Systems Approach to Water Resources Management

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Abstract Water resources management is mostly executed in a complex environment consisting of several subsystems related to water, economy, ecology and legislative as well as administrative structure. The formulation of a water resources problem within a systems analytical approach requires a set of definitions which are given in this paper.

In general five elements including input, state, output, state transition and objective function are necessary to describe a system. Often it is grouped into desirable, undesirable output. This requires a set of predefined goals, objectives to evaluate the output with respect to its degree of goal attainment. Finally, some examples are given to demonstrate the methodology and some basic mathematical expressions are elaborated to enable the formal description of a system.

1. Introduction and Problem Definition

The formulation of a water resources decision/management problem within a system analytical approach requires a set of definitions. Here one of the possible methods, the state space approach is described briefly including the five elements such as input, state, output, state transition and output function. In order to evaluate the output, preferences have to be specified either by identifying a goal point or an aspiration level or requirements which should be met in any case. The terms goal, attributes, criteria and constraints are described. Definitions of decision space and objective space are given.

Since the early sixties (Maass et al., 1962) serious attempts have been made to redefine the water resources development problems within the framework of systems analytical concepts. The analysis of the problems within this context implies the introduction of new terms and terminology as well as requiring the formulation of goals and aspirations to fit the new approach. The most important conceptual details will be introduced along with the definition of the most essential terms. Systems analysis being a 'young' scientific discipline with wide applications in resource management is certainly prone to diverging interpretations. Therefore the definitions presented here do not claim universal acceptance. Rather, they follow the mainstream interpretations widely accepted and used in the field of water resources management.

In general it can be said that 'water resources management' consists of the following major steps:

Assessment:	- of Water Resources
-	Uses, Needs, Future Demands
-	Disasters
-	Financial Capabilities and Constraints
-	Technical Options
-	etc.
Planning:	- Siting, Scaling, Sizing, Selecting, Sequencing,
Design:	- Structural design, Costing, Tender documents
Implementation:	- Construction, Supervision
-	Enforcement of Laws
Operation:	- Monitoring and Regulating of System Performance
Maintenance:	- Control, Repair, Replacement

2. Systems

The term 'system ' is freqeuntly used with quite different meanings. To give some examples we speak about a groundwater system, or a river system or a sewage system etc. These examples have in common that only a part of the real world is being considered for a specific problem. In modern water resources management the framework for evaluation and deciion making is being widened including economic, ecological and social objectives. Therefore we often face a problem consisting of several subsystems which are linked through the decisions being made. The planning, design and implementation of a reservoir is not only a problem of hydraulic engineers because the scheme should serve purposes like flood protection, it should perhaps support irrigation and /or recreation and has therefore a broad range of longlasting impacts.

Sometimes a single decision is taken like to build a reservoir but the most frequent case is that a series of actions, decision is required to develope and operate a scheme.While a system in not related to any specific size, purpose or context, there are obvious limitations, applied to identify a system. By using adjectives like social, natural, environmental, legal, or production the essence of the system considered becomes evident. Moreover these systems are not only limited by their scope but also by our ability to grasp, identify and last but not least to characterize the interrelationships among the elements involved. By focusing only on the most essential, or readily quantifiable interactions the system derived becomes itself a model of reality.

