Multicriteria Decision Analysis in Water Resources Management

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21 INCORPORATING RISK AND IMPRECISION INTO WATER RELATED DECISION MAKING: AN AUSTRIAN CASE STUDY FOR INSTREAM WATER REQUIREMENTS

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ABSTRACT The purpose of this paper is to demonstrate how small hydropower projects may be evaluated with respect to both economic and environmental objectives. This approach will be applied to the decision making process for a rational selection of the design discharge. The economic objective is taken as the net benefits from energy generation while the environmental objective refers to the preservation of the environmental functions in the diverted section.
Evaluating environmental consequences is subjected to both randomness and imprecision. To account for the latter characteristic the objective is expressed in a fuzzy way and fuzzy set membership functions are assessed to evaluate changes in water temperature, dissolved oxygen and minimum water depth for that river section. Randomness on the other hand, necessitates encoding of the random characteristics of the hydrological and ecological variables. In either case composite programming, an extension of compromise programming, may be applied to perform a two-level trade-off analysis to assist decision making. At the first level a compromise is sought within the environmental objective for example between dissolved oxygen and water temperature. At the second level the two objectives are traded-off.

21.1 INTRODUCTION

In Austria the percentage of the hydro-electric power amounts to approximately two thirds of the total electric power generation. Increasing fuel costs in the last decades have stimulated additional utilization of the hydropower potential. As a result attention has also focused on an increased hydropower utilization by small schemes. Presently, 1200 small hydropower schemes are operated in Austria generating about 8% of the total hydro-electric power. This percentage corresponds to 2000 GWh per year. A remarkable increase in the power generation is economically attractive but because of environmental concerns the implementation of new schemes is retarded.

To describe the utilization of the hydropower potential and to assess the environmental impacts of small hydropower schemes several Austrian catchments have been investigated in detail (Nachtnebel, 1983; Nachtnebel et al., 1985). It was found that 90% of the hydropower schemes are located at diversions which sum up in some river basins to 30-50% of the length of the river course. In other words 30-50% of the river course are endangered to dry out. The reason to implement such diversion type plants is given in reduced investment costs for flood protection, as well as for water intake structures and shared maintenance costs for the channel.

In particular, diversion-type plants exhibit environmental degradation of the diverted river section. The existing guidelines for decision making upon the amount of water intake are based on economic criteria and as a consequence the run-off is diverted over long river sections to such an extent that the river bed falls dry during the summer and autumn season. Only flood run-off is observed in the river bed within that period. Obviously, a drastic degradation of the aquatic environment occurs.

The crucial point in the decision process is the lack of guidelines to determine the compensation discharge - the amount of water which must be released downstream the weir - (Akeret et al., 1982; Bayerisches Landesamt, 1983; Hanisch, 1984; Broggi & Reith, 1983; Duckstein et al., 1989).

The purpose of this paper is to assist in a rational selection of the compensation discharge. Due to the fact that both environmental and economic concerns are simultaneously but adversely affected by the amount of the release a compromise must be achieved to resolve the conflict. For that purpose a bi-objective framework considering simultaneously both concerns is developed.

In this paper the only decision variable under concern is the compensation discharge which generate the set of alternatives. Several other alternatives such as the length of the diversion including $l = 0$, the length of the impounded river section upstream from the weir, the implementation of small additional hydraulic structures reducing environmental impacts in the diverted river section are neglected. Additionally it is assumed that the remaining or compensation discharge is constant throughout the year. Although this will lead to a "suboptimal" solution this assumption conforms with the present Austrian practice which is substantiated by a simplified inspection procedure.

The paper is organized as follows. First, a model is described and is developed, relating the amount of the compensation discharge and the amount of water which must be released downstream the weir to primary water quality characteristics, morphometric measures and economic indicators.

In the subsequent section the alternatives are evaluated within a bi-objective framework. The evaluation of the environmental consequences is subjected to both uncertainty, because of the stochastic character in the model input, and imprecision due to soft information about environmental degradation. The uncertainty in the economic objective is disregarded.

A compromise between the economic and the environmental objective is then achieved by the application of composite programming, an extension of compromise programming (Bardossy, 1981; Bogardi et al., 1984). Numerical results for a typical diversion-type plant are derived and compared with the outcomes from existing guidelines. A discussion of the results concludes the paper.

21.2 DESCRIPTION OF THE SYSTEM

To demonstrate the proposed methodology, a hydropower scheme which was built about ten years ago has been selected as a case study. Some hydraulic structures of a previously existing scheme could be integrated. The scheme has an installed capacity of 1.07 MW and generates about 5.2 GWh per year. The run-off river scheme situated at a 1100 m diversion channel (Fig. 21.1) and cutting of a 2200 m river section is designed for 15 m^3/s. The mean annual discharge is somewhat lower and is given with 13.9 m^3/s. The mean annual low flow is estimated at 3.8 m^3/s and the lowest observed run-off within thirty years is 1.87 m^3/s. The legally prescribed minimum release of 20 l/s downstream the river is insufficient to maintain the viability of the aquatic system. Under unaffected hydrologic conditions the river landscape is of scenic beauty and due to a good water quality the river is also quite attractive for sport fishery.

