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Research on Comprehensive Planning of Water-Resource Systems

Maynard M. Hufschmidt

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RESEARCH ON COMPREHENSIVE PLANNING OF WATER-RESOURCE SYSTEMS

MAYNARD M. HUFSCHMIDT*

Enactment of the Water Resources Research Act of 1964[1] provides water-resource planners and managers with a splendid opportunity to support their planning and action programs with research in scope and depth never before possible. The act also presents a challenge to those concerned with water resources to make the most effective use of the research resources at universities and other research centers. This challenge exists both for the users of research results—the planners and managers—and for those responsible for administration and accomplishment of research—primarily the universities.

Fortunately, the attention given to water resources research at the national level since publication of the report of the Senate Select Committee on National Water Resources in 1961[2] has had highly favorable consequences. Information on federal programs of water resources research has been assembled and a start has been made on coordinating these activities.[3] Many universities have begun to pull together their research activities in the water resources field, usually by establishing some form of water resources research center. By December 1964, at least forty-eight such centers were in existence;[4] most covered a broad spectrum of academic disciplines, including many of the social sciences and law, as well as engineering and the natural sciences.

The current breadth of research interest is in sharp contrast to the situation in 1955 when the Harvard Water Program was established. At that time, there were no inter-disciplinary water-resource centers at universities; water resources research was largely oriented toward engineering and the physical sciences; and the modest re-

* Professor, Departments of City and Regional Planning and Environmental Sciences and Engineering, University of North Carolina, Chapel Hill.

1. 78 Stat. 329-33, 42 U.S.C. §§ 1961 to 1961c-6 (1964).
2. S. Rep. No. 29, 87th Cong., 1st Sess. (1961).
3. See Federal Council for Science and Technology, Federal Water Resources Research Program for Fiscal Year 1966 (1965).
4. Universities Council on Water Resources, Roster of University Water Resources Organizations (1964).

search under way in the social sciences[5]—largely economics and political science—and in the law was carried on with little relation to work in the physical sciences. Another striking development of the 1955-1964 decade was the increasing application to water resources of the concepts and techniques of operations research and systems analysis, with their orientation to the electronic computer. In 1955, such applications to water-resource problems were rare; today they are commonplace. Of major significance is the fact that use of these concepts and techniques requires the contributions of many disciplines—mathematics, statistics, economics, political science, sociology, as well as engineering and the physical sciences.

These developments of recent years place us in a good position to capitalize on the opportunities now available to expand and intensify water resources research and to orient the research toward inter-disciplinary problems carried out in a systems context.

I

CLASSIFICATION: COMPREHENSIVE WATER-RESOURCE PLANNING

There are many ways of classifying water resources research. There is the familiar classification by broad fields of knowledge: social sciences, natural sciences and technology. For example, Allen Kneese's article in this symposium deals with water resources research in the social sciences. Other classifications often used are: (1) by the agency sponsoring or conducting the research; (2) by the areas of research need, and (3) by the fundamental physical characteristics and processes involved—the hydrologic cycle, surface water, ground water, and the like.

A somewhat different classification is suggested here, one that focuses on the processes used by man to control and adapt water resources for his use. In broadest terms these processes are: (1) collection and analysis of basic data; (2) planning; (3) construction or development, and (4) management. Under each of these processes one can further classify research into basic and applied, and into natural science, social science, and technology. Systems analysis and computer technology are also applicable to each process. Classifying research in this way serves to emphasize certain important kinds of research involving the "interface" of social science and

5. The major impact of Resources for the Future on social science research in water resources occurred only in the late 1950's; 1955 was the first year of full operation for RFF.

technology, whose significance tends to be obscured in conventional classifications.

This paper is concerned with research associated with one of these processes—comprehensive water-resource planning or, an alternative term, water-resource system design. The federal government, in cooperation with the states, is now well started on an ambitious program of preparing comprehensive plans for all major United States river systems by the early 1970's. The cost of this program in money and manpower will be large; money costs for planning will exceed $100 million by 1970. And the construction, development and management programs expected to flow from these planning studies will cost many billions of dollars. Yet, very little research is now being applied to the water resource planning process, despite the high payoff that may be expected both in terms of more effective performance of planning studies and, more important, in developing water-resource plans that are more nearly optimal.

