



Project Summary

Planning Models for Urban Water Supply Expansion

David H. Marks, Fadi Karaa, Ellie Guggenheim, and Roger Kilgore

A three-volume report was developed relative to the modelling of investment strategies for regional water supply planning. Volume 1 is the study of capacity expansion over time. Models to aid decision making for the deterministic case are presented, and a planning process under uncertainty in future demands is suggested. Two methods for solving the capacity expansion problem are analyzed: a heuristic method and a mixed-integer programming method.

Volumes 2 and 3 are successive parts of this research related to the study of cost allocation policies among participants in a regional system. Such policies are evaluated and two methods, the Proportional Use of Facilities and the Shapley Value, are distinguished from the other techniques for practicality and theoretical soundness considerations, respectively. The Shapley Value method is then extended for the case allocation over time.

This Project Summary was developed by EPA's Water Engineering Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in three separate volumes (see Project Report ordering information at back).

Introduction

Escalating costs of new supplies have pushed many local water supply systems into some form of regional organization. Through economies of scale on upgraded water sources, treatment, and distribution, such organization helps to ease burdens on participants. In this context,

this research focused on two major problems. The first problem is related to deriving the combination of sources and network interconnections that would meet future demands at minimum cost. Also, the issue of uncertainties in future demands are addressed within the planning framework. In this first research effort, the major objectives were the modelling of the capacity expansion of regional systems over time and the evaluation of solution methods for the derivation of expansion strategies. In Volume 1, two solution methods are described: one, a simple but locally optimizing method; the other, a globally optimizing, more computationally difficult method.

The second problem was analyzing cost allocation schemes that can generate the willingness of different participants to join in the regional system. Various cost allocation methods were examined and evaluated in the context of a case study involving the Tampa Bay region in Florida. The Proportional Use of Facilities method was found to be most practical, although lacking some theoretical soundness. A more complete but complex approach using the Shapley Value was therefore suggested. The cost allocation problem is first analyzed in Volume 2, and its latest results are found in Volume 3.

Capacity Expansion

The capacity expansion research concerned developing an approach that could deal most efficiently with sizing and scheduling the expansion of a defined regional water supply configuration. Scheduling problems are stated as minimizing the present value of capital and

operational costs as related to water supply and conveyance facilities, under constraints such as reliably meeting demands and budget limitations. Given that the cost functions associated with the development of water supply facilities exhibit economies of scale, simple linear optimization techniques could not be used. Among the possible methods to solve the dynamic expansion problem, two different approximate approaches were believed to be most promising: a heuristic method and a mixed integer programming method. Both methods were based on deterministic projected levels of demands over a given time.

Details of the final results of the capacity expansion problem under deterministic levels of demands are given in Volume 1. The two different approaches are described in the following.

The Heuristic Algorithm

The heuristic approach is iterative, and involves the decomposition of the problem so it can be solved in two successive steps, which significantly reduces computational requirements. In addition to solving the problem in a logically sound manner, the heuristic method allows gains in economies of scale to be tracked accurately.

The heuristic algorithm belongs to a "satisfying" category of methods designed to obtain a local (satisfactory) solution, which may not be the global (exact) optimal solution. The algorithm employs the decomposition technique so that linear programming (LP) and dynamic programming can be used, while keeping the original cost functions unchanged.

The heuristic algorithm is based on the following two steps:

1. The definition of a set of linear coefficients to approximate the different cost functions according to the time period. This permits solving a simple LP flow program, which derives a feasible set of flows in the area of the network for the sequence of time periods. The flows in the different time periods are "priced" or "weighted" accordingly using the results of the previous iteration. Except for the first iteration, the algorithm develops an improved solution by introducing the linear coefficients based on the updated last best solution. Further details on the expressions of such linear coefficients can be found in Volume 3.

2. The second step utilizes a dynamic programming procedure to process each arc alternative developed in the solution obtained in the first step. This process derives the optimal scheduling of capacities that can meet the flow levels of the first iteration. The net present value of the original cost function is used, and a cost matrix allows one to compare the different strategies and retain the dominant one.

Given this decomposition into two steps, the dimensionality of the original problem is not a blocking factor to the capacity algorithm. In a large case study with 67 arcs and 40 nodes with two time periods, it was found that the higher the real discount rate, the less significant was the "economies of scale" effect on the final solution. In other, smaller case studies, an improved solution after the very first iteration was shortly followed by a certain settlement around a preferred expansion strategy. Hence, the number of iterations needed was relatively small, and, consequently, the required computer time was also small. However, the use of the heuristic algorithm is only efficient when all facilities considered are of the "expandable" or "replicable" type. The model and its testing on the Tampa Bay case study are completely described in Volume 1.

The Mixed Integer Programming Approach

The mixed integer programming approach involves the minimization of the cost-related objective function in such a manner that it is possible to obtain the exact least cost (global) solution if enough computational iterations are performed. The mixed-integer procedure used in this study requires that the objective function be approximated by piecewise linear segments. The simplest approximation of a nonlinear function is a linear line with a fixed charge associated with it, and this method is used in the study.

