493Y212+   6269310X214+  12142688Y214+
  5927393X216+  10650634Y218+   9969452Y220+  11851291X309+  11010054X311+
 16934241Y312+  15732203Y314+   9159018X316+   8508886X318+  13578041Y318+
 12614235Y320+  71763796X411+  66669806X413+  64260054X414+  59698700X416+
 55461124X418+  51524342X420+  29367882X507+  26297127X510+  25346629X511+
 23547456X513+  22696343X514+  21085295X516+  19588603X518+  18198151X520
CONSTRAINTS
  Y212+Y214+Y218+Y220+Y312+Y314+Y318+Y320 .LE. 1
  X309-Y212 .GE. 0
  X309+X311-Y214 .GE. 0
  X309+X316-Y218 .GE. 0
  X207-Y312 .GE. 0
  X207+X210-Y314 .GE. 0
  X207+X214-Y318 .GE. 0
   49184X207+ 36755X507 .LE. 49804
   49184X207+ 36755X507+ 78776X309 .LE. 83582
   49184X207+ 36755X507+ 78776X309+ 49184X210+ 36755X510 .LE. 100471
   49184X207+ 36755X507+ 78776X309+ 49184X210+ 36755X510+ 78776X311+
  112856X411+ 36755X511 .LE. 117360
   49184X207+ 36755X507+ 78776X309+ 49184X210+ 36755X510+ 78776X311+
  112856X411+ 36755X511+ 40957Y212+ 70549Y312 .LE. 134249
   49184X207+ 36755X507+ 78776X309+ 49184X210+ 36755X510+ 78776X311+
  112856X411+ 36755X511+ 40957Y212+ 70549Y312+112856X413+ 36755X513
    .LE. 151138
   49184X207+ 36755X507+ 78776X309+ 49184X210+ 36755X510+ 78776X311+
  112856X411+ 36755X511+ 40957Y212+ 70549Y312+112856X413+ 36755X513+
   49184X214+ 40957Y214+ 70549Y314+112856X414+ 36755X514 .LE. 168027
   49184X207+ 36755X507+ 78776X309+ 49184X210+ 36755X510+ 78776X311+
  112856X411+ 36755X511+ 40957Y212+ 70549Y312+112856X413+ 36755X513+
   49184X214+ 40957Y214+ 70549Y314+112856X414+ 36755X514+ 49184X216+
   78776X316+112856X416+ 36755X516 .LE. 201805
   49184X207+ 36755X507+ 78776X309+ 49184X210+ 36755X510+ 78776X311+
  112856X411+ 36755X511+ 40957Y212+ 70549Y312+112856X413+ 36755X513+
   49184X214+ 40957Y214+ 70549Y314+112856X414+ 36755X514+ 49184X216+
   78776X316+112856X416+ 36755X516+ 40957Y218+ 78776X318+ 70549Y318+
  112856X418+ 36755X518 .LE. 235583
   49184X207+ 36755X507+ 78776X309+ 49184X210+ 36755X510+ 78776X311+
  112856X411+ 36755X511+ 40957Y212+ 70549Y312+112856X413+ 36755X513+
   49184X214+ 40957Y214+ 70549Y314+112856X414+ 36755X514+ 49184X216+
   78776X316+112856X416+ 36755X516+ 40957Y218+ 78776X318+ 70549Y318+
  112856X418+ 36755X518+ 40957Y220+ 70549Y320+112856X420+ 36755X520
    .LE. 269361
```

```
    X207+X210+Y212+X214+Y214+X216+Y218+Y220 .LE. 1
    X309+X311+Y312+Y314+X316+X318+Y318+Y320 .LE. 1
    X411+X413+X414+X416+X418+X420 .LE. 1
    X507+X510+X511+X513+X514+X516+X518+X520 .LE. 1
BNDINT 1
PRINT
LIMIT 10000
OPTIMIZE


 BBMIP
TITLE
     UMATILLA BASIN PROJECT SEQUENCING EXERCISE BUILD BEACON DAM FIRST
INTEGER
    X107 X110 X112 X114 X116 X118 X120
    Y308 Y310 Y312 Y314 Y316 Y318 Y320
    X410 X412 X414 X416 X418 X420
    X506 X510 X512 X514 X516 X520
MAXIMIE
  59310008X107+  53108455X110+  49338672X112+  45826479X114+  42582881X116+
  39560232X118+  36752138X120+  19620866Y308+  18228123Y310+  16934241Y312+
  15732203Y314+  14615488Y316+  13578041Y318+  12614235Y320+  74454938X410+
  69169924X412+  64260054X414+  59698700X416+  55461124X418+  51524342X420+
