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A MULTICRITERION APPROACH TO SETTING INSTREAM FLOW STANDARDS*

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ABSTRACT

This article conceptualizes the task of setting instream flow standards as a multicriterion problem, and discusses the development of the multicriterion approach into a general instream flow standard methodology. Although designed to be of general applicability, the approach is motivated by circumstances in Hawaii whose Commission on Water Resource Management has been charged with setting such standards, potentially for more than 360 perennial streams. The procedure integrates the use of value trees, interactive multiobjective programming, multiattribute assessment, and possibly voting methods.

1. INTRODUCTION

Nearly every part of the world depends to some degree on streams and rivers to satisfy water needs. Using water for drinking, farming, and manufacturing normally requires its diversion or extraction from the stream channel. Other uses require water to be kept in the stream. These include: swimming, boating, and other forms of aquatic recreation; artisanal and commercial fishing; waste dilution; maintenance of habitat for both plants and animals; hydroelectric power

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generation; navigation and the transport or conveyance of products (e.g., floating of logs); practice of ceremonies and other traditional and customary activities; and maintenance and management of fluvial-geomorphological processes (e.g., floodplain maintenance and bank stabilization). Many such uses might better be termed "environmental services," some of which are rendered when streamflow periodically *leaves the channel* under the natural process of flooding. Such instream uses and services compete with diversions for the limited streamflow, and deciding how much to leave in the channel is a crucial and challenging task facing water managers. This has come to be know as the *instream flow (IF) problem* and the amount in question is referred to as the *instream flow standard (IFS).*

The purpose of this article is to cast the IF problem in a multicriterion decision-making (MCDM) framework and to present and discuss a generic MCDM methodology useful in determining IF standards. The methodology is generic because it is designed to respond to several aspects of the IF problem found everywhere, such as stochastic and indeterminate uncertainty and its general resource-allocation structure. However, setting an IF standard is specific to a particular place and (usually, though not always) stream and is a public-sector task. This means the decision-making context should play an important role in fashioning the methodology to employ. The next section, then, identifies several important characteristics of the general IF problem and raises a number of issues which may be primarily context-specific. Among the latter are several questions which have arisen in Hawaii, and those discussed here are meant to illustrate the issues rather than describe or comment on the peculiarities of the Hawaiian situation. Section 3 then presents the methodology, identifies and discusses several methods which may be utilized for its different tasks, and indicates various issues and situations which must be considered carefully in an actual application. The final section enumerates a number of factors likely to determine the ultimate effectiveness of the methodology.

2. CHARACTERISTICS OF THE INSTREAM FLOW PROBLEM

At least four general features seem to characterize the IF problem wherever it occurs. First, it is a multiobjective, multiparty resource-allocation problem. In deciding how to allocate streamflow between instream uses and diversions, as well as among the out-of-channel uses themselves, one considers factors running from cost, revenues, and other economic concerns, to the benefits and harms that may befall certain species and ecosystems, social and cultural groups, and particular regions or economic sectors. Consequences may also be assessed with respect to the time period(s) in which they can be expected. For example, additional waste-dilution capacity might be more desirable in one season than in another, and additional revenues might be preferred sooner rather than later. Not only does each person view some consequences as more important than others, but different parties have different opinions about the relative importance that each consequence should be given. Indeed, the parties may not even agree on the effects that should be considered. Thus, different allocations will lead to conflicts among uses and the objectives associated with them, giving rise to conflicts among the parties promoting those uses.

A second characteristic of the general IF problem is uncertainty. Streamflow is a random process, and since it can only be predicted probabilistically, the same often holds for many of the uses and services dependent on it, such as irrigation flows, hydropower generation, and waste dilution. For some streams, the predicted flow will lie within a very narrow interval for any given confidence level. For others, basic morphology can interact with hydrologic processes to produce highly variable streamflow regimes, for which precise predictions cannot be made with any degree of confidence. Most streams are not gaged, however, and what data there may be is often inaccurate, imprecise, sporadic, of limited historical coverage, or otherwise insufficient for statistical analyses. In such cases, the probabilistic predictions are of little use or reliability, and the situation tends toward one of nonstochastic (indeterminate) uncertainty. Other common sources of indeterminacy are relationships between streamflow and habitat and between streamflow and climate change, and the legal status of water rights and customary practices in the light of new actions or developments in a particular place. Such developments include diversions, the discharge of unregulated substances, or the effect on water rights when some stream biota are declared "endangered," "threatened," or otherwise ecologically significant.