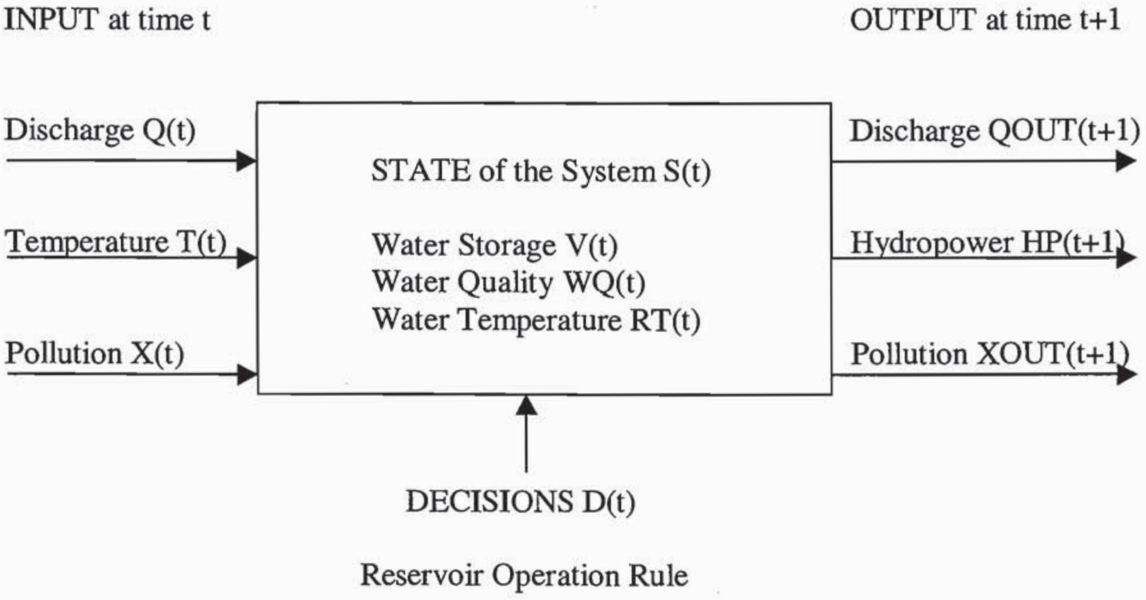

Fig. 1 System elements for a single reservoir example

As it is seen, the system is 'carved out' of its environment. Inputs and outputs substitute the severed interactions between elements of the defined system and elements left outside. In the dynamic case there will be a sequence of such blocks where the state at time t will define together with the decision taken at time t the state in the next time period. Of course there may be also a feedback loop which means that an output may influence the next decision step. It is obvious, that this setup implies the factor 'time' in order to accommodate the time lag necessary for the feedback and corresponding adaptation, thus indicating the very dynamic nature of the system.

From the point of view of the system analyst both inputs and outputs can be classified into different subsets. While the controlled and partially controllable inputs are described by **decision variables**, the uncontrolled input influence the state of the system without being subject to any direct influence. The set of feasible realizations of decision variables constitutes the **decision space.**

On the output side desirable and undesirable outputs are of particular interest. It is aimed to maximize the desirable and/or minimize the undesirable output while selecting the course of decision (by assigning numerical values to the decision variables).

The transformation of the system due to both decision variables and uncontrolled input are described by a set of variables called **state variables**, while the system response behaviour (rate of change of the state variables due to variable inputs) is characterized by

system parameters.

As equivalent of the general terms, described previously the following list can be compiled without providing an exhaustive set.

Inputs D:	controlled:	- costs allocated for construction, operation and maintenance
	partially controlled:	- reservoir releases (spilling might occur)
I:	uncontrolled:	- precipitation (streamflows) depending on whether the watershed response is included in the model or not
Outputs O:	desirable:	- water utilization (benefits)
	undesirable:	- water deficiencies, floods (losses)
	neutral:	- system outflow, seepage, percola tion, evaporation etc.
State variables S:		- reservoir volumes in timestep t
	-	soil moisture in timestep t
	-	vegetation cover in timestep t
	-	(winter, summer)
System parameters:		reservoir capacities, slopes, soils, runoff coefficient, (e.g. K and n, parameters of a linear reservoir cascade model for rainfall/runoff modeling or streamflow routing)

While a hydro-minded engineer would almost be satisfied with this system, water resources management is not left alone to them. In fact, just a slice pulled out horzontally from a tall 'pie' of different disciplines (subsystems) has been displayed.