  30469178X506+  26297127X510+  24430486X512+  22696343X514+  21085295X516+
  18198151X520

CONSTRAINTS
    36755X506 .LE. 52150
    36755X506+ 68419X107 .LE. 69039
    36755X506+ 68419X107+ 70549Y308 .LE. 85928
    36755X506+ 68419X107+ 70549Y308+ 68419X110+ 70549Y310+112856X410+
    36755X510 .LE. 119706
    36755X506+ 68419X107+ 70549Y308+ 68419X110+ 70549Y310+112856X410+
    36755X510+ 68419X112+ 70549Y312+112856X412+ 36755X512 .LE. 153484
    36755X506+ 68419X107+ 70549Y308+ 68419X110+ 70549Y310+112856X410+
    36755X510+ 68419X112+ 70549Y312+112856X412+ 36755X512+ 68419X114+
    70549Y314+112856X414+ 36755X514 .LE. 187262
    36755X506+ 68419X107+ 70549Y308+ 68419X110+ 70549Y310+112856X410+
    36755X510+ 68419X112+ 70549Y312+112856X412+ 36755X512+ 68419X114+
    70549Y314+112856X414+ 36755X514+ 68419X116+ 70549Y316+112856X416+
    36755X516 .LE. 221040
    36755X506+ 68419X107+ 70549Y308+ 68419X110+ 70549Y310+112856X410+
    36755X510+ 68419X112+ 70549Y312+112856X412+ 36755X512+ 68419X114+
    70549Y314+112856X414+ 36755X514+ 68419X116+ 70549Y316+112856X416+
    36755X516+ 68419X118+ 70459Y318+112856X418 .LE. 254818
    36755X506+ 68419X107+ 70549Y308+ 68419X110+ 70549Y310+112856X410+
    36755X510+ 68419X112+ 70549Y312+112856X412+ 36755X512+ 68419X114+
    70549Y314+112856X414+ 36755X514+ 68419X116+ 70549Y316+112856X416+
    36755X516+ 68419X118+ 70549Y318+112856X418+ 68419X120+
    70549Y320+112856X420+ 36755X520 .LE. 288596
```

```
    X107+X110+X112+X114+X116+X118+X120 .LE. 1
    Y308+Y310+Y312+Y314+Y316+Y318+Y320 .LE. 1
    X410+X412+X414+X416+X418+X420 .LE. 1
    X506+X510+X512+X514+X516+X520 .LE. 1
BNDINT 1
PRINT
LIMIT 10000
OPTIMIZE
```

```
BBMIP
TITLE
    UMATILLA BASIN PROJECT SEQUENCING EXERCIE BUILD STAGE DAM FIRST
INTEGER
    X109 X111 X112 X114 X116 X118 X120
    Y207 Y210 Y212 Y214 Y216 Y218 Y220
    X412 X414 X416 X418 X420
    X507 X510 X511 X514 X516 X518 X520
MAXIMIZE
  55100022X109+  51188872X111+  49338672X112+  45836479X114+  42582881X116+
  39560232X118+  36752138X120+  15285074Y207+  13838707Y210+  12959493Y212+
  12146288Y214+  11383862Y216+  10650634Y218+   9969452Y220+  69169924X412+
  64260054X414+  59698700X416+  55461124X418+  51524342X420+  29367882X507+
  26297127X510+  25346629X511+  22696343X514+  21085295X516+  19588603X518+
  18198151X520
CONSTRAINTS
   36755X507+ 40957Y207 .LE. 39447
   36755X507+ 40957Y207 .LE. 56336
   36755X507+ 40957Y207+ 68419X109 .LE. 73225
   36755X507+ 40957Y207+ 68419X109+ 40957Y210+ 36755X510 .LE. 90114
   36755X507+ 40957Y207+ 68419X109+ 40957Y210+ 36755X510+ 68419X111+
   36755X511 .LE. 107003
   36755X507+ 40957Y207+ 68419X109+ 40957Y210+ 36755X510+ 68419X111+
   36755X511+ 68419X112+ 40957Y212+112856X412 .LE. 123892
   36755X507+ 40957Y207+ 68419X109+ 40957Y210+ 36755X510+ 68419X111+
   36755X511+ 68419X112+ 40957Y212+112856X412+ 68419X114+ 40957Y214+
  112856X414+ 36755X514 .LE. 157670
   36755X507+ 40957Y207+ 68419X109+ 40957Y210+ 36755X510+ 68419X111+
   36755X511+ 68419X112+ 40957Y212+112856X412+ 68419X114+ 40957Y214+