Uncertainty regarding the hydrologic system and its relationship to aquatic biota is especially pronounced in the tropics. Many species have yet to be identified or studied, and, especially on tropical islands, endemism is high. Precipitation regimes characterized by frequent and intense showers of short duration give a flashy and highly variable character to streamflow. Where coinciding with short, steep watersheds, typical for volcanic islands, this variability can be immense, with the very frequent discharge "spikes" commonly exceeding base flows by an order of magnitude or more. In places like the Hawaiian islands, the effects of, and impacts upon, such variability are important aspects of the IF problem. Although relatively little is known about its significance for the ecology of aquatic biota, the marked variability is thought to be important in the life cycle of some species. Some fishes, for example, move farther upstream than normal during the brief periods of torrential flow (so-called "freshets"), and may engage in certain functions (e.g., spawning) only or primarily during those times. It has been shown that even small diversions significantly alter flow variability, modifying the absolute and relative frequencies, timing, and duration of peaks of different magnitudes [1]. The likely effects of such changes are largely unknown.

Another feature of the IF problem is that it is a public-sector problem, and the institutional and administrative apparatus have had difficulty in developing structures and procedures to deal with it effectively. The responsibilities and jurisdictions of different governmental agencies concerned with the problem are typically poorly defined and articulated, leading to contradictory policies, rules and regulations, prescribed processes, and sometimes even laws themselves. In Hawaii, for example, IF protection is affected by the interpretation and enforcement of riparian water rights, and interpretations vary in accord with which of two doctrines is most closely followed: a *natural flow* doctrine requiring riparian uses to maintain a stream's natural flow without "substantial" changes in its magnitude and dynamics; and a *reasonable flow* doctrine that requires uses to be "reasonable." Although neither "substantial" nor "reasonable" are quantified in the legal code, evaluation of competing claims or proposals requires some degree of quantification. For instance, the State Water Code mandates the weighing of the relative importance of instream versus out-of-channel uses, thus implying the consideration of tradeoffs and support for the "reasonable flow" perspective. In addition to these different views on riparianism, a decision in a landmark Hawaii court case invoked a *public-use doctrine* by holding that not only the riparians' rights and uses, but also the public interest should be considered in determining water-rights protection and water-use allocation. How and by whom such interests should be considered can vary: in some places and situations, a single agency head may render an executive decision, while decisions in others may be made through public meetings or referenda. In Hawaii, it is the responsibility of the State's Commission on Water Resources Management to define reasonable and beneficial uses, to establish criteria for water-use priorities, and to assure existing riparian rights. All these tasks depend on a stream's "instream resources" and "instream values," terms used in the State Water Code, yet no formal administrative procedure exists for identifying them. To be effective for the general IF problem, a methodology must be able to deal with such institutional contexts.

Finally, setting instream flow standards must also deal with potential conflicts between local and nonlocal interests. This is often just another case of inter-party conflict, but with a spatial dimension. A stream and its watershed define a local area, and the likely benefits and costs accruing to that basin under a given streamflow allocation may be of little significance to outsiders contemplating the expected payoffs for their areas. For example, local irrigation water may be sacrificed to maintain the instream flow needed to generate hydroelectric power, some or all of which will be exported out of the watershed. Such cases display distributional effects and raise questions about local sovereignty and social, sectoral, and spatial equity.

