9 Performance Criteria

Water resource systems typically provide a variety of economic, environmental, and ecological services. They also serve a variety of purposes (e.g., water supply, flood protection, hydropower production, navigation, recreation, and waste assimilation and transport). Performance criteria provide measures of just how well a plan or management policy performs. There are a variety of criteria one can use to judge and compare alternative system performances. Some of these performance criteria may be conflicting. In these cases tradeoffs exist among conflicting criteria and these tradeoffs should be considered when searching for the best compromise. This chapter presents ways of identifying and working with these performance criteria in the political process of selecting the best decision.

9.1 Introduction

Decision-makers and those who influence them are people, and people's opinions and experiences and goals may differ. These differences force one to think in terms of tradeoffs. Decisions in water resources management inevitably involve making tradeoffs among competing opportunities, goals or objectives. One of the tasks of water resource system planners or managers involved in evaluating alternative designs and management plans or policies is to identify the tradeoffs, if any, among competing opportunities, goals or objectives. It is then up to the largely political process involving all interested stakeholders to find the best compromise decision.

If every system performance measure or objective could be expressed in the same units, and if there was only one decision-maker and one objective or goal, then decision-making would be relatively straight forward. Such is not the case when dealing with the public's water resources.

A cost-benefit framework, used for many decades in water resources planning and management, converted the different types of impacts into a single monetary metric. Once that was done, the task was to find the plan or policy that maximized the net benefits, i.e., the benefits less the costs. If the maximum difference between benefits and costs was positive, that was the best plan or policy. But not all system performance criteria we consider today can be easily expressed in monetary units. Even if monetary units could be used for each objective, that in itself does not address the distributional issues involving who benefits and who pays and by how much. While all stakeholders may agree that maximizing total net benefits is a desirable objective, not everyone, if indeed anyone, will likely agree on to how best to allocate or share those net benefits among them.

Clearly, water resource planning and management takes place in a multiple criteria environment. A key element of many problems facing designers and managers is the need to deal explicitly with multiple ecological, economical, and social impacts, expressed in multiple metrics that may result from the design, management,

D.P. Loucks and E. van Beek, *Water Resource Systems Planning and Management*,
DOI 10.1007/978-3-319-44234-1_9

and operation of water resource systems. Approaches that fail to recognize and explicitly include ways of handling conflict among multiple system performance measures and objectives and among multiple stakeholders are not likely to be very useful (Hipel et al. 2015).

Successful decision-making involves creating a consensus among multiple participants in the planning and management process. These include stakeholders—individuals or interest groups who have an interest in the outcome of any management plan or policy. The relatively recent acknowledgement that stakeholders need to be fully included in the decision-making processes only complicates the life of professional planners and managers. Increasingly important sources of information come from discussion groups, public hearings, negotiations, and dispute-resolution processes. Using the types of modeling methods discussed in this chapter can potentially inform the debates that occur in these meetings. In addition, the application of game theory may be helpful in reaching a consensus among stakeholders having different objectives and desires (Madani 2010; Madani and Hipel 2011).

Eventually someone or some organization must make a decision. Even if water resource analysts view their job as one of providing options or tradeoffs for someone else to consider, even they are making decisions that define or limit the range of those options or tradeoffs. The importance of making informed effective decisions applies to everyone.

9.2 Informed Decision-Making

Informed decision-making involves both, qualitative thinking and analysis as well as quantitative modeling (Hammond et al. 1999). Qualitative thinking and analysis typically follows quantitative analyses. Qualitative analyses are useful for identifying

- the real objectives of concern to all stakeholders (which may be other than those expressed by them),
- the likelihoods of events for which decisions are needed,
- the socially acceptable alternatives that address and meet each objective, and
- the key tradeoffs among all interests and objectives involved.

When the objectives and general alternative ways of meeting these objectives are not well defined, no amount of quantitative modeling and analysis will make up for this weakness. The identification of objectives and general alternatives are the foundation upon which water resource managers can develop appropriate quantitative models. These models will provide additional insight and definition of alternatives and their expected impacts. Models cannot identify new ideas or so called ‘out-of-the-box’ alternatives that no one has thought of before. Neither can they identify the best criteria that should be considered in specific cases. Only our minds can do this, individually, and then collectively.

For example, periodic municipal water supply shortages might be reduced by increasing surface water reservoir storage capacity or by increasing groundwater pumping. Assuming the objective in this case is to increase the reliability of some specified level of water supply, models can be developed to identify the tradeoffs between the cost of increased reservoir storage and pumping capacities and the increased reliability of meeting the supply target. However these models will not identify and evaluate completely different alternatives, such as importing water by trucks or the use of canals or pipelines from other river basins, implementing water use restrictions, or water reuse, unless of course those options are included in those models. Someone has to think of these general alternatives before models can help identify just how many trucks or the capacities of canals or pipes or how to best implement water reuse and for what uses.

Time needs to be taken to identify the relevant objectives and general alternatives that then can be included in quantitative analyses. Clearly some preliminary screening of general alternatives is and should be carried out at the qualitative level, but the alternatives that remain (assuming the best is not obvious) should then be further analyzed using quantitative modeling methods. This includes the methods of quantifying qualitative objectives and constraints discussed in Chap. 5.

Being creative in the identification of possible objectives and general alternatives is helped by addressing the following questions: What is an ideal decision? What does each stakeholder think other stakeholders' ideal decisions would be? What is to be avoided? What makes a great alternative, even an infeasible one, so great? What makes a terrible alternative so terrible? How would each individual's best alternative be justified to someone else? When each manager and stakeholder has gone through such thinking, the combined set of responses may be more comprehensive and less limited by what others say or believe. They can become a basis for group discussions and consensus building.

General statements defining objectives can be converted to ones that are short and include the words maximize or minimize. For example, minimize cost, maximize net benefits, maximize reliability, maximize water quality, maximize ecosystem biodiversity, minimize construction time, or minimize the maximum deviations from some target storage volume or a target water allocation. Economic, environmental, ecological, and purely physical objectives such as these are able to become the objective functions that drive the solutions of optimization models, as illustrated in many of the previous chapters. Social objectives should also be considered. Examples might include maximize employment, maximize interagency coordination, maximize stakeholder participation, and minimize legal liability and the potential of future legal action and costs.

Quantitative modeling is employed to identify more precisely the design and operation of structural and nonstructural alternatives that best satisfy system performance criteria, and the impacts and tradeoffs among these various performance criteria. Once such analyses have been performed, it is always wise to question whether or not the results are reasonable. Are they as expected? If not, why not? If the results are surprising, are the analyses providing new knowledge and understanding or have errors been made? How sensitive are the results to various assumptions with respect to the input data and models themselves?

Thus the modeling process ends with some more qualitative study. Models do not replace human judgment. Humans, not quantitative models, are responsible for water resources planning and management decisions as well as the decision-making process itself that identifies performance criteria and general alternatives.

9.3 Performance Criteria and General Alternatives

There is a way to identify performance criteria that matter most to stakeholders (Gregory and Keeney 1994). One can begin with very broad fundamental goals, such as public health, national as well as individual security, economic development, happiness, and general wellbeing. Almost anyone would include these as worthy objectives. Just how these goals are to be met can be expressed by a host of other more specific objectives or criteria.

By asking "how" any specified broad fundamental criterion or objective can be achieved usually leads, eventually, to more specific system performance criteria or objectives and to the means of improving these criteria, i.e., to the general system design and operating policy alternatives themselves. As one gets further from the fundamental objective that most will agree to, there is a greater chance of stakeholder disagreement. For example we might answer the question "How can we maximize public health?" by suggesting the maximization of surface and groundwater water quality. How? By minimizing wastewater discharges into surface water bodies and groundwater aquifers. How? By minimizing wastewater production, or by maximizing removal rates at wastewater treatment facilities, or by minimizing the concentrations of pollutants in runoff or by increasing downstream flow augmentation from upstream reservoirs or by a combination of flow augmentation and wastewater treatment. How? By increasing reservoir storage capacity and subsequent releases upstream and by upgrading wastewater treatment to a tertiary level. And so on.

Each 'how' question can have multiple answers. This can lead to a tree of branches, each branch representing a different and more specific performance criterion or an alternative way to accomplish a higher level objective. In the example just illustrated, the answer to how to improve water quality might include a combination of water and wastewater treatment, flow augmentation, improved wastewater collection systems and reduced applications of fertilizers and pesticides on land to reduce nonpoint source pollutant discharges. There are others. If the lower level objective of minimizing point source discharges had been the first objective considered, many of those other alternatives may not have been identified. The more fundamental the objective, the greater will be the range of alternatives that might be considered.

If any of the alternatives identified for meeting some objective are not considered desirable, it is a good sign that there are other objectives that should be considered. For example, if flow augmentation is not desired, it could mean that in addition to water quality considerations, the regime of water flows, or the existing uses of the water are also being considered and flow augmentation may detract from those other objectives. If a stakeholder has trouble explaining why some alternative will not work, it is a possible sign there are other objectives and alternatives waiting to be identified and evaluated. What are they? Get them identified. Consider them along with the others that have been already defined.

More fundamental objectives can be identified by asking the question "why?" Answers to the question "why?" will lead one back to increasingly more fundamental objectives. A fundamental objective is reached when the only answer to why is "it is what everyone really wants" or something similar. Thinking hard about "why" will help clarify what is considered most important.

9.3.1 Constraints on Decisions

Constraints limit alternatives. There are some laws of physics that obviously we cannot change. Water will naturally flow downhill unless of course we pump it uphill. Society can limit what can be done to satisfy any performance criterion as well, but it is not the time to worry about them during the process of objective and general alternative identification. Be creative, and don not get stuck in the status quo, i.e., carrying on as usual or depending on a default (and often politically risk-free) alternative. It may turn out these default or risk-free alternatives are the best alternatives, but that can be determined later. When performing qualitative exercises to identify objectives and general alternatives enlarge the number of options and think creatively. If something seems really worth further consideration, then assume it can happen. If it is really worth it, engineers can do it. Lawyers can change laws. Society can and will want to adapt—again if it is really important.

Consider for example the water that is pumped uphill at all pumped storage hydroelectric facilities, or the changing objectives over time related to managing water and ecosystems in the Mekong, Rhine and Senegal Rivers, or in the Great Lakes, the Sacramento-San Joaquin Delta, and Florida Everglades regions in the US.

There are other traps to avoid in the planning and management process. Do not become anchored to any initial feasible or best-case or worst-case scenario. Be creative when identifying scenarios. Consider the whole spectrum of possible events that your decision responds to. Do not focus solely on extreme events to the exclusion of the more likely events. While toxic spills and floods bring headlines, and suffering, they are not the usual more routine events that one must also plan for.

It is tempting to consider past or sunk costs when determining where additional investments should be made. If past investments were a mistake, it is only our egos that motivate us to justify those past investments by spending more money on them instead of taking more effective actions.

Finally, target values of objectives and goals should not be set too low (easy to meet). The chances of finding good unconventional alternatives are increased if targets are set high, even beyond reach. High aspirations often force individuals to think in entirely new ways. Politically it may end up that only marginal changes to the status quo will be acceptable, but it is not the time to worry about that when identifying objectives and general alternatives.

9.3.2 Tradeoffs Among Performance Criteria

Tradeoffs are inevitable when there are conflicting multiple objectives, and multiple objectives are inevitable when there are many stakeholders or participants in the planning and management process. We all want clean water in our aquifers, lakes, rivers and streams, but if it costs money to achieve that desired quality there are other activities or projects involving education, health care, security, or even other environmental restoration or pollution prevention and reduction efforts, that compete for those same, and often limited, amounts of money.

Tradeoffs arise because we all want more of good things, and many of these good things are conflicting. We cannot have cleaner water in our homes or in our environment without spending money, and minimizing costs is always worthy of consideration. Identifying these tradeoffs is one of the tasks of qualitative as well as quantitative analyses. Qualitatively we can identify what the tradeoffs will involve, e.g., cleaner water in our streams and rivers require increased costs. Just how much money it will cost to increase the minimum dissolved oxygen concentration in a specific lake by 3, or 4, or 5 mg/l is the task of quantitative analyses.

Finding a balance among all conflicting performance criteria characterizes water management decision-making. Understanding the technical information that identifies the efficient or nondominated tradeoffs is obviously helpful. Yet if the technical information fails to address the real objectives or system performance measures of interest to stakeholders, significant time and resources can be wasted in the discussions that take place in stakeholder meetings, as well as in the analyses that are performed in technical studies.

Finding the best compromise among competing decisions is a political or social process. The process is helped by having available the tradeoffs among competing objectives. Models that can identify these tradeoffs among quantitative objectives cannot go the next step, i.e., identify the best compromise decision. While models can help identify and evaluate alternatives, they cannot take the place of human judgments that are needed to make the final decision—the selection of the best tradeoffs.

Models can help identify nondominated tradeoffs among competing objectives or system performance indicators. These are sometimes called efficient tradeoffs. Efficient decisions are those that cannot be altered so as to gain more of one objective without worsening one or more other objective values. If one of multiple conflicting objective values is to be improved, some worsening of one or more other objective values will likely be necessary. Dominated or so called inferior decisions are those in which it is possible to improve at least one objective value without worsening any of the others.

Many will argue that these dominated decisions can be eliminated from further considerations, since why would any rational individual prefer such decisions when there are better ones available with respect to all the objectives being considered. However, some may consider a quantitatively nondominated or efficient solution inferior and dominated with respect to one or more other objectives that were omitted from the analysis. Eliminating inferior or dominated alternatives from the political decision-making process may not always be very helpful. One of these inferior alternatives could be viewed as the best by some who are considering other criteria either not included or, in their opinions, not properly quantified in such analyses.

Tradeoffs exist not only among conflicting outcome objectives, system performance indicators, or impacts. Tradeoffs can also exist among alternative processes of decision-making. Some of the most important objectives—and toughest tradeoffs—involve process decisions that establish *how* a decision is going to be made. What is, for example, the best use of time and financial resources in performing a quantitative modeling study, who should be involved in such a study, who should be advising such a study, and how should stakeholders be involved? Such questions often lie at the heart of water and other resource use disputes and can significantly influence the trust and cooperation among all who participate in the process. They can also influence the willingness of stakeholders to support any final decision or selected management policy or plan.

9.4 Quantifying Performance Criteria

So far this chapter has focused on the critical qualitative aspects of identifying objectives and general alternatives. The remainder of this chapter will focus on quantifying various criteria and how to use them to compare various alternatives and to identify the tradeoffs among them. What is important here, however, is to realize that considerable effort is worth spending on getting the general objectives and alternatives right before spending any time on their quantification. There are no quantitative aids for this, just hard thinking, perhaps keeping in mine some of the advice just presented.

Quantification of an objective is the adoption of some quantitative (numerical) scale that provides an indicator for how well the objective would be achieved. For example, one of the objectives of a watershed conservation program might be protection or preservation of wildlife. In order to rank how various plans meet this objective, a numerical criterion is needed, such as acres of preserved habitat or populations of key wildlife species.

Quantification does not require that all objectives be described in comparable units. The same watershed conservation program could have a flood control objective quantified as the height of the protected flood stage. It could have a regional development objective quantified as increased income. Quantification does not require that monetary costs and benefits be assigned to all objectives.

The following subsections review various economic, environmental, ecological, and social criteria.

9.4.1 Economic Criteria

Water resource system development and management is often motivated by economic criteria. It goes without saying that money is important; it's completing uses often makes it a limiting resource Most reservoirs, canals, hydropower facilities, groundwater-pumping systems, locks, and flood control structures have been built and are operated for economic reasons. The benefits and costs of such infrastructure can be expressed in monetary units. Typical objectives have been either to maximize the present value of the net benefits (total benefits less the costs) or minimize the costs of providing some purpose or service. To achieve the former involves benefit-cost analyses and to achieve the latter involves cost-effectiveness analyses.

Applied to water resources, maximization of net benefits requires the efficient and reliable allocation, over both time and space, of water (in its two dimensions: quantity and quality) to its many uses, including hydropower, recreation, water supply, flood control, navigation, irrigation, cooling, waste disposal and assimilation and habitat enhancement. The following example illustrates the maximization of net benefits from a multiple-purpose reservoir.

Consider a reservoir that can be used for irrigation and recreation. Irrigation and recreation are not very compatible. Recreation benefits are greater when reservoir elevations remain high throughout the summer recreation season, just when satisfying an irrigation demand that exceeds the inflow would normally cause a drop in the reservoir storage level. Thus the project has two conflicting purposes: provision of irrigation water and of recreation opportunities.