This paper discusses research needs in water-resource system design, and presents, as background, some information on current work at Harvard in this field.[6] Research topics are presented under three headings corresponding to three major steps of the planning process: (1) establishing the objectives of design; (2) translating objectives into design criteria, and (3) designing the system, through use of the design criteria, for maximum realization of the objectives. The rationale for organizing the planning process in this way is presented elsewhere;[7] this form of organization is used here as a convenient way of presenting research needs in a consistent format.

II

ESTABLISHING OBJECTIVES OF DESIGN

A clear and unambiguous statement of objectives is a prerequisite to the development of workable design criteria which are, in turn, essential for effective preparation of plans. An important set of questions on which research is urgently needed therefore concerns the ability of the governmental process to arrive at the required decisions on objectives.

6. In May, 1965, this work was being supported by research contracts with the U.S. Army Corps of Engineers and the U.S. Public Health Service and by a grant from Resources for the Future.

7. Maass, Hufschmidt, Dorfman, Thomas, Marglin & Fair, Design of Water-Resource Systems, ch. 1 (Harvard Univ. 1962).

Insofar as the federal government is concerned, to what extent can the legislative process, operating through the President and the Congress, express the objectives for water-resource development in forms useful for field-level planners? Widely divergent views on this are now held by economists and political scientists. One point of view, stated most explicitly by Arthur Maass,[8] holds that Congress and the Executive have the capacity, under strong executive leadership, to express planning objectives in a form which planners can effectively use.[9] In contrast, the point of view reflected by Lindblom, Wildavsky, Tullock and Downs[10] emphasizes the group pressure and bargaining nature of the legislative process and casts doubt on the ability of the process to produce a set of consistent policy objectives that planners can use directly in preparation of plans. The question is so fundamental to effective operation of the planning process in all fields of public investment that a substantial program of research in this difficult field of political economy is urgently needed. Although the key disciplines involved are economics and political science, there is also an important technological dimension; the manner in which objectives are stated has effects which can be traced all the way to the detailed designs of individual projects in a comprehensive plan.

A second problem involving the setting of objectives arises from the increased participation of state and local governments in comprehensive water-resource studies. In situations where federal, state and local agencies all participate in planning, it is not clear whose objectives are to govern. Obviously, the objectives of these jurisdictions will not always be identical and there may well be major conflicts among them. One solution to problems of conflict is to rank objectives by level of government; thus, in cases of conflict, federal objectives would prevail over state objectives, while state objectives would override local government objectives. Although this approach can be justified in terms of primacy of the national interest over regional and local interests, serious problems arise when at-

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8. *Id.*, ch. 15.

9. A recent study at Harvard University investigates this hypothesis empirically by examining the federal highway and area redevelopment programs. See Major, Decision-Making for Public Investment in Water Resource Development in the United States, chs. 5-6 (unpublished Ph.D. thesis in economics, Harvard Univ. 1965).

10. Lindblom, *The Science of Muddling Through*, 19 Pub. Admin. Rev. 79 (1959); Wildavsky, The Politics of the Budgetary Process (Little, Brown 1964); Downs, An Economic Theory of Democracy (Harper 1957); Buchanan & Tullock, The Calculus of Consent, Logical Foundations of Constitutional Democracy (Univ. of Mich. 1962).

tempts are made to carry it out. Where conflicts of this type arise among government jurisdictions, the planning process often breaks down; that is, a definitive plan is not forthcoming. Even should a final plan or alternative plans be recommended by a federal agency, prospects for approval by Congress are usually poor because states and localities can marshal their forces against the proposals and Congress is reluctant to approve projects in the face of such opposition. Some case-studies have been made on conflict in objectives between different government jurisdictions,[11] but further research is needed, both to identify the important issues and to set up and test model strategies for planning under conditions of multiple jurisdictions and multiple objectives.

