SEMINAR ON WATER RESOURCES

Development and Planning
CE 539 C U Denver Center
Spring 1969

ECONOMIC AND SCIENTIFIC ASPECTS OF
STAGED DEVELOPMENT OF WATER RESOURCES
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Introduction

Water development programs for a river basin are nearly always carried out in stages. Complete control of the basin resources and maximum economic use can take many years to secure and may never be fully achieved. Staging is usually in the form of constructing certain structures first, second, third, and so forth; however, it may also consist of completing any one structure to a usable stage and later adding to it.

Staging should be planned but in many cases is only partially planned and in some cases totally unplanned. In planning, the following items are some that should be considered: (1) the initial investment, (2) the beneficial use to be achieved in a reasonable time, (3) economical alternatives that will achieve the basic needs, and (4) does the investment bring a return commensurate with other investment opportunities.

Reasons for Staged Development

A river basin development, or an individual structure, may be constructed in stages for a number of reasons.

1. Change in Needs. The magnitude of the need may change. For example, electric power and municipal water supply needs may be small in the beginning compared with later years. An example of staging for this reason is the Guri Hydroelectric Project on the Caroni River in Venezuela, now under construction. The ultimate potential of this project is about 6,000,000 kw, whereas the present total power demand within transmission reach is less than 1,000,000 kw. Obviously, full utilization will take many years. This project has been planned for development in stages. The much-discussed Rampart Canyon Project in Alaska could possibly benefit from a similar approach.

The type of need may change. For example, water for agricultural needs may change to industrial needs.

2. Availability of Funds. Availability of funds to invest may be a reason for staging. Funds for essential needs must be made available; and, therefore, development of resources for these needs must be first. Development for less essential needs such as flood control, reclamation, and irrigation may be staged for

development as funds become available. An example of such staging is the reclamation program for the Indus River plains in West Pakistan. Millions of acres could benefit immediately from improved drainage and supplemental irrigation. However, several billions of dollars would be needed for full development, far beyond the assured funds. Therefore, storage dams are being designed for future raising and tube-well installations are proceeding as a part of individual salinity control and reclamation projects at a pace governed by the available capital.

3. Availability of Basic Data. Development of a water resource may be carried on in stages as data about the resource become available. Sometimes the potential of the water resources for a given basis is unknown and not readily available. Yet, early realization of benefits is urgently needed. Examples of this type of staging occur in the jungle and mountain areas of South America. In many cases, either the lower reaches or the headwaters are closer to population centers where some data on the water resource are available; whereas, the remainder of the basin is uninhabited and relatively unexplored. The Caroni River in Venezuela is presently being usefully developed in its lower reaches, although almost nothing is known of its potential in the inaccessible headwaters. Conversely, the upper reaches of the Pataza River in Equador are being continually developed, although the effects on the lower reaches on this tributary to

the Amazon River are completely unknown. Still, these developments are of such economic importance that they must proceed regardless of hypothetical imperfections.

4. International Boundaries. International boundaries are sometimes a reason for staged development. Full development is delayed until agreements can be reached between countries. The Columbia River, and in particular the Grand Coulee Dam, is an example. A second stage in the construction of Grand Coulee Dam is now underway to provide for a third powerplant. The powerplant itself will be staged construction because of the large initial investment and the relative low initial need. The ultimate stage for the third powerplant is to be completed about 1992. This second stage, the addition of the third powerplant, was made possible by a treaty between the United States and Canada, whereby Canada will construct two dams upstream from Grand Coulee on the main stem of the river which originates in the United States and then flows through Canada before reaching Coulee. The two dams will regulate the flow into reservoir behind Coulee such that virtually all of the water behind the dam can be used to generate power without wasting it over the spillway as the case is now.

Other Reasons. There are still other reasons for staged development including uncertain water rights, legal authorization, and political preference.

Types of Staged Development

Staged development of water resources can take many forms, and insofar as possible should be planned. Planning engineers should be alert in choosing the best type of staging that fits the situation.

1. Series of Independent Projects. The simplest type of staging is that involving a number of independent projects, each of which is economical and of a size appropriate to the needs. Planning is then limited to a choice of the most favorable initial project, without concern that future projects will be adversely affected. Such a situation usually occurs: (a) in the selection of hydroelectric projects in the headwater areas of a river basin; (b) in irrigation structures along rivers that have a much greater flow than the irrigable land can use; (c) in flood control protection by levees without adverse downstream influence; and (d) in other projects which have minor consumptive use, only beneficial downstream effects, and which cannot be harmed by upstream development. Much of the Missouri River Basin Project has been developed in stages without conflict between the independent projects.