Further, we have to add two more elements from systems analysis, namely the output function and the state transition function. An output function relates the output O (it is used as a vector) to the state S and the Input I:

$$\mathbf{O(t+1)= F(S(t); I(t), D(t))} \quad (1)$$

While the state transition function describes the dynamic behaviour of the system:

$$\mathbf{S(t+1)=G(S(t); I(t),D(t))} \quad (2)$$

These two function represent the models which are generally apllied in water management. For the case of reservoir operation the output function may constitute the reservoir operation rule like

$$\begin{array}{ll} Qout(t)=Qin(t) & \text{for } Qmin<Qin<Qmaxtol \\ Qout(t)=Qmaxtol & \text{for } Qin(t)>Qmaxtol \\ Qout(t)=Qmin & \text{for } Qin(t)<Qmin \end{array} \qquad (3)$$

While the state transition function is defined by the water balance equation

$$S(t+1)=S(t) + Qin(t)*1 - Qou(t)*1 \qquad (4)$$

The symbol ‘1’ stand here only to consider the time interval.

3 Goals, objectives

Each plan, either for design or for operation, is based on goals and objectives. The difference between these two terms is not clerly defined. Goals may rather be defined by a clear target while an objective indicates rather a direction of developement.

Objectives indicate the directions of state change of a system desired by the decision maker(s). They reflect the aspirations of whoever is providing the value structure and as such indicate the directions sought (Armijo, 1981; Hwang & Yoon, 1981; Tecle et al, 1987a). There are three possible ways to improve an objective:

maximizing it,
minimizing it or
maintaining it at an existing position.

The first two are self-evident. An example of the third situation would be a farmer wishing to maintain a constant supply of water to a field where both an excess or deficient amount of water will adversely affect output. Another viewpoint is to consider five types of "aspirations", which are objectives over a range: near a target, greater than a threshold, less than a threshold, inside of an interval, outside of an interval. Extended definitions of objectives with respect to these concepts are available in references such as Monarchi et al. (1973) Keeney and Raiffa (1976), Zeleny (1982), Osyczka (1984), Tecle et al. (1987a), Bogardi and Duckstein (1992).

Another aspect of an objective which needs to be raised at this point has to do with its generation. There is substantial information on the process in the literature, for example, in Manheim and Hall (1968), MacCrimmon (1969), Keeney and Raiffa (1976) and Wymore (1992). Approaches include:

- examination of relevant literature to see how others have been modeling on the same kind of problem,
- analytical study of the problem and
- casual empiricism as explained in Keeney and Raiffa (1976). The analytical approach suggests that by building a model of the system under consideration and

identifying the relevant input and output variables, the appropriate objectives for the problem will crystallize. The casual empiricism approach, on the other hand, suggests observing people to see how, in fact, they are presently making decisions relevant to the given problem. Any one of these approaches can help in generating objectives and a combination may help even further.

The process of modeling and solving a problem with two or more noncommensurable and conflicting objectives is known in the literature as multiobjective decision making (MODM). Objectives are noncommensurable if their level of attainment, with respect to given attributes cannot be measured in common units (Szidarovszky et al., 1978; Duckstein & Opricovic, 1980; Duckstein & Gershon, 1983; Tecle & Duckstein, 1989). Objectives are conflicting if an increase in the level of one objective can only be achieved by decreasing the attainment level of another objective (Gershon, 1981b; Steuer, 1986; Szidarovszky et al., 1986). Usually, a conflict arises when the attainment of each objective in a problem requires the shared use of limited available resources (Fraser & Hipel, 1984; 1988; 1989). Examples of objectives are optimization of economic payoff, environmental quality, water supply, water quality and mitigation of natural and man-made hazards.

3.1 Attributes

These refer to the characteristics, factors, qualities, performance indices or parameters of alternative management schemes or other decision processes. An attribute should provide a means for evaluating the levels of an objective; as such, it is defined here as a measurable aspect of judgement by which a dimension of the various decision variables or alternative management schemes under consideration can be characterized. This characterization, in turn, is made possible through determination of at least one empirical indicator (dissolved salt concentration) for each attribute (water quality). Then, to make the measurement complete, scales are constructed one for each attribute in the form of a set of estimates with an order relation.