III

TRANSLATING OBJECTIVES INTO DESIGN CRITERIA

Closely related to the setting of objectives is the translation of objectives into a set of planning or design criteria that planners can use in detailed design of water-resource systems. Included here is the familiar set of questions relating to federal standards and criteria, the subject of so much discussion in recent years. The 1962 revision of federal standards by the President's Water Resources Council[12] has not solved all outstanding problems. Many questions of detail, including theory and technique of deriving benefits, are left open, and certain ambiguities remain. In his article in this symposium, Kneese deals with several important unresolved problems of this type, including the difficult questions of the appropriate discount rate to be used and appropriate methods of handling risk and uncertainty in formulating public investment plans.[13] In addition to these important questions, there are three problems relating to standards and criteria that require much further research.

11. One such study is Dola, Passaic Valley Flood Control: A Study in Water Resource System Design (Harvard Water Program 1962) (mimeo.).

12. S. Doc. No. 97, 87th Cong., 2d Sess. (1962). See also U.S. Bureau of the Budget, Report of Panel of Consultants to the Bureau of the Budget on Standards and Criteria for Formulating and Evaluating Federal Water Resources Developments (1961) (mimeo.).

13. For a thorough discussion of the social rate of time discount, see Marglin, *The Social Rate of Discount and the Optimal Rate of Investment*, 77 Q.J. Econ. 95 (1963), and *The Opportunity Costs of Public Investment*, *id.* at 274; and the comments by Tullock & Lind, 78 Q.J. Econ. 331, 336 (1964), Nichols, *id.* at 449, and Usher, *id.* at 641. Treatment of uncertainty in water resources planning is discussed in Report of Panel of Consultants to the Bureau of the Budget, *op. cit. supra* note 12.

A. Standards and Criteria and the Political Process

An important question concerns the respective roles of Congress, the Chief Executive and the departments and agencies in the derivation of standards and criteria. Although closely related to the problem of setting objectives, discussed above, this question has wider ramifications. One hypothesis which should be tested is that many of the difficulties which have arisen concerning federal water-resource standards and criteria can be traced to the fact that standards-setting has been incorrectly viewed as solely an executive responsibility, rather than a task to be shared by the executive and the legislature. While some recent research has been done on this question,[14] more is necessary to test the validity of this hypothesis or alternative hypotheses that may be formulated.

B. The Role of Alternative Cost as a Substititute for Benefits in Plan Formulation

For want of a better measure, alternative costs are often used as a measure of benefits for some outputs of water resource projects. There is theoretical validity, as well as strong practical advantages, to this use of alternative cost, but the rules for its correct application have never been rigorously defined. A beginning on this problem has recently been made by Peter Steiner,[15] but more work is needed to define and illustrate with actual cases the various situations in which the alternative cost test can be validly applied.

C. Definition of the Planning Region and the Scope of Water-Resource Planning

The current program of preparing framework plans for all major United States river basins makes the definition of appropriate planning regions an important problem at this time. As Kneese points out in his discussion of the question, the goal is to "internalize" the important externalities; alternatively, the goal is to define a region so that strong links are internal to the system and all external links are weak. Links as used here would be defined in terms of the objectives of design and would include economic and social characteristics, as well as technological relationships.

It is by no means clear, at least in the densely populated sections

14. See Major, *op. cit. supra* note 9; Maass et al., *op. cit. supra* note 7, at 588.

15. Steiner, *The Role of Alternative Cost in Project Design and Selection*, 79 Q.J. Econ. 417 (1965). Steiner's paper was written for the Harvard Water Program.

of the country, that the river basin is the appropriate planning region for water-resources. For example, the applicable water-use area of the Delaware Basin includes the New York City metropolitan region and much of New Jersey outside the Delaware Basin. As the metropolitan complex from Boston to Washington expands and becomes more densely populated, the major contiguous river basins—the Merrimack, Connecticut, Hudson, Delaware, Susquehanna and Potomac—will become closely linked in terms of use. Perhaps it will soon be necessary to consider these basins together as a single unit for planning in relation to the needs of the large metropolitan complex.

These questions, and more general questions of how to relate water-resource planning to planning for highways, recreation, open spaces, and urban and suburban land-use, need to be examined under a research strategy combining the technological, economic, social, and institutional points of view.