The annual cycle in the run-off pattern, the air and water temperature is given in Fig. 21.2 indicating that critical periods caused by low flow with simultaneously increased water temperature will occur during June to September.

As indicated in Fig. 21.1 the diverted river reach was subdivided into six sections each of which exhibited rather homogeneous hydraulic conditions. For different run-off values the water depth, stream velocity and width were measured together with the diurnal cycle of dissolved oxygen concentration, air and water temperature at the end of the sections in the diverted river reach.

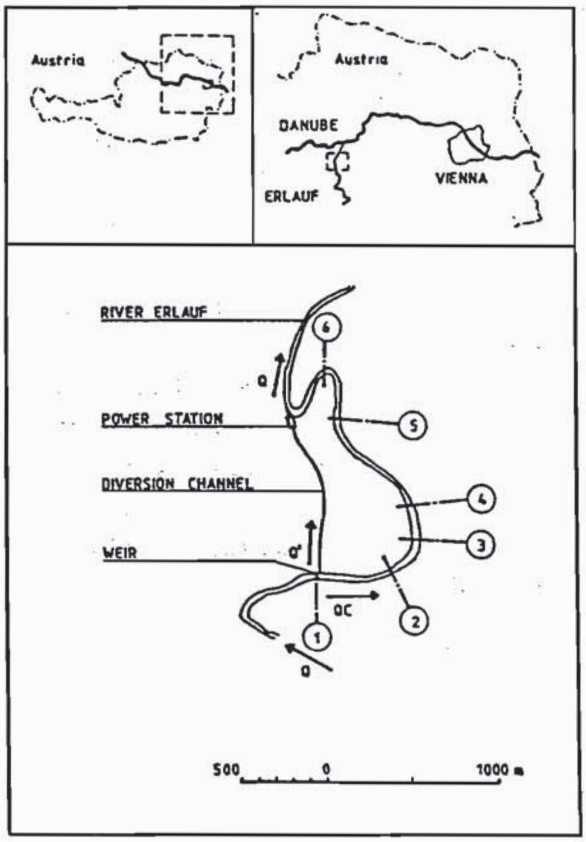

FIG. 21.1 Location of the hydropower station

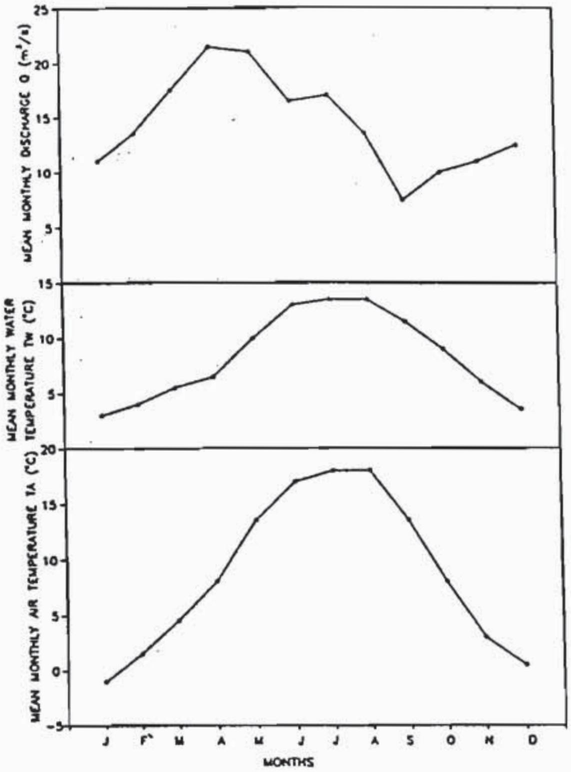

FIG. 21.2 Annual cycle in run-off, water- and air temperature

Due to the obvious biased selection of the compensation discharge favourizing economic objectives and disregarding environmental objectives a methodology is sought to analyze the problem and to assist in rational decision making.

21.2.1 Objectives

Next, the two objectives and their components are explained. The economic objective has two components: first a monetary benefit and second, economic losses expressed by the number of days of shutdown because of water shortage. The second measure is especially of importance for locally operated power stations.