  112856X414+ 36755X514+ 68419X116+ 40957Y216+112856X416+ 36755X516
    .LE. 191448
   36755X507+ 40957Y207+ 68419X109+ 40957Y210+ 36755X510+ 68419X111+
   36755X511+ 68419X112+ 40957Y212+112856X412+ 68419X114+ 40957Y214+
  112856X414+ 36755X514+ 68419X116+ 40957Y216+112856X416+ 36755X516+
   68419X118+ 40957Y218+112856X418+ 36755X518 .LE. 225226
   36755X507+ 40957Y207+ 68419X109+ 40957Y210+ 36755X510+ 68419X111+
   36755X511+ 68419X112+ 40957Y212+112856X412+ 68419X114+ 40957Y214+
  112856X414+ 36755X514+ 68419X116+ 40957Y216+112856X416+ 36755X516+
   68419X118+ 40957Y218+112856X418+ 36755X518+ 68419X120+ 40957Y220+
  112856X420+ 36755X520 .LE. 259004
```

```
    X109+X111+X112+X114+X116+X118+X120 .LE. 1
    Y207+Y210+Y212+Y214+Y216+Y218+Y220 .LE. 1
    X412+X414+X416+X418+X420 .LE. 1
    X507+X510+X511+X514+X516+X518+X520 .LE. 1
BNDINT 1
PRINT
LIMIT 10000
OPTIMIZE
```

```
BBMIP
TITLE
    UMATILLA BASIN PROJECT SEQUENCING EXERCISE BUILD PUMPING PLANT FIRST
INTEGER
    X111 X113 X114 X116 X118 X120
    X210 X212 X214 X216 Y214 Y216 Y218 Y220
    X312 X314 X316 X318 Y314 Y316 Y318 Y320
    X509 X512 X513 X514 X516 X518 X520
MAXIMIZE
  51188872X111+  47555347X113+  45836479X114+  42582881X116+  39560232X118+
  36752138X120+   7033515X210+   6637352X212+   6269310X214+  12146288Y214+
  11383862Y216+  10650634Y218+   9969452Y220+  10612100X312+   9858824X314+
   9159018X316+   8508886X318+  15732203Y314+  14615488Y316+  13578041Y318+
  12614235Y320+  27283270X509+  24430486X512+  23547456X513+  22696343X514+
  21085295X516+  19588603X518+  18198151X520+  5927393X216
CONSTRAINTS
    X312-Y214 .GE. 0
    X312+X314-Y216 .GE. 0
    X312+X316-Y218 .GE. 0
    X210-Y314 .GE. 0
    X210+X212-Y316 .GE. 0
    X210+X214-Y318 .GE. 0
   36755X509 .LE. 39145
   36755X509+ 49184X210 .LE. 56034
   36755X509+ 49184X210+ 68419X111 .LE. 72923
   36755X509+ 49184X210+ 68419X111+ 49184X212+ 78776X312+ 36755X512
     .LE. 89812
   36755X509+ 49184X210+ 68419X111+ 49184X212+ 78776X312+ 36755X512+
   68419X113+ 36755X513 .LE. 106701
   36755X509+ 49184X210+ 68419X111+ 49184X212+ 78776X312+ 36755X512+
   68419X113+ 36755X513+ 68419X114+ 49184X214+ 40957Y214+ 78776X314+
   70549Y314+ 36755X514 .LE. 123590
   36755X509+ 49184X210+ 68419X111+ 49184X212+ 78776X312+ 36755X512+
   68419X113+ 36755X513+ 68419X114+ 49184X214+ 40957Y214+ 78776X314+
   70549Y314+ 36755X514+ 68419X116+ 49184X216+ 40957Y216+ 78776X316+
   70549Y316+ 36755X516 .LE. 157368
   36755X509+ 49184X210+ 68419X111+ 49184X212+ 78776X312+ 36755X512+
   68419X113+ 36755X513+ 68419X114+ 49184X214+ 40957Y214+ 78776X314+
```

```
   70549Y314+ 36755X514+ 68419X116+ 49184X216+ 40957Y216+ 78776X316+
   70549Y316+ 36755X516+ 68419X118+ 40957Y218+ 78776X318+ 70549Y318+
   36755X518 .LE. 191146
   36755X509+ 49184X210+ 68419X111+ 49184X212+ 78776X312+ 36755X512+
   68419X113+ 36755X513+ 68419X114+ 49184X214+ 40957Y214+ 78776X314+
   70549Y314+ 36755X514+ 68419X116+ 49184X216+ 40957Y216+ 78776X316+
   70549Y316+ 36755X516+ 68419X118+ 40957Y218+ 78776X318+ 70549Y318+