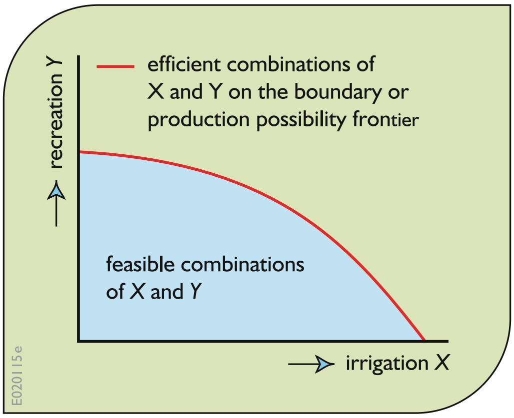


Fig. 9.1 A two-purpose planning problem showing the feasible and efficient combinations of irrigation water *X* and recreation visitor days *Y*

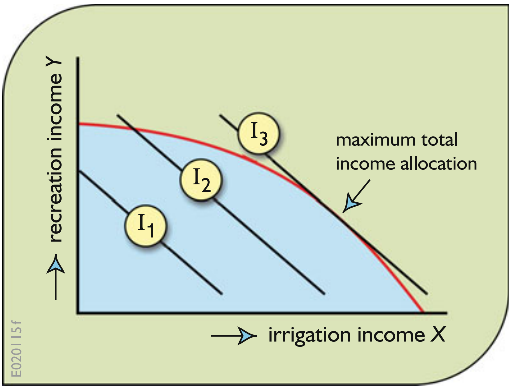


Fig. 9.2 Two-purpose project involving tradeoffs between irrigation and recreation income and various constant total income levels, $I_1 < I_2 < I_3$

Let *X* be the quantity of irrigation water to be delivered to farmers each year and *Y* the number of visitor days of recreation use on the reservoir. Possible levels of irrigation and recreation are shown in Fig. 9.1. The solid line in Fig. 9.1, termed the *production-possibility frontier* or *efficiency frontier,* is the boundary of the feasible combinations of *X* and *Y*.

Any combination of *X* and *Y* within the shaded blue area can be obtained by operation of the reservoir (i.e., by regulating the amount of water released for irrigation and other uses). Obviously the more of both *X* and *Y* the better. Thus attention generally focuses on the production-possibility frontier which comprises those combinations of *X* and *Y* that are on the frontier. They are said to be *technologically efficient* in the sense that more of either *X* or *Y* cannot be obtained without a decrease in the other. The shape and location of the production-possibility frontier is determined by the quantity of available resources (water, reservoir storage capacity, recreation facilities, etc.) and their ability to satisfy various demands for both *X* and *Y*.

Assume that a private entrepreneur owns this two-purpose reservoir in a competitive environment (i.e., there are a number of competing irrigation water suppliers and reservoir recreation sites). Let the unit market prices for irrigation water and recreation opportunities be p_X and p_Y, respectively. Also assume that the entrepreneur's costs are fixed and independent of *X* and *Y*. In this case the total income is

$$I = pxX + pyY \tag{9.1}$$

Values of *X* and *Y* that result in fixed income levels $I_1 < I_2 < I_3$ are plotted in Fig. 9.2. The value of *X* and *Y* that maximizes the entrepreneur's income is indicated by the point on the production-possibility frontier yielding an income of I_3. Incomes greater than I_3 are not possible.

Now assume the reservoir is owned and operated by a public agency and that competitive conditions prevail. The prices p_X and p_Y reflect the *value* of the irrigation water and recreation opportunities to the users. The aggregated value of the project is indicated by the user's *willingness to* pay for the irrigation and recreation outputs. In this case, this willingness to pay is $p_X X + p_Y Y$, which is equivalent to the entrepreneur's income. Private operation of the reservoir to maximize income or government operation to maximize user benefits both should, under competitive conditions, produce the same result.

When applied to water resources planning, benefit-cost analysis presumes a similarity between decision-making in the private and public sectors. It also assumes that the income resulting from the project is a reasonable surrogate for the project's social value.

9.4.1.1 Benefit and Cost Estimation

In a benefit-cost analysis, one may need to estimate the monetary value of irrigation water, shoreline property, land inundated by a lake, lake recreation, fishing opportunities, scenic vistas, hydropower production, navigation, or the loss of a wild river. The situations in which benefits and costs may need to be estimated are sometimes grouped into four categories, reflecting the way prices can be determined. These situations are

1. market prices exist and are an accurate reflection of marginal social values (i.e., marginal willingness to pay for all individuals). This situation often occurs in the presence of competitive market conditions. An example would be agricultural commodities that are not subsidized, i.e., do not have supported prices (some do exist!).
2. market prices exist but for various reasons do not reflect marginal social values. Examples include price-supported agricultural crops, labor that would otherwise be unemployed, or inputs whose production generates pollution, the economic and social cost of which is not included in its price.
3. market prices are essentially nonexistent, but for which it is possible to infer or determine what users or consumers would pay if a market existed. An example is outdoor recreation.
4. no real or simulated market-like process is easily conceived. This category may be relatively rare. Although scenic amenities and historic sites are often considered appropriate examples, both are sometimes privately owned and managed to generate income.

For the first three categories, benefits and costs can be measured as the *aggregate net willingness to pay of* those affected by the project. Assume, for example, that alternative water resources projects X_1, X_2, …, are being considered. Let $B(X_j)$ equal the amount beneficiaries of the plan X_j are willing to pay rather than forego the project. This represents the aggregate value of the project to the beneficiaries. Let $D(X_j)$ equal the amount the non-beneficiaries of plan X_j are willing to pay to prevent it from being implemented. This includes the social value of the resources that will be unavailable to society if project or plan X_j is implemented. The aggregate net willingness to pay $W(X_j)$ for plan X_j is equal to the difference between $B(X_j)$ and $D(X_j)$,

$$W\left(X_j\right) = B\left(X_j\right) - D\left(X_j\right) \tag{9.2}$$

Plans X_j can be ranked according to the aggregate net willingness to pay, $W(X_j)$. If, for example, $W(X_j) > W(X_k)$, it is inferred that plan X_j is preferable or superior to plan X_k.

One rationale for the willingness to pay criterion is that if $B(X_j) > D(X_j)$, the beneficiaries could compensate the losers and everyone would benefit from the project. However, this compensation rarely happens. There is usually no mechanism established for this compensation to be paid. Those who lose favorite scenic sites or the opportunity to use a wild river or who must hear the noise or breathe dirtier air or who suffer a loss in their property value because of the project are seldom compensated.

This compensation criterion also ignores the resultant income redistribution, which should be considered during the plan selection process. The compensation criterion implies that the marginal social value of income to all affected parties is the same. If a project's benefits accrue primarily to affluent individuals and the costs are borne by lower-income groups, $B(X)$ may be larger than $D(X)$ simply because the beneficiaries can pay more than the non-beneficiaries. It matters who benefits and who pays, i.e., who gets to eat the pie and how much of it as well as how big the pie is. Traditional benefit-cost analyses typically ignore these distributional issues.

In addition to these and other conceptual difficulties related to the willingness-to-pay criterion, practical measurement problems also exist. Many of the products of water resources plans are public or *collective goods*. This means that they are essentially indivisible, and once provided to any individual it is very difficult not to provide them to others. Collective goods often also have the property that their nonconsumptive use by one person does not prohibit or infringe upon their use by others.

Community flood protection is an example of a public good. Once protection is provided for one individual, it is often simultaneously provided for many others. As a result, it is not in an individual's self-interest to volunteer to help pay for the project by contributing an amount equal to his or her actual benefits if others are willing to pay for the project. However, if others are going to pay for the project (such as the taxpayers), individuals may exaggerate their own benefits to ensure that the project is undertaken.

Determining what benefits should be attributed to a project is not always simple and the required accounting can become rather involved. In a benefit-cost analysis, economic conditions should first be projected for a base case in which no project is implemented and the benefits and costs are estimated for that scenario. Then the benefits and costs for each project are measured as the incremental economic impacts that occur in the economy over these baseline conditions due to the project. The appropriate method for benefit and cost estimation depends on whether or not the market prices reflecting true social values are available or if such prices can be constructed.

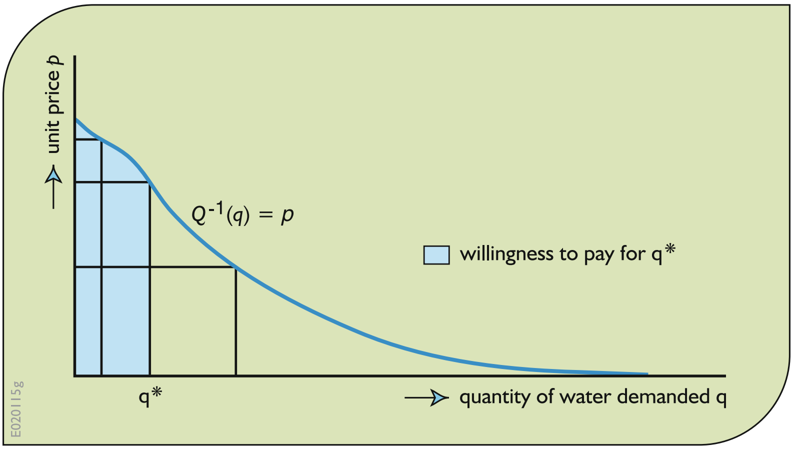
Market Prices Equal Social Values

Consider the estimation of irrigation benefits in the irrigation-recreation example discussed in the previous section. Let X be the quantity of irrigation water supplied by the project each year. If the prevailing market price p_X reflects the marginal social value of water and if that price is not affected by the project's operation, the value of the water is just $p_X X$. However, it often happens that large water projects have a major impact on the prices of the commodities they supply. In such cases, the value of water from our example irrigation district would not be based on prices before or after project implementation. Rather, the total value of the water X to the users is the total amount they would be willing to pay for it.

Let $Q(p)$ be the amount of water the consumers would want to buy at a unit price p. For any price p, consumers will continue to buy the water until the value of another unit of water is less than or equal to the price p. The function $Q(p)$ defines what is called the demand function. As illustrated by Fig. 9.3, the lower the unit price, the more water individuals are willing to buy, i.e., the greater will be the demand.

The willingness to pay a given unit price p is defined by the area under the demand curve. As Fig. 9.3 suggests, there are some who would be willing to pay a higher price for a given amount of water than others. As the unit price decreases, more individuals are willing to buy more water. The total willingness to pay for a given amount

Fig. 9.3 Demand function defining how much water Q will be purchased for a specified unit price p. The shaded area represents the willingness to pay for a quantity q^*



of water q^* is the area under the demand curve from $Q = 0$ to $Q = q^*$.

$$\text{Willingness to pay for } q^* = \int_0^{q^*} Q^{-1}(q)dq \tag{9.3}$$

Consumer's willingness to pay for a product is an important concept in welfare economics.

Market Prices not Equal to Social Values

It frequently occurs that market prices do not truly reflect the true social value of the various goods and services supplied by a water resources project. In such cases it is necessary for the planner to estimate the appropriate values of the quantities in question. There are several procedures that can be used depending on the situation. A rather simple technique that can reach absurd conclusions if incorrectly applied is to equate the benefits of a service to the cost or supplying the service by the least expensive alternative method. Thus the benefits from hydroelectricity generation could be estimated as the cost of generating that electricity by the least-cost alternative method using solar, wind, geothermal, coal-fired, natural gas, or nuclear energy sources. Clearly, this approach to benefit estimation is only valid if in the absence of the project's adoption, the service in question would in fact be demanded at, and supplied by, the least-cost alternative method. The pitfalls associated with this method of benefit and cost estimation can be avoided if one clearly identifies reasonable with—and without project scenarios.

In other situations, simulated or imagined markets can be used to derive the demand function for a good or service and to estimate the value of the amount of that good or service generated or consumed by the project. The following hypothetical example illustrates how this technique can be used to estimate the value of outdoor recreation.

Assume a unique recreation area is to be developed which will serve two population centers. Center *A* has a population of 10,000 and the more distant Center *B* has a population or 30,000. From questionnaires it is estimated that if access to the recreation area is free, 20,000 visits per year will be made from Center *A* at an average round-trip travel cost of \$1. Similarly 30,000 visits per year will come from Center *B*, at an average round-trip cost of \$2.

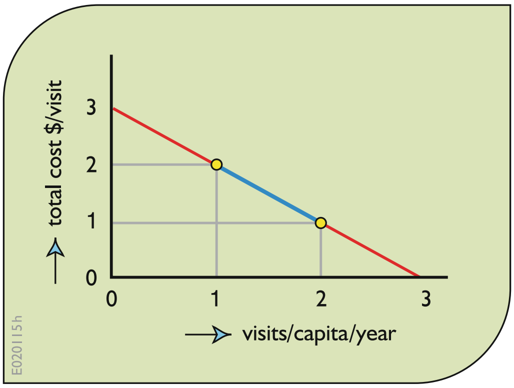


Fig. 9.4 Estimated relationship between travel cost and visits per capita

The benefits derived from the proposed recreation area can be estimated from an imputed demand curve. First, as illustrated in Fig. 9.4, a graph of travel cost as a function of the average number of visits per capita can be constructed. Two points are available: an average of two visits per capita (from center *A*) at a cost of \$1/visit, and an average of one visit per capita (from Center *B*) at a cost of \$2 visit. These travel cost data are extrapolated to the ordinate and abscissa.

Even assuming that there are no plans to charge admission at the site, if users respond to an entrance fee as they respond to travel costs, it is possible to estimate what the user response might be if an entrance fee were to be charged. This information will provide a demand curve for recreation at the site.

Consider first a \$1 admission price to be added to the travel cost for recreation. The total cost to users from population Center *A* would then be \$2 per visit. From Fig. 9.4 at \$2 per visit, one visit per capita is made; hence 10,000 visits per year can be expected from Center *A*. The resulting cost to users from Center *B* is \$3 per visit, and hence from Fig. 9.4 no visits would be expected. Therefore, one point on the demand curve (10,000 visits at \$1) is obtained. Similarly,

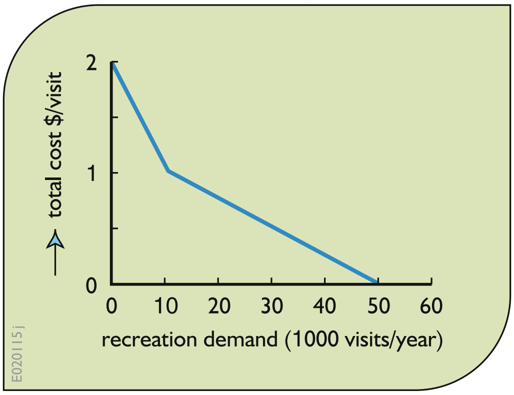


Fig. 9.5 Demand function for recreation facility

it can be inferred that at a $2 admission price there will be no visits from either center. A final point, corresponding to a zero admission price (no added costs) is just the expected site attendance (20,000 + 30,000 = 50,000 visits). The resulting demand curve is shown in Fig. 9.5. Recreation total willingness to pay benefits are equal to the area under the demand curve or $35,000. Assuming no entrance fee is charged, this amounts to $0.70 per visitor-day based on the expected 50,000 visits.

Obviously, this example is illustrative only. The average cost of travel time (which differs for each population center) and the availability of alternative sites must be included in a more detailed analysis.

No Market Processes

In the absence of any market-like process (real or simulated) it is difficult to associate specific monetary values with benefits. The benefits associated with esthetics and with many aspects of environmental and ecosystem quality have long been considered difficult to quantify in monetary terms. Although attempts (some by highly respected economists) have been made to express environmental benefits in monetary terms, the results have had limited success. In most regions in the world, water resources management guidelines, where they exist, do not encourage the assignment of monetary values to these criteria. Rather the approach is to establish environmental and ecological requirements or regulations. These constraints are to be met perhaps while maximizing other economic benefits. Their shadow prices or dual variables (indicating the marginal cost associated with a unit change in the regulation or requirement) is likely to be as close to monetizing such non-monetary impacts as one can get, yet recognizing the actual monetary benefits could be greater. Legislative and administrative processes rarely if ever determine the explicit benefits derived from meeting these environmental and ecological requirements or regulations.

To a certain extent, environmental (including esthetic) objectives, if quantified, can be incorporated into a multiobjective decision-making process. However, this falls short of the assignment of monetary benefits that is often possible for the first three categories of benefits.

9.4.1.2 A Note Concerning Costs

To be consistent in the estimation of net benefits from water resources projects, cost estimates should reflect opportunity costs, the value of resources in their most productive alternative uses. This principle is much easier stated than implemented, and as a result true opportunity costs are seldom included in a benefit-cost analysis. For example, if land must be purchased for a flood control project, is the purchase price (which would typically be used in a benefit-cost analysis) the land’s opportunity cost? Suppose that the land is currently a natural area and its alternative use is as a nature preserve and camping area. The land’s purchase price may be low, but this price unlikely reflects the land’s true value to society. Furthermore, assume that individuals who would otherwise be unemployed are hired to work on the land. The opportunity cost for such labor is the marginal value of leisure forgone, since there is no alternative productive use of those individuals. Yet, the labors must be paid and their wages must be included in the budget for the project.

The results of rigorous benefit-cost analyses seldom dictate which of competing water resources projects and plans should be implemented. This is in part because of the multiobjective nature of the decisions. One must consider environmental impacts, income redistribution effects, and a host of other local, , and national goals.

Other important considerations are the financial, technical, and political feasibilities of alternative plans. Particularly important when plan are proposed by government agencies is the relative political and legal clout of those who support the plans and those who oppose them. Still, a plan's economic efficiency is an important measure of a plan's value to society and often serves as an indicator of whether it should be considered at all.