If a large design discharge is selected the energy output might be increased but at the same time several shutdowns of the scheme have to be considered because of an inefficient operation during low flows. This requires a careful operation which is disadvantageous especially for remote schemes.

$$Z_{1,1} = \text{Max (ANB)}$$
$$Z_{1,2} = \text{Min (OPD)} \qquad (21.1)$$

ANB Annual net benefits

OPD Shut down days per year

$$\text{ANB} = \text{AE } (P_o) \; . \; p(t) - dT(i) \; . \; C(P_o)$$
$$\text{OPD} = F \;\; (P_o, P_{MIN}) \qquad (21.2)$$

$$\text{AE } (P_o) = C_o \int Q'(t) \; . \; H(Q'(t)) \; . \; \eta \; (H(t), Q'(t)) \; dt$$

$$\text{QMIN} \leq Q'(t) \leq \text{Min } (Q(t) - \text{QC}, \text{QMAX})$$

$$P_{MIN} < P < P_O$$

$AE(P_o)$	annual power generation (kWh)
C_o	conversion coefficient
$C(P_o)$	cost function, dependent of installed capacity P_o
dT	discounting factor for interest rate i and lifetime T
H	utilizable head
P_o	plant capacity
P_{MIN}	minimal utilizable capacity
p(t)	a daily and seasonally dependent energy tariff rate (ATS/kWh) ATS = Austrian Shilling
QC	compensation discharge (legal prescription)
QMAX	maximum utilizable discharge

QMIN minimum utilizable discharge
η plant efficiency.

Cost functions are derived from either published data (Gordon, 1983) or from available data from plants with similar capacity.

Many environmental impacts caused by a reduced discharge are referenced. Analyzing these impacts a few abiotic indicators are selected which can be seen as variables characterizing both the river and changes in the fluvial corridors. They can also either be easily measured or obtained by model simulations which are based on available data.

The environmental objective tries so preserve environmental functions of the diverted section as well as possible and is composed by five components taking in to account:

$Z_{2,1}$: the environmental consequences due to a change in the water depth

$Z_{2,2}$: the environmental consequences related to a change in the dissolved oxygen concentration

$Z_{2,3}$: the environmental consequences related to an increase in the water temperature

$Z_{2,4}$: the environmental consequences related to a reduced volume of the water body

$Z_{2,5}$: the environmental consequences related to a change of the variation in the river width.

Obviously, these consequences should be minimized to prevent any degradation of the river section (Hjorth et al., 1991; Nachtnebel et al., 1991).

21.2.2 State variables

The water temperature and the dissolved oxygen concentration characterizing the quality and morphometric measures such as water depth, volume of the water body and variation in the river width were selected to describe the state of the environment. The temperature dependence of the development of fish species which are typical for our case study has been investigated by Jungwirth and Winkler (1984). Dissolved oxygen constitutes a fundamental measure for the aquatic system and has thus been included into the model.

The level of the groundwater table and consequently its impact on riparian vegetation is mainly controlled by the surface water table in the river reach. Water depth is a simple measure for the aquatic habitat and also accounts for fish passage. The total water body volume is a criterion representing environmental quality for the remaining aquatic habitat. The variation of river width constitutes a valuable indicator for the variety of fish species and their respective population densities (Jungwirth, 1983) and it can further be easily measured.

21.2.3 State equations

Next, for each river section, a set of state equations similar to the QUAL II- model (EPA, 1981; Böhm, 1974) is established to estimate the state and the output from the environmental subsystem.

The set of equations is explained in appendix 21.7 and consists of a hydraulic equation, an energy balance equation and a dissolved oxygen balance equation.

21.2.4 Input

The model input includes meteorological data such as global radiation, long wave radiation, wind velocity and frequency, frequency of cloudiness, air temperatures and air humidity. The set of hydrologic input variables consists of the run-off pattern, water temperature, BOD load together with dissolved oxygen and algal biomass concentration. The required topographic input is given by six cross sections, a longitudinal section of the river bed, the flow velocity for each section. Additionally the riparian lands and its vegetation are considered to account for a reduced radiation exposure of the water table.

Fig. 21.3 exhibits some computational results together with the corresponding measurements for a low flow situation. Although the required coefficients in the model were taken from literature instead being obtained from a calibration procedure, a satisfactory fit between the model and measurements was achieved. A sensitivity analysis was performed by MOR (1986) applying the model to two prealpine river sections in Lower Austria.

21.3 EVALUATION OF ALTERNATIVES

The consequences of each alternative which depend only on the amount of water release at the weir site, are characterized by two economy related criteria and five environmental criteria. This section is devoted to the evaluation of environmental consequences subject to both imprecision and randomness.