Local-nonlocal conflicts can also arise from concerns about scale. Suppose a stream has a large and robust population of an endemic, threatened, or otherwise biologically significant species found in only a few if any other places. A diversion or instream use that would yield handsome benefits for some purposes and would only threaten a small portion of the species' habitat might be quite acceptable to local interests. A broader, "global" perspective may well trigger opposition, however. That the species is already in some degree of jeopardy could suggest to some, locals and outsiders alike, that ecological limits are near, and that any further loss of habitat would be unethical and could propel the species across the sustainability threshold. Similar reasoning could be (and has been) applied to questions relating to cultural sustainability, when for example ever further sacrifices are demanded of ethnic minorities or indigenous peoples already decimated by modernity and sociocultural and economic homogenization. This perspective may give rise to "no-further-concessions" postures in which no tradeoff whatsoever would be acceptable. As Daly has pointed out, sustainability relates to questions of scale while equity and fairness relate to questions of distribution [2]. Conflicts due to scale issues are qualitatively different from those arising from questions of distribution.

3. TOWARD A METHODOLOGY FOR SETTING INSTREAM FLOW STANDARDS

To be effective for the general IF problem, a decision-support methodology should be able to deal with the types of issues and concerns discussed above: its multiobjective, multiparty character; stochastic and indeterminate uncertainty; public-sector decision making amidst institutional deficiencies; and local-global conflicts and the problem of scale. The following methodology, utilizing both multicriterion optimization and discrete evaluation methods, has the potential to address such problems.

3.1 The Methodology

The general methodology consists of six tasks, conducted more or less sequentially but with the possibility, and likelihood, of iteration among them.

Task 1. Identify parties at interest and elicit and articulate their concerns.

Task 2. Measure the consequences with respect to each concern resulting from changes in streamflow allocation.

Task 3. Formulate a baseline multiobjective programming model of the streamflow-allocation problem.

Task 4. Formulate and use an operational form of the baseline model to design one or more candidate IF standards.

Task 5. Screen out undesirable IF standards. If none are left, return to Task 4.

Task 6. Evaluate the IF standard(s) remaining from Task 5, and
  (a) Select one as the standard to adopt; or
  (b) Select two or more among which to identify a compromise standard to adopt; or
  (c) Select one or more as seeds from which to generate new candidates and return to step 4.

3.2 Discussion and Elaboration

Each of the above tasks can be executed in a number of different ways, with context making some approaches preferred over others.

3.2.1 Task 1: Identifying Parties and Their Concerns

In almost any problem, and especially in public problems, this is probably the most difficult task to execute well and indisputably the most crucial: omitting or misrepresenting concerns can lead to the "type 3 error" of solving the wrong problem. A number of methods for group decision making can be adapted for public-sector application [3-6], and the institutional and other dimensions of the decision-making context will indicate which have the most potential. Construction and use of objectives hierarchies, or values trees [7-12], are particularly helpful and have seen application to related problems involving biotic conservation and estuarine management [13-16]. In the hierarchical structures which result, general, high-order but vague goals and concerns are disaggregated into a set of more specific, lower-order criteria capable of being measured and which, collectively, can depict how well each general concern or goal is satisfied. Another procedure that has been used to elicit concerns and objectives in the water-resources arena, and could be very useful in this phase of the analysis, is the Nominal Group Technique [5, 17].

3.2.2 Task 2: Measuring Consequences

In this step, one tries to assess how well any given streamflow will satisfy the lowest-level elements of the objectives hierarchy. This is a measurement problem, and the value measured for each criterion is here termed its *criterion score*. These scores will be used as coefficients in the multiobjective programs in Tasks 3 and 4. Such scores can be in "natural" units or in value units, the latter usually called *value* or *utility scores* when they range between 0 and 1.0 and are measured on an artificial scale developed for that purpose. (One exception to this dichotomy is money, an "intermediate" value unit that through almost universal use has apparently come to be considered a "natural" unit. "Intermediate" refers to the fact that amount of money is rarely synonymous with its (context-specific) worth, and that monetary levels can thus in turn be mapped onto the 0-to-1 interval through value transformations.) A number of methods are available for determining value/utility scores or their close relatives, AHP-derived priorities [10, 12, 18].