9.4.1.3 Long- and Short-Run Benefit Functions

When planning the capacities and target values associated with water resource development projects, it is often convenient to think of two types of benefit functions: the long-run benefits and the short-run benefits. In *long-run planning,* the capacities of proposed facilities and the target allocations of flows to alternative uses or target storage volumes in reservoirs are unknown decision variables. The values of these variables are to be determined in a way that achieves the most beneficial use of available resources, even when the available resources vary in magnitude over time. In *short-run planning,* the capacity of facilities and any associated targets are assumed known. The problem is one of managing or operating a given or proposed system under varying supply and demand conditions.

For example, if a water-using firm is interested in building a factory requiring water from a river, of interest to those designing the factory is the amount of water the factory can expect to get. This in part may dictate the capacity of that factory, the number of employees hired, and the amount of product produced, etc. On the other hand, if the factory already exists, the likely issue is how to manage or operate the factory when the water supply varies from the target levels that were (and perhaps still are) expected.

Long-run benefits are those benefits obtained if all target allocations are met. Whatever the target, if it is satisfied, long-run benefits result, Short-run benefits are the benefits one actually can obtain by operating a system having fixed capacities and target values. If the water resources available in the short run are those that can meet all the targets that were established when long-run decisions were made, then estimated long-run benefits can be achieved. Otherwise the benefits actually obtained may differ from those expected. The goal is to determine the values of the long-run decision variables in a way that maximizes the present value of all the short run benefits obtained given the varying water supply and demand conditions.

The distinction between long-run and short-run benefits can be illustrated by considering again a potential water user at a particular site. Assume that the long-run net benefits associated with various target allocations of water to that use can be estimated. These long-run net benefits are those that will be obtained if the actual allocation Q equals the target allocation Q^T. This long-run net benefit function can be denoted as $B(Q^T)$. Next assume that for various fixed values of the target Q^T the actual net benefits derived from various allocations Q can be estimated. These short-run benefit functions $b(Q|Q^T)$ of allocations Q given a target allocation Q^T are dependent on the target Q^T and obviously on the actual allocation Q. The relationship between the long-run net benefits $B(T)$ and the short-run net benefits $b(Q|Q^T)$ for a particular target Q^T is illustrated in Fig. 9.6.

The long-run function $B(Q^T)$ in Fig. 9.6 reflects the benefits users receive when they have adjusted their plans in anticipation of receiving an allocation equal to the target Q^T and actually receive it. The short-run benefits function specifies the benefits users actually receive when a particular allocation is less (e.g., Q_1) or more (e.g., Q_2) than the anticipated allocation, Q^T, and they cannot completely adjust their plans to the resulting deficit or surplus.

Clearly the short-run benefits associated with any allocation cannot be greater than the long-run benefits obtainable had the firm planned or targeted for that allocation. The short-run benefit function is always going to be under, or tangent to, the long-run benefit function, as shown in Fig. 9.6. In other words the short-run

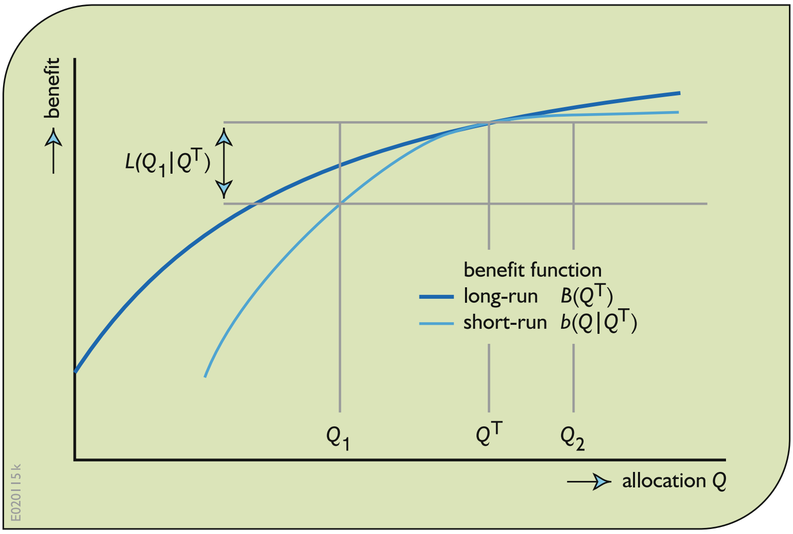


Fig. 9.6 Long-run and short-run benefit functions, together with the loss, $L(Q_1|Q^T)$, associated with a deficit allocation Q_1 and target allocation Q^T

benefits $b(Q|Q^T)$ will never exceed the long-run benefits $B(Q)$ that could be obtained if the target Q^T were equal to the allocation Q. When the target Q^T equals the allocation Q, the values of both functions are equal.

Flipping the short-run benefit function upside down along a horizontal axis running through the long-run benefit function at the target Q^T defines the short-run loss function, as illustrated in Fig. 9.7. The short-run loss of any actual allocation Q equals the long-run benefit of the target allocation Q^T minus the short-run benefit of the actual allocation, Q.

$$L(Q|Q^T) = B(Q^T) - b(Q|Q^T) \qquad (9.4)$$

This function defines the losses that occur when the target allocation cannot be met. When the actual allocation equals the target allocation, the short-run loss is zero. It is possible there might be short-run gains or benefits if there is a surplus allocation over the target allocation, possibly for a limited range of excess allocations.

The short-run benefit function, or its corresponding loss function, usually depends on the value of the target allocation. However, if the short-run losses associated with any deficit allocation $(Q^T - Q_1)$ or surplus allocation $(Q_2 - Q^T)$ are relatively constant over a reasonable range of targets, it may not be necessary to define the loss as a function of the target Q^T. In this case the loss can be defined as a function of the deficit D and/or as a function of the surplus (excess) E. Both the deficit D or excess E can be defined by the constraint

$$Q = Q^T - D + E \qquad (9.5)$$

Denote the loss function for a deficit allocation as $L^D(D)$ and for a surplus allocation, $L^E(E)$. As indicated above, the later may be a negative loss, i.e., a gain, at least for some range of E, as shown in Fig. 9.7.

The costs of the capacity of many components or multipurpose projects are not easily expressed as functions of the targets associated with each use. For example the capacity, K, of a multipurpose reservoir is not usually equal to, or even a function of, its recreation level target or its active or flood storage capacities. The costs of its total capacity, $C(K)$, are best defined as functions of that total capacity. If expressed as an annual cost it would include the annual amortized capital costs as well as the annual operation, maintenance, and repair costs.

Assuming that the benefit and loss functions reflect annual benefits and losses, the annual net benefits, NB, from all projects j is the sum of

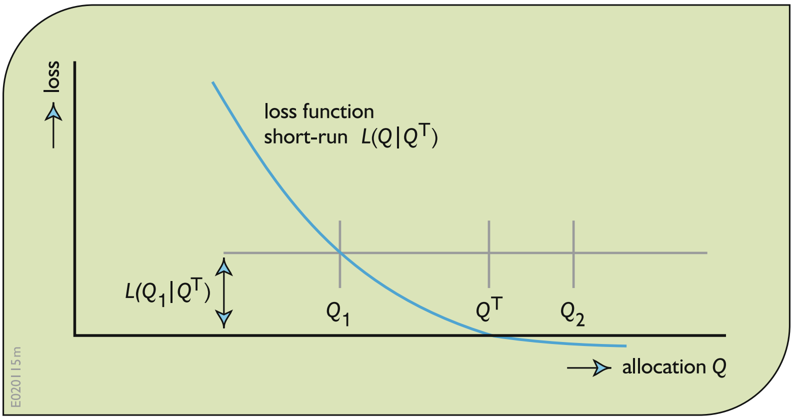


Fig. 9.7 Short-run loss function, $L(Q|Q^T)$, associated with an allocation Q and target allocation Q^T

each project's long-run benefits $B_j(T_j)$ that are functions of their targets, T_j, less short-run losses $L_j(Q_j|T_j)$ and capacity costs $C_j(K_j)$.

$$NB = \sum_j \left[B_j(T_j) - L_j(Q_j|T_j) - C_j(K_j)\right] \quad (9.6)$$

The monetary net benefits accrued by each group of water users can also be determined so that the income redistribution effects of a project can be evaluated.

The formulation of benefit functions as either long- or short-run is, of course, a simplification of reality. In reality, planning takes place on many time scales and for each time scale one could construct a benefit function. Consider the planning problems of farmers. In the very long run, they decide whether or not to own farms, and if so how big they are to be in a particular area. On a shorter time scale, farmers allocate their resources to different activities depending on what products they are producing and on the processes used to produce them. Different activities, of course, require capital investments in farm machinery, storage facilities, pipes, pumps, etc., some of which cannot easily be transferred to other uses. At least on an annual basis, most farmers reappraise these resource allocations in light of the projected market prices of the generated commodities and the availability and cost of water, energy, labor and other required inputs. Farmers can then make marginal adjustments in the amounts of land devoted to different crops, animals, and related activities within the bounds allowed by available resources, including land, water, capital and labor. At times during any growing season some changes can be made in response to changes in prices and the actual availability of water.

If the farmers frequently find that insufficient water is available in the short run to meet livestock and crop requirements, then they will reassess and perhaps change their long-run plans. They may shift to less water-intensive activities, seek additional water from other sources (such as deep wells), or sell their farms (and possibly water rights) and engage in other activities. For the purposes of modeling, however, this planning hierarchy can generally be described by two levels, denoted as long-run and short-run. The appropriate decisions included in each category will depend on the time scale of a model.

These long-run and short-run benefit and loss functions are applicable to some water users, but not all. They may apply in situations where benefits or losses can be attributed to particular allocations in each of the time periods being modeled. They do not apply in situations where the benefits or losses result only at the end of a series of time periods, each involving an allocation decision. Consider irrigation, for example. If each growing season is divided into multiple periods, then the benefits derived from each period's water allocation cannot be defined independent of any other period's allocation, at least very easily. The benefits from irrigation come only when the crops are harvested, e.g., at the end of the last period of each growing season. In this case some mechanism is needed to determine the benefits obtained from a series of allocations over time, as will be presented in the next chapter.

9.4.2 Environmental Criteria

Environmental criteria for water resource projects can include water quantity and quality conditions. These conditions are usually expressed in terms of targets or constraints for flows, depths, hydroperiods (duration of flooding), storage volumes, flow or depth regimes and water quality concentrations that are considered desirable for esthetic or public health reasons or for various ecosystem habitats. These constraints or targets could specify desired minimum or maximum acceptable ranges, or rates of changes, of these values, either for various times within each year or over an *n*-year period.

Water quality constituent concentrations are usually expressed in terms of some maximum or minimum acceptable concentration, depending on the particular constituents themselves and the intended uses of the applicable water body. For example, phosphorus would normally have a maximum permissible concentration and dissolved oxygen would normally have a minimum acceptable concentration. These limiting concentrations and their specified reliabilities are often based on standards established by governmental or international environmental or health organizations. As standards they are viewed as constraints. These standards could also be considered as targets and the maximum or average adverse deviations from these standards or targets could be a system performance measure.

Few water quality criteria may be expressed in qualitative terms. Qualitative quality criteria can provide a 'fuzzy' limit on the concentration of some constituent in the water. Such criteria might be expressed as, for example, "the surface water shall be virtually free from floating petroleum-derived oils and non-petroleum oils of vegetable or animal origin." Stakeholder membership functions can define what is considered virtually free, and these can be included as objectives or constraints in models (as discussed in Chap. 5).

Environmental performance criteria can vary depending on the specific sites and on the intended uses of water at that site. They should be designed to assess, or define, the risks of adverse impacts on the health of humans and aquatic life from exposure to pollutants.

Environmental performance criteria of concern to water resource planners and managers can also relate to recreational and land use activities. These typically address hydrologic conditions, such as streamflows or lake or reservoir storage volume elevations during specified times or land use activities on watersheds. For example, to increase the safety of boaters and individuals fishing downstream of hydropower reservoirs, release rules may have to be altered to reduce the rate of flow increase that occurs during peak power production. Performance criteria applicable to the adverse environmental impacts of sediment loads, say caused by logging or construction activities, or to the impact of nutrient loads in the runoff, perhaps from agricultural and urban areas, are other examples.

9.4.3 Ecological Criteria

Criteria that apply to aquatic ecosystems involve both water quantity and quality and are often compatible with environmental criteria. It is the time-varying regimes of water quantities and qualities, not minimum or maximum values that benefit and impact ecosystems. It is not possible to manage water and its constituent concentrations in a way that maximizes the health or well being, however, measured, of all living matter in an ecosystem. (Like people, it's hard to satisfy everyone all the time.) If one species feeds on another, it is hard to imagine how to maximize the health of both. The conditions that favor one species group may not favor another. Hence variation in habitat conditions is important for the sustainability of both, and indeed for achieving resilient biodiverse ecosystems.

While ecosystem habitats exhibit more diversity when hydrologic conditions vary, as in nature, than when they are relatively constant, hydrologic variation is often not desired by many human users of water resource systems. Reducing hydrologic variation and increasing the reliability of water resource systems has often been the motivating factor in the design and operation of hydraulic engineering works.

The state of ecological habitats is in part functions of how water is managed. One way to develop performance indicators of ecosystems is to model the individual species making up the ecosystem, or at least a subset of important indicator species. This is often difficult. Alternatively one can define habitat suitability indices for these important indicator species. This requires (1) selecting the indicator species representative of each particular ecosystem, (2) identifying the hydrological attributes that affect the wellbeing of those indicator species during various stages of their life cycles, and (3) quantifying the functional relationships between the wellbeing of those species and values of the applicable hydrological attributes, usually on a scale from 0 to 1. A habitat suitability value of 1 is considered an ideal condition. A value of 0 is considered to be very unfavorable.

Examples of hydrological attributes that impact ecosystems could include flow depths, velocities, constituent concentrations and temperatures, their durations or the rate of change in any of those values over space and/or time at particular times of the year. In wetlands the hydrologic attributes could include the duration of inundation (hydroperiod), time since last drawdown below some threshold depth, the duration of time below or above some threshold depth, and time rates of change in depth. The applicable attributes themselves, or perhaps just their functional relationships, can vary depending on the time of year and on the stage of species development.

Figure 9.8 illustrates three proposed habitat suitability indices for periphyton (algae) and fish in parts of the Everglades region of southern Florida in the US. All are functions of hydrological attributes that can be managed. Shown in this figure is the impact of hydroperiod duration on the habitat of three different species of periphyton located in different parts of the Everglades, and the impact of the duration of the hydroperiod as well as the number of years since the last dry period on a species of fish.

There are other functions that would influence the growth of periphyton and fish, such as the concentrations of phosphorus or other nutrients in the water. These are not shown. Figure 9.8 merely illustrates the construction of habitat suitability indices.

There are situations where it may be much easier and more realistic to define a range of some hydrological attribute values as being ideal. Consider fish living in streams or rivers for example. Fish desire a variety of depths, depending on their feeding and spawning activities. Ideal trout habitat, for example, requires both deeper pools and shallower riffles in streams. There is no one ideal depth or velocity or even a range of depths or velocities above or below some threshold value. In such cases it is possible to divide the hydrologic attribute scale into discrete ranges and identify the ideal fraction of the entire stream or river reach or wetland that ideally would be within each discrete range. This exercise will result in a function resembling a probability density function. The total area under the function is 1. (The first and last segments of the function can represent anything less or greater than some discrete value, where appropriate, and if so the applicable segments are understood to cover those ranges.) Such a function is shown in Fig. 9.10. Figure 9.9 happens to be a discrete distribution, but it could have been a continuous one as well.

Any predicted distribution of attribute values resulting from a simulation of a water management policy can be compared to this ideal distribution, as is shown in Fig. 9.10. The fraction of overlapping areas of both distributions is an indication of the suitability of that habitat for that indicator species.