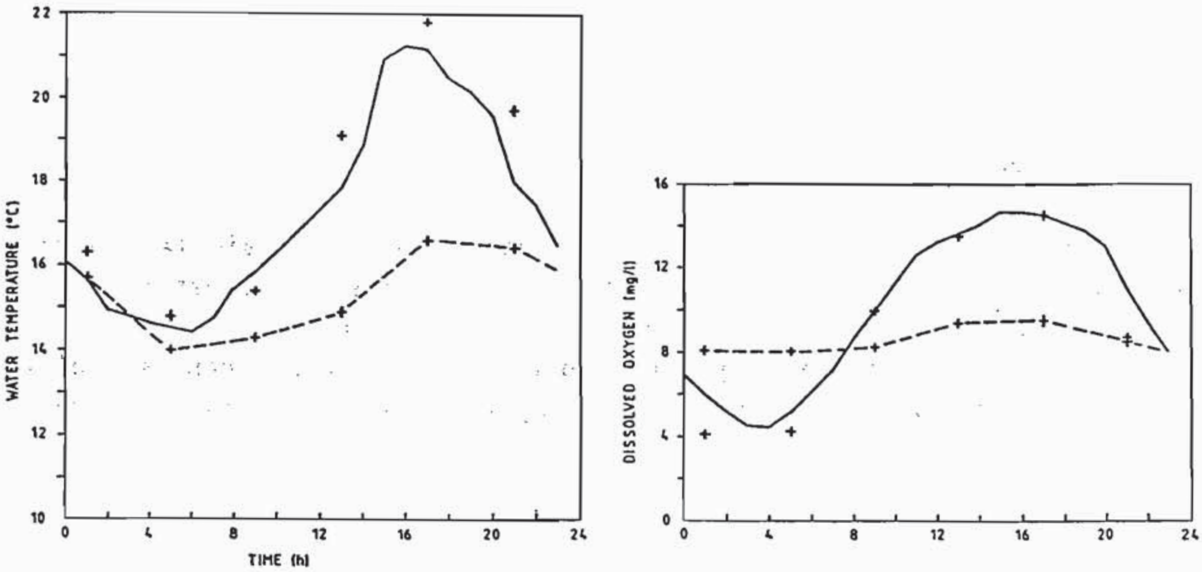

FIG. 21.3 Daily cycle in the water temperature and in the dissolved oxygen for QC = 0,18 m^3/s (summer day)
Cross-section 1 (observed) -----
Cross-section 6 (computed) ——
Cross-section 6 (observed) +++++

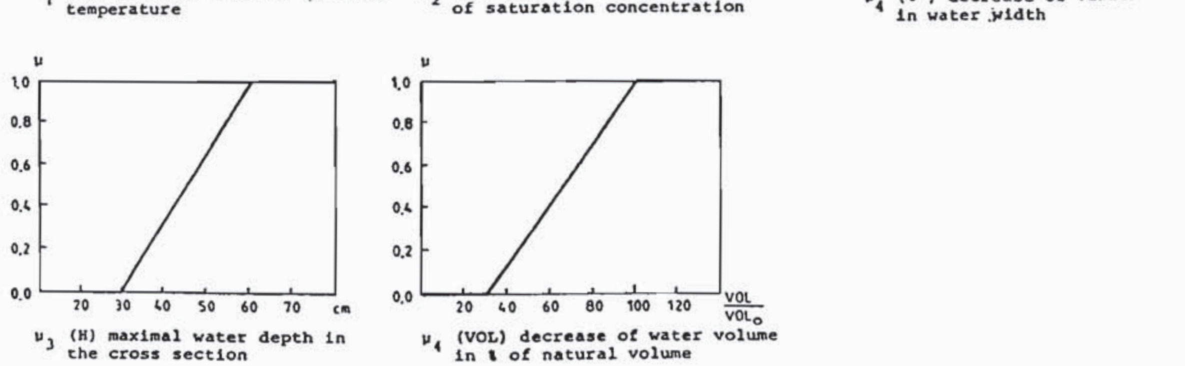

FIG. 21.4 Membership functions for environmental indicators

21.3.1 Fuzziness

Due to a lack of consensus in setting proper evaluation scales for the environmental indicators, fuzzy membership functions are assessed. Fuzzy sets have been widely applied to multicriteria problems (Dubois & Prade, 1980; Duckstein et al., 1986; Korhonen et al., 1989; Bellman & Zadeh, 1980; Brown et al., 1984; Hipel, 1982; Siskos, 1982; Bogardi et al., 1984; Bardossy et al., 1988).

In our problem the membership-functions $\mu_i(X)$ indicate the degree of relevancy of a certain environmental indicator X for a sound environment. For example, the increase in the water temperature will be considered as a full member of the fuzzy set of sound environmental conditions with grade 1.0, if experts evaluate the increase with "good".

According to existing Austrian guidelines for the thermal pollution of rivers, an upper limit of 3°C should not be exceeded while an increase of 1°C appears to be acceptable. Together with the data about temperature preference of various Austrian fish species, summarized in Humpesch et al. (1981), a membership function was derived.