   36755X518+ 68419X120+ 40957Y220+ 70549Y320+ 36755X520 .LE. 224924
   Y214+Y216+Y218+Y220+Y316+Y314+Y318+Y320 .LE. 1
    X111+X113+X114+X116+X118+X120 .LE. 1
    X210+X212+X214+X216+Y214+Y216+Y218+Y220 .LE. 1
    X312+X314+X316+X318+Y314+Y316+Y318+Y320 .LE. 1
    X509+X512+X513+X514+X516+X518+X520 .LE. 1
BNDINT 1
PRINT
LIMIT 10000
OPTIMIZE
```

```
 BBMIP
 TITLE
     UMATILLA BASIN PROJECT BUILD SNIPE & DENNING DAMS FIRST
 INTEGER
     X107 X110 X111 X113 X114 X116 X118 X120
     X206 X210 X212 X216 Y210 Y214 Y216 Y220
     X307 X311 X314 X318 Y310 Y314 Y316 Y320
     X409 X412 X413 X414 X416 X418 X420
 MAXIMIZE
   59310008X107+  53108455X110+  51188872X111+  47555347X113+
   45836479X114+  42582881X116+  39560232X118+  36752138X120+
    7918961X206+   7033515X210+   6637352X212+   5927393X216+
   13838707Y210+  12146288Y214+  11383862Y216+   9969452Y220+
   12756804X307+  11010054X311+   9858824X314+   8508886X318+
   18228123Y310+  15732203Y314+  14615488Y316+  12614235Y320+
   77246998X409+  69169924X412+  66669806X413+  64260054X414+
   59698700X416+  55461124X418+  51524342X420
 CONSTRAINTS
    X307-Y210 .GE. 0
    X307+X311-Y214 .GE. 0
    X307+X314-Y216 .GE. 0
    X206-Y310 .GE. 0
    X206+X210-Y314 .GE. 0
    X206+X212-Y316 .GE. 0
     49184X206 .LE. 64579
     49184X206+ 68419X107+ 78776X307 .LE. 81468
     49184X206+ 68419X107+ 78776X307+112856X409 .LE. 115246
     49184X206+ 68419X107+ 78776X307+112856X409+ 68419X110+ 49184X210+
     40957Y210+70549Y310 .LE. 132135
```

```
 49184X206+ 68419X107+ 78776X307+112856X409+ 68419X110+ 49184X210+
 40957Y210+ 70549Y310+ 68419X111+ 78776X311 .LE. 149024
 49184X206+ 68419X107+ 78776X307+112856X409+ 68419X110+ 49184X210+
 40957Y210+ 70549Y310+ 68419X111+ 78776X311+ 49184X212+112856X412
  .LE. 165913
 49184X206+ 68419X107+ 78776X307+112856X409+ 68419X110+ 49184X210+
 40957Y210+ 70549Y310+ 68419X111+ 78776X311+ 49184X212+112856X412+
 68419X113+112856X413 .LE. 182802
 49184X206+ 68419X107+ 78776X307+112856X409+ 68419X110+ 49184X210+
 40957Y210+ 70549Y310+ 68419X111+ 78776X311+ 49184X212+112856X412+
 68419X113+112856X413+ 68419X114+ 40957Y214+ 78776X314+70549Y314+
112856X414 .LE. 199691
 49184X206+ 68419X107+ 78776X307+112856X409+ 68419X110+ 49184X210+
 40957Y210+ 70549Y310+ 68419X111+ 78776X311+ 49184X212+112856X412+
 68419X113+112856X413+ 68419X114+ 40957Y214+ 78776X314+70549Y314+
112856X414+ 68419X116+ 49184X216+ 40957Y216+70549Y316+112856X416
  .LE. 233469
 49184X206+ 68419X107+ 78776X307+112856X409+ 68419X110+ 49184X210+
 40957Y210+ 70549Y310+ 68419X111+ 78776X311+ 49184X212+112856X412+
 68419X113+112856X413+ 68419X114+ 40957Y214+ 78776X314+70549Y314+
112856X414+ 68419X116+ 49184X216+ 40957Y216+70549Y316+112856X416+
 68419X118+ 78776X318+112856X418 .LE. 267247
 49184X206+ 68419X107+ 78776X307+112856X409+ 68419X110+ 49184X210+
 40957Y210+ 70549Y310+ 68419X111+ 78776X311+ 49184X212+112856X412+
 68419X113+112856X413+ 68419X114+ 40957Y214+ 78776X314+70549Y314+
112856X414+ 68419X116+ 49184X216+ 40957Y216+70549Y316+112856X416+
 68419X118+ 78776X318+112856X418+ 68419X120+ 40957Y220+70549Y320+