IV

WATER RESOURCE SYSTEM DESIGN

This third step of the planning process encompasses the full range of studies and analyses included in the preparation of a regional water-resource plan. Much of the research under the Harvard Water Program has been concerned with the substance of this step. Important aspects considered in the Harvard program and requiring further research are discussed below.

A. Techniques for Regional Economic Projections

Water-resource planning agencies need projections of population and economic activity by water-resource regions to serve as the basis for projecting demands for water-resource products or services. In recent years, the United States Army Corps of Engineers and Public Health Service have commissioned the preparation of such projections for many regions, including the Potomac, Delaware, Ohio, Upper Mississippi, New England and Colorado River basins.

In the absence of any over-all federal program for preparing regional projections, the water-resources agencies have been forced to commission them on an *ad hoc* basis. For example, the water-resource agencies have obtained projections from a sister federal agency, the Office of Business Economics of the Department of Commerce; a non-profit research organization, the National Planning Association; and a private research firm, Arthur D. Little, Inc.[16]

Obviously, consistent sets of national, regional and local projections are required for a wide variety of planning purposes, transcending the water-resources field. Federal water-resource agencies have been among the leading promoters for development of regional projections, and there is hope that the federal government will soon regularize the process of developing regional projections as a basis for public investment planning.

For some time, econometricians and regional scientists have been developing new and improved methods for projecting regional economic activity.[17] Regional input-output models are an important example. As research proceeds on such models, it is important that the relationships between projections of the various sectors and subsectors of the economy (e.g., by major industrial classifications) and water uses be built into these models. The research on water uses by major industries, mentioned by Kneese in his paper, will contribute to this end. Another fruitful approach is to combine research on an economic projection model for a specific region with studies of unit water requirements for major economic sectors, in which technological change, alternative water pricing and water management policies are explicitly taken into account. In this way it will be possible to analyze the relative sensitivity of water demands to changes in levels of economic activity by sectors, versus changes in technology, water pricing and management policies.

B. Derivation of Water-Resource Benefit Functions

While there is wide agreement among economists on the basic concepts involved in deriving benefit functions, at least where economic efficiency is the objective, much remains to be learned on the application of concepts to specific cases. In this symposium Allen Kneese discusses some of these deficiencies, including problems

16. Projections of the Office of Business Economics for the Delaware River Basin are contained in *Delaware River Basin, New York, New Jersey, Pennsylvania and Delaware*, H.R. Doc. 522, 87th Cong., 2d Sess., vol. 2, app. B (1962), and for the Potomac River Basin in U.S. Army Engineer (Baltimore District), Potomac River Basin Report, vol. 9, app. L (1963). The National Planning Association is preparing projections for the Upper Mississippi, Chesapeake Bay and Susquehanna River Basins, and Arthur D. Little, Inc., is preparing projections for the Ohio River Basin and the New England region.

17. See Isard, Methods of Regional Analysis (MIT Press and Wiley 1960), and Regional Science Ass'n, Papers and Proceedings, vols. 1-10 (1955-1964).

of deriving benefits for water-based recreation, water quality improvement, inland waterway transportation, and flood damage prevention. Some research has also been done by the Harvard Water Program on deriving flood damages for industrial plants and for estimating water-based recreation benefits;[18] and work is in progress on factors influencing demand and, hence, benefits for domestic and industrial water supply.[19] But further research is needed on the derivation of benefit functions, especially for non-marketable effects, such as flood-control measures, control of low-flows, and some aspects of water-based recreation. In particular, research is urgently needed on the economic losses associated with short-term deficits in irrigation, domestic and industrial water supply, and in electric energy, and short-term changes in reservoir level from the level established for best recreation use of the reservoir.