Whether or not value scores or their kin are needed, and which method is used, will depend on context, the criterion score being measured, and how one plans to use the multiobjective programming analyses in the next phases. The assessment problem can be visualized as a graph, with streamflow on the horizontal axis and the specific criterion on the vertical one. As streamflow increases—or as the amount of flow diverted from the stream for a given purpose increases—one must specify the corresponding value on the vertical axis. Where possible, it will be more meaningful to use natural rather than artificial units on the y-axis. In assessing payoffs to an irrigation objective, for example, one might use units of hectare-months of crop X that can be irrigated per year. Objectives such as municipal water supply might use streamflow directly (or volume expressed in terms of flow, e.g., [m^3/sec][days]), thus obviating the use of a vertical axis. In both these cases, no valuation of scores is made in this step, but rather is conducted in the programming phase (Tasks 3 and 4).

Other criteria might be treated with only minimal value transformations. One way which relegates further valuation to the programming models in Tasks 3 and 4, is to treat the vertical axis essentially as a nominal or categorical scale. For an instream use like swimming, for example, different depth-velocity intervals might first be defined as offering particular swimming environments (e.g., excellent, good, fair, and poor; safe and dangerous), and then via stage-discharge relations one can compute the areal extent of each category associated with any given flow. If flows are also divided into intervals, integer and/or goal programming formulations can then be employed in the optimization models and the areas of the categories used as payoff measures. It is likely that an instream concern about the preservation of an aquatic species could be handled similarly, with stage-discharge relations augmented where possible with more sophisticated habitat-assessment models (e.g., IFIM), and the areas of stream habitat falling into different quality classes being the payoff measures.

Where more complete value transformations are desired or necessary, AHP [18] and SMART [12, 19-20] are two sophisticated yet simple approaches that should be considered. Although reservations have been expressed about AHP (e.g., [21]), and the method has been the subject of trenchant debate (e.g., [22]), it has seen wide and successful application to many public problems [13, 15, 16, 23-26]. One of the merits of AHP is its straightforward ability to handle two kinds of non-stochastic uncertainty, that associated with the effects of exogenous events or developments (represented through scenarios), and that related to fuzziness (treated by mapping qualitative comparisons onto a numerical scale). Excellent software packages are available to implement both methods; these include EXPERT CHOICE [27] for AHP and VISA [28] for SMART, while HIPRE [29] implements them both.

3.2.3 Tasks 3 and 4: Multiobjective Optimization

Since setting IF standards is a classic resource-allocation problem, multiobjective programming offers a logical way to try to identify flow allocations that satisfy the concerns articulated in previous stages. The uses of and techniques available for the application of multiobjective optimization in water resources are quite varied [30-32], but in this context I wish only to differentiate them along three lines: baseline versus operational models; approaches based on prior versus progressive or posterior articulation of preferences [33]; and strategic versus operational uses.

3.2.3.1 The Baseline Model—As used by Ignizio [34], the "baseline model" is the most general and accurate representation of the problem under study. Since it reflects all objectives, goals and aspirations, general concerns, and constraints, but no (relative) preference information, conflicts among these elements will make it impossible to solve it directly to yield a unique solution that optimizes all desiderata. Rather, one will have to convert the baseline model into an operational form that can be solved with an appropriate optimization procedure (cf., [32, 35]). As is well documented, such transformation requires new information and/or assumptions about the parties' preferences. The nature of these assumptions, the type and timing of the information required, and the way the information is elicited, will clearly affect the acceptability and ultimate effectiveness of applying multiobjective programming to this problem [30, 33, 36].

Although the baseline model will clearly be case-specific, the following schematic model illustrates some of the elements that any particular one might exhibit.