112856X420 .LE. 301025
Y210+Y214+Y216+Y220+Y310+Y314+Y316+Y320 .LE. 1
X107+X110+X111+X113+X114+X116+X118+X120 .LE. 1
X206+X210+X212+X216+Y210+Y214+Y216+Y220 .LE. 1
X307+X311+X314+X318+Y310+Y314+Y316+Y320 .LE. 1
X409+X412+X413+X414+X416+X418+X420 .LE. 1
BNDINT 1
PRINT
BNDOBJ 140000000.000
LIMIT 20000
OPTIMIZE
```

APPENDIX B-4

COMPUTER PROGRAM FOR VERSION III

```
BBMIP
TITLE
   UMATILLA BASIN PROJECT MPVNB MODEL VERSION III
INTEGER
   X104 X106 X108 X109 X110 X111 X113 X114 X116 X118 X120
   X203 X205 X206 X208 X209 X210 X211 X213 X214 X215 X216 X217 X218 X220
   X305 X307 X308 X310 X311 X312 X313 X315 X316 X317 X318 X320
   X408 X411 X412 X413 X414 X415 X416 X417 X418 X420
   X503 X505 X506 X507 X509 X510 X513 X515 X516 X517 X518 X520
MAXIMIZE
   38239259X104+  36346043X106+  34587211X108+  33755182X109+  32953226X110+
   32180257X111+  30717125X113+  30024979X114+  28714834X116+  27497687X118+
   26366936X120+  12978871X203+  12185251X205+  11809832X206+  11099199X208+
   10763029X209+  10439010X210+  10126702X211+   9535183X213+   9255890X214+
    8863496X215+   8726543X216+   8461739X217+   8206506X218+   7723381X220+
   17237431X305+  16013871X307+  15435057X308+  14339434X310+  13821141X311+
   13321582X312+  12840079X313+  11928655X315+  11497499X316+  11081927X317+
   10681375X318+   9923182X320+  87238660X408+  76869564X411+  73659991X412+
   70566427X413+  67584678X414+  64710703X415+  61940607X416+  59270635X417+
   56697168X418+  51825923X420+  31033725X503+  28839057X505+  27800853X506+
   26800173X507+  24906015X509+  24009968X510+  21511512X513+  19992757X515+
   19274299X516+  18581808X517+  17914347X518+  16650929X520
CONSTRAINTS
   44147X203+ 36640X503 .LE. 50667
   44147X203+ 36640X503+ 56851X104 .LE. 67556
   44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505
    .LE. 84445
   44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505+
   56851X106+ 44147X206+ 36640X506 .LE. 101334
   44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505+
   56851X106+ 44147X206+ 36640X506+ 75250X307+ 36640X507 .LE. 118223
   44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505+
   56851X106+ 44147X206+ 36640X506+ 75250X307+ 36640X507+ 56851X108+
   44147X208+ 75250X308+124785X408 .LE. 135112
   44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505+
   56851X106+ 44147X206+ 36640X506+ 75250X307+ 36640X507+ 56851X108+
   44147X208+ 75250X308+124785X408+ 56851X109+ 44147X209+ 36640X509
    .LE. 152001
   44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505+
   56851X106+ 44147X206+ 36640X506+ 75250X307+ 36640X507+ 56851X108+
   44147X208+ 75250X308+124785X408+ 56851X109+ 44147X209+ 36640X509+
   56851X110+ 44147X210+ 75250X310+ 36640X510 .LE. 168890
   44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505+
   56851X106+ 44147X206+ 36640X506+ 75250X307+ 36640X507+ 56851X108+
   44147X208+ 75250X308+124785X408+ 56851X109+ 44147X209+ 36640X509+
   56851X110+ 44147X210+ 75250X310+ 36640X510+ 56851X111+ 44147X211+
   75250X311+124785X411 .LE. 185779