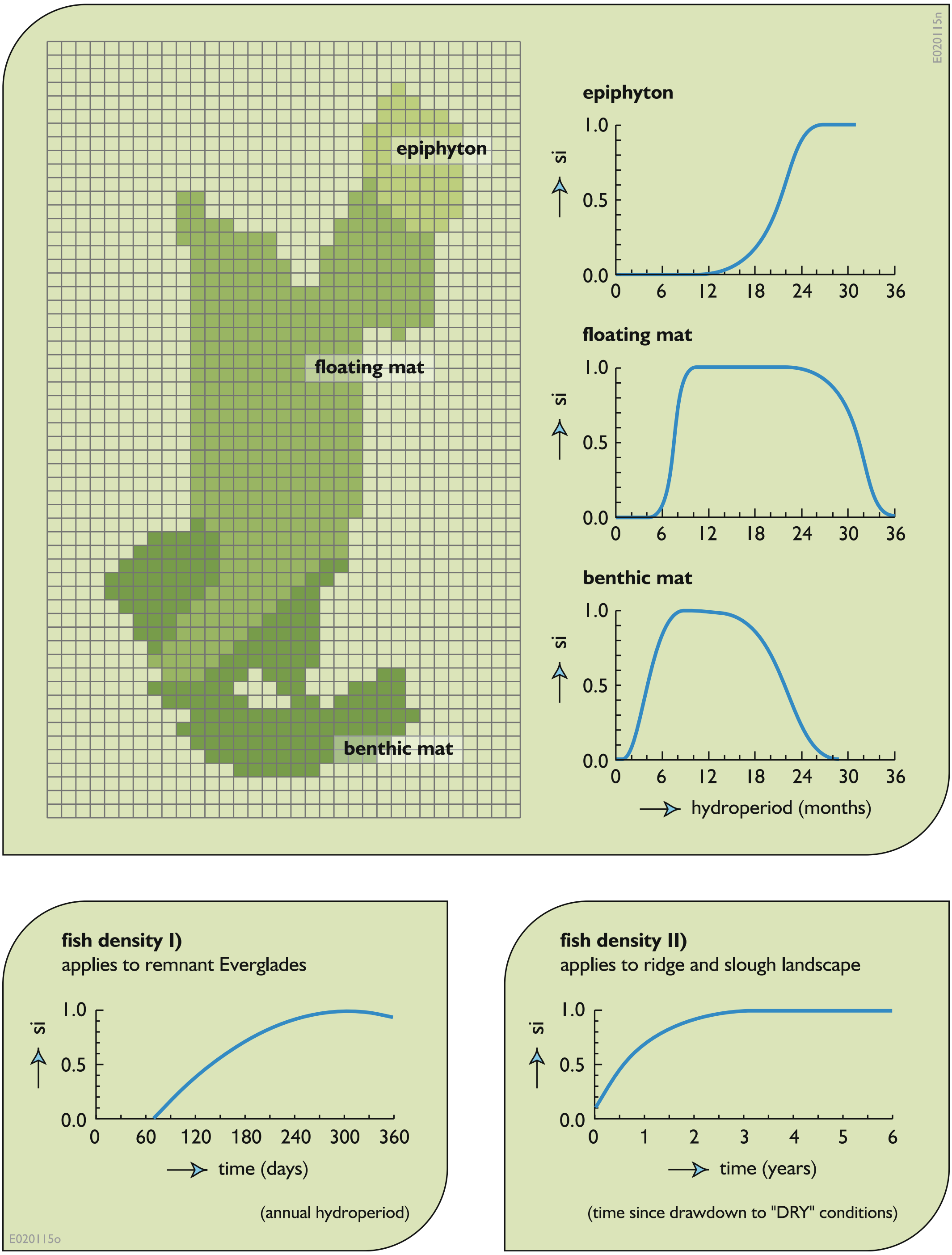


Fig. 9.8 Some proposed habitat suitability indices (SI) for three types of periphyton (algae) and a species of fish in portions of the Everglades region in southern Florida of the US

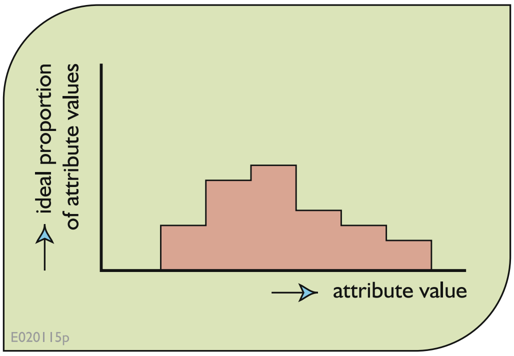


Fig. 9.9 Ideal range of values of a hydrologic attribute for a particular component of an ecosystem

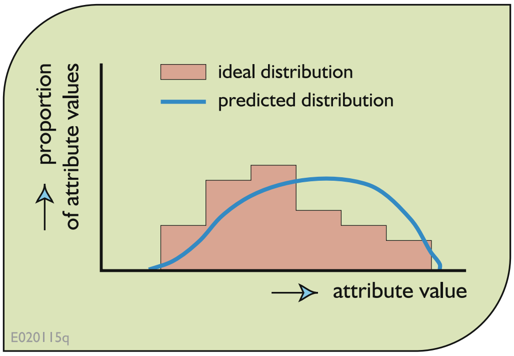


Fig. 9.10 Predicted (simulated indicated in *blue*) and ideal (indicated in *red*) distributions of attribute values for some ecosystem indicator species. The fraction of the area common to both distributions is a measure of habitat suitability

$$\begin{aligned}\text{Habitat suitability} = &\text{Fraction of area under}\\ &\text{the ideal and simulated}\\ &\text{distributions of attribute values.}\end{aligned} \tag{9.7}$$

In Fig. 9.10, this is the red shaded area under the blue curve.

To identify a representative set of indicator species of any ecosystem, the hydrologic attributes or 'stressors' that impact those indicator species, and finally the specific functional relationships between the hydrologic attributes and the habitat suitability performance indicators, is not a trivial task. The greater the number of experienced individuals involved in such an exercise, the more difficult it may be to reach some agreement or consensus. This just points to the complexity of ecosystems and the nontrival task of trying to simplify it to define habitat suitability performance criteria. However once identified, these habitat suitability performance criteria can give water resource planners and managers an admittedly incomplete but at least relative indication of the ecosystem impacts of alternative water management policies or practices.

The use of these habitat suitability functions along with other performance criteria in optimization and simulation models will be discussed later in this chapter.

9.4.4 Social Criteria

Social performance criteria are often not easily defined as direct functions of hydrological attributes. Most social objectives are only indirectly related to hydrological attributes or other measures of water resource system performance. Economic, environmental, and ecological impacts resulting from water management policies directly affect people. One social performance criterion that has been considered in some water resources development projects, especially in developing regions, has been employment. Where employment is considered important, alternatives that provide more jobs may be preferred to those that use more heavy machinery in place of labor, for example.

Another social performance criterion is human settlement displacement. The number of families that must move from their homes because of, for example, flood plain restoration or reservoir construction, is always of concern. These impacts can be expressed as a function of the extent of flood plain restoration or reservoir storage capacity, respectively. Often the people most affected are in the lower-income groups, and this raises legitimate issues of social justice and equity. Human resettlement impacts have both social and economic dimensions.

Social objectives are often the more fundamental objectives discussed earlier in this chapter. Asking 'why' identifies them. Why improve water quality? Why prevent flood damage? Why, or why not, build a reservoir? Why restore a flood plain or wetland? Conversely, if social objectives are first identified, by asking and then answering 'how' they can be achieved usually results in the identification of economic, environmental and ecological objectives more directly related to water management.

The extent of press coverage or of public interest and participation in the planning and evaluation processes can also be an indicator of social satisfaction with water management. In times of social stress due to, for example, floods, droughts, or disease caused by waterborne bacteria, viruses, and pollutants, press coverage and public involvement often increases. (Public interest also increases when there is a lot of money to be spent but this is often a result of substantial public interest as well.) It is a continuing challenge to actively engage an often disinterested public in water management planning at times when there are no critical water management impacts being felt and not a lot of money is being spent. Yet this is just the time such planning for more stressful conditions should take place.

9.5 Multicriteria Analyses

Given multiple performance criteria measured in multiple ways, how can one determine the best decision, i.e., the best way to develop and manage water? Just what is best, or as some put it, rational? The answer to these questions will often differ depending on who is being asked. There is rarely an alternative that makes every interest group or impacted stakeholder the happiest. When agreement is not universal and when some objectives conflict with others, we can identify the efficient tradeoffs among the objective values each stakeholder would like to have. In this section some ways of identifying efficient tradeoffs are reviewed. These methods of multicriteria or multiobjective analyses are not designed to identify the best solution, but only to provide information on the tradeoffs among conflicting quantitative performance criteria. Again, any final decision will be based on qualitative as well as this quantitative information in a political and social process, not by or in a computer.

Even if the same units of measure, e.g., monetary ones, can be used for each performance measure or objective, it is not always appropriate to simply sum them together into a single measure or objective that can be maximized or minimized. Consider for example a water resources development project to be designed to maximize net economic benefits. In the US this is sometimes designated the national economic development (NED) objective. Another objective may be to distribute the costs and benefits of the project in an equitable way. Both objectives are measured in the same monetary units. While everyone may agree that the biggest pie (i.e., the maximum net benefits) should be obtained, subject to various environmental and ecological constraints perhaps, not everyone will likely agree as to how that pie should be divided up among all the stakeholders. It also matters who pays and who benefits, and by how much. Again, issues of equity and social justice involve judgments, and the challenge of water resource planners and managers, and elected politicians, is to make good judgments. The result is often a plan or policy that does not maximize net economic benefits. Requiring all producers of wastewater effluent to treat their wastes to the best practical level before discharging the remaining effluent, regardless of the quality or assimilative capacity of the receiving bodies of water, is one example of this compromise between economic, environmental, and social criteria.

The irrigation-recreation example presented earlier in this chapter illustrates some basic concepts in multiobjective planning. As indicated in Fig. 9.1, one of the functions of multiobjective planning is the identification of plans that are technologically efficient. These are plans that define the production-possibility frontier. Feasible plans that are not on this frontier are inferior in the sense that it is always possible to identity alternatives that will improve one or more objective values without making others worse.

Although the identification of feasible and efficient plans is seldom a trivial matter, it is conceptually straightforward. Deciding which of these efficient plans is the best is quite another matter. One needs some way to compare them. Social welfare functions that could provide a basis for comparison is impossible to construct, and the reduction of multiple objectives to a single criterion (as in Fig. 9.2), especially if they are conflicting, is seldom acceptable in practice.

When the various objectives of a water resources planning project cannot be combined into a single scalar objective function, a *vector optimization* representation of the problem may be applicable. Let the vector $\boldsymbol{X}$ represent the set of unknown decision variables whose values are to be determined and let $Z_j(\boldsymbol{X})$ be a performance criterion or objective that is to be maximized. Each performance criterion or objective j is a function of these unknown decision variable values. Assuming that all objectives $Z_j(\boldsymbol{X})$ are to be maximized, the model can be written

$$\text{maximize}\left[Z_1(\boldsymbol{X}), Z_2(\boldsymbol{X}), \ldots, Z_j(\boldsymbol{X}), \ldots, Z_J(\boldsymbol{X})\right]$$

subject to:

$$g_i(\boldsymbol{X}) = b_i \quad i = 1, 2, \ldots, m \tag{9.8}$$

The objective in Eq. 9.8 is a vector consisting of J separate objectives. The m constraints $g_i(\boldsymbol{X}) = b_i$ define the feasible region of solutions. Again, the vector $\boldsymbol{X}$ represents all the unknown decision variables whose values are to be determined by solving the model.

The vector optimization model is a concise way of representing a multiobjective problem but it is not very useful when trying to solve it. In reality, a vector can be maximized or minimized only if it can be reduced to a scalar. Thus the multiobjective planning problem defined by Model 9.8 cannot, in general, be solved without additional information. Various ways of solving this multiobjective model are discussed in the following subsections.

The goal of multiobjective modeling is the generation of a set of technologically feasible and efficient plans. Recall that an efficient plan is one that is not dominated.

9.5.1 Dominance

A plan $\boldsymbol{X}$ dominates all others if it results in an equal or superior value for all objectives, and at least one objective value is strictly superior to those of each other plan. In symbols, assuming that all objectives j are to be maximized, plan alternative i, $\boldsymbol{X}_i$, dominates if

$$Z_j(\boldsymbol{X}_i)Z_j(\boldsymbol{X}_k) \quad \text{for all objectives}\, j\, \text{and plans}\, k \tag{9.9}$$

and for each plan $k \neq i$ there is at least one objective $j*$ such that

$$Z_{j*}(\boldsymbol{X}_i) > Z_{j*}(\boldsymbol{X}_k) \tag{9.10}$$

Not very often does one plan dominate all others. If it does, pick it! More often different plans will dominate all plans for different objectives. However, if there exists two plans k and h such that the values of all objectives j for plan k are never less than that for plan h ($Z_j(\boldsymbol{X}_k) \geq Z_j(\boldsymbol{X}_h)$), and for some objective $j*$, plan k provides a higher value than does plan h, ($Z_{j^*}(\boldsymbol{X}_k) > Z_{j^*}(\boldsymbol{X}_h)$), then plan k dominates plan h and plan $\boldsymbol{X}_h$ can be dropped from further consideration. This assumes of course that all objectives are being considered. If some objectives are not included in the analysis, perhaps because they cannot be quantified, inferior plans with respect to those objectives that are included in the analysis should not be rejected from eventual consideration just based on this quantitative analysis. To work, dominance analysis must consider all objectives. In practice this condition is often impossible to meet.

Dominance analysis requires that participants in the planning and management process specify all the objectives that are to be considered. It does not require the assessment of the relative importance of each objective. Non-inferior, efficient, or nondominated solutions are often called

Pareto optimal or Pareto efficient because they satisfy the conditions proposed by the Italian economist and social theorist Vilfredo Pareto (1848–1923). A set of objective values is efficient if in order to improve the value of any single objective, one must accept a diminishment of at least one other objective.

Consider for example three alternatives *A*, *B*, and *C*. Assume, as shown in Fig. 9.11, that plan *C* is inferior to plan *A* with respect to objective $Z_1(\boldsymbol{X})$ and also inferior to plan *B* with respect to objective $Z_2(\boldsymbol{X})$. Plan *C* might still be considered the best with respect to both objectives $Z_1(\boldsymbol{X})$ and $Z_2(\boldsymbol{X})$. While plan *C* could have been inferior to both *A* and *B*, as is plan *D* in Fig. 9.11, it should not necessarily be eliminated from consideration just based on a pair-wise comparison. In fact plan *D*, even though inferior with respect to both objectives $Z_1(\boldsymbol{X})$ and $Z_2(\boldsymbol{X})$, might be the preferred plan if another objective were included.

Two common approaches for identifying nondominated plans that together identify the efficient tradeoffs among all the objectives $Z_j(\boldsymbol{X})$ in the Model Eq. 9.8 are the *weighting* and *constraint* methods. Both methods require numerous solutions of a single objective management model to generate points on the objective functions' production-possibility frontier (the blue line in Fig. 9.11).

9.5.2 The Weighting Method

The weighting approach involves assigning a relative weight to each objective to convert the objective vector (in Eq. 9.8) to a scalar. This scalar is the weighted sum of the separate objective functions. The multiobjective Model 9.8 becomes

$$\text{maximize } Z = [w_1 Z_1(\boldsymbol{X}) + w_2 Z_2(\boldsymbol{X}) \ldots + w_j Z_j(\boldsymbol{X}) \ldots + w_J Z_J(\boldsymbol{X})]$$

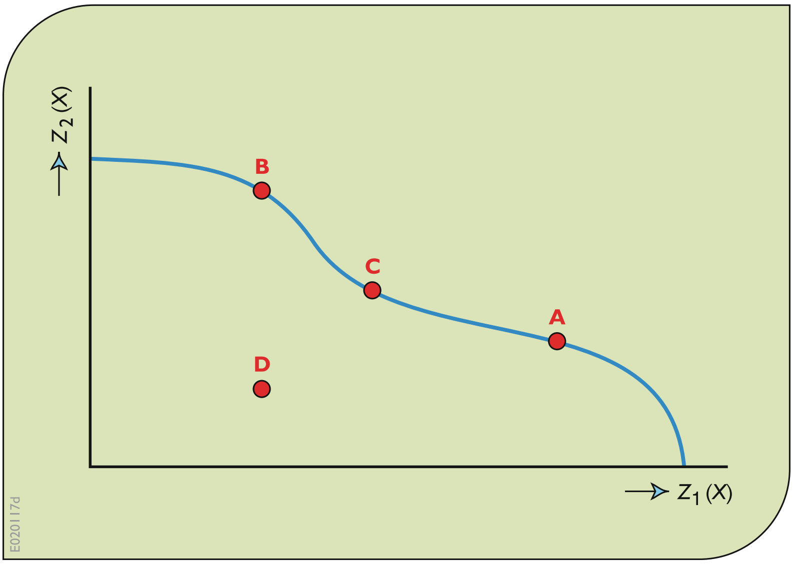
subject to:

$$g_i(\boldsymbol{X}) = b_i \quad i = 1, 2, \ldots, m \tag{9.11}$$

where the nonnegative weights w_j are specified constants. The values of these weights w_j are varied systematically, and the model is solved for each combination of weight values to generate a set of technically efficient (or non-inferior) plans.

The foremost attribute of the weighting approach is that the tradeoffs or marginal rate of substitution of one objective for another at each identified point on the objective functions' production-possibility frontier is explicitly specified by the relative weights. The marginal rate of substitution between any two objectives Z_j and Z_k, at a specified constant value of $\boldsymbol{X}$, is

Fig. 9.11 Four discrete plans along with a continuous efficiency frontier associated with two objectives, Z_1 and Z_2. A pair-wise comparison of plans or objectives may not identify all the nondominated plans. All objectives should be considered before declaring a plan inferior



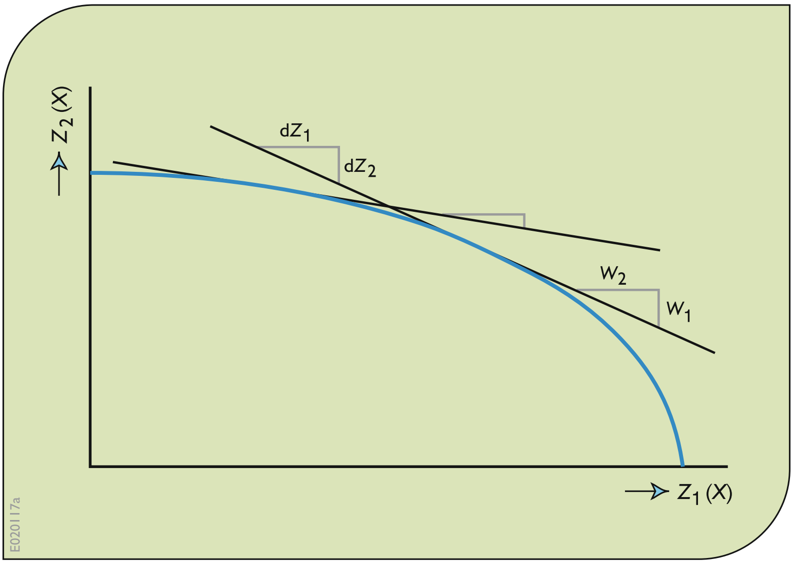


Fig. 9.12 The efficiency frontier between two objectives, $Z_1(\boldsymbol{X})$ and $Z_2(\boldsymbol{X})$, showing the reduction in one objective, say $Z_1(\boldsymbol{X})$, as the relative weight, w_2, associated with the other objective, increases

$$-\left[\mathrm{d}Z_j/\mathrm{d}Z_k\right]\big|_{x=\text{constant}} = w_k/w_j \tag{9.12}$$

This applies when each of the objectives is continuously differentiable at the point $\boldsymbol{X}$ in question. This is illustrated for a two-objective maximization problem in Fig. 9.12.