Let:

Q(s,t) = streamflow at site s at or during time t;
W(s,t,u) = withdrawal for use or user u from stream between sites s and s-1 at or during time t;
RETFLO(s,t,u) = return flow (after withdrawal) from use/user u to stream between sites s and s-1 at or during time t;
INFLO(s,t) = inflow (other than return flow) to stream between sites s and s-1 at or during time t;
f(.) = function representing a concern, criterion, objective, or "hard" (inviolable) constraint;
g(.) = goal function representing a "soft" (violable) constraint;
n(r), p(r) = negative and positive deviations from goal r;
N,P = vectors of deviation variables n(r) and p(r);
b(r) = target or desired goal level;
b(m) = inviolable bound or value

Then, the general problem is to:

(1) minimize f_i (Q,W,RETFLO,INFLO) $i = 1, \ldots, I$
(2) maximize f_j (Q,W,RETFLO,INFLO) $j = 1, \ldots, J$
(3) minimize f_k (N,P) $k = 1, \ldots, K$

subject to:

(4) g_r(Q,W,RETFLO,INFLO) + n(r) − p(r) = b(r) $r = 1, \ldots, R$

(5) $Q(s-1,t) + \text{RETFLO}(s,t) + \text{INFLO}(s,t) - W(s,t) = Q(s,t) \qquad s = 1, \ldots, S;\ t = 1, \ldots, T$

(6) $f_m(Q, W, \text{RETFLO}, \text{INFLO})\ \{\leq, =, \geq\}\ b(m) \qquad m = 1, \ldots, M$

(7) $Q, W, \text{RETFLO}, \text{INFLO} \geq 0$

Decision variables are defined as the flow to be allocated to both instream (Q) and out-of-channel uses (via withdrawals W). Conventional objective functions are given in (1) and (2), while (3) are achievement functions corresponding to the goals in (4). Such objectives and goals could relate to the concerns of different parties, thus preparing the ground for explicit consideration in the operational models of local-nonlocal conflicts arising from both scale and distribution questions. Hard constraints are shown by (5) and (6), with the former depicting hydrological continuity (i.e., flow balance). Notice that RETFLO could include controlled discharges from storage for flow-augmentation purposes. Some of the uncertainty bound to be present can be treated by allowing the right-hand sides b(r) and b(m) to be intervals, and letting the functions in (4) and (6) refer to probabilities. For example, the intervals could reflect indeterminate relationships between streamflow and habitat, while probabilistic constraints could represent stochastic hydrologic processes.

3.2.3.2 The Operational Model—As often advocated for public planning contexts (cf., [30]), the position taken here is that models which generate many different candidate allocations will have a better chance of formulating a consensus allocation than will approaches that rely on previously-defined preferences and attempt to identify "the best" one. The most effective approaches will likely use interactive procedures that iterate among three main phases: (i) a *generation* phase in which candidate solutions are identified and presented to decision makers and stakeholders; (ii) an *evaluation* phase, in which these parties indicate one or more preferred candidates, new or altered constraints, and possibly priorities, preference weights, or other wishes; (iii) and a *focussing* phase, in which this new information is used to formulate a modified optimization model for application in the next iteration. A number of specific interactive procedures could probably be used effectively in this phase, such as iterative compromise programming [37], interactive multiple goal programming [38], the interactive Tchebycheff method [39], and the reference-point approach [40]. Their utility notwithstanding, there are apt to be some concerns difficult or impossible to model adequately, and consensus may be hard to achieve. Since allocations responding to these problems might correspond to models' dominated solutions, there might be good reasons to intentionally generate and consider some that are "slightly dominated" [41]. Techniques and applications are described in [42-45].

There also exist several different methods to handle uncertainty, and these can be integrated within the above-mentioned procedures or as hybrids of them (cf., [46]). Imprecision can be modeled with fuzzy multiobjective programming and related techniques using intervals for parameters. The method of Urli and Nadeau is particularly attractive for such cases [47]. It blends goal-programming notions with those of fuzzy and interval linear programming, allowing one to consider and trade off goals relating to *satisfaction thresholds*, where "satisfaction" increases when goals are met under pessimistic or worst-case conditions. Where uncertainty can be represented by probability distributions, various stochastic programming techniques are available [46, 48], among which are conventional chance-constrained programming [49-50]. One that explicitly distinguishes consequences of different magnitude and likelihood, with obvious applicability to flow frequency-duration concerns, is the partitioned multiobjective risk method [51]. Situated somewhere in between these two cases are those in which either probabilities themselves can be estimated only roughly, or where it is only necessary to distinguish among probability *intervals*. Again, issues related to flow frequency-duration relationships may exhibit these characteristics, and both discrete chance-constrained (goal) programming [52] and the prospect ranking vector [53-54] may be suitable in these cases.