   There is little chance of significant error in the planning of such developments as long as the structures are structurally safe and reasonably economical. Any mistake in the order of priority becomes unimportant as more of the individual projects are built.

2. Series of Interrelated Multiple-purpose Projects. Staged development of interrelated projects requires careful planning. The headwaters of one reservoir are often the tailwaters of the next upstream and storage dams on the tributaries contribute to the regulation of the flow through the main trunk stream. These projects are usually multiple-purpose projects and may include navigation, power development, flood control, irrigation, municipal water supply, and recreation. Storage dams usually benefit downstream projects while reservoirs may encroach on upstream projects; irrigation and water supply projects will reduce critical river flows, and variable releases from upstream projects may adversely affect navigation and recreation. The selection of an initial project and the design of each project should consider these interrelationships.

The main Columbia River is a good example of river planning for staged development of interrelated projects and of the effect of each upon the other. With a few exceptions, downstream powerplants have been planned to utilize future upstream storage. Most reservoirs have been planned for the economic limit of encroachment on upstream powerplants. Flood control storage has been distributed among the reservoirs for maximum effectiveness in combination with downstream levees.

There are many other examples of this type of stage development in the United States including the Tennessee Valley, the Mississippi River, the Colorado-Big Thompson Project, the Fryingpan-Arkansas Project, the Upper Colorado River Basin Project, and many others.

3. Series of Interrelated Single-purpose Projects. A series of interrelated projects for a single-purpose is another type of stage development within a river basin. An example of this type is the development of the municipal water supply in the Hudson-Mohawk River Basin and Long Island for a population of 13,000,000 people spread over an area of 15,000 square miles. Projects to serve the New York City area were considered for three time periods: 1970 to 1990 (Program I), 1990 to 2020 (Program II), and after 2020.

4. Incremental Expansion of Individual Structures. Nearly every type of dam can be designed for future raising. Ross Dam, a thin concrete arch on the Skagit River, has been raised twice - from an initial height of 290 feet to a present height of 540 feet - and is designed for a further increment of 118 feet. Similarly, concrete gravity and rockfill dams have been designed for staged

construction. Often it is desirable to plan for additional power-generating units to be installed at some future date as has been done at many of the TVA dams and is now being planned for the Grand Coulee Third Powerplant.

Leveed areas can change from agricultural to urban use, justifying increased flood protection. Larger barges and heavier water traffic may require deeper channels, bigger locks, and faster transit. Traffic on the Tennessee River and through the Panama Canal are examples. These and similar changes in the future use of water projects should be considered in economic planning. Wherever possible, initial projects should be designed for future expansion.

5. Planned Obsolescence. A rather rare type of premeditated staging, but more common in actual occurrance, is the replacement of an early stage with a new and larger project even though the original structure is still useful.

An example of unpremeditated obsolescence has happened on the Rio Grande in Texas where Amistad Reservoir has inundated the Lake Walk and Devil's Lake hydroelectric plants on an upstream tributary. Deliberate staging of this type has occurred on the Michipicoten River in Canada where a storage dam was built in 1948 with the intention that it should be flooded out within 10 years by construction of a downstream power dam.

Most water resource structures have a theoretical useful life of 50 years or more. Designers are naturally reluctant to recommend that any project be built for only 5 years or 10 years of use. Nevertheless, a smaller structure which can meet an immediate need and also defer a large investment for even a few years may make a very economical contribution to staged development. Planned obsolescence should not be overlooked.

6. Changes in Project Functions. Changes in the function of the project development should be planned for in staged development. Of increasing importance to the planning of staged development are the changes in economic values of water uses. These in turn can alter the function and operation of a project, especially a storage reservoir. The selection of initial spillway and outlet capacities should consider such future possibilities.

Some areas, formerly agricultural and depending upon stored water for irrigation, may become urban with a need for municipal water. Where storage releases of low-valued water were governed initially by the irrigation cycle, more uniform releases may be required of high-valued water for domestic and industrial consumption. Return flow may be greater and the project thus relieved from imposed releases to downstream users.