The dissolved oxygen concentration is evaluated similarly to the NSF value function (Dee et al., 1972) using data from Brown (1975). The water depth and the water volume are evaluated by a piecewise linear function. The membership function for the water volume refers to the change in volume while the water depth is given in absolute values. In harmony with published data in Jungwirth (1983), indicating that a linear relationship between variation of water width and fish species appears to hold, a piecewise linear membership function is assumed.

The set of membership functions characterizing the degree of indicators pertaining to a sound environment is given in Fig. 21.4.

There is obviously some freedom in establishing a membership function. In the given examples (Fig. 21.4) the membership function express preferences (values) over an attribute and these functions could be replaced by a value function with minor modification. This in turn provides a tool to derive membership functions. The only notable difference may be the range assigned to the respective functions m(X) and V(X) (Duckstein & Heidel, 1988).

Another approach assisting in establishing a membership function is related to statistical analysis (Civanlar & Trussez, 1986). It is worth to mention here that the subsequent analysis which is based on min. or max. operations is rather robust to the local shape of the membership function.

21.3.2 Randomness

To incorporate the stochastic component into the decision process, a simulation approach has been selected.

For that purpose a series of 300 summer run-off events was generated together with the model input to analyze the randomness in the environmental degradation due to water intake. For instance starting with the same water temperature at the weir site different environmental consequences will result in the diverted river section because of different meteorological conditions. A meteorological observation series of more than ten years was available for that region.

The randomness in the components of the economic objective such as interest rate, tariff rate and the fluctuation in the annual power generation, is not considered.

Next, the set of criteria characterizing respectively each of the two objectives are to be aggregated to apply a trade-off procedure.

21.4 COMPOSITE PROGRAMMING APPROACH

In this section, an extension of compromise programming (Zeleny, 1973 and 1981) called composite programming (Bardossy, 1981), is adopted to perform a two level trade-off analysis. At the first level a trade-off is performed among the economic and environmental criteria; and then a different Lp-norm is applied to trade-off the two objectives. The distance ρ is called a composite metric on Rn if for each $\underline{x}$ and $\underline{y}$:

$$\rho(\underline{x},\underline{y}) = \left(\sum \beta_i^q \left(\sum \alpha_j^{p_j} \mid x_j - y_j \mid^{p_j} \right)^{\frac{q}{p_j}} \right)^{\frac{1}{q}} \qquad (21.3)$$

with $\alpha_j,\ \beta_i > 0$

and $1 < p_j < \infty \qquad 1 < q < \infty$

To give an illustration of the methodology a simple example is briefly outlined. To avoid trapping of fish in some sections of the river the remaining discharge could be narrowed in its wetted cross section by some artificial measures. This could also reduce the warming up of the water but the morphometric variability could be decreases. So, a sound trade-off among the environmental indicator is required and similar conclusions hold for the criteria characterizing the economic objective. As can be easily seen equ. (21.3) consists of two interrelated compromise approaches. The inner term with exponent p_j is the lower level and the second level is characterized by exponent q.

As has been shown by Bardossy (1981) composite programming is a proper extension of compromise programming. That is, a composite metric cannot be replaced by a compromise metric with similar weights. In other words, the solutions obtained by compromise programming constitute a subset from composite programming solutions.

After identifying the "ideal point" the composite metric is defined so as to be able to minimize the distance between the ideal point X^* and the point X in the pay-off space. The ideal point is

$$\underline{X}^* = (ANB^*,\ OPD_*,\ \mu_1\ (TW_*),\ \mu_2\ (O2^*),\ \mu_3\ (H^*),\ \mu_4\ (VOL^*),\ \mu_5(\sigma^*)) \quad (21.4)$$

An upper asterisk indicates that the ideal value represents a maximum, a lower asterisk correspond to the ideal value being a minimum.

To describe each environmental indicator by its corresponding membership function, the values obtained for every cross section are aggregated according to basic set-theoretical operations:

$$\mu_i(X) = \min\ (\mu_{i,1}(X),..\mu_{i,j}(X),..\mu_{i,6}(X)) \quad (21.6)$$

The index i refers to the membership function under concern, for example the dissolved oxygen concentration, while the index j refers to the number of the cross-section. According to the environmental objective we have to maximize simultaneously:

$$Z_{2,i} = \max\ (\mu_i(X)) \quad \text{for} \quad i = (1,5) \quad (21.7)$$

Another approach might be in applying again basic set theoretical fuzzy operations on the set of $\mu_i(X)$. In the case of intersection

$$\mu(X) = \min(\mu_i(X))$$

would be obtained. In other words the worst indicator would define the environmental quality which is in general true. Considering an increasing exponent p_2 in equ. (21.8) the value of O_2 would converge again towards the worst indicator.