We can also distinguish uncertainty at a level above that considered thus far. If different sets of exogenous conditions are thought to be significant, then they can be portrayed as different scenarios. Climate change and actions by upstream riparians, especially where they belong to different political jurisdictions, are two dimensions of obvious import to the instream flow problem for which scenarios could be usefully employed. For example, scenarios describing different futures of the Rhine Action Programme, and the resultant quality of flows entering the Netherlands from upriver, were used in a recent evaluation of estuary-management policies in the Rhine delta [13, 15, 16]. Once the scenarios are defined, the various concerns and consequences, whether deterministic, imprecise, or stochastic, can be determined and represented for each one. Multiobjective programming can then be used to explore tradeoffs among objectives and goals pertaining to the same as well as different scenarios. One can also incorporate objectives relating to classical criteria for decisions under uncertainty—such as those associated with Savage, Wald, Laplace, Hurwicz, and Agarwal-Heady—and use them to suggest attractive initial solutions [50, 55].

The treatment of water rights, especially in conjunction with the stochasticity of streamflow, raises another set of challenging operational questions. Consider again the various views toward water rights in Hawaii. One could adopt lexicographic (preemptive) priority structures if some rights were considered *absolutely* superior to others, thus admitting no tradeoffs; or, one could use hard constraints to represent the inviolability of such rights; or, one could express them as targets and then try to get as close as possible. The "public interest" could be taken into account by expressing the relative importance of such rights to that interest through weights, either on conventional objective functions, or on the deviations from the targets represented in the achievement functions in Archimedean goal programming.

But do, or should, rights depend on the probabilistic nature of the system? Are deviations from required instream flow acceptable if they occur below a certain percentage of the time but unacceptable otherwise? How should such threshold probabilities be determined, which statistical parameters should one use, and should the procedure vary with the amount of information one has on flow frequency-duration relationships? Since both lexicographic and tradeoff structures can be employed in stochastic as well as in deterministic models, it is intriguing to ask whether some are to be preferred from legal or water-rights viewpoints (as contrasted with those pertaining to data availability). For example, would chance-constrained models be consistent with legal interpretations while those based on *discrete* chance constraints would not be?

Several operational approaches may prove useful in confronting the problems of conflict arising from the scale and distribution questions discussed earlier. Game-theoretical notions can be used to suggest various normative prescriptions for distributive conflicts, and a number of different procedures utilizing or departing from them have been proposed for use in related bargaining and negotiation situations. Ratick [56] and Ratick et al. [57] discuss approaches using solutions obtained by multiobjective programming to augment and provide insight into resolutions suggested by cooperative game theory. (As pointed out by Zhu et al. [58], a drawback of the latter is the need for "prohibitive enumeration of alternatives in reasonably large problems," and these authors present the dual of a single-objective plant-location model—with application to cost allocation among wastewater treatment plants located along a river—as a computationally efficient alternative.) Dufournaud and Harrington also use single-objective linear programming to generate Shapley-consistent imputations that consider both the spatial and temporal distributions of monetary benefits and costs among a set of riparians [59, 60]. Interesting and insightful as these last two approaches are, their single-objective character and their consideration of cost- and/or benefit-allocation in solely monetary terms render them not directly applicable to the above baseline model.

Conflicts engendered by scale considerations can be viewed as having a hierarchical structure, and these suggest a role for programming models displaying similar structures. Anandalingam [61] and Anandalingam and Apprey [62] present and discuss bi- and multi-level programming models applicable to such situations and suitable for *non-cooperative* contexts. The former considers situations defined as:

> (i) *decentralized systems*, where there is one higher-level decision-maker (who is referred to as the centre or leader) and many lower-level decision-makers (who are referred to as divisions or followers); and
> (ii) *multi-level hierarchy*, where there are many levels, with one decision-maker in each level [62, p. 1021].