These relative weights can be varied over reasonable ranges to generate a wide range of plans that reflect different priorities. Alternatively, specific values of the weights can be selected to reflect preconceived ideas of the relative importance of each objective. It is clear that the prior selection of weights requires value judgments. If each objective value is divided by its maximum possible value, then the weights can range from 0 to 1 and sum to 1, to reflect the relative importance given to each objective.

For many projects within developing countries, these weights are often estimated by the agencies financing the development projects. The weights specified by these agencies can, and often do, differ from those implied by national or regional policy. But regardless of who does it, the estimation of appropriate weights requires a study of the impacts on the economy, society, and development priorities involved.

Fortunately here we are not concerned with finding the best set of weights, but merely using these weights to identify the efficient tradeoffs among conflicting objectives. After a decision is made, the weights that produce that solution might be considered the best, at least under the circumstances and at the time when the decision was made. They will unlikely be the weights that will apply in other places in other circumstances at other times.

A principal disadvantage of the weighting approach is that it cannot generate the complete set of efficient plans unless the efficiency frontier is strictly concave (decreasing slopes) for maximization, as it is in Figs. 9.1 and 9.12. If the frontier, or any portion of it, is convex, only the endpoints of the convex region will be identified using the weighting method, as illustrated in Fig. 9.13.

9.5.3 The Constraint Method

The constraint method for multiobjective planning can produce the entire set of efficient plans for any shape of efficiency frontier, including that shown in Fig. 9.13, assuming there are tradeoffs among the objectives. In this method one objective, say $Z_k(\boldsymbol{X})$ is maximized subject to lower limits L_j, on the other objectives, $j \neq k$. The solution of the model, corresponding to any set of feasible lower limits L_j, produces an efficient

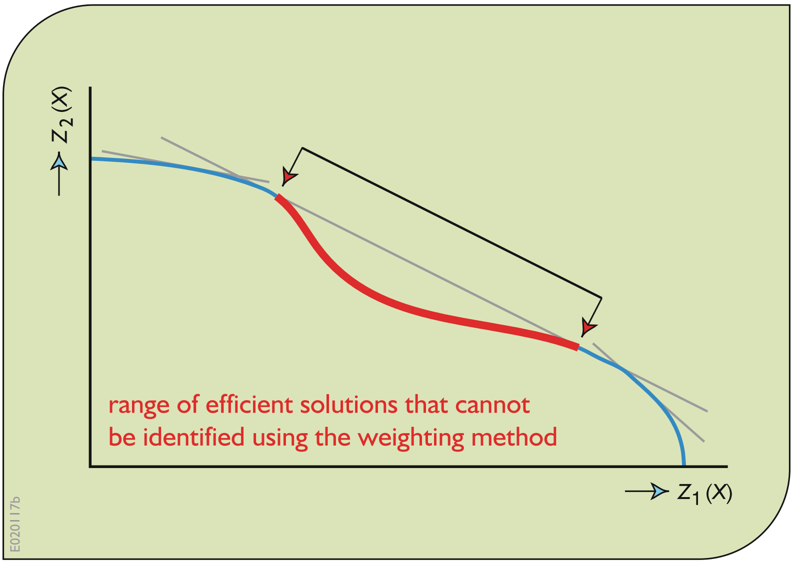


Fig. 9.13 An efficiency frontier that cannot be completely identified within its convex region using the weighting method when objectives are being maximized. Similarly for concave regions when objectives are being minimized

alternative if the lower bounds on the other objective values are binding.

In its general form, the constraint model is

$$\text{maximize}\, Z_k(\boldsymbol{X}) \tag{9.13}$$

subject to

$$g_i(\boldsymbol{X}) = b_i \quad i = 1, 2, \ldots, m \tag{9.14}$$

$$Z_j(\boldsymbol{X}) \geq L_j \quad \forall j \neq k. \tag{9.15}$$

Note that the dual variables associated with the right-hand-side values L_j are the marginal rates of substitution or rate or change *of* $Z_k(\boldsymbol{X})$ per unit change in L_j (or $Z_j(\boldsymbol{X})$ if binding).

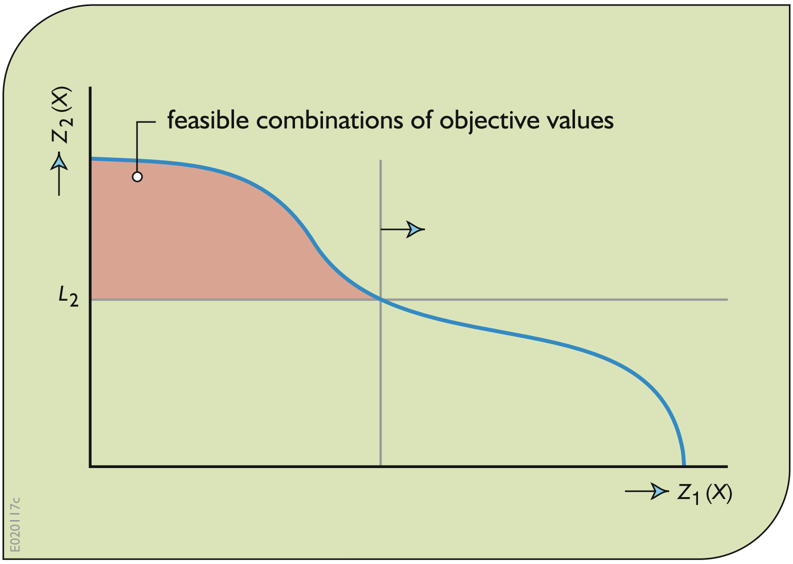
Figure 9.14 illustrates the constraint method for a two-objective problem.

An efficiency frontier identifying the tradeoffs among conflicting objectives can be defined by solving the model many times for many values of the lower bounds. Just as with the weighting method, this can be a big job if there are many objectives. If there are more than two or three objectives the results cannot be plotted. Pair-wise tradeoffs that can easily be plotted do not always clearly identify nondominated alternatives, as previously demonstrated.

The number of solutions to a weighting or constraint method model can be reduced considerably if the participants in the planning and management process can identify the acceptable weights or lower limits. However this is not the language of decision-makers. Decision-makers who count on the support of each stakeholder interest group are not happy in assigning weights that imply the relative importance of those various stakeholder interests. In addition, decision-makers should not be expected to know what they may want until they know what they can get, and at what cost (often politically as much as economically). However, there are ways of modifying the weighting or constraint methods to reduce the amount of effort in identifying these tradeoffs as well as the amount of information generated that is of no interest to those making decisions. This can be done using interactive methods that will be discussed shortly.

The weighting and constraint methods are among many methods available for generating efficient or non-inferior solutions (see, for example, Steuer 1986). The use of methods that generate many solutions, even just efficient ones, assumes that once all the non-inferior alternatives have been identified, the participants in the planning and management process will be able to

Fig. 9.14 The constraint method for identifying the efficiency frontier by maximizing $Z_1(\boldsymbol{X})$ while constraining $Z_2(\boldsymbol{X})$ to be no less than L_2



select the best compromise alternative from among them. In some situations this has worked. Undoubtedly, there will be planning activities in the future where the use of these non-inferior solution generation techniques alone will continue to be of value. However, in many other planning situations, they alone will not be sufficient. Often, the number of feasible non-inferior alternatives is simply too large. Participants in the planning and management process will not have the time or patience to examine, evaluate and compare each alternative plan. Planners or managers may also need help in identifying which alternatives they prefer. If they are willing to work with analysts, these analysts can help them identify what alternatives they prefer without generating and comparing all the other plans.

There are a number of methods available for assisting in selecting the most desirable non-dominated plan. Some of the more common and simpler ones are described next.

9.5.4 Satisficing

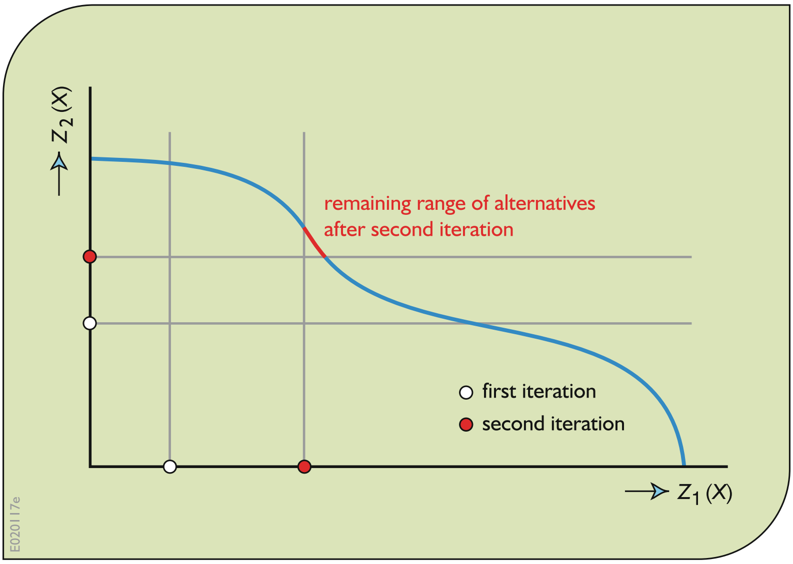
One method of further reducing the number of alternatives is called satisficing. It requires that the participants in the planning and management process specify a minimum acceptable value for each objective that is to be maximized. Those alternatives that do not meet these minimum performance values are eliminated from further consideration. Those that remain can again be screened if the minimal acceptable values of one or more objectives are increased. When used in an iterative fashion, the number of non-inferior alternatives can be reduced down to a single best compromise or a set of plans which the participants in the planning and management process are essentially indifferent. This process is illustrated in Fig. 9.15.

Of course, sometimes the participants in the planning process will be unwilling or unable to sufficiently narrow down the set of available non-inferior plans with the iterative satisfying method. Then it may be necessary to examine in more detail the possible tradeoffs among the competing alternatives.

9.5.5 Lexicography

Another simple approach is called lexicography. To use this approach, the participants in the planning process must rank the objectives in order of priority. This ranking process takes place without considering the particular values of these multiple objectives. Then, from among the

Fig. 9.15 Two successive iterations of the satisficing method in which minimum levels of each objective are set thereby eliminating those alternatives that do not meet these minimum levels



non-inferior plans that satisfy minimum levels of each objective, the plan that is the best with respect to the highest priority objective will be the one selected as superior.

If there is more than one plan that has the same value of the highest priority objective, then among this set of preferred plans the one that achieves the highest value of the second priority objective is selected. If here too there are multiple such plans, the process can continue until there is a unique plan selected.

This method assumes such a ranking of the objectives is possible. Often the relative values of the objectives of each alternative plan are of more importance to those involved in the decision-making process. Consider, for example, the problem of purchasing apples and oranges. Assuming you like both types of fruit, which type of fruit should you buy if you have only enough money to buy one type? If you know you already have lots of apples, but no oranges, perhaps you would buy oranges, and vice versa. Hence the ranking of objectives can depend on the current state and needs of those who will be impacted by the plan.

9.5.6 Indifference Analysis

Another method of selecting the best plan is called indifference analysis. To illustrate the possible application of indifference analysis to plan selection, consider a simple situation in which there are only two alternative plans (*A* and *B*) and two planning objectives (1 and 2) being considered. Let Z_1^A and Z_2^A be the values of the two respective objectives for plan *A* and let Z_1^B and Z_2^B be the values of the two respective objectives for plan *B*. Comparing both plans when a different objective is better for each plan can be difficult. Indifference analysis can reduce the problem to one of comparing the values of only one objective.

Indifference analysis first requires the selection of an arbitrary value for one of the objectives, say Z_2^* for objective 2 in this two-objective example. It is usually a value within the range of the values Z_2^A and Z_2^B, or in a more general case between the maximum and minimum of all objective 2 values.

Next, a value of objective 1, say Z_1 must be selected such that the participants involved are indifferent (equally happy or satisfied) between the hypothetical plan that would have as its objective values $(Z_{1,}\ Z_2^*)$ and plan *A* that has as its objective values (Z_1^A, Z_2^A). In other words, Z_1 must be determined such that $(Z_{1,}\ Z_2^*)$ is as desirable as or equivalent to (Z_1^A, Z_2^A).

$$\left(Z_1, Z_2^*\right) \approx \left(Z_1^A, Z_2^A\right). \tag{9.16}$$

Next another value of the first objective, say $Z_1^{'}$, must be selected such that the participants are indifferent between a hypothetical plan $(Z_1^{'}, Z_2^*)$ and the objective values (Z_1^B, Z_2^B) of plan *B*.

$$\left(Z_1', Z_2^*\right) \approx \left(Z_1^B, Z_2^B\right) \tag{9.17}$$

These comparisons yield hypothetical but equally desirable plans for each actual plan. These hypothetical plans differ only in the value of objective 1 and hence they are easily compared. If both objectives are to be maximized and Z_1 is larger than $Z_1^{'}$, then the first hypothetical plan yielding Z_1 is preferred to the second hypothetical plan yielding $Z_1^{'}$. Since the two hypothetical plans are equivalent to plans *A* and *B*, respectively, plan *A* must be preferred to plan *B*. Conversely, if $Z_1^{'}$ is larger than Z_1 then plan *B* is preferred to plan *A*.

This process can be extended to a larger number of objectives and plans, all of which may be ranked by a common objective. For example, assume that there are three objectives Z_1^i, Z_2^i, Z_3^i, and *n* alternative plans *i.* A reference value Z_3^* for objective 3 can be chosen and a value z_1^i estimated for each alternative plan *i* such that one is indifferent between (Z_1^i, Z_2^i, Z_3^*) and (Z_1^i, Z_2^i, Z_3^i). The second objective value remains the same as in the actual alternative in each of the hypothetical alternatives. Thus the focus is on the tradeoff between the values of objectives 1 and 3. Assuming that each objective is to be maximized, if Z_3^* is selected so that $Z_3^* < Z_3^i$, then z_1^i will no doubt be greater than Z_3^i. Conversely, if $Z_3^* > Z_3^i$, then z_1^i will be less than Z_3^i.

Next, a new hypothetical plan containing a reference value Z_2^* and Z_3^* can be created. The focus now is on the tradeoff between the values of objectives 1 and 2 given the same Z_3^*. A value $\mathrm{z}z_1^{i'}$ must be selected such that the participants are indifferent between (z_1^i, Z_2^i, Z_3^*) and $(\mathrm{z}\underline{\mathrm{z}}_1^i, Z_2^*, Z_3^*)$. Hence for all plans *i*, the participants are indifferent between two hypothetical plans and the actual one. The last hypothetical plans differ only by the value of the first objective. The plan that has the largest value for objective 1 will be the best plan. This was achieved by pair-wise comparisons only.

In the first step objective 2 remained constant and only objectives 1 and 3 were compared to get

$$\left(Z_1^i, Z_2^i, Z_3^i\right). \approx (\mathrm{z}_1^i, Z_2^i, Z_3^*) \tag{9.18}$$

In the next step involving the hypothetical plans just defined objective 3 remained constant and only objectives 1 and 2 were compared to get

$$(\underline{\mathrm{z}}_1^i, Z_2^i, Z_3^*) \approx \left(zz_1^i, Z_2^*, Z_3^*\right) \tag{9.19}$$

Hence

$$\left(Z_1^i, Z_2^i, Z_3^i\right) \approx (\mathrm{z}_1^i, Z_2^i, Z_3^*) \approx \left(\mathrm{z}z_1^i, Z_2^*, Z_3^*\right) \tag{9.20}$$

Having done this for all *n* plans, there are now *n* hypothetical plans (zz_1^i, Z_2^*, Z_3^*) that differ only in the value of zz_1^i. All *n* plans can be ranked just based on the value of this single objective.

Each of these plan selection techniques requires the prior identification of discrete alternative plans.

9.5.7 Goal Attainment

The goal attainment method combines some of the advantages of both the weighting and constraint plan generation methods already discussed. If the participants are unable to specify these weights, the analyst must select them and then later change them on the basis of their reactions to the generated plans.

