Evolutionary Multi-objective Optimization Algorithms To Environmental Management and Planning With Water Resources Case Studies

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Abstract: - Environmental management and planning problems cover important real life areas. These problems may include the scarcity of groundwater resource, the optimality of a multi-reservoir system, the management of forest resources, the air quality monitoring networks, the municipal solid waste policies, etc. Management and planning targets by authorities consist in allocations at appropriate places and times, protection from disasters, maintenance of quality (e.g., water quality, water pollution control, nitrate concentration diminishing), sustainable development of the groundwater resources. The formalization of such optimization problems includes multiple objectives and constraints. The multiple objectives consist in maximizing/minimizing of various aspects of environmental management, e.g., maximizing of irrigation releases, maximizing the hydropower production, maximizing net returns, minimizing costs, minimizing the investment in water development, minimizing groundwater quality deterioration, etc.. Physical, biological, economic and environmental constraints are e. g., constraint of surface water balance, water supply constraints, water quality constraints, economic constraints (demand, resource costs, etc.), reservoir storage constraints. The eco-environmental objectives are often conflicting (e.g., the optimum use of water resources under conflicting demands. The use of multi-objective optimization allows a simultaneous treatment of all the objectives and constraints. The solutions take the form of non-dominated Pareto solutions, which enable the decision makers to study the tradeoffs between the objectives (e.g. , between profitability and risks). Most of the environmental domains are faced to uncertainties due to variability (e.g., climate, rainfalls, hydrologic variability, environmental policy, markets, etc.), imprecision and lack of data, vagueness of judgments by decision makers. These uncertainties lead to extend the analysis to fuzzy environments. This presentation is then concerned with decision-making methods in an environmental management and planning, where multiple conflicting objectives are used under a fuzzy environment by using a niched Pareto algorithm.

Key-Words: multi-objective optimization – evolutionary algorithm – genetic search method - fuzzy data - environmental management – water resources and forest planning.

1 Introduction

This paper introduces to the environmental management and planning problems by using evolutionary[1] multi-objective optimization algorithms. Natural genetic and natural selection based algorithms (GA's) belong to this class of methods and consist in search procedures[2]. GA's are flexible and effective methods for solving complex real life optimization problems. GA's have been adapted to multi-objective optimization problems where all objectives are optimized simultaneously and where a Pareto front of optimal solutions is approximated (e.g., the tradeoff between the sustainability of groundwater use and economic development [5]).

Evolutionary methods have been used to solve large scale real world eco-environmental problems, such as the irrigation water resource for determining optimal crop patterns and irrigation water resources allocation, the optimization of

[1] Evolutionary approaches refer to search optimization algorithms inspired by the process of natural evolution. They include evolutionary programming, evolution strategies, genetic algorithms and genetic programming.

[2] A bees algorithm has been also proposed by Tapkan, *et al.* [25] for solving multiple objective programs. It is a swarm based optimization algorithm inspired by the foraging behaviour of honey bees.

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multi-reservoir systems for hydropower and irrigation purposes (in Reddy and Kumar, 2006 [19]), water quality management, forest planning, etc. This study is focused on water resources and forest management[3], with applications using mostly GA's. An example problem is drawn from Reddy and Kumar [19] to illustrate the technical pattern of such formulation. The case studies for this paper have been selected only for water resources management problems, such as with Shiyang river and Hai river basin in China, and Godavari river in India[4].

Uncertainties are in water resources and forest data and planning decisions. They are due to numerous factors, such as, a lack of information, inexact or imperfect data, statistical estimation errors, imprecisions, vagueness of qualitative jugments by the decision makers (DM's), etc. For this context, fuzzy optimization techniques have been developed in water resources and forest management [14,18,33]. Fuzziness in multi-objective optimization problems may be the aspiration values of the objectives, the limit values for resources in the constraints with tolerance threshold, fuzzy coefficients in the objectives and constraints.

2 Multi-Objective Optimization

2.1 Nonfuzzy multi-objective optimization

The classical maximizing linear programming (LP) problem states

$$\text{maximize } \; z = \mathbf{c}^T \mathbf{x}, \; \left(\mathbf{c}, \mathbf{x} \in \mathbb{R}^n\right) \text{ s.t. } \mathbf{x} \in X$$

where the feasible region

$$X = \left\{ \mathbf{x} \in \mathbb{R}^n \,\middle|\, \mathbf{A}\mathbf{x} \le \mathbf{b},\, \mathbf{x} \ge \mathbf{0} \right\},$$

with $\left(\mathbf{A} \in \mathbb{R}^{m \times n}, \mathbf{b} \in \mathbb{R}^m, \mathbf{x} \in \mathbb{R}^n\right)$, is defined by all the constraints.