The L_p-norms for the two aggregated objective functions O_1,O_2 are given in (21.8) where ANB- and OPD- stand for the worst outcomes.

$$O_1 = \left\{\alpha_{11}\left(\frac{ANB^* - ANB}{ANB^* - ANB_-}\right)^{p_1} + \alpha_{12}\left(\frac{OPD_* - OPD}{OPD_* - OPD_-}\right)^{p_1}\right\}^{1/p_1} \tag{21.8}$$

$$O_2 = \left\{\sum \alpha_{21}\left(\mu_i(X^*) - \mu_i(X)\right)^{p_2}\right\}^{1/p_2}$$

The overall composite goal function is written as:

$$O_0 = (\beta_1 O_1^q + \beta_2 O_2^q)^{1/q} \tag{21.9}$$

In each group of indicators a compromise programming parameter p_i and a set of weights α_{ij} has to be defined. The weights in (21.3) given in Table 21.1 reflect the dominance of annual net benefits over the shutdown days per year. This holds for a scheme which is connected to a grid and which serves only partly local users.

The environmental indicators are of equal importance but to emphasize the limiting character of the worst indicator a value $p_2 = 4$ was selected for the trade-off among the environmental elements. $p_2 = \infty$ would indicate that the environmental quality is always determined by the worst case.

TABLE 21.1 Weights and parameters in the objective functions

Objective	Weights	CP-Parameters
Economic	O_1 α_{11} α_{12} 0.8 0.2	p_1 2
Environmental	O_2 $\alpha_{21} = \alpha_{22} = \alpha_{25}$ 0.2	p_2 4
Overall	O_0 β_1 β_2 0.5	q 2

To display the influence of the weights β_i on the compensation discharge, a trade-off curve was derived in Fig. 21.5 for a typical summerday. The observed discharge was given with 8.71 m^3/s. Any reduction of the discharge results in a decreased membership value of one of the environmental indicators. The trade-off curve was obtained by variation of β. A value of β_1 equal to one considers only economic aspects yielding maximal net benefits. Decreasing the importance of the economic objective by assigning a weight $\beta_1 = .90$ results in a compensation discharge of QC = 0.88 m^3/s.

This results are displayed in Fig. 21.5 and Table 21.2. The curve was obtained under the assumption that the plant capacity had not been set previously; in other words, a new scheme is to be installed with a capacity determined by the compromise solution.

If the proposed procedure is to be a applied to an existing plant, the capacity and the investment costs are given and the compromise solution then accounts only for energy generation losses.

TABLE 21.2 Composite solutions for various weights β_i EL[(1)] economic losses in % of annual net benefit.

β_1	β_2	O_1	O_2	QC (m^3/s)	P (kW)	EL (%)
1.00	0.00	1.00	0.00	0.00	812	0
0.90	0.10	0.89	0.36	0.88	724	12
0.80	0.20	0.85	0.42	1.23	692	17
0.70	0.30	0.82	0.45	1.44	680	21
0.60	0.40	0.78	0.48	1.65	662	25
0.50	0.50	0.75	0.50	1.86	649	29
0.40	0.60	0.71	0.52	2.20	626	32
0.30	0.70	0.45	0.64	4.00	540	56
0.20	0.80	0.36	0.69	4.84	508	64
0.10	0.90	0.08	0.90	7.60	360	90
0.00	1.00	0.00	1.00	8.71	235	100

If only economic concerns are considered the optimal plant capacity is found to be 812 kW. This is about 20% below the installed capacity. The explanation is given in the fact that cost savings due to existing hydraulic structures which could be incorporated into the new scheme give an economic justification for a capacity increase.

Assuming equal weights for the two objectives yield a minimal release of 1.86 m^3/s. Even if the weight for the economic objective is nine times higher than that of environmental concerns a minimal release of .88 m^3/s is still necessary.

21.5 DISCUSSION OF THE RESULTS

In its approach the analysis is quite general but the results obtained and displayed in Fig. 21.5 hold only for specific hydrological and meteorological conditions. For instance, a day with lower air temperature and cloudy sky will yield a some what lower compensation discharge. To account for the randomness in the hydro-meteorological input 300 typical "summer events" were generated and then the described trade-off procedure was carried out yielding another compensation discharge.

The obtained cumulative distribution of the compensation discharge QC is given in Fig. 21.6. On the basis of the distribution and with a prespecified failure probability, a final decision can be made.

With $\beta_1 = \beta_2 = 0.5$ the minimum required release downstream the weir was 1.72 m^3/s, while 90% of the simulated events exhibited a discharge of 1.80 to 1.90 m^3/s. In two percent of the simulated results the compensation discharge range varied from 2.0 to 2.5 m^3/s. These discharge values are required for extremely warm summer days coincidencing with remarkably raised water temperatures and high algal biomass concentrations. Such conditions are typically observed at the end of extreme low flow periods occurring in July or August.