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44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505+
56851X106+ 44147X206+ 36640X506+ 75250X307+ 36640X507+ 56851X108+
44147X208+ 75250X308+124785X408+ 56851X109+ 44147X209+ 36640X509+
56851X110+ 44147X210+ 75250X310+ 36640X510+ 56851X111+ 44147X211+
75250X311+124785X411+ 75250X312+124785X412 .LE. 202668
44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505+
56851X106+ 44147X206+ 36640X506+ 75250X307+ 36640X507+ 56851X108+
44147X208+ 75250X308+124785X408+ 56851X109+ 44147X209+ 36640X509+
56851X110+ 44147X210+ 75250X310+ 36640X510+ 56851X111+ 44147X211+
75250X311+124785X411+ 75250X312+124785X412+ 56851X113+ 44147X213+
75250X313+124785X413+ 36640X513 .LE. 219557
44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505+
56851X106+ 44147X206+ 36640X506+ 75250X307+ 36640X507+ 56851X108+
44147X208+ 75250X308+124785X408+ 56851X109+ 44147X209+ 36640X509+
56851X110+ 44147X210+ 75250X310+ 36640X510+ 56851X111+ 44147X211+
75250X311+124785X411+ 75250X312+124785X412+ 56851X113+ 44147X213+
75250X313+124785X413+ 36640X513+ 56851X114+ 44147X214+124785X414
.LE. 236446
44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505+
56851X106+ 44147X206+ 36640X506+ 75250X307+ 36640X507+ 56851X108+
44147X208+ 75250X308+124785X408+ 56851X109+ 44147X209+ 36640X509+
56851X110+ 44147X210+ 75250X310+ 36640X510+ 56851X111+ 44147X211+
75250X311+124785X411+ 75250X312+124785X412+ 56851X113+ 44147X213+
75250X313+124785X413+ 36640X513+ 56851X114+ 44147X214+124785X414+
44147X215+ 75250X315+124785X415+ 36640X515 .LE. 253335
44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505+
56851X106+ 44147X206+ 36640X506+ 75250X307+ 36640X507+ 56851X108+
44147X208+ 75250X308+124785X408+ 56851X109+ 44147X209+ 36640X509+
56851X110+ 44147X210+ 75250X310+ 36640X510+ 56851X111+ 44147X211+
75250X311+124785X411+ 75250X312+124785X412+ 56851X113+ 44147X213+
75250X313+124785X413+ 36640X513+ 56851X114+ 44147X214+124785X414+
44147X215+ 75250X315+124785X415+ 36640X515+ 56851X116+ 44147X216+
75250X316+124785X416+ 36640X516 .LE. 270224
44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505+
56851X106+ 44147X206+ 36640X506+ 75250X307+ 36640X507+ 56851X108+
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56851X110+ 44147X210+ 75250X310+ 36640X510+ 56851X111+ 44147X211+
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75250X313+124785X413+ 36640X513+ 56851X114+ 44147X214+124785X414+
44147X215+ 75250X315+124785X415+ 36640X515+ 56851X116+ 44147X216+
75250X316+124785X416+ 36640X516+ 44147X217+ 75250X317+124785X417+
36640X517 .LE. 287113
44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505+
56851X106+ 44147X206+ 36640X506+ 75250X307+ 36640X507+ 56851X108+
44147X208+ 75250X308+124785X408+ 56851X109+ 44147X209+ 36640X509+

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     56851X110+ 44147X210+ 75250X310+ 36640X510+ 56851X111+ 44147X211+
     75250X311+124785X411+ 75250X312+124785X412+ 56851X113+ 44147X213+
     75250X313+124785X413+ 36640X513+ 56851X114+ 44147X214+124785X414+