The value of increasing recreational use of a reservoir may eventually outweigh the value of the original storage function (e.g., power or flood control) so that large fluctuations of the reservoir are no longer desirable. Cherry Creek Dam to the south of Denver is an example of a flood control project being converted to a recreational facility while sacrificing some of the potential flood control benefit.

While such future changes are not readily predictable, their possibilities should be considered in the planning of water developments. Although different from the preceding types of staging which involve choices among structures, functional and operational staging can be of great economic significance. Initial commitments to water users should permit future withdrawal and diversion to uses of greater economic and social benefit.

Economic Factors in Staged Development

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The three principle economic factors which influence staged development could be listed as: (1) Requirements and benefits; (2) Costs of water development; and (3) Costs of nonwater alternatives.

Requirements and Benefits

Staged development becomes more important when prospective uses of water vary over a long period of time. Functions such as electric power and municipal water supply will usually show a continually increasing demand representing an essential need. For these functions benefits are rarely evaluated. Economic analyses are usually based upon the costs of the most economic alternatives.

Other functions such as irrigation and flood control may be desirable but in some cases may not be essential. Increasing use of water development for these purposes is usually a matter of policy, with goals more or less arbitrarily set. For these, monetary benefits are the measure of economic justification.

Regardless of essential need or mere desirability, a projection must be made of the use of each function over a period of time sufficiently long to establish the justification of the initial project. Either alternative costs or benefits must be estimated for 10 years to 50 years in the future for comparison with the costs of a proposed water development. The nature of staged development is such that annual values may vary greatly over the period of analysis

Under the premise that investment capital is limited, and will find one outlet or another, indirect benefits which reflect increased economic activity due to the investment will occur in any event. The majority of investment and executing agencies in the water resource field may not want to consider the use of such indirect benefits in project evaluation.

Costs of Water Development

The most important objective of economic planning is to select the initial project, its size, and its characteristics. In order to arrive at these selections, relationships must be established between costs and functions. And for the analysis of staged development an additional factor must be introduced - the cost of achieving functional levels through intermittent construction efforts.

The planning of staged developments involves many more alternatives than a single-stage project. Yet the time and money available for study are usually limited, therefore there is need for simplified demonstrations of relative merit or cost between alternatives. Planning engineers must use parameters and short-cut methods of preliminary screening which they can supplement with their experience and judgement to reduce the number of alternatives to a manageable total. Even with the high speed electronic computer a rational reduction is necessary.

Sequence and Timing

The International Columbia River Engineering Board report to the International Joint Commission, United States and Canada said that "The total flood control benefit for the lower Columbia River could be distributed to storage reservoirs by at least three methods:"

(1) Incremental method, in which each storage is credited for the flood control benefit it provides at the time the storage is made available. This method would apportion most of the benefits to the first storage projects constructed. An equal volume of storage added at a later time would receive a much smaller portion of flood-control benefit. In this method an order of development would have to be assumed.

(2) Equal-share method, in which the total flood-control benefit at any stage of development is distributed equally to each acre-foot of effective storage that is provided. Thus, as a new storage project is added to the system the benefit to existing storage development would be reduced.

(3) System-benefit-distribution method, in which the total benefits from achieving a basic flood control objective are prorated equally to each acre-foot of effective storage needed to reach that objective. Projects added after this degree of control has been

achieved would only be credited with minor benefits as a result of augmenting the basic control requirements.

Methods (2) and (3) do not differ in principle in that surplus benefits (total benefits less total cost of project) of first added storage projects (this assumes that the most economic site is first added in order not to incur prematurely higher costs than are warrented by available alternatives) are systematically reduced over time to cover costs of less economic projects. In short, the total benefits are averaged over projects irrespective of the time they are introduced and of their relevant incremental value. The only difference between the two methods is that the averaging is done within the two arbitrarily defined brackets. That is, the larger benefit per acre-foot of storage for the basic flood control plan is averaged among all projects participating in meeting that objective. A smaller benefit per acre-foot of storage for the "augmented" flood control plan is averaged among all projects participating in the second and higher level of flood control. The breaking down of the flood control plan is averaged among all projects participating in the control plan into two levels of flood control objectives admits the principle of diminishing incremental returns to the two blocks of storage projects, but does not eliminate the averaging of benefits among projects within the two blocks of storage projects.