Mixed integer programs often require a large number of computational iterations to obtain the exact best solution. If the given problem to be solved is large, this may result in expending a large amount of computer time. However, the mixed integer approach has the potential for obtaining near-optimal solutions efficiently. In this study, the most favorable approach to optimizing the capacity expansion problem was by synthesizing the heuristic and mixed integer procedures (see Volume 2).

Approaches To Uncertainty

The deterministic capacity expansion models serve as the central analytical tools for obtaining initial strategies in the planning of regional water systems. The initial solution of the expansion strategy using projected levels of demand over time must be subjected to a re-evaluation program. The purpose of this is to modify the original strategy, if needed, to meet the reliability standards under the level of uncertainty about the parameters of the probability distributions of demands. The modified strategy is then implemented in its first period. At the end of that period, a new planning cycle is performed using the new information. A new expansion strategy might be derived that possibly leads to a deviation from the budgeted capital costs for the next period. Under this scenario, a goal programming approach is suggested to minimize the deviation from the predetermined budgets. In this latter mode, deviation from budgets are "discounted" on a time priority basis.

Cost Allocation of Multiperiod Regional Water Supply Systems

A cost allocation policy is concerned with how costs are divided and among whom. The structure of the regional system and the financial viability of the expansion plan depend on the way cost allocation is carried out. Ten cost allocation methods, in three categories (see below), were examined and are described in Volume 2. Two case studies were performed: one hypothetical and the other related to the Tampa Bay area in Florida.

Proportional Methods

1. Proportional to Demand
2. Proportional to the Use of Facilities

Core Methods

3. Least Core
4. Nucleolus
5. Proportional Least Core
6. Weak Least Core

Miscellaneous

7. Shapley Value
8. Separable Costs Remaining Benefits (SCRB)
9. Alternative Justifiable Expenditure (AJE)
10. Minimum Cost Remaining Savings (MCRS)

The criteria used to evaluate the cost allocation methods were simplicity, theoretical soundness, economic attractiveness, and practicality. As an example, Table 1 presents the factors associated with the simplicity criteria.

Table 1. Evaluation of Cost Allocation Policies According To The Simplicity Criterion

Cost Allocation Policy	Data Requirements	Computational Requirements	Intuitiveness
Proportional to Demand	- Total Project Costs - Demands	Simple Arithmetic	Intuitive
Proportional to Use of Facilities	- Component Costs - Demands - Flow Routing	Simple Arithmetic	Intuitive
Least Core	- Total Project Costs - All Alternative Costs	Linear Programming	Somewhat Intuitive
Nucleolus	- Total Project Costs - All Alternative Costs	Multiple Linear Programs	Somewhat Intuitive
Proportional Least Core	- Total Project Costs - All Alternative Costs	Linear Programming	Somewhat Intuitive
Weak Least Core	- Total Project Costs - All Alternative Costs	Linear Programming	Somewhat Intuitive
Shapely Value	- Total Project Costs - All Alternative Costs	Extensive Arithmetic	Very Difficult to explain to lay audiences

Evaluation of the Cost Allocation Methods

Proportional Methods

Allocating costs proportional to demand lacked theoretical rigor. It also performed poorly with regard to economic attractiveness. If this allocation method was considered, many competing coalitions would see economic disincentives uniformly absent from the other nine policies.

This is not to say that proportional methods are categorically undesirable. The Use of Facilities method may be the best of the ten conventional methods. It is simple to use and understand and presents only minor difficulty at determining flow paths. Theoretically, it was much better at recognizing contributions to economies of scale and expanding spatial extent by tying allocations to the cost of each facility. However, such a close association forces the method to ignore alternatives given up by a particular city in joining the grand coalition. Consequently, adjustments by the regional authority may be required.

The Core Methods

The Core Methods — Least Core, Nucleolus, Proportional Least Core, and Weak Least Core — have the potential for being very useful. By explicitly considering alternative costs of each competing coal-

ition, the methods are theoretically sound and also allocate costs in an economically attractive manner. The proportional Least Core approach is slightly superior because it considers alternative costs when selecting an allocation from the set of feasible solutions; the others do not.

Unfortunately, the two case studies suggest two critical difficulties. The first is the derivation of alternative costs. The other is related to the fact that expressing alternative costs is foreign to water supply accounting and planning practices. The problems of intertemporal cost allocation seem to be intractable if Core Methods are employed.

Use of Facilities Versus Core Methods

The Use of Facilities and Core Methods are both attractive schemes because they are practical. The Tampa Bay area regional authority, however, has adopted a Use of Facilities approach partly because that approach does not present the computational sophistication of the Core Methods and the data required are consistent with common planning practice. The solid performance of this approach with respect to the different criteria and its acceptability by practitioners make it more promising for widespread application than the Core Methods.

SCRB, AJE, and MCRS

SCRB is a hybrid procedure based on alternative costs and on a proportional allocation of remaining benefits. AJE is a hybrid that also includes the Use of Facilities Method to the extent that specific costs are considered. Since SCRB and AJE combine a relatively poor allocation mechanism (Proportional to Demand) with relatively good ones (Use of Facilities and the Core Methods), one would be better off using the superior ones.