     44147X215+ 75250X315+124785X415+ 36640X515+ 56851X116+ 44147X216+
     75250X316+124785X416+ 36640X516+ 44147X217+ 75250X317+124785X417+
     36640X517+ 56851X118+ 44147X218+ 75250X318+124785X418+ 36640X518
      .LE. 304002
     44147X203+ 36640X503+ 56851X104+ 44147X205+ 75250X305+ 36640X505+
     56851X106+ 44147X206+ 36640X506+ 75250X307+ 36640X507+ 56851X108+
     44147X208+ 75250X308+124785X408+ 56851X109+ 44147X209+ 36640X509+
     56851X110+ 44147X210+ 75250X310+ 36640X510+ 56851X111+ 44147X211+
     75250X311+124785X411+ 75250X312+124785X412+ 56851X113+ 44147X213+
     75250X313+124785X413+ 36640X513+ 56851X114+ 44147X214+124785X414+
     44147X215+ 75250X315+124785X415+ 36640X515+ 56851X116+ 44147X216+
     75250X316+124785X416+ 36640X516+ 44147X217+ 75250X317+124785X417+
     36640X517+ 56851X118+ 44147X218+ 75250X318+124785X418+ 36640X518+
     56851X120+ 44147X220+ 75250X320+124785X420+ 36640X520 .LE. 337780
     X104+X106+X108+X109+X110+X111+X113+X114+X116+X118+X120 .LE. 1
     X203+X205+X206+X208+X209+X210+X211+X213+X214+X215+X216+X217+X218+X220
     .LE. 1
     X305+X307+X308+X310+X311+X312+X313+X315+X316+X317+X318+X320 .LE. 1
     X408+X411+X412+X413+X414+X415+X416+X417+X418+X420 .LE. 1
     X503+X505+X506+X507+X509+X510+X513+X515+X516+X517+X518+X520 .LE. 1
BNDINT 1
PRINT
BNDOBJ 160000000
LIMIT 50000
OPTIMIZE
```

APPENDIX B-5

COMPUTER PROGRAM FOR VERSION IV

```
BBMIP
TITLE
     UMATILLA BASIN PROJECT MPVNB MODEL VERSION IV
INTEGER
    X104 X106 X107 X109 X111 X113 X114 X116 X118 X120
    X203 X206 X207 X209 X211 X213 X214 X216
    Y208 Y210 Y211 Y213 Y215 Y217 Y218 Y220
    X305 X307 X309 X311 X313 X315 X316 X318
    Y308 Y310 Y311 Y313 Y315 Y317 Y318 Y320
    X408 X411 X413 X414 X415 X416 X417 X418 X420
    X503 X506 X507 X509 X510 X511 X513 X515 X516 X517 X518 X520
MAXIMIZE
   38239259X104+  36346043X106+  35450441X107+  33755182X109+  32180257X111+
   30717125X113+  30024979X114+  28714834X116+  27497687X118+  26366936X120+
    7947114X203+   7304204X206+   7105202X207+   6729518X209+   6378571X211+
    6053104X213+   5899670X214+   5608557X216+  14238544Y208+  13355516Y210+
   12937792Y211+  12146734Y213+  11412522Y215+  10715699Y217+  10378997Y218+
    9741663Y220+  13731503X305+  12756804X307+  11851291X309+  11010054X311+
   10228530X313+   9502481X315+   9159018X316+   8508886X318+  19620866Y308+
   18228123Y310+  17569275Y311+  16322160Y313+  15163569Y315+  14087217Y317+
   13087268Y318+  12614235Y320+  87238660X408+  76869564X411+  70566427X413+
   67584678X414+  64710703X415+  61940607X416+  59270635X417+  56697168X418+
   51825923X420+  31033725X503+  27800853X506+  26800173X507+  24906015X509+
   24009968X510+  23146309X511+  21511512X513+  19992757X515+  19274299X516+
   18581808X517+  17914347X518+  16650929X520
CONSTRAINTS
   X104+X106+X107+X109+X111+X113+X114+X116+X118+X120 .LE. 1
   X203+X206+X207+X209+X211+X213+X214+X216+Y208+Y210+Y211+
   Y213+Y215+Y217+Y218+Y220 .LE. 1
   X305+X307+X309+X311+X313+X315+X316+X318+Y308+Y310+Y311+
   Y313+Y315+Y317+Y318+Y320 .LE. 1