Optimizing with respect to the expected value results in a compensation discharge of 1.85 m^3/s.

Accepting a two percent failure probability (corresponding to the probability of environmental damage) requires a release of at least 2.0 m^3/s.

The release presently prescribed by law is 20 l/s. The owner of the plant releases at least 200 l/s into the diverted river section to avoid drastic degradation of the environment.

Other procedures proposed to estimate the necessary compensation discharge are often related to hydrological parameters derived from the flow duration curve.

Assuming 5-10% of mean daily discharge would yield 0.67 - 1.35 m^3/s. The approach proposed for example in Akeret (1982), which, uses the formula

$$QC\ (l/s) = 15\ E/(\ln E)^2$$

where E = discharge exceeded at 300 days in a year yields with E = 6500 l/s a compensation discharge QC equal to 1.23 m^3/s.

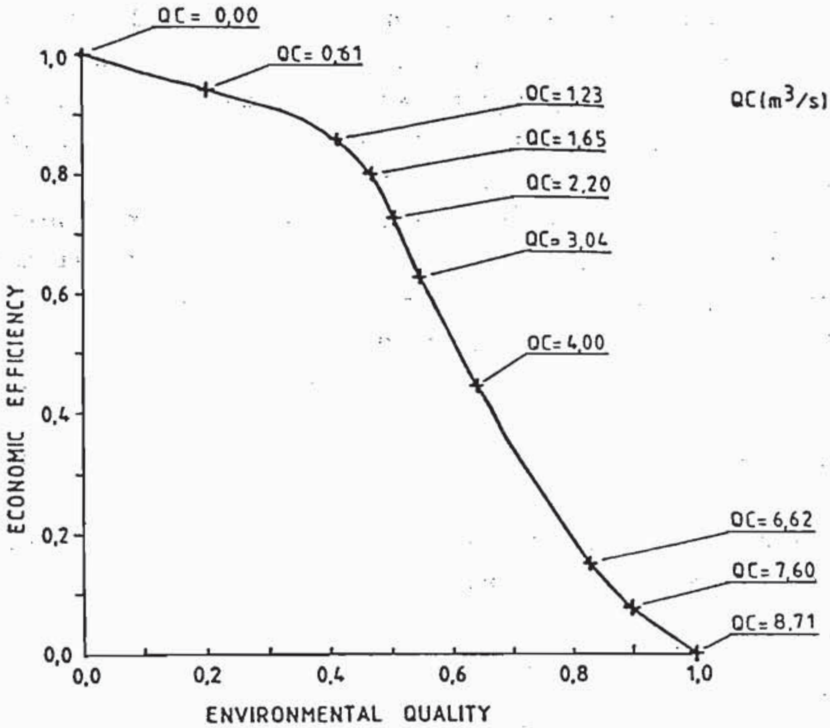

FIG. 21.5 Nondominated Solutions Derived for a Typical Summer Day (Q = 8.71 m^3/s)

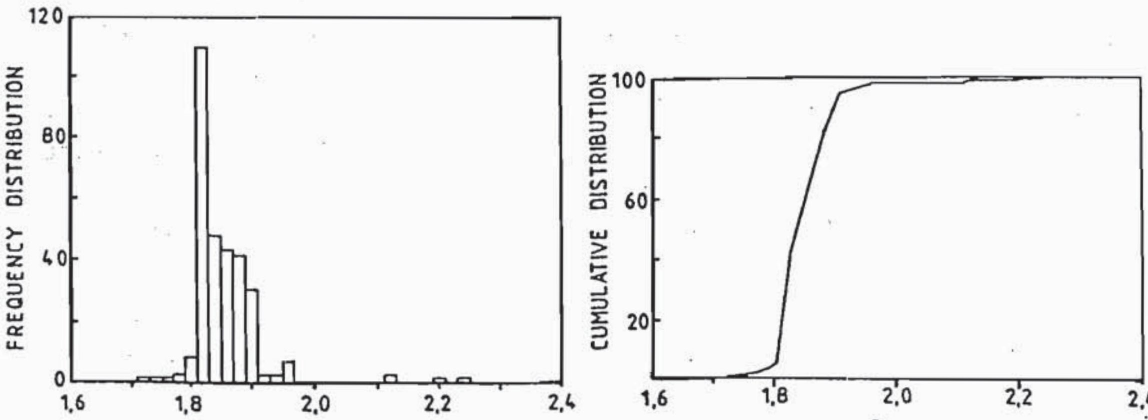

FIG. 21.6 Frequently and cululative distribution of compensation discharge QC obtained by simulation

21.6 SUMMARY AND CONCLUSIONS

The following concluding points can be drawn:

1) The proposed procedure accounts for both randomness and imprecision in the evaluation of environmental consequences.
2) The randomness associated with the decision process is explicitly taken into account by a simulation procedure.
3) The composite programming approach appears to be an appropriate technique for problems that posses different groups of criteria pertaining to each objective.
4) The proposed procedure appears to lead a rational selection of the compensation discharge that is, the minimal amount of water which must be released downstream the weir.
5) The biobjective framework also satisfies environmental concerns, thus preventing any drastic degradation of the river section.
6) The proposed decision procedure requires hydrological and meteorological information which can be easily obtained.
7) A remarkably higher compensation discharge is obtained than the one corresponding to existing guidelines.