The goal attainment method identifies the plans that minimize the maximum weighted deviation of any objective value, $Z_j(\boldsymbol{X})$, from its specified target, T_j. The problem is to

$$\text{minimize D} \tag{9.21}$$

subject to

$$g_i(\boldsymbol{X}) = b_i \quad i = 1, 2, \ldots, m \tag{9.22}$$

$$w_j\left[T_j - Z_j(\boldsymbol{X})\right] \leq D \quad j = 1, 2, \ldots, J \tag{9.23}$$

Constraints 9.22 contain the relationships among the decision variables in the vector $\boldsymbol{X}$. They define the feasible region of decision variable values.

This method of multicriteria analysis can generate efficient or non-inferior plans by adjusting the weights and targets. It is illustrated for a two-objective problem in Fig. 9.16.

If the weights are equal, then the deviations will be equal and the resulting feasible solution will be the closest to the ideal but infeasible one. Unless $T_j \geq Z_j(\boldsymbol{X})$ some plans generated from a goal attainment method may be inferior with respect to the objectives being considered.

9.5.8 Goal Programming

Goal programming methods also require specified target values along with relative losses or penalties associated with deviations from these target values. The objective is to find the plan that minimizes the sum of all such losses or penalties. Assuming for this illustration that all such losses can be expressed as functions of deviations from target values, and again assuming each objective is to be maximized, the general goal programming problem is to

$$\text{minimize} \sum_j L_j(D_j) \tag{9.24}$$

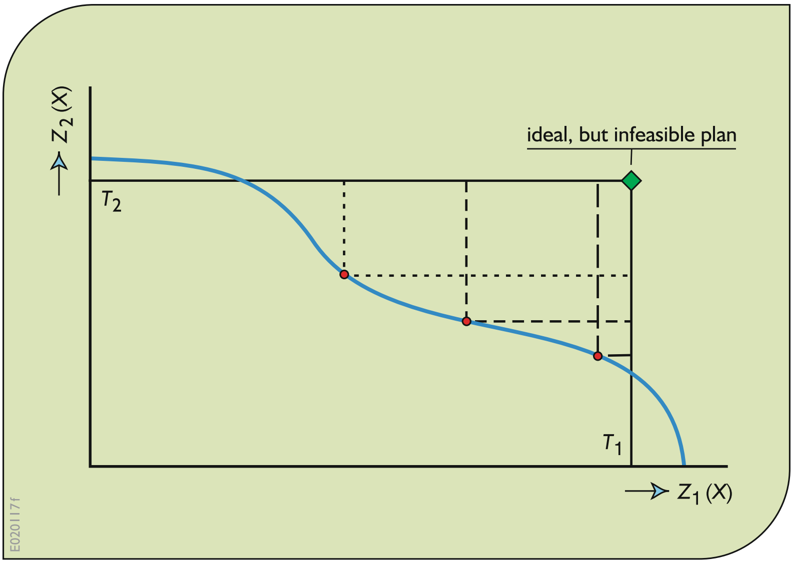
subject to:

$$g_i(\boldsymbol{X}) = b_i \quad i = 1, 2, \ldots, m \tag{9.25}$$

$$T_j - Z_j(\boldsymbol{X}) \leq D_j \quad j = 1, 2, \ldots, J \tag{9.26}$$

If the loss functions are linear or piecewise linear the model can be solved using linear programming methods. Again, the target and loss values can be changed to generate alternative plans $\boldsymbol{X}$.

Fig. 9.16 The goal attainment method of generating points on the efficiency frontier using different values of the weights w_1 and w_2 for fixed objective target values T_1 and T_2



9.5.9 Interactive Methods

Interactive methods allow participants in the planning process to explore the range of possible decisions without having to generate all of them, especially those of little interest to the participants.

One such iterative approach, called the step method, requires, at each iteration preference, information from the participants in the process. This information identifies constraints on various objective values. The weighting method is used to get an initial solution on the efficiency frontier. The weights, w_j, are calculated based on the relative range of values each objective j can assume, and on whether or not the participants have indicated satisfaction regarding a particular objective value obtained from a previous solution. If they are satisfied with the value of, say, an objective $Z_j(\boldsymbol{X})$, they must indicate how much of that value they would be willing to give up to obtain unspecified improvements in objectives whose values they consider unsatisfactory. This defines a lower bound on $Z_j(\boldsymbol{X})$. Then the weight w_j for that objective is set to 0, and the weights of all remaining objectives are recalculated. The problem is again solved. The process is repeated until some best compromise plan is identified.

This step method guides the participants in the planning and management process among non-inferior alternatives toward the plan or solution the participants consider best without requiring an exhaustive generation of all non-inferior alternatives. Even if the best compromise solution is not identified or agreed upon, the method provides a way for participants to learn what the tradeoffs are in the region of solutions of interest to them. However, the participants must be willing to indicate how much of some objective value can be reduced to obtain some unknown improvement of other objective values. This is not as easy as indicating how much more is desired of any or all objectives whose values are unsatisfactory.

To overcome this objection to the step method, other interactive methods have been developed. These begin with an obviously inferior solution. Based on a series of questions concerning how much more important it is to obtain various improvements of each objective, the methods proceed from that inferior solution to more improved solutions. The end result is either a solution everyone agrees is best, or an efficient one where no more improvements can be made in one objective without decreasing the value of another.

These iterative interactive approaches are illustrated in Fig. 9.17. To work, they require the participation of the participants in the planning and management process.

9.5.10 Plan Simulation and Evaluation

The methods outlined above provide a brief introduction to some of the simpler approaches available for plan identification and selection. Details on these and other potentially useful techniques can be found in many books, some of which are devoted solely to this subject of multiobjective planning (Cohon 1978; Steuer 1986). Most have been formulated in an optimization framework. This section describes ways of evaluating alternative water management plans or policies based on the time series of performance criteria values derived from simulation models.

Simulation models of water resource systems yield time series of output variable values. These values in turn impact multiple system performance criteria, each pertaining to a specific interest and measured in its appropriate units. A process for evaluating alternative water resource management plans or policies based on these simulation model results includes the following steps:

1. Identify system performance indicators that are impacted by one or more hydrologic attributes whose values will vary depending on the management policy or plan being simulated. For example, navigation benefits, measured in monetary units, might depend on water depths and velocities. Hydropower production is affected by water heads and

Fig. 9.17 Two interactive iterative multiple criteria approaches for identifying the tradeoffs of interest and possibly the best decision

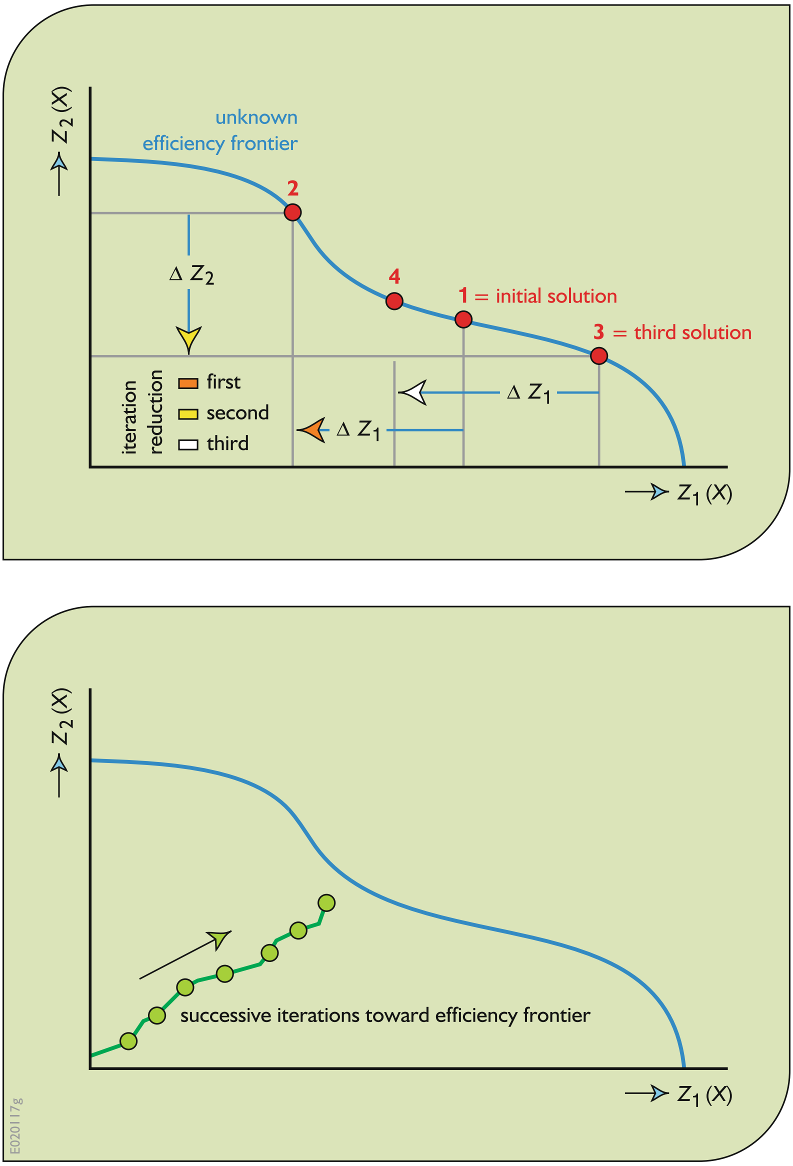
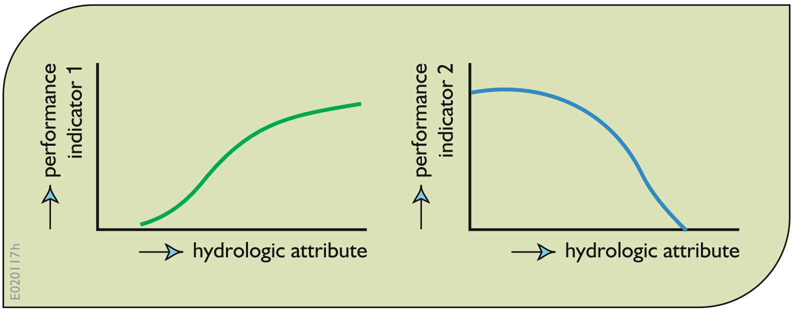


Fig. 9.18 Performance indicators expressed as functions of simulated hydrological attributes



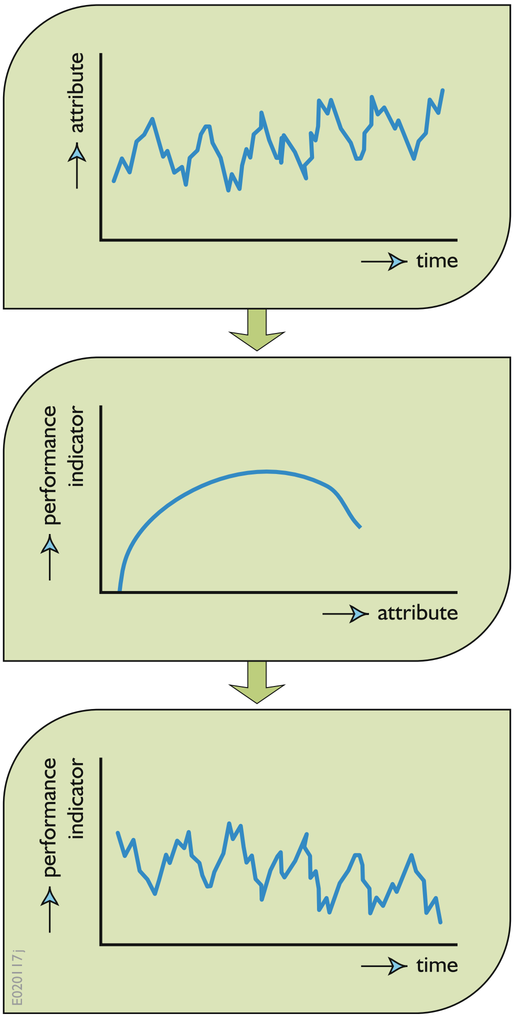


Fig. 9.19 Mapping a time series of hydrological attribute values into a corresponding time series of performance indicator values

discharges through the power plant. Water quality might be expressed as the average or maximum concentration of various potential pollutants over a fixed time period at certain locations, and will depend in part on the flows. Ecological habitats may be impacted by flows, water depths, water quality, flooding frequency or duration, and/or rates of changes in these attributes.

2. Define the functional relationships between these performance indicators and the hydrologic attributes. Figure 9.18 illustrates such functions. The units on each axis may differ for each such function.

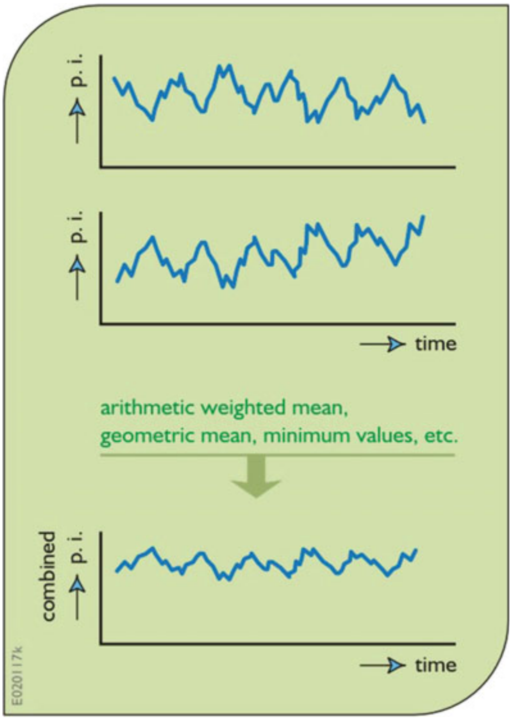


Fig. 9.20 Combining multiple time series of values of a specified performance indictor into a single time series of values of that performance indicator

3. Simulate to obtain time-series of hydrologic attribute values and map them into a time series of performance indicator values using the functional relationships defined in step 2. This step is illustrated in Fig. 9.19.
4. Combine multiple time series values for the same performance criterion, as applicable, as shown in Fig. 9.20. This can be done using maximum or minimum values, or arithmetic or geometric means, as appropriate. For example, flow velocities, depths, and algal biomass concentrations may impact recreational boating. The three sets of time series of recreational boating benefits or suitability can be combined into one time series, and statistics of this overall time series can be compared to similar statistics of other

performance indicators. This step gives the modeler an opportunity to calibrate the resulting single system performance indicator.

5. Develop and compare system performance exceedance distributions, or divide the range of performance values into color-coded ranges and display on maps or in scorecards, as illustrated in Fig. 9.21.

The area under each exceedance curve is the mean. Different exceedance functions will result from different water management policies, as illustrated in Fig. 9.22.

One can establish thresholds to identify discrete zones of performance indicator values and assign a color to each zone. Measures of reliability, resilience and vulnerability can then be calculated and displayed as well.

Scorecards can show the mean values of each indicator for any set of sites. The best value for each indicator can be colored green; the worst value for each indicator can be colored red. The water management alternative having the most number of green boxes will stand out and will probably be considered more seriously than the alternative having the most number of red (worst value) boxes.

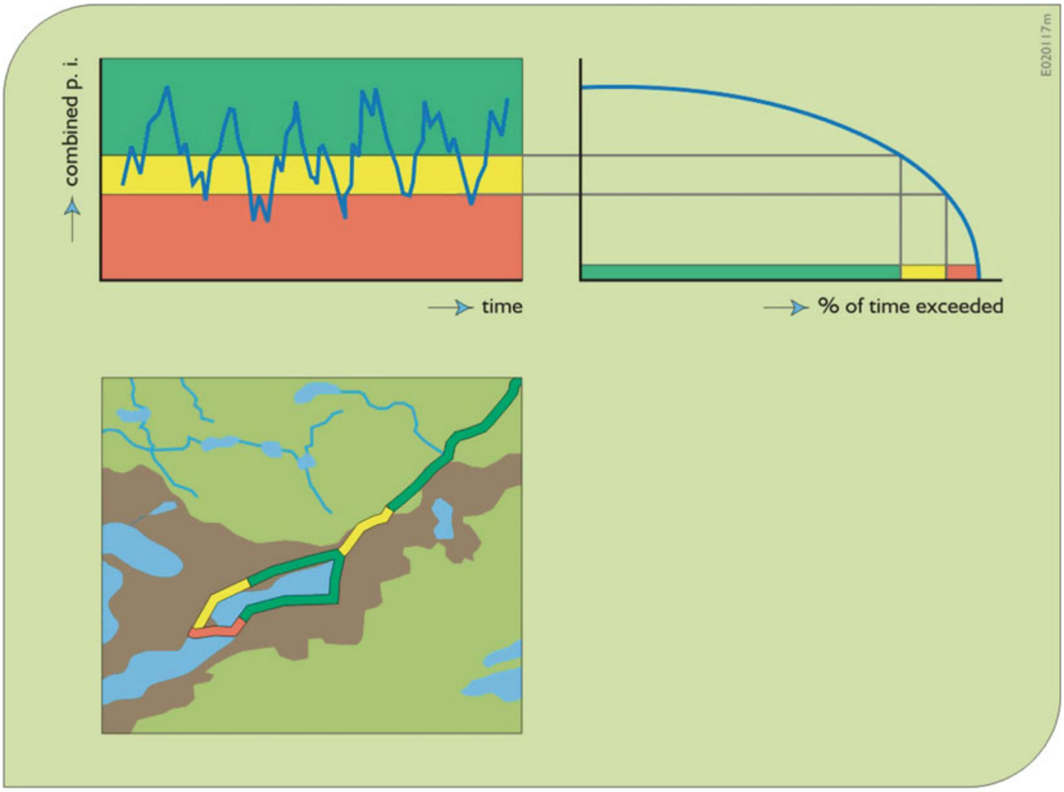
This five-step process has been used in a study of improved ways of managing lake levels and flows in Lake Ontario and its discharges into the St. Lawrence River in North America. Performance criteria were defined for domestic and industrial water supplies, navigation depths, shore bank erosion, recreational boating, hydropower production, flooding, water quality, ecological habitats. The performance measures for each of these interests were identified and expressed as functions of one or more hydrologic variable values related to flow and lake level management. Models designed to simulate alternative lake level and flow management policies were used to generate sets of time series for each system performance criterion. These in turn were combined, summarized and compared.