Comparative Analysis of Staged and Simultaneous Approaches to Benefit Evaluation. The function of a storage project in a hydroelectric system is to capture excess run-off which otherwise would have to be spilled at powerplants and store it for release during periods of subnormal run-off, thus permitting a higher proportion of the streamflow to be used and increasing the power capability of run-of-river plants and the system's output. In a hydroelectric system, however, equal additional increments of storage ultimately produce diminishing incremental prime power benefits; the reason for this is that as storage in the system grows the drawdown period lengthens, so that a given volume of energy in storage produces a smaller prime power gain.

Consider four storage projects on one watershed which are identical in every respect (inflow, capacity, developed head downstream, etc.) except for cost of the projects. Under the conditions posted, the gross benefits (B) are identical if any one site is substituted alternatively for any other site in any specified sequence of development (say, next added) as illustrated in Figure 1a. Any of the projects, however, added subsequently in the sequence has an incremental value less than preceding elements in the sequence in a manner illustrated in Figure 1b, whenever this added storage has the effect of lengthening the storage drawdown period. Now assume, as in reality, projects differ with respect to cost per acre-foot of storage. For purposes of this simplified exposition, assume that costs per acre-foot vary for the four projects as indicated in Figure 2.

Given projects of these illustrative cost and gross benefit characteristics, we can analyze the consequences of the difference between the two methods of benefit assignment.

Under these circumstances, the sum of the benefits of the four projects collectively (sum of projects benefits illustrated in Figure 1b) can be shown as in Figure 3, along with the total cost of all four projects (taken from Figure 2).

Figure 3 reveals that total benefits exceed total costs. Accordingly, if the benefits are averaged among the four projects, the average benefit will exceed the average cost. A system-benefit distribution method for flood control, or the delta storage distribution method for power (used in the International Columbia study) prorates the benefits in this special case equally to each of the four storage projects. Now, since the average benefit in this illustration is just higher than the cost of the highest cost storage project, an exhibit showing costs and benefits under this method of benefit assignment will indicate that all projects are justified in terms of their benefits exceeding their costs. Yet, since the incremental benefit from the addition of the fourth storage project (B_{p4}, Figure 1b) is appreciably less than the cost of the least economic of the four sites (C_{p4}, Figure 2), the implicit sequence of project introduction over time for the methods under review is similar to that shown in Figure 4. That is, the least economic must be constructed before the most economic, to permit all projects "justified" by the method to qualify for construction.

Under the incremental method the most economical project would be selected for two reasons: (1) to ensure that a noneconomic project is not incorporated early into a system only because benefits evaulated on a first added basis, exceed its cost, and (2) to ensure that higher costs are not prematurely incurred, even by construction of a project which would subsequently be justified on a "last added" basis, when there are more economical alternatives to rely on, thus realizing savings over some period of time.

Sequencing project construction based on the least cost per unit contribution to the system, in our simplified illustrative case, would require an ordering of projects as indicated in Figure 5.

The first project to be added would be the least costly per acre-foot, thereby ensuring the largest surplus of benefits over costs. When, for example, area power loads expand sufficiently to warrant addition of a second project, again the most economic of the remaining projects would be built to avoid incurring higher costs for power than would be incurred from existing alternatives. As the demand for power expanded to require additional capacity, project three would be included. However, even with continued expansion of the demand for power, project four would not be undertaken. Here we observe that the incremental benefits from undertaking the fourth project (benefit on the last added basis) falls short of covering costs.

The value of benefits from a project, for purposes of evaluation, are recognized to be no greater than the cost of equivalent services obtained from the least expensive alternative source of supply. The choice of a source of power would be an alternative to hydro at a cost equivalent to the benefit bar (B_{p4}) which is less than the cost of the fourth project (C_{p4}). Accordingly, the cost incurred by bringing the fourth project into the system exceeds the cost of available alternative sources of supply.

To provide additional perspective on the different results obtained by the "simultaneous" and "incremental" methods of system planning and project evaluation, Figure 6 is presented juxtaposed to Figure 3.

It is apparent that the simultaneous method in the example leads to a larger construction program, larger public expenditures and larger gross benefits (since gross benefits can always be purchased with excessive costs) than the incremental method when coupled with appropriate attention to the most economical order of project construction. Yet, while gross benefits are greater under the former, net benefits, the surplus of gains over costs, are smaller. This is shown by the difference between total benefits less total costs in Figure 6, or net benefits, which are greater for a smaller expenditure of resources than are the net benefits of the larger construction program.