   X408+X411+X413+X414+X415+X416+X417+X418+X420 .LE. 1
   X503+X506+X507+X509+X510+X511+X513+X515+X516+X517+X518+X520 .LE. 1
   X305-Y208 .GE. 0
   X305+X307-Y210 .GE. 0
   X305+X309-Y211 .GE. 0
   X305+X307+X309+X311-Y213 .GE. 0
   X305+X313-Y215 .GE. 0
   X305+X307+X313+X315-Y217 .GE. 0
   X305+X309+X313+X316-Y218 .GE. 0
   X203-Y308 .GE. 0
   X203+X206-Y310 .GE. 0
   X203+X207-Y311 .GE. 0
   X203+X206+X207+X209-Y313 .GE. 0
   X203+X211-Y315 .GE. 0
   X203+X206+X211+X213-Y317 .GE. 0
   X203+X207+X211+X214-Y318 .GE. 0
   Y208+Y210+Y211+Y213+Y215+Y217+Y218+Y220+Y308+Y310+Y311+Y313+
   Y315+Y317+Y318+Y320 .LE. 1
```

48838X203+36640X503 .LE. 50667
48838X203+36640X503+56851X104 .LE. 67556
48838X203+36640X503+56851X104+78776X305 .LE. 84445
48838X203+36640X503+56851X104+78776X305+56851X106+48838X206+
36640X506 .LE. 101334
48838X203+36640X503+56851X104+78776X305+56851X106+48838X206+
36640X506+56851X107+48838X207+78776X307+36640X507 .LE. 118223
48838X203+36640X503+56851X104+78776X305+56851X106+48838X206+
36640X506+56851X107+48838X207+78776X307+36640X507+40611Y208+
70549Y308+124785X408 .LE. 135112
48838X203+36640X503+56851X104+78776X305+56851X106+48838X206+
36640X506+56851X107+48838X207+78776X307+36640X507+40611Y208+
70549Y308+124785X408+56851X109+48838X209+78776X309+36640X509
.LE. 152001
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40611Y210+70549Y310+36640X510 .LE. 168890
48838X203+36640X503+56851X104+78776X305+56851X106+48838X206+
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40611Y210+70549Y310+36640X510+56851X111+48838X211+40611Y211+
78776X311+70549Y311+124785X411+36640X511 .LE. 185779
48838X203+36640X503+56851X104+78776X305+56851X106+48838X206+
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78776X311+70549Y311+124785X411+36640X511+56851X113+48838X213+
40611Y213+78776X313+70549Y313+124785X413+36640X513 .LE. 219557
48838X203+36640X503+56851X104+78776X305+56851X106+48838X206+
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40611Y213+78776X313+70549Y313+124785X413+36640X513+56851X114+
48838X214+124785X414 .LE. 236446
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36640X506+56851X107+48838X207+78776X307+36640X507+40611Y208+
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78776X311+70549Y311+124785X411+36640X511+56851X113+48838X213+
40611Y213+78776X313+70549Y313+124785X413+36640X513+56851X114+

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48838X214+124785X414+40611Y215+78776X315+70549Y315+124785X415+
36640X515+56851X116+48838X216+78776X316+124785X416+36640X516
  .LE. 270224
48838X203+36640X503+56851X104+78776X305+56851X106+48838X206+
36640X506+56851X107+48838X207+78776X307+36640X507+40611Y208+
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36640X515+56851X116+48838X216+78776X316+124785X416+36640X516+
40611Y217+70549Y317+124785X417+36640X517 .LE. 287113
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70549Y320+124785X420+36640X520 .LE. 337780
BNDINT 1
PRINT
BNDOBJ  160000000
LIMIT 20000
OPTIMIZE
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