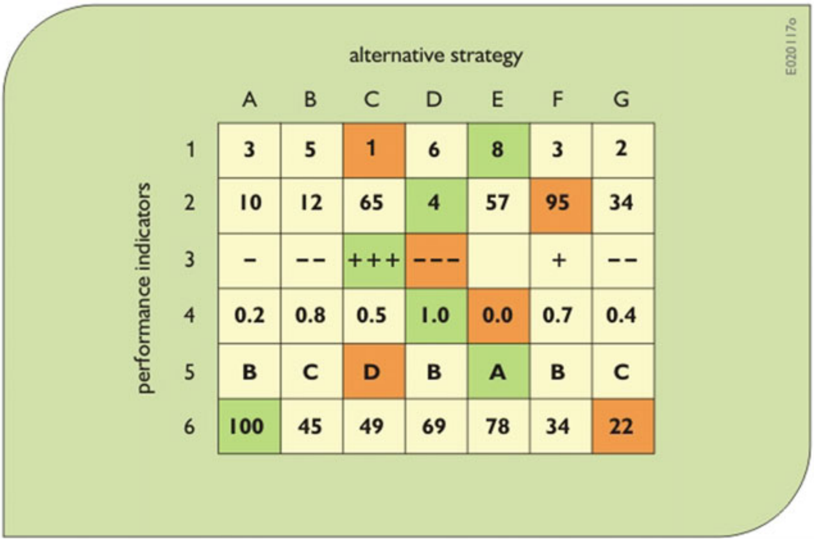
The same five-step process has been implemented in the Everglades restoration project in southern Florida. The Everglades is a long very wide and extremely flat ‘river of grass’ flowing generally south into, eventually, the Atlantic Ocean and Gulf of Mexico. This ecosystem restoration project has involved numerous local, state and federal agencies. The project impacts a large population and agricultural industry that want secure and reliable water supplies and flood protection. Its current estimated cost over some three decades is about $8 billon. Hence it involves politics. But its goal is primarily focused on restoring a unique ecosystem that is increasingly degraded due to extensive alterations in its hydrology over the past half-century.

The motto of the Everglades restoration project in south Florida is ‘to get the water right.’ Those who manage the region’s water are attempting to restore the ecosystem by restoring the hydrologic regime, i.e., the flows, depths, hydroperiods, and water qualities, throughout this region to what they think existed some 60 years ago. The trick is to accomplish this and still meet water supply, flood protection, and land development needs of those who live in the region. Clearly achieving a hydrologic condition that existed before people began populating that region in significant numbers will not be possible. Hence the question: what if water managers are not able to ‘get the water right?’ What if they can only get the water right on 90 % of the area, or what if they can only get 90 % of the water right on all the area? In either case what will be its likely impact on the ecosystem? Are there opportunities for changing hydrology to improve ecology? Where?

To address questions such as these in the Everglades, at least in a preliminary way prior to when more detailed ecological models will become available, this five-step approach outlined above is being applied. It is being used to extend their simulated hydrological predictions to produce relative values of ecological habitat suitability indicators for selected indicator species, as illustrated in Fig. 9.8, and topographic characteristics.

This five-step procedure does not find an ‘optimal’ water management policy. It can however contribute useful information to the political debate that must take place in the search of that





alternative strategy

performance indicators

	A	B	C	D	E	F	G
1	3	5	1	6	8	3	2
2	10	12	65	4	57	95	34
3	–	– –	+++	– – –		+	– –
4	0.2	0.8	0.5	1.0	0.0	0.7	0.4
5	B	C	D	B	A	B	C
6	100	45	49	69	78	34	22

Fig. 9.21 Ways of summarizing and displaying time series performance indicator data involving exceedance distributions, and color-coded maps and scorecards. Color-coded map displays on computers can be dynamic, showing changes over time. *Green* and *red* colored scorecard entries indicate best and worst plan or strategy, respectively, for associated performance indicator

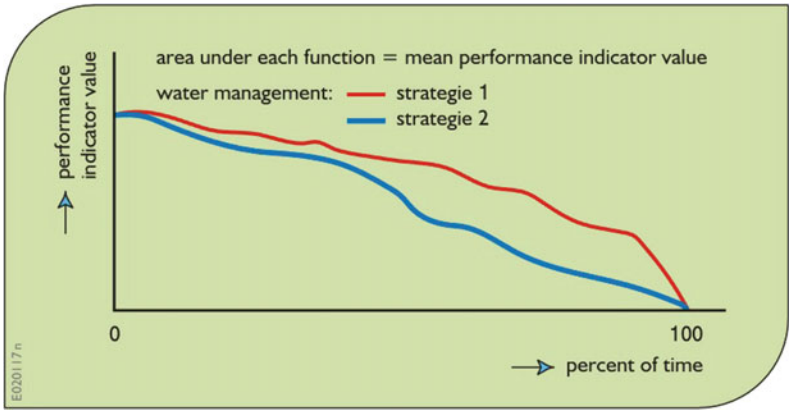


Fig. 9.22 Two exceedance functions showing decrease in mean performance value if policy 2 is followed compared to Policy 1

optimum. Each step of the approach can and should include and involve the various stakeholders and publics in the basin. These individuals are sources of important inputs in this evaluation process. Stakeholders who will be influencing or making water management decisions need to understand just how this multiobjective evaluation process works if they are to accept and benefit from its results. Stakeholder involvement in this process can help lead to a common understanding (or ‘shared vision’) of how their system works and the tradeoffs that exist among conflicting objectives. The extent to which all stakeholders understand this evaluation approach or procedure and how it is applied in their basin will largely determine their ability to participate effectively in the political process of selecting the best water management policy or practice.

9.6 Statistical Summaries of Performance Criteria

There are numerous ways of summarizing time series data in addition to the methods just mentioned above. Weighted arithmetic mean values or geometric mean values are two ways of summarizing multiple time series data. The overall mean itself generally provides too little information about a dynamic process. Multiple time series plots themselves are often hard to compare.

Another way to summarize and compare time series data is to calculate and compare the variance of the data.

Consider a time series of T values X_t whose mean is X. For example, suppose the time series consisted of 8, 5, 4, 9, 2, 1, 1, 3, 6, and 7. The mean of these 10 values is 4.6. The variance is

$$\begin{aligned}&\sum\nolimits_t^T (X_t - \underline{X})^2/T = \\ &\left[(8-4.6)^2 + (5-4.6)^2 + \ldots + (7-4.6)^2\right]/10 \\ &= 7.44\end{aligned} \tag{9.27}$$

A plot of these values and their mean is shown in Fig. 9.23.The mean and variance for the time series shown in Fig. 9.23 however are the same for its upside down image, as shown in Fig. 9.24. They do not even depend on the order of the time series data.

Consider these two sets of time series shown again in Fig. 9.25, each having the same mean and variance. Assume that any value equal or less than the dashed line (just above 2) is considered unsatisfactory. This value is called a threshold value, dividing the time series data into satisfactory and unsatisfactory values.

It is clear from Fig. 9.25 that the impact of these two time series could differ. The original time series shown in a red line remained in an unsatisfactory condition for a longer time than did the time series shown in blue. However, the

Fig. 9.23 Plot of time series data having a mean value of 4.6 and a variance of 7.44

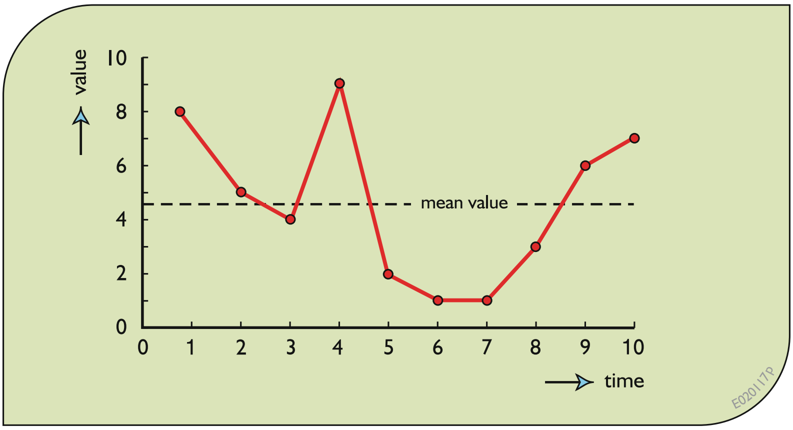


Fig. 9.24 A plot of two different time series having the same mean and variance

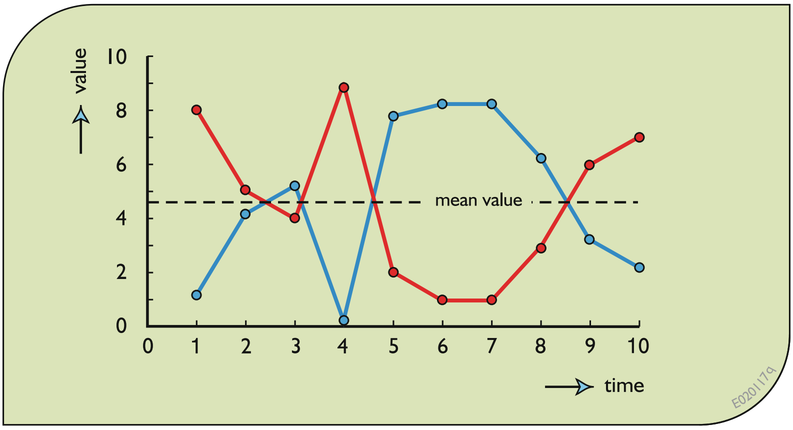
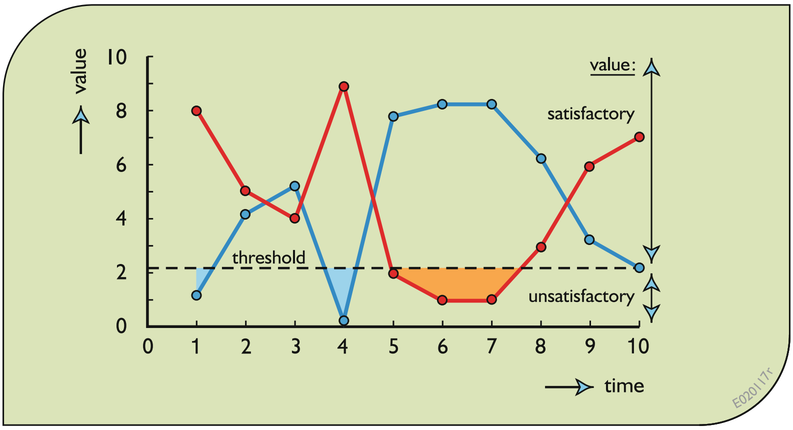


Fig. 9.25 Threshold value distinguishing values considered satisfactory, and those considered unsatisfactory



maximum extent of failure when it, the red series, failed was less than the blue time series. These characteristics can be captured by the measures of reliability, resilience and vulnerability (Hashimoto et al. 1982).

9.6.1 Reliability

The reliability of any time series can be defined as the number of data in a satisfactory state divided by the total number of data in the time series. Assuming satisfactory values in the time series X_t containing n values are those equal to or greater than some threshold X^T, then

$$\text{Reliabilty}[\boldsymbol{X}] = [\text{number of time periods } t \text{ such that } X_t \geq X^T]/n \tag{9.28}$$

The reliability of the red time series is 0.7. It failed three times in 10. The reliability of the blue time series is also 0.7, failing three times in 10.

Is a more reliable system better than a less reliable system? Not necessarily. Reliability measures tell one nothing about how quickly a system recovers and returns to a satisfactory value, nor does it indicate how bad an unsatisfactory value might be should one occur. It may well be that a system that fails relatively often, but by insignificant amounts and for short durations will be preferred to one whose reliability is much higher, but when a failure does occur, it is likely to be much more severe. Resilience and vulnerability measures can provide measures of these system characteristics.

9.6.2 Resilience

Resilience can be expressed as the probability that if in an unsatisfactory state, the next state will be satisfactory. It is the probability of having a satisfactory value in time period t + 1 given an unsatisfactory value in any time period t. It can be calculated as

$$\text{Resilience}[\boldsymbol{X}] = [\text{number of times a satisfactory value follows an unsatisfactory value}]/[\text{number of times an unsatisfactory value occurred}] \tag{9.29}$$

Resilience is not defined if no unsatisfactory values occur in the time series. For the time series shown in red, the resilience is 1/3, again assuming the value of 2 or less is considered a failure. For the time series shown in blue the resilience is 2/2 = 1. We cannot judge the resilience of the blue time series based on the last failure in period 10 because we do not have an observation in period 11.

9.6.3 Vulnerability

Vulnerability is a measure of the extent of the differences between the threshold value and the unsatisfactory time series values. Clearly this is a probabilistic measure. Some use expected values, some use maximum observed values, and others may assign a probability of exceedance to their vulnerability measures. Assuming an expected value measure of vulnerability is to be used

$$\text{Vulnerability}[\mathbf{X}] = \left[\text{sum of positive values of} \left(X^T - X_t\right)\right] /[\text{number of times an unsatisfactory value occurred}] \tag{9.30}$$

The expected vulnerability of the original red time series is [(2 − 2) + (2 − 1) + (2 − 1)]/3 = 0.67. The expected vulnerability of the time series shown by the blue line in Fig. 9.25 is [(2 − 1.2) + (2 − 0.2)]/2 = 1.3.

So, while in this example the reliability of red time series equals that of the blue time series, the resilience of the blue time series is better than that of the red time series. Yet the expected vulnerability of the red time series is less than that of the rotated blue time series. This shows the typical tradeoffs one can observe using these three measures of system performance.

9.7 Conclusions

Many theoretical and practical approaches have been proposed in the literature for identifying and quantifying objectives and for considering multiple criteria or objectives in water resources planning. The discussion and techniques presented in this chapter serve merely as an introduction to this subject. These tools, including their modifications and extensions, are designed to provide information that can be of value to the planning and decision-making process.

Water resource systems planners and managers and the numerous other participants typically involved in decision-making face a challenge when they are required to select one of many alternatives, each characterized by different values among multiple performance criteria. It requires a balancing of the goals and values of the various individuals and groups concerned with the project. There is virtually no way in which the plan selection step can be a normative process or procedure; there can be no standard set of criteria or methods which will identify the preferred project. At best, an iterative procedure in which those using tools similar to those described in this chapter together with all the interested stakeholders may reach some shared vision of what is best to do, at least until conditions change or new knowledge or new goals or new requirements emerge. This may be the only way to identify a plan that is politically as well as technically, socially, financially, and institutionally feasible.

To many participants in the planning process some of these approaches for objective quantification and multiobjective planning may seem theoretical or academic. Many may be reluctant to learn quantitative policy analysis techniques or to spend time answering seemingly irrelevant questions that might lead eventually to a "compromise" plan. Reluctance to engage in quantification of tradeoffs among particular objectives of alternative plans, and by implication tradeoffs among the interests of multiple stakeholder groups, may stem from the support decision-makers desire from all of these conflicting interest groups. In such situations it is obviously to their advantage not to be too explicit in quantifying political values. They might prefer that the "analyst" make these tradeoffs and just not discuss them. (We writers have participated in such situations.) Planners, engineers, or analysts are often very willing to make these tradeoffs because they pertain to subject areas in which they often consider themselves expert. However when political tradeoffs are at issue, no one is an expert. No one has the 'optimal' answer, but professionals should be engaged in and informing and facilitating the process of coming to an acceptable, and often compromise, decision.

Through further development and use of practical analytical multiobjective planning techniques, analysts can begin to interact with all participants in the planning and management process and can enlighten any who would argue that water resources policy evaluation and analyses should not be political. Analysts, managers and planners have to work in a political environment. They need to understand the process of decision-making, what information is most useful to that process, and how it can best be presented. Knowledge of these facts in a particular planning situation might dictate substantially the particular approach to objective identification and quantification and to plan selection that is most appropriate.

The method deemed most appropriate for a particular situation will depend not only on the physical scale of the situation itself but also on the decision-makers, the decision-making process, and the responsibilities accepted by the analysts, the participants, and the decision-makers.