For many decision contexts, these approaches may well be applicable to the instream flow problem. For example, Anandalingam and Apprey illustrate their use for conflict resolution in international rivers [62]. And for the case of Hawaii, a decentralized system may have the Commission on Water Resource Management (CWRM) as the "leader" and all other parties as "followers"; or, a multilevel hierarchy may exist, in which the federal government is the highest-level decision maker, the CWRM is intermediate in rank, and all others exist at the third level. A possible restriction in both cases is the assumption of Stackleberg behavior, in which the divisions react by optimizing their objective functions after learning of the leader's actions [61].

More robust yet is the "7-Leagues Boots" approach [63], in which no such behavior is assumed and interactive multiple goal programming is employed in a hierarchical, noncooperative framework. It uses a heuristic procedure to converge in very few iterations to consensus solutions, and requires minimal information from the participants. It assumes the need to divide resources between a central decision maker and lower decision makers as well as among the latter. It seems reasonable that such resources could be water or streamflow. All these features suggest its great potential for application to the instream flow problem.

3.2.3.3 Uses and Roles of the Optimization Models—It is important to distinguish between strategic and operational *uses* of the optimization models and techniques discussed above. Consider the concern about the reduction in flow variability due to diversions. As Lee has suggested, one potential mitigation response is to gradually store in reservoirs or retention basins some portion of the water diverted, and then to release large amounts of it as pulses of much shorter duration [1]. The periodic spikes thus produced might restore some of the original variability. To explore this response, the model could include variables related to such storage structures, such as the portion of the flow diverted from amount withdrawn to a storage structure, the amount stored at time t, the flow released at time t for some duration d (part of RETFLO), and so on. Then one could optimize one or more of them or simply check to see the amount of storage that would be required to achieve a given flow-restoration goal. Thus, an assessment could be made whether or not average flows would be sufficient to make diversion feasible (given desired achievement levels on competing goals), and whether or not storage facilities would have to be impracticably large to restore flow variability. However, the flow and storage amounts would be in terms of *average* amounts over long periods, such as a year. For *operational* purposes, determination of the timing, magnitude, and duration of releases would be required. Other models, among which might be one quite similar to this one but with shorter time periods (each one a week, say), could be used for that purpose; simulated streamflows could then test the prescribed release patterns.

Typical institutional and administrative processes give a dynamic character to the consideration of instream flow standards, and these present a particularly challenging context in which to apply formal multiobjective modeling. Consider the scale (sustainability) concerns and the "no-further-concessions" attitude mentioned above. In Hawaii and elsewhere, one proposed response is so-called *categorization and set-aside*. In that strategy, streams of exceptional value would be classified ("categorized") as such and then placed off limits ("set aside") to further diversion. This approach can be criticized for two reasons. First, the potential harm to any such stream depends crucially on the amount and timing of the water that would be diverted. Secondly, it implicitly employs a set of criteria and accords them different weights. But neither the weights nor how they are determined is known, and hence the corresponding tradeoffs also remain unknown and unexplicated. Consequently the decision-making process is obscured rather than illuminated. Such tradeoffs can be made more clear in the models discussed here, yet timing may hinder full evaluation of the tradeoffs. One might claim that the conservation value of a stream can only be assessed relative to that of other streams, hence arguing for simultaneous evaluation of all streams. But in the real world, this rarely happens; they are usually considered piecemeal and incrementally. Thus, a robust multiobjective methodology would allow incorporation of new streams into the comparison as conditions permit (such as data availability, public interest, legal considerations like filing deadlines, and so on). This should also allow the possibility of revising a stream's relative conservation priority as new streams are considered, and hence changing its IF standard.