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21.7 APPENDIX: STATE EQUATIONS AND COMPONENTS

21.7.1 The hydraulic characteristics of the river section are given by (Radler, 1964)

$$H_x + \frac{v_x^2}{2g} + H_R = + H_x + \Delta x + \frac{v_x^2 + \Delta x}{2g} + I \cdot \Delta x$$

$$H_R = \frac{1}{\lambda^2} \frac{v_x^2}{2g} \cdot \frac{\Delta x}{4R} \qquad \text{(A21.1)}$$

$$\lambda = 2 \cdot \log \frac{4R}{S} + 1.14$$

R	mean effective hydraulic radius
H_x	water depth at location x
I	slope
v_x	velocity
S	roughness factor
g	gravity constant
Δx	length of a river sub-section

21.7.2 The energy balance equation is (Böhm, 1974)

$$TW_{t+1} = TW_t + \frac{1}{H_x} \cdot C\, E_t \cdot \Delta t \qquad \text{(A21.2)}$$

$$E_t = ESW_t + ELW_t + EEV_t + EC_t + ES_t$$

C	conversion factor
E	net energy input
ESW	net short wave radiation
ELW	net long wave radiation
EEV	heat losses by evaporation
EC	heat losses by conduction
ES	heat losses into the soil.

In equation (A21.2) the net short wave radiation ESW is:

ESW = ESUN + ESKY

ESUN = F_1 (CLOUD, t, H_x) . F_2 (HORIZON) . SUN

ESKY = F_3 (CLOUD, H_x) . F_4 (HORIZON) . SKY.

CLOUD	cloudiness
HORIZON	correction factor for diurnal exposure to radiation
ESUN	effective short wave radiation
ESKY	effective longwave radiation
SUN	short wave radiation
SKY	long wave radiation

The net long wave radiation ELW is:

$$ELW = b_1 \cdot TW^4 - b_2 \cdot TA^4 \cdot F_5 \text{ (CLOUD, HORIZON)}$$

TA air temperature.

The evaporative heat losses are:

$$EEV = -(PW - PA) \cdot b_3 \cdot (b_4 + b_5 \cdot WIND)$$

PW	saturation vapour pressure of air at water temperature
PA	vapour pressure of air at temperature TA
WIND	wind velocity

The conduction EC is calculated by the Bowen Ratio Method as:

$$EC = B \cdot EEV = -b_6 (TW - TA) \cdot (b_4 + b_5 \cdot WIND)$$

The conduction into/from soil ES is:

$$ES = TW_o \cdot b_7 \cdot \cos (wt + \rho_2)$$

TW_o	amplitude in daily water temperature changes
b_i	parameters, coefficients taken from literature
F_i	functions considering the dampening of solar radiation flux due to cloudiness, reflectivity, horizontal effects (taken from the literature)

21.7.3 The oxygen balance equation is (Wolf, 1974)

$$O2_{t+1} = O2_t + (REAR_t + PT_t + RM_t + BO2DEM_t) \cdot \Delta t \qquad (A21.3)$$

02	dissolved oxygen concentration
02SAT	concentration of saturated dissolved oxygen
REAR	reaeration rate
PT	rate of photosynthesis

RM rate of algael respiration
BO2DEM biological oxygen demand

with reaeration rate REAR (Churchill, 1962):

$$REAR = \frac{e_1 V_x}{H_x e_2} \cdot (02\ SAT - 02) \cdot G_1\ (TW)$$

$$02\ SAT = e_3 + e_4 \cdot TW + e_5 \cdot TW^2 + e_6\ TW^3$$

- Rate of photosynthesis PT (Wolf, 1974; Owens et al., 1969):

$$PT = e_7\ (TW)\ .\ \gamma\ .\ ESW^{e_8}$$

- Rate of algal respiration RM:

$$RM = e_g \cdot \gamma \cdot 02^{e_{10}}$$

- Biological oxygen demand BO2DEM:

$$BO2DEM = \frac{f_1}{H_x} \cdot BO2 \cdot (1 - 10^{f_2} \cdot TW)$$

e_i, f_i coefficients, parameters taken from the literature
G_i functions, considering the temperature dependency
γ specific algal biomass (kg/m^3).