C. *Deriving the Technological Function*

The basic problems associated with deriving the input-output relationships for water resource developments have been discussed in two recent papers;[20] thus, only a brief summary of problems is presented here as an introduction to discussion of needed research. In recent years much research has been directed to removing the two major limitations of conventional techniques for deriving the water-resources production function: (1) inability to deal adequately with the stochastic aspect of streamflow, and (2) inadequate treatment of the complex physical interactions found in multi-unit, multi-purpose systems. Major accomplishments include new and improved models for generating synthetic sequences of streamflows,[21] mathematical models (including queueing theory and linear, quasi-linear and dynamic programming models), and sophisticated simulation

18. Kates, Industrial Flood Losses: Damage Estimation in the Lehigh Valley (Geography Research Paper No. 98, Univ. of Chicago, publication forthcoming); Merewitz, Recreation Benefits of Water Resource Development (Harvard Water Program 1964) (mimeo.).

19. In their Ph.D. dissertations in economics at Harvard University, Louis Falkson and Edwin Johnson are analyzing factors influencing demand for industrial and domestic water supplies.

20. Hufschmidt, *Field-Level Planning of Water-Resource Systems*, 1 J. Water Resources Research 147 (1965), and Dorfman, *Formal Models in the Design of Water-Resource Systems*, *id.* at ——.

21. Thomas, A Method of Generating Synthetic Streamflow Hydrography (Harvard Water Program 1958) (mimeo.); Maass et al., *op. cit. supra* note 7, ch. 12; Hufschmidt & Fiering, Simulation Techniques for Design of Water-Resource Systems (Harvard Univ., publication forthcoming). Some references to application of synthetic streamflow sequences are contained in Amorocho & Hart, *A Critique of Current Methods in*

models that use synthetic streamflow sequences and flexible operating policies. These techniques rely on the modern digital computer to perform the truly enormous number of computations required for application of the models to an actual design problem.

Although there has been good progress in research on synthetic streamflow generation,[22] there is need for further research on application and adaptation of the technique to many different types of streams and patterns of water-resource development. Another desirable expansion of research is in creation and testing of synthetic flow models in which the relatively plentiful meteorological data—rainfall and temperature—become the inputs in lieu of relatively scarce streamflow data.[23] A third field of study concerns predictive models in which forecasts of streamflow probabilities, derived from analysis of meteorological data, are used to develop improved operating policies for water-resource systems. And, finally, much more research is needed to develop practical models for synthesizing flood hydrographs for use in river system simulation analyses.

D. Preliminary Screening Techniques for System Design

Conventional techniques for preliminary screening of development alternatives do not adequately take into account the physical and economic linkages between individual system units. Three approaches to application of systems analysis to preliminary screening have been suggested, each relying on the digital computer. They are: (1) rough simulation of a skeletonized system; (2) simplified mathematical models (involving discrete or continuous functions) assuming deterministic streamflows, and (3) mathematical models involving stochastic treatment of streamflow.

Research on these methods of preliminary screening using the systems approach is still largely in the conceptual state. Required is

Hydrologic Systems Investigation, 45 Transactions Am. Geophysical Union 307 (1964); see also Fiering, *Queueing Theory and Simulation in Reservoir Design*, 127 Transactions Am. Soc. Civil Engineers 1114 (1962). Synthesis of Indus River flows is reported in Thomas, Indus River Basin Studies (Harvard Water Resources Group 1965) (mimeo.), and synthesis of Jordan River flows in Yagil, *Generation of Input Data for Simulation*, 2 IBM Systems J. 288 (1963).

22. Fiering, *Multivariate Technique for Synthetic Hydrology*, 90 J. Hyd. Div. Proceedings Am. Soc. Civil Engineers 43 (1964).

23. Linsley and his group at Sanford University have done extensive work on models of this type. For a brief description and reference to the literature, see Amorocho & Hart, *supra* note 21, at 315; see also Chow & Ramaseshan, Sequential Generation of Rainfall and Runoff Data, Conference Preprint No. 40 (Am. Soc. Civil Engrs. Water Resources Engineering Conference, Mobile, Ala., March 1965).

the experimental application of available models to a number of actual water-resource planning problems. Because simulation is currently the technique most nearly operational, initial emphasis could be given to simulation experiments for preliminary screening purposes, but work should also proceed on the theory and practice of applying optimization methods, such as linear and dynamic programming models.