According to Ozernoy and Gaft (1977), the choice of scale type depends on the technique of measurement to be used and on the magnitude of the properties being measured. Then, depending on the desired accuracy of measurement, values are determined for the magnitude characterized by the empirical indicator and these values need to be in the region of feasible estimates (Ozernoy, 1985). In model-based mathematical system theory, a distinction is made between performance indices (or attributes) such as reliability, and resource indices, such as money or land (Wymore 1976, 1992).

A decision analysis problem consisting of more than two attributes is known as a multiattribute decision problem and may be solved using a multiattribute decision making (MADM) procedure. The procedure involves the selection of the "best" alternative course of action from a given number of alternatives described in terms of their attributes. This kind of methodology is illustrated in Gershon and Duckstein (1983), Duckstein and Bogardi (1987), Tecle et al. (1987a, b). Examples of attributes are flood damages sediment yield, nitrate concentration.

3.2 Criteria

The dictionary meaning of criteria is standards, rules or tests on which iudgements or decisions can be based. In decision making theory, however, a criterion may represent either an attribute or an objective. In this sense, a multicriterion decision problem means either a multiattribute or a multiobjective decision problem or both. Multicriterion decision making (MCDM) is, therefore, used to indicate the general field of study which includes decision making in the presence of two or more conflicting objectives and/or decision analysis processes involving two or more attributes.

3.3 Decision variables, alternative schemes and parameters

Decision variables are the vehicles used to specify decisions made by a decision maker (DM). In mathematical programming, they represent the numerical variables whose values are to be determined and are denoted by x_j, j = l, ... , J. The symbol x_j is a j = l, ... , J decision variable representing the j^{th} quantity within a set of J quantities, for example, water release from a reservoir at a given time j = l, ... , J.

In mathematical programming problems, variables are usually assumed to be nonnegative. In most cases these decision variables are continuous and also assumed to have implicit upper boundaries. In problems involving mixed numerical and non-numerical data, the different objectives can only be approached using a set of discrete alternative actions. The members of this set are carefully selected by considering all important, relevant information on the problem and its objectives and the alternative actions themselves (Gershon et al., 1982). Different ways of selecting alternatives are presented in Jantsch (1967) and Ozernoy (1983, 1985, 1987). If too many alternatives are made available in the process, then some sort of filtering or screening mechanisms such as ELECTRE I (Benayoun et al., 1966; Gershon et al., 1982; Tecle 1988; Tecle & Duckstein, 1990) and exclusionary screening (Hobbs, 1979; Goicoechea et al., 1982) can be used to eliminate the dominated alternatives. Once the selection process for the set of alternatives to be considered is complete, a one to one relationship between the alternatives and the criteria of the problem under consideration is developed using some measurement scales (Rietveld, 1980; Voogd, 1983; Tecle, 1986). The information consisting of criteria, alternatives and measurement scales is then used to construct an evaluation matrix of criteria versus alternatives, upon which MCDM solution techniques are applied in order to select the "best" alternative possible plan(s). This concept has been extensively developed in many case studies such as in Voogd, 1983; Tecle et al., 1988a,b to mention a few.

During the problem formulation stage of the mathematical decision process, one should decide which quantities are to be treated as decision variables and which ones are to be taken as fixed. The quantities whose values are fixed are called parameters. These quantities remain relatively fixed because the values are either objectively assigned and we are not at liberty to change them or we have learned from experience that particular values of the respective quantities always give good results, leaving us with no reason to treat such quantities as decision variables. In any case, mathematical relationships between the decision variables and the parameters constitute a major part of the problem formulation stage of the decision analysis process.

3.4 Constraints

These are restrictions on attributes and decision variables which may or may not be expressed mathematically. They are usually dictated by such factors as environment, physical processes, economics, cultural, legal and/or resources aspects which must be satisfied in order to produce an acceptable solution. In mathematical form, constraints describe dependencies between decision variables and parameters, and may be stated in the form of equalities (mass balance), inequalities (resources constraints) or probabilistic statements (reliability constraints).