MCRS shares the drawbacks of the Core Methods — a reliance on elusive alternative costs and an inability to approach the intertemporal problem. It also lacks their theoretical rigor. No particular advantages of the method were revealed in either of the case studies.

The Shapley Value

The Shapley Value is a cost allocation formula that can be intuitively understood as a "marginal cost average." The entire system is formed as participants join it successively. For any particular order of formation, each participant should pay its corresponding marginal cost, i.e., the cost added to the system when it joins. As different orders of joining the system lead to different marginal costs, the Shapley Value adjusts this problem by taking the average of these marginal costs over all possible orders of formation of the system.

The Shapley Value depends heavily on the evaluation of alternative costs and is consequently very complex, although not requiring mathematical programming techniques. It is an "efficient" allocation rule in the sense that it allocates exactly the total cost of the regional system.

The complexity of the method was reduced by two simplifications. First, it was shown that costs could be ignored for those facilities that benefit one member and would be built no matter which regional configuration is adopted. Second, methodologies were established to identify in advance the redundant coalitions with similar savings.

The Shapley Value method was applicable, in a straightforward manner, to the problem of cost allocation over time, which is relevant in optimal capacity expansion problems. Fairness requires that "new consumers" be separated from earlier ones. The Shapley Value addresses this issue directly, which is one of its advantages. In the Tampa, Florida, case study, the validity of the various assumptions and proposed simplifications were tested. The system contained four main

demand centers, which were in a state of balanced equilibrium as far as their water needs were concerned. An existing configuration of sources and pipelines met all the present water demands of the communities. The Planning Authority was interested in the evolution of this regional system over the next 20 years, given some projections of future demands. By eliminating operations and maintenance costs, which was theoretically justified for this case, only capital investments were considered. The results were very encouraging and supportive of the assumptions and approximations made and of the Shapley Value Method in general. It was also shown that by applying a "naive" rule, based on the idea of beginning the repayment of the corresponding capital investment at every period, the obtained results seriously and consistently differed from the correct allocation. Unacceptable distortions occurred not only in terms of cost shares but even in terms of annual rates, thus strongly suggesting that a Shapley Value cost allocation method be used instead of a "naive" rule, both over time and space. Using the Shapley Value, a method recognized as theoretically very sound, in a simplified form is particularly appealing. Its use as a decision-making tool provided many new insights into the problem of cost allocation and explored the potential for successfully applying the Shapley Value method in future practical problems.

Conclusions

Capacity Expansion Methods

Both the heuristic and mixed integer capacity expansion solution methods exhibit advantages and drawbacks. Although

the heuristic approach is simpler and can be used on mini- or microcomputers, it is a locally optimizing method and can deal only with expandable facilities. On the other hand, the mixed integer method has the capability to obtain the exact best solution, but may require large computer resources. Ideally, the use of both methods in an iterative manner can lead to more efficient expansion schemes.

Cost Allocation Methods

The cost allocation policies were evaluated and tested on a case study using the Tampa Bay area. The results of this effort show that the Proportional Use of Facilities

method for cost allocation is the most promising policy due to its satisfactory evaluation according to several criteria.

The Shapley Value method, theoretically the best allocation scheme over time, was the focus of a significant part of this research. Important modifications were suggested to decrease its complexity while keeping its superior theoretical attractiveness.

The full report was submitted in fulfillment of Cooperative Agreement No. CR806802 by the Massachusetts Institute of Technology, under the sponsorship of the U.S. Environmental Protection Agency.

D. Marks, F. Karaa, E. Guggenheim, and R. Kilgore are with the Massachusetts Institute of Technology, Cambridge, MA 01239.

Robert M. Clark is the EPA Project Officer (see below).

The complete report consists of three volumes, entitled "Planning Models for Urban Water Supply Expansion:" (Set Order No. PB 88-109 590/AS; Cost: \$53.50)

"Volume 1. Planning for the Expansion of Regional Water Supply Systems," (Order No. PB 88-109 608/AS; Cost: \$18.95)

"Volume 2. Cost Allocation Policies for Regional Water Supply Systems," (Order No. PB 88-109 616/AS; Cost: \$18.95)

"Volume 3. The Regional Intertemporal Cost Allocation Problem: A Simplified Methodology Based on the Shapely Value," (Order No. PB 88-109 624/AS; Cost: \$24.95)

The above reports will be available only from: (costs subject to change)

*National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650*

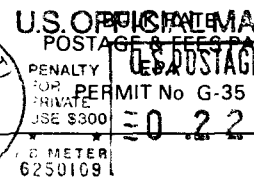
*The EPA Project Officer can be contacted at:
Water Engineering Research Laboratory
U.S. Environmental Protection Agency
Cincinnati, OH 45268*

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati OH 45268

Official Business
Penalty for Private Use \$300

EPA/600/S5-87/002



0000329 PS

U S ENVIR PROTECTION AGENCY
REGION 5 LIBRARY
230 S DEARBORN STREET
CHICAGO IL 60604