A dam will cost more if constructed in 2, 3, or 4 stages rather than being built to its utlimate height at one time. Powerplants, water supply aquaducts, irrigation canals, flood control levees, and similar works will also be more expensive if their final size is reached through incremental expansions.

Thus the cost function relationship for staged development cannot be represented by a single curve, but by a family of curves differentiated by the number of increments required to reach any given level. Some typical examples are shown in Figure 7.

Costs of Nonwater Alternatives

Some of the functions of water development can be achieved by other means. Thermal electric plants can be substituted for hydroelectric generation and land transportation might be substituted for navigation. In such cases economic justification may be measured by the relative cost of the alternative that would accomplish the same objective. In most cases the nonwater alternatives in comparison to a water resource project has smaller initial investment, but they have a higher cost of operation and maintenance, and shorter useful lives.

Once constructed, many water resource projects have their annual costs well established. Long-term contracts at fixed rates can be made for the product of many water resource projects, but not for those of the nonwater alternatives.

Criteria for Economic Analysis

The standard benefit cost criteria in use by the Federal Agencies are not appropriate for economic analysis of staged development. With the standard benefit cost analyses it is not necessarily true that a project showing a benefit to cost ratio of 1.5 to 1 is economically superior to one showing a ratio of 1.4 to 1 for instance. Only rarely is it true that a project would be built to the limit that produces an incremental benefit to cost ratio of 1 to 1.

A criteria that best suits analysis of stage development will relate to the rate of return on invested capital to the benefits achieved or to the cost of alternative solutions.

Criteria are needed that will: (1) disclose the best use of capital, not merely a favorable benefit cost ratio; (2) reflect the relative merits of immediate and deferred investments; (3) permit comparison among projects of different sizes, functions and investment; and (4) be independent of interest that any particular agency can command.

The stages of development that will yield the greatest return are preferred provided that the return is at least equal to other investment opportunities. Under such criteria the nominal or arbitrary interest rate that the owner may happen to command at the moment would not influence the economic analysis.

The procedures for obtaining the rate of return are well known present-worth computations (also called capitalized value, discounted cash flow, etc.). These should be carried out of a range of interest rates to determine at what rate the present worth of costs and benefits (or alternative costs) is equal. These rates of return can then be compared for selection of the most economical alternative.

A judgement must be made of the minimum attractive rate of return for each stage of development and for the final increment of each stage. This minimum rate should reflect the return that could be achieved from other long-term investment, or the general cost of money within the country. The rate or rates to be used should be set by economists and bankers rather than by water resource planners.

In the short capital developing nations, a world bank favors annual returns on investment of 8 percent to 10 percent and sometimes higher. In the United States the minimum acceptable rate would probably be no less than the current prime interest rate or the yield on tax-exempt utility revenue bonds.

The rate should also reflect the conditions existing at the time of the decision to invest rather than a weighted long-term projection of them. The investment cannot be made retroactive and future rates are uncertain. Present conditions govern the terms under which the investment is to be made and the immediate competition for development.

Two examples of economic analysis for staged development are given.

In the first example, Figure 8, a large single-purpose hydroelectric development with a potential greatly in excess of immediate needs is considered. Economic planning for the project requires the selection of the most economical initial stage and proof that the hydroelectric development would be more economical than alternative thermal generation. In the example a minimum attractive rate of return is set at 8 percent.

In a second example, a dual-purpose irrigation and hydroelectric reservoir project is being planned. A relative large dam is required, which will provide irrigation water to 200,000 acres of land, plus some hydroelectric power. Full development of irrigation will require 15 years. Economic planning in this example includes the comparison of a single-stage and a two-stage development analysis of the economic justification of the total development, and demonstration of the value of the initial stage. The minimum attractive rate of return in this case is 10 percent.

Appendix - References

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2. "The Economists Role in Water Pricing Policy," by W. E. Johnston.

3. "Economic Planning for Staged Development," by Kenneth E. Sorensen and Robert O. Jackson.

4. "Surface Water Resources Planning in Hudson Basin," by Gerald T. McCarthy and Nicholas L. Barbarosa.

5. "The Economist and the Engineer: Economic Dynamics of Water Resource Development," by Kenneth Boulding.

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7. "A Million Acre Program for the Columbia Basin Project," Supporting Resolutions.