3.5 Decision space and objective space

A multicriterion programming problem can be represented in a vectorial notation as:

"Satisfice" $f(\underline{x}) = (f_1(\underline{x}), f_2(\underline{x}), \ldots, f_I(\underline{x}))$ (5)

Subject to $g_k(\underline{x}) \leq 0, \; k = 1, 2, \ldots, K$ (6)

$x_j > 0, \quad j = 1,2,\ldots,J$ (7)

Here there are I objective functions $f_i(\underline{x})$, each of which is to be "satisficed" subject to the constraint sets (6) and (7). The region defined by this constraint set is referred to as the feasible region in the J-dimensional decision space. In this expression, the set of all J-tuples of the decision variable $\underline{x}$, denoted by X forms a convex subset of a finite J-dimensional Euclidian space; in many other applications X is defined to be discrete (Zionts, 1981; Voogd, 1981, 1983; Szidarovszky et al., 1986). In the further special case when X is finite, then the most satisficing alternative plan has to be selected from that finite set X. It is important to note at this point that the word "optimum" which includes both the maximization of desired outcomes and minimization of adverse criteria is replaced by the word "satisfactum" and "optimize" is replaced by "satisfice" in this discussion. The reason is that when dealing with two or more conflicting objectives one cannot, in general, optimize all the objectives simultaneously as an increase in one objective usually results in a decrease of the other(s). In such circumstances trade offs between the objectives are made in order to reach solutions that are not simultaneously optimum but still acceptable to the DM with respect to each objective (Cohon et al., 1979; Gershon, 1981a; Goicoechea et al. 1982; Bogardi et al., 1984; Roy, 1985; Szidarovszky et al. 1986).

In a mathematical programming problem such as the one defined by Eqs. (5-7), the vector of decision variables X and the vector of the objective functions f(x) define two different Euclidian spaces. These are
the J-dimensional space of the decision variables in which each coordinate axis corresponds to a component of vector X, and
the I-dimensional space F of the objective functions in which each coordinate axis corresponds to a component of vector f(x). Every point in the first space represents a solution and gives a certain point in the second space which determines the quality of that solution in terms of the values of the objective functions. This is made possible through a mapping of the feasible region in the decision space X into the feasible region in the objective space F, using the I-dimensional objective function.

The definition and concepts given above can be easily understood with the help of a simple continuous example. For this purpose, consider the following bicriterion and bivariate linear problem.

max. $f_1(x) = 2x1 - x_2$
max. $f_2(x) = -x1 + 3x_2$

subject to	$g_1(x)$:	x_1	+	x_2	$\leq$	10
	$g_2(x)$:	x_1			$\leq$	7
	$g_3(x)$:			x_2	$\leq$	6
	$g_4(x)$:	$-x_1$	+	x_2	$\leq$	4
	$g_5(x)$:	$-x_1$			$\leq$	0
	$g_6(x)$:		-	x_2	$\leq$	0

The feasible region in the decision space X of this problem is shown in Fig. 2. It is the space bounded by all the relevant constraints, that is, any point x in the feasible region satisfies these constraints. On the other hand, any constraint whose boundary does not intersect the feasible space is redundant.

The feasible region in the objective or payoff space f(x) is a transformation of the feasible decision space and is determined by enumeration of all the extreme points and subsequent computation of the value of each objective function at each of the corner solutions as shown in Fig. 3 This figure illustrates how the nondominated set can be identified in this feasible region. To find a final satisficing solution, an interaction between the analyst and decision maker is required. Possible mechanisms for this interaction are provided next.