3.2.4 Task 6: Evaluating Instream Flow Standards

After a set of candidate IF standards has been identified, further evaluation will be needed to select one or to combine them to form a better alternative yet. Here the methods discussed under Task 2 can be used. For example, the decision maker (DM) (e.g., a water commission) might use an AHP model with different levels corresponding to actors (different water users or interests), scenarios (climate change, water-rights legislation, future water demand), and criteria not included in the programming models. The candidate IF standards would be the alternatives to evaluate. After making its assessments, the DM could select the IF standard with the highest priority. Alternatively, it could define a new, hybrid IF standard from the convex combination of the original alternatives multiplied by their respective priorities. This latter would have the virtue of being a "compromise" standard: the advocates of each of the alternatives could see that their "candidate" had influenced the composition of the new one, and no advocate would become the sole "winner."

A different approach would consider the task at this stage much like a social-choice problem. The alternative IF standards are the candidates, and either the stakeholders or the members of the decision-making unit are the voters. A number of different voting procedures could be employed [64, 65]. Hwang and Lin describe a hybrid, voting-eigenvector procedure that yields a normalized vector of weights which, as in the preceding paragraph, can then be used like AHP-produced priorities to fashion a compromise IF standard [3]. It differs from the

AHP in that the matrix it uses has as its pairwise-comparison entries the ratios of "votes for candidate i" to "votes for candidate j." Another approach would have the voters rank the candidates and then use a method, such as that of Cook and Seiford [66], to find a "consensus" ranking; several such techniques are described in the literature (e.g., see [3] and [67]). In all of these approaches, a key question is, "Who votes?": members of the decision-making unit (e.g., a water commission), the stakeholders directly, or both sets of actors? Although the answer is likely to be found within a place's existing institutional and administrative processes, those processes will determine to a large degree the relative effectiveness of each of these methods.

If a process is used which includes an "actors" level in an AHP hierarchy, should those actors be differentially weighted, and, if so, on what basis and by whom? This clearly depends on context, and in the absence of a clear DM, or of an entity that is willing to wield its legitimate power in this respect, little in the way of unqualified recommendations can be given. If there *is* a willing DM, then it can use whatever criteria it chooses. One way would be to assign weights a number of different ways, see how the competing IF standard would fare, and then come to some holistic decision without ever relating the final selection to any particular weight set. This is essentially what happened in a recent evaluation of alternative management policies for a Rhine estuary [13, 15-16].

Finally, one can return to Task 4 and use one of the candidate IF standards as a seed from which to cultivate new, somewhat similar standards in Task 4. A number of multiobjective programming techniques could prove useful for this: the HSJ method of generating new alternatives offers one approach [42], as would the interactive Tchebycheff procedure [39].

CONCLUSION

Probably the most important aspect of the roles and uses of the multiobjective procedures discussed here concerns the interface between them and the parties involved in the IF problem. Their effectiveness is apt to be directly related to the degree to which they:

(i) Avoid requiring or prescribing normative behaviors or particular objectives or desires not expressly given or approved by the parties;
(ii) Minimize the information or interaction load required of the parties and provide quick feedback;
(iii) Are transparent in their treatment of uncertainty and avoid assuming or imposing prespecified structures or functions to represent it (e.g., "convenient" probability distributions or membership functions);
(iv) Avoid commensuration of goals, objectives, or criteria;
(v) Identify new alternatives and options and relate those to the wishes and preferences elicited from the parties at interest;

(vi) Employ simple or intuitive computational concepts and operations; and
(vii) Are compatible with existing institutional structures and administrative processes.

To realize such goals will require skillful management not only of the interaction between the actors (decision makers, stakeholders) and the multiobjective procedures, but also of the interaction among the actors themselves. For example, the degree to which the "leader" in a hierarchical decision-making context plays the role of arbitrator versus that of decision maker, and the effort made by that entity to find compromise solutions, can have a great influence on the parties' ultimate satisfaction with the process.

These relationships, of course, belong to the *decision-making context*. It is clear that for any planning, evaluation, or decision-making methodology to be successful, it must be compatible with the context in which it is to be used (cf., [68]). Although I believe that the multiobjective methodology presented here has the general features necessary for effective public-sector application, this will clearly depend on the specific context. This context will suggest which methods will be most suitable and the ways to execute them. Only through actual applications, however, will we be able to assess the true utility of the methodology as a whole.

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