Finally, a reminder that the decisions being made at the current time are only those in a sequence of decisions that will continue to be made on into the future. No one can predict with certainty what future generations will consider as being important or what they will want to do, but spending some time trying to guess is not an idle exercise. It pays to plan ahead, as best one can, and ask ourselves if the decisions being considered today will be those we think our descendants would have wanted us to make. This kind of thinking gets us into issues of adaptive management and sustainability (ASCE 1999).

References

American Society of Civil Engineers (ASCE). (1999). Sustainability criteria for water resource systems, ASCE Press, Reston, Va. (also in D. P. Loucks & J. S. Gladwell (Eds.), 2000. Cambridge, UK: Cambridge University Press.

Cohon, J. L. (1978). *Multiobjective programming and planning*. New York: Academic Press.

Gregory, R. S., & Keeney, R. L. (1994). Creating policy alternatives using stakeholder values. *Management Science, 40*, 1035–1048.

Hammond, J. S., Keeney, R. L., & Raiffa, H. (1999). *Smart choices: A practical guide to making better decisions*. Boston, Mass: Harvard Business School Press.

Hipel, K. W., Fang, L., Cullman, J., & Bristow, M. (Eds.). (2015). *Conflict resolution in water resources and environmental management, conflict resolution in water resources and environmental management*. Heidelberg, New York, Dordrecht, London: Springer Cham.

Madani, K. (2010). Game theory and water resources. *Journal of Hydrology, 381*(3), 225–238.

Madani, K., & Hipel, K. W. (2011). Non-cooperative stability definitions for strategic analysis of generic water resources conflicts. *Water Resources Management, 25*(8), 1949–1977.

Steuer, R. E. (1986). *Multiple criteria optimization: Theory, computation, and application*. New York: Wiley.

Additional References (Further Reading)

Chen, H. W., & Chang, N.-B. (1998). Water pollution control in the river basin by fuzzy genetic algorithm-based multiobjective programming modeling. *Water Science and Technology, 37*(8), 55–63.

Cieniawski, S. E., Eheart, J. W., & Ranjithan, S. (1995). Using genetic algorithms to solve a multiobjective groundwater monitoring problem. *Water Resources Research, 31*(2), 399–409.

Eschenauer, H., Koski, J., & Osyczka, A. (1990). *Multicriteria design optimization*. Berlin: Springer-Verlag.

Gupta, H. V., Sorroshian, S., & Yapo, P. O. (1998). Towards improved calibration of hydrologic models: Multiple and non-commensurable measures of information. *Water Resources Research, 34*(4), 751–763.

Haimes, Y. Y., Hall, W. A., & Freedman, H. T. (1975). *Multiobjective optimization in water resources systems*. Amsterdam: Elsevier Scientific.

Halhal, D., Walters, G. A., Ouazar, D., & Savic, D. A. (1997). Multi-objective improvement of water distribution systems using a structure messy genetic algorithm approach. *Journal of Water Resources Planning and Management ASCE, 123*(3), 137–146.

Hashimoto, T., Stedinger, J. R., & Loucks, D. P. (1982a). Reliability resiliency and vulnerability criteria for water resource system performance evaluation. *Water Resources Research, 18*(1), 14–20.

Hashimoto, T., Loucks, D. P., & Stedinger, J. R. (1982b). Robustness of water resource systems. *Water Resources Research, 18*(1), 21–26.

Keeney, R. L., & Raiffa, H. (1976). *Decisions with multiple objectives: Preferences and value tradeoffs*. New York: Wiley.

Loucks, D. P., Stedinger, J. R., & Haith, D. A. (1981). *Water resource systems planning and analysis*. Englewood Cliffs, NJ: Prentice Hall.

Maas, A., et al. (1962). *Design of water resource systems*. Cambridge: Harvard University Press.

Reed, P. M., Minsker, B. S., & Goldberg, D. E. (2001). A multiobjective approach to cost effective long-term groundwater monitoring using an elitist nondominated sorted genetic algorithm with historical data. *Journal of Hydroinformatics, 3*(2), 71–89. April.

Ritzel, B. J., Eheart, J. W., & Ranjithan, S. (1994). Using genetic algorithms to solve a multiple objective groundwater pollution containment problem. *Water Resources Research, 30*(5), 1589–1603. May.

Sawaragi, Y., Nakayama, H., & Tanino, T. (1985). *Theory of multiobjective optimization*. Orlando, Florida: Academic Press Inc.

Statnikov, R. B., & Matusov, J. B. (1995). *Multicriteria optimization and engineering*. New York: Chapman and Hall.

Yeh, C.-H., & Labadie, J. W. (1997). Multiobjective watershed-level planning of storm-water detention systems. *Journal of Water Resources Planning and Management, 123*(6), 336–343. November/December.

Zeleny, M. (1982). *Multiple criteria decision making*. New York: McGraw-Hill.

Exercises

9.1 Distinguish between multiple purposes and multiple objectives and give some examples of complementary and conflicting purposes and objectives of water resources projects.

9.2 Assume that farmers' demand for water q is a linear function $a - b(p)$ of the price p, where $a,\ b > 0$. Calculate the farmers' willingness to pay for a quantity of water q. If the cost of delivering a quantity of water q is cq, $c > 0$, how much water should a public agency supply to maximize willingness to pay minus total cost? If the local water district is owned and operated by a private firm whose objective is to maximize profit, how much water would they supply and how much would they earn? The farmers' consumer surplus is their willingness to pay minus what they must pay for the resource. Compare the farmers' consumer surplus in two cases. Do the farmers loose more than the private firm gains by moving from the social optimum to the point that maximizes the firm's profit? Illustrate these relationships with a graph showing the demand curve and the unit cost *c* of water. Which areas on the graph represent the firm's profits and the farmers' consumer surplus?

9.3 Consider the water allocation problem used in the earlier chapters of this book. The returns, $B_i(X_i)$ from allocating X_i amount of water to each of three uses *i* are as follows, along with the optimal allocations from the point of view of each use.

$$\begin{aligned}
B_1(X_1) &= 6X_1 - X_1^2 && \rightarrow && X_1^{\text{opt}} = 3 \\
& && \text{and} && B_1^{\max} = B_1\left(X_1^{\text{opt}}\right) = 9 \\
B_2(X_2) &= 7X_2 - 1.5X_2^2 && \rightarrow && X_2^{\text{opt}} = 7/3 \\
& && \text{and} && B_2^{\max} = B_2\left(X_2^{\text{opt}}\right) = 147/18 \\
B_3(X_3) &= 8X_3 - 0.5X_3^2 && \rightarrow && X_3^{\text{opt}} = 8 \\
& && \text{and} && B_3^{\max} = B_3\left(X_3^{\text{opt}}\right) = 32
\end{aligned}$$

Consider this a multiobjective problem. Instead of finding the best overall allocation that maximizes the total return assume the objectives are to maximize the returns from each user.

Show how the weighting, constraint, goal attainment, and goal programming methods can be used to identify the tradeoffs among each of the three objectives for any limiting total amount of water, for example, 6.

9.4 Under what circumstances will the weighting and constraint methods fail to identify efficient solutions?

9.5 A reservoir is planned for irrigation and low flow augmentation for water quality control. A storage volume of 6×10^6 m^3 will be available for those two conflicting uses each year. The maximum irrigation demand (capacity) is 4×10^6 m^3. Let X_1 be the allocation of water to irrigation and X_2 the allocation for downstream flow augmentation. Assume that there are two objectives, expressed as

$$Z_1 = 4X_1 - X_2$$
$$Z_2 = -2X_1 + 6X_2$$

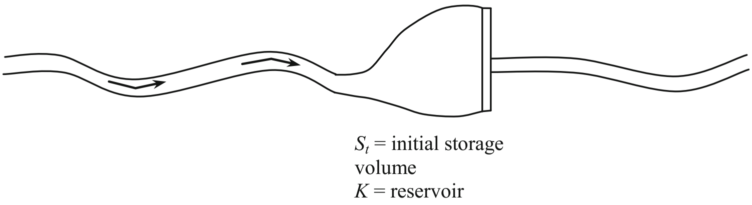
(a) Write the multiobjective planning model using a weighing approach and a constraint approach.

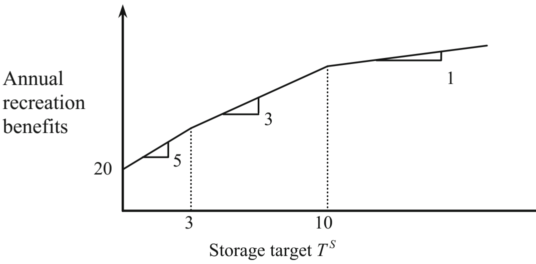
(b) Define the efficient frontier. This requires a plot of the feasible combinations of X_1 and X_2.

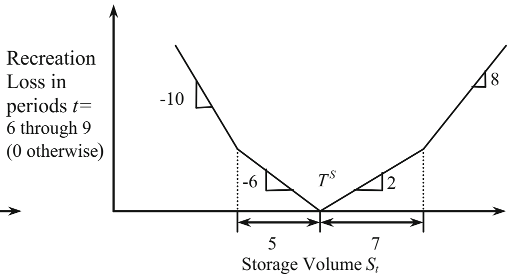
(c) Assume that various values are assigned to a weight W_1 for Z_1 whereas weight W_2 for Z_2 is constant and equal to 1, verify the following solutions to the weighing model.

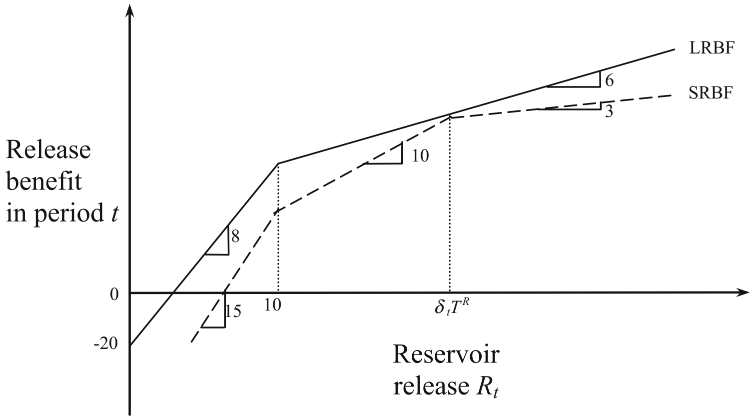
W_1	X_1	X_2	Z_1	Z_2
>6	4	0	16	−8
6	4	0 to 12	16 to 14	−8 to 4
<6 to >1.6	4	2	14	4
1.6	4 to 0	2 to 6	14 to −6	4 to 36
<1.6	0	6	−6	36

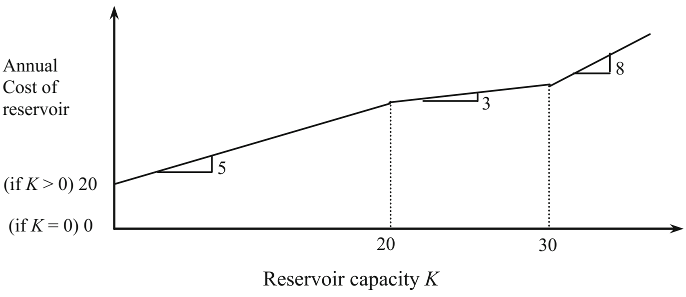
9.6 Show that the following benefit, loss, and cost functions can be included in a linear optimization problem for finding the active storage volume target T^s, annual release target T^R and the actual storage releases R_t in each within-year period *t*, and the reservoir capacity *K*. The objective is to maximize annual net benefits from the construction and operation of the reservoir. Assume that the inflows are known in each of 12 within-year periods *t*. Note that the loss function associated with reservoir recreation is independent of the value of T^s, unlike the loss function associated with reservoir releases. Structure the complete linear programming model. Define all variables used that are not defined below. Let $\delta_t T^R$ be the known release target in period t.



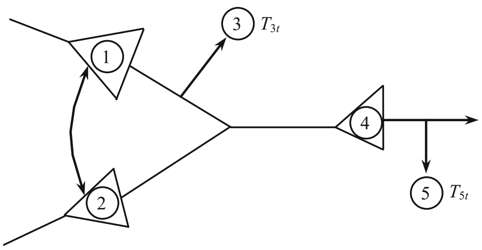








9.7 For the river basin shown, potential reservoirs exist at sites $i = 1$, 2, and 4 and a diversion can be constructed between sites 1 and 2. The cost $C_i(K_i)$ of each reservoir i is a function of its active storage capacity K_i. The cost of the diversion canal is $C_i(Q_i)$ where Q is the flow capacity of the canal. The cost of diverting a flow Q_{ijt} from site i to site j is $C_{ij}(Q_{ijt})$. The two users at sites 3 and 5 have known target allocations (demands) T_{it} in each period t. The return flow from use 3 is 40 % of that allocated to use 3. Construct a model for finding the least cost of meeting various percentages of the target demands. Assume that the natural streamflows Q_t^i at each site i in each period t, are known.



9.8 Suppose that there exist two polluters, A and B, who can provide additional treatment, X_A and X_B, at a cost of $C_A(X_A)$ and $C_B(X_B)$, respectively. Let W_A and W_B be the waste produced at sites A and B, and $W_A(1 - X_A)$ and $W_B(1 - X_B)$ be the resulting waste discharges at site A and B. These discharges must be no greater than the effluent standards $E_{\text{A}}^{\max}$ and $E_{\text{B}}^{\max}$. The resulting pollution concentration $a_{\text{A}j}(W_A(1 - X_A)) + a_{\text{B}j}(W_B(1 - X_B)) + q_j$ at various sites j must not exceed the stream standards $S_j^{\max}$. Assume that total cost and cost inequity [i.e., $C_A(X_A) + C_B(X_B)$ and| $C_A(X_A) - C_{\text{B}}(X_{\text{B}})$] are management objectives to be determined

(a) Discuss how you would model this multiobjective problem using the weighting and constraint (or target) approaches.

(b) Discuss how you would use the model to identify efficient, non-inferior (Pareto-optimal) solutions.

(c) Effluent standards at sites A and B and ambient stream standards at sites j could be replaced by other planning objectives (e.g., the minimization of waste discharged into the stream). What would these objectives be, and how could they be included in the multiobjective model?

9.9 (a) What conditions must apply if the goal attainment method is to produce only non-inferior alternatives for each assumed target T_k and weight w_k?

(b) Convert the goal programming objective deviation components $w_{\text{i}}\ (z_i^* - z_i(\bar{x}))$ to a form suitable for solution by linear programming.

9.10 Water quality objectives are sometimes difficult to quantify. Various attempts have been made to include the many aspects of water quality in single water quality indices. One such index was proposed by Dinius (Social Accounting Systems for Evaluating Water Resources, Water Resources Research, Vol. 8, 1972. pp. 1159–1177). Water quality, Q, measured in percent is given by

$$Q = \frac{w_1 Q_1 + w_2 Q_2 + \ldots + w_n Q_n}{w_1 + w_2 + \ldots + w_n}$$

where Q_i is the ith quality constituent (dissolved oxygen, chlorides, etc.) and w_i is the weight or relative importance of the ith quality constituent. Write a critique on the use of such an index in multiobjective water resources planning.

9.11 Let objective $\text{Z}_1(\boldsymbol{X}) = 5X_{1-2}X_2$ and objective $\text{Z}_2(\boldsymbol{X}) = -X_1 + 4\ X_2$. Both are to be maximized. Assume that the constraints on variables X_1 and X_2 are:

1. $-X_1 + X_2 \leq 3$
2. $X_1 \leq 6$
3. $X_1 + X_2 \leq 8$
4. $X_2 \leq 4$
5. $X_1, X_2 \geq 0$

(a) Graph the Pareto-optimal or non-inferior solutions in decision space.

(b) Graph the efficient combination of Z_1 and Z_2 in objective space.

(c) Reformulate the problem to illustrate the weighting method for defining all efficient solutions of part (a) and illustrate this method in decision and objective space.

(d) Reformulate the problem to illustrate the constraint method of defining all efficient solutions of part (a) and illustrate this method in decision and objective space.

(e) Solve for the compromise set of solutions using compromise programming as defined by

$$\text{Minimize } \left[w_1\left(Z_1^* - Z_1\right)^{\alpha} + w_2\left(Z_2^* - Z_2\right)^{\alpha}\right]^{1/\alpha}$$

where Z_i* represents the best value of objective *i* with all weights *w* equal to 1 and α equal to 1, 2, and ∞.

9.12 Illustrate the procedure for selecting among three plans, each having three objectives, using indifference analysis. Let Z_{ji} represent the value of objective *i* for plan *j*. The values of each objective for each plan are given below. Assume that each objective is to be maximized. Assume that an identical indifference function for all trade-offs between pairs of objectives, namely one that implies you are willing to give up twice as many units of your higher (larger) objective value to gain one unit of your lower (smaller) objective value. [For example, you would be indifferent to two plans having as their three objective values (30, 5, 10) and (20, 5, 15).] Rank these three plans in order of preference.

$$\text{Plan 1}: (5,\ 25,\ 15);$$
$$\text{Plan 2}: (10,\ 20,\ 10);$$
$$\text{Plan 3}: (15,\ 10,\ 15)$$