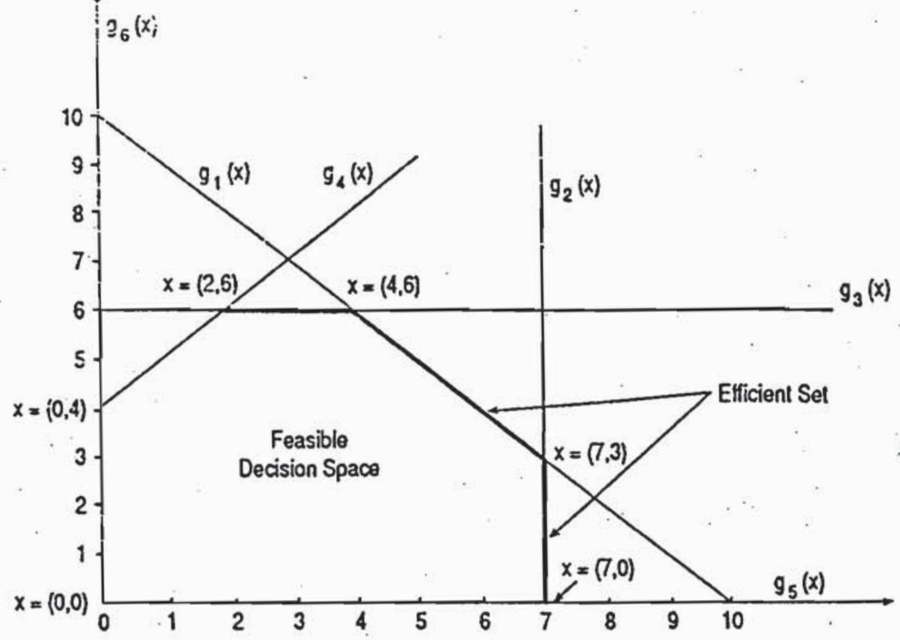

FIG. 3.1 Feasible decision space.

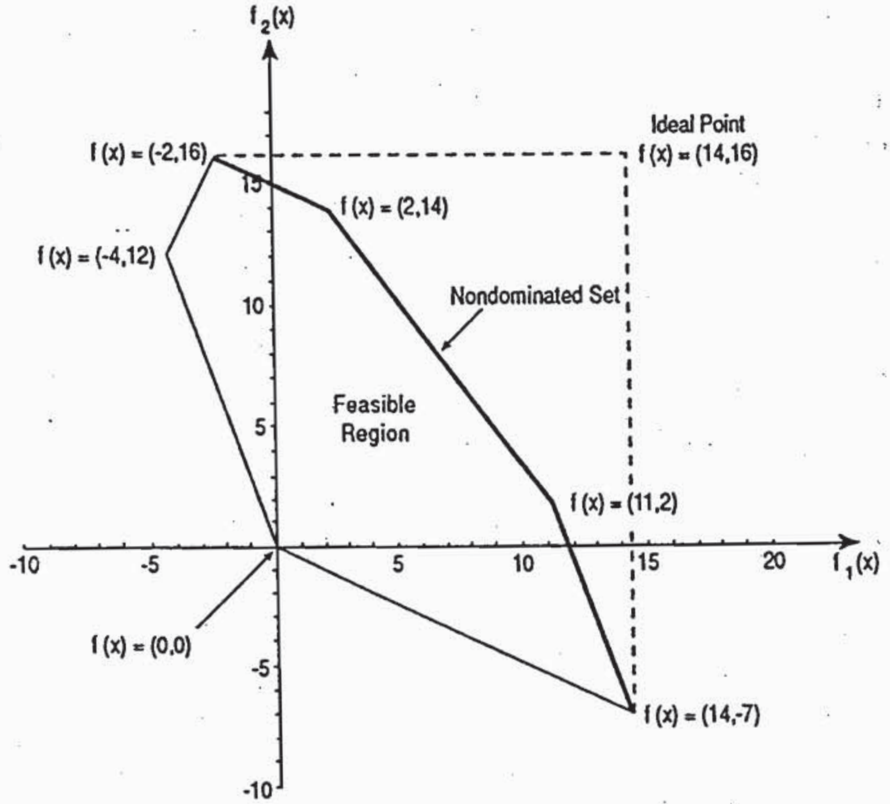

FIG. 3.2 Feasible region of objective functions, or payoff space.

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