Storage Benefits

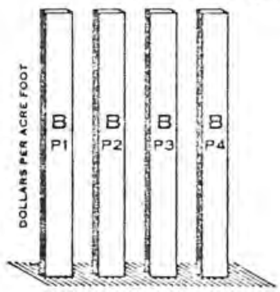


FIGURE 1*a*

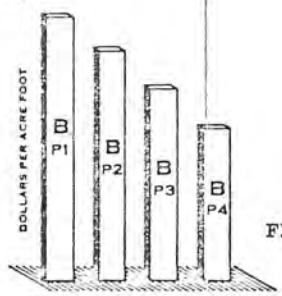
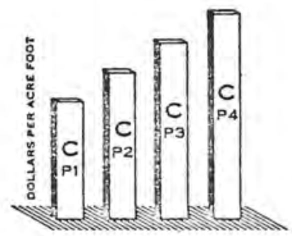


FIGURE 1*b*

FIGURE 2. *Project Costs*



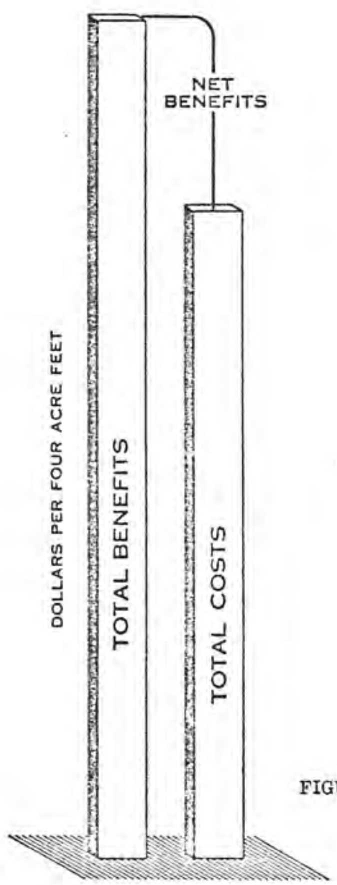


FIGURE 3. *Gross Benefits and Costs*

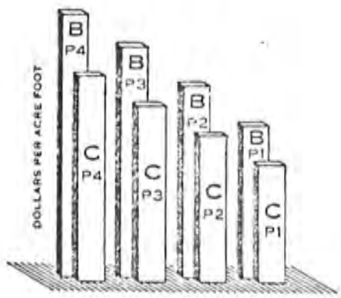


FIGURE 4

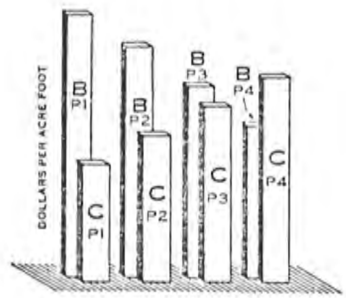


FIGURE 5

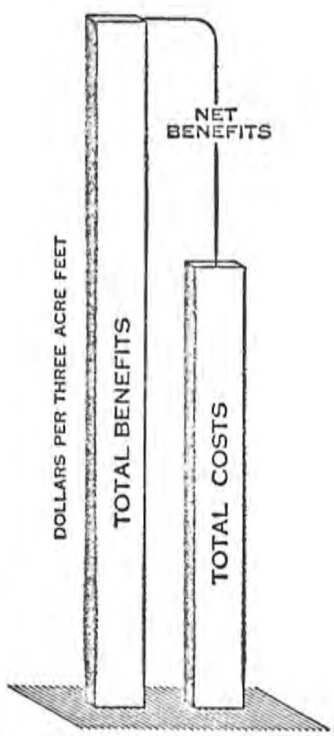


FIGURE 6. *Incremental*