E. Systems Analysis Techniques Suitable for Detailed Studies Leading to Optimization

Simulation appears to be the most practical current technique to use in the present state of system design. Research on application of simulation methods is rapidly expanding. The Harvard Water Program has recently completed large-scale simulation models and associated computer programs for the Lehigh and Delaware River systems, using synthetic stream flow sequences and analysis of both physical and economic performance of the system.[24]

Simulation models approaching the scope and complexity of those of the Harvard Water Program have yet to be developed and tested for actual planning situations. Large-scale simulation models have been constructed and used by the Corps of Engineers for planning the Columbia River system,[25] but they have been used to optimize a single output—hydro-power—and, unlike the Harvard models, have not combined synthetic streamflows, flood control operations, and cost and benefit analysis with a standard for routine simulation operation on a monthly basis. It is now timely to experiment with application of the more complex simulation techniques to actual planning situations throughout the country.

F. The System Design Process as a Whole

Finally, there is a class of research projects concerned with the water-resource system design process itself. This research deals with application of the principles of operations research, systems analysis, information theory, and production economics to define the major elements of the planning task and the content, depth and scope of the various studies and analyses required. It deals with planning theory that includes the concepts of optimization, decision-making

24. Hufschmidt & Fiering, *op. cit. supra* note 21.

25. See Lewis & Shoemaker, *Hydro System Power Analysis by Digital Computer*, 128 Transactions Am. Soc. Civil Engineers 1074 (1963).

under uncertainty, dynamic planning, linkages, feedback, cost, benefits, and production functions. It takes account of the continuing nature of planning and the relation of water-resource planning to planning for other types of public investment and to regional planning in general. Research in this important field can be approached in two ways:

(1) Selection of typical water-resource systems as test areas and developing the strategy and tactics for preparing a plan, from statement of theory through development of the plan and schedule of work to the selection of techniques to be applied. A number of typical systems should be examined, ranging from the large-scale complex river systems being studied by federal agencies, to smaller systems being studied by state and local agencies; included here would be small watershed systems, and, possibly, single-purpose water supply schemes. Some systems should involve combinations of regulatory and management measures, in addition to the conventional water storage and control works; some should have combinations of ground water and surface water management problems; some should be concerned with arid-zone situations typical of the West, while others should deal with water use situations in heavily industrialized areas of the East.

The object of such research would not be to design a system, but rather to gain an understanding of the process involved in such design.

(2) The second approach would be that of conducting case studies and evaluations of actual water-resource planning operations to provide a basis for policy recommendations for future planning. A number of such studies and evaluations have already been undertaken, primarily from the standpoint of administration; others are currently under way.[26] But more studies of this type should be undertaken, including the major river-basin planning ac-

26. Previous studies include Fox & Picken, The Upstream-Downstream Controversy in the Arkansas-White-Red Basins Survey (Inter-University Case Program Series No. 35, Univ. of Ala. 1960); Pealy, Comprehensive River Basin Planning: The Arkansas-White-Red Basins Inter-Agency Committee Experience (Governmental Studies No. 37, Univ. of Mich. 1959), and Pealy, Organization for Comprehensive River Basin Planning: The Texas and Southeast Experiences (Governmental Studies No. 46, Univ. of Mich. 1964). Performance of the Southeast River Basins Commission was evaluated at a conference held at Georgia Institute of Technology in November 1963. See Organization and Methodology for River Basin Planning (Ga. Inst. Tech. 1964). In his paper in this symposium, Kneese mentions RFF-sponsored case studies under way for the Potomac and Miami River basins.

tivities led by federal agencies and the smaller watershed planning operations being conducted by states and local groups. Some water-resource research centers can perhaps function as participant-observers in such research by helping with the planning as well as observing performance.

CONCLUSION

The preceding list of research topics on comprehensive planning is far from exhaustive. Many items of research dealing with specific physical, economic and social aspects of water resources are obviously related to planning and would be included in a more complete listing. For example, studies on the legal and institutional aspects of water management, including those on the water quality and irrigation water transfer mentioned by Kneese, have implications for planning. Those concerned with developing and evaluating research programs will find it useful to analyze research topics from the standpoint of their relation to the process of comprehensive planning as set forth in this paper.