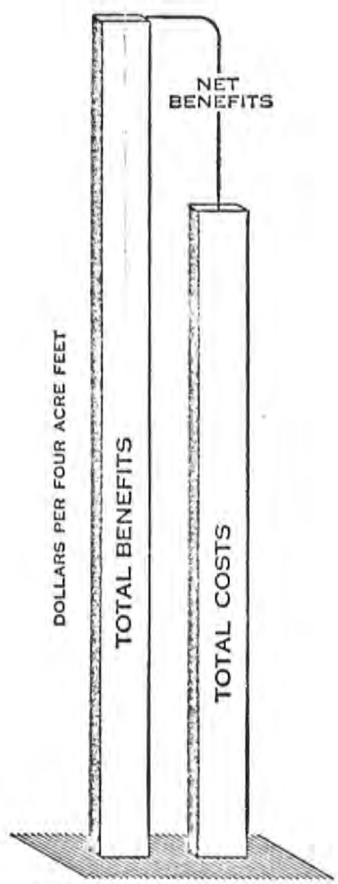


FIGURE 3 (repeated). *Simultaneous*

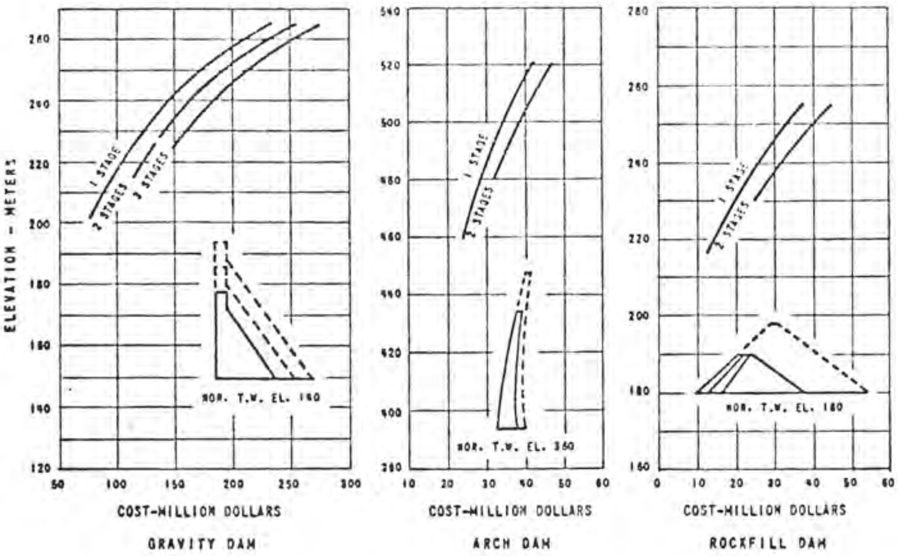


FIGURE 7. Example of Costs of Multistage Dams (Including Spillways)

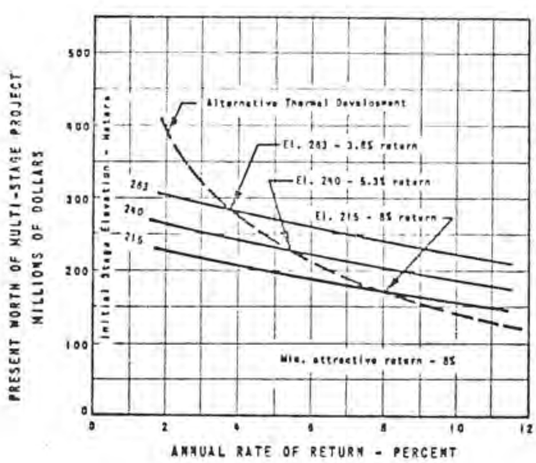


FIGURE 8. Economic Analysis to Determine Initial Stage Elevation for Hydroelectric Project to be Developed in Stages

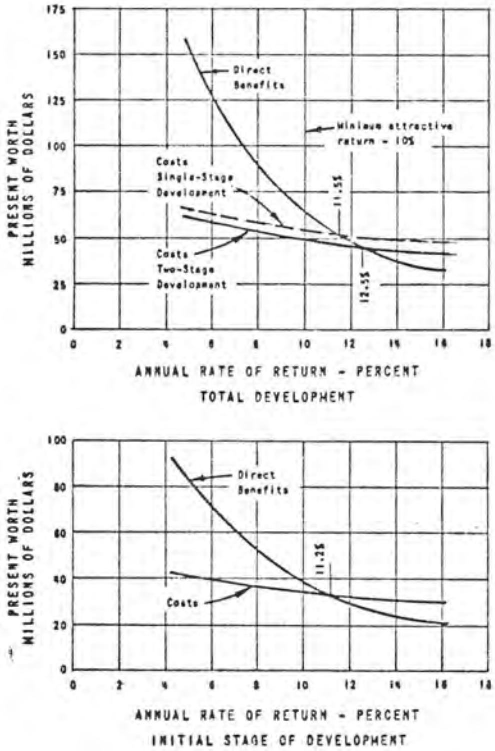


FIGURE 9. Economic Analysis of Irrigation and Power Development to be Built in Stages