[3] In the literature, other multi-objective environmental applications are with energy problems, solid waste management, air quality, fisheries management, agricultural land use, etc.

[4] Other case studies are the Fengman reservoir (Sonhua river) in China by Chuntian and Chau [3], the Xingkaihu Lake Irrigation District in China by Zhou, *et al.* [34], the Bhadra reservoir system in India by Reddy and Kumar [19], the Bagmati river basin in Nepal by Onta, *et al.* [17], the Rio Colorado river in Argentina ([4], pp. 243-280), etc. The groundwater management in arid regions is analysed by Dawoud (2006)[5].

2.1.1 Multiple objective formulation and solution

In practice, the decision makers (DM's) are confronted to multiple objectives. The multi-objective linear problem (MOLP) is

$$\text{maximize } \; \mathbf{Z}(\mathbf{x}) = \mathbf{C}_{k \times n}\mathbf{x} \text{ s.t. } \mathbf{x} \in X,$$

where $\mathbf{Z}(\mathbf{x})$ states a k-vector valued objective function $\left(z_1(\mathbf{x}), z_2(\mathbf{x}), \dots, z_k(\mathbf{x})\right)^T$.

Definition 1. *Let* $\left\{\text{maximize } \mathbf{Z}(\mathbf{x}) \,\middle|\, \mathbf{x} \in X\right\}$ *be a vector-maximum problem,* $\hat{\mathbf{x}} \in X$ *is an efficient Pareto optimal solution, if and only if, there is no* $\mathbf{x} \in X$ *such that* $z_i(\mathbf{x}) \ge z_i(\hat{\mathbf{x}})$ $(i \in \mathbb{N}_k)$ *and* $z_i(\mathbf{x}) > z_i(\hat{\mathbf{x}})$ *for at least one* i.

2.1.2 Pareto optimal solution search using genetic algorithms

Genetic algorithms (GA's) are stochastic search techniques. Their procedures are inspired from the genetic processes of biological organisms by using encodings and reproduction mechanisms [6,8]. These principles may be well adapted to more complex real-world optimization problems. Let $P(t)$ be a population of potential solutions at generation t, and new individuals (or offspring) $C(t)$, the pseudo-code of a simple algorithm is the following.

```
begin          /* initial random population */
t:=0
generate initial P(t)
evaluate fitness of P(t)
  while (NOT finished) do
  begin                     /* new generation */
    for population Size/2 do
    begin              /* reproduction cycle */
      select two individuals for mating;
      recombine P(t) to yield offspring C(t);
      evaluate P(t+1) from P(t) and C(t);
      t:=t+1;
     end if population has converged then
        finished:=TRUE
  end
end
```

An initial population of individuals (chromosomes) is generated at random, and will evolve over successive improved generations towards the global optimum. Usually, a gene has converged when 95% of the population has the same

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value, and the population has converged when all the genes have converged. There are three types of operators for the reproduction phase: the selection operator for more fitted individuals, the crossover operator that creates new individuals by combining parts of strings of two individuals and the mutation that make one or more changes in a single individual string.

Real optimization problems often require the identification of multiple optima due to multivariate objective functions and multiple objective functions. In this study, the evolutionary GA's are used to approximate the Pareto-optimal set in the objective function space.

2.1.3 Niched Pareto genetic algorithm

To sample non-dominated solutions from the Pareto-optimal set it is important to maintain the diversity of solutions which can be lost due to the stochastic selection process of a simple GA procedure. Niching methods have been introduced to reduce the effect of the "random genetic drift" and to preserve the genetic diversity of the optimal solutions. Niching is based on the mechanics of natural ecosystems[5]. Goldberg and Richardson [9] suggested the use of a sharing function to estimate the number of solutions belonging to each optimum, such as

$$\mathrm{sh}\left(d_{ij}\right)=\begin{cases}1-\left(d_{ij}/\sigma_{share}\right)^{\alpha}, & \text{if } d_{ij}<\sigma_{share}\\ 0, & \text{otherwise}\end{cases}$$

where d_{ij} is a similarity metric between individuals *i* and *j*, σ_{share} the threshold of dissimilarity and α, a constant which regulates the shape of the function. The niche count m_i approximating the number of individuals that share the fitness f_i is $m_i=\sum_{j=1}^{N}\mathrm{sh}\left(d_{ij}\right)$, where N is the population size.

The Niched Pareto Genetic Algorithm (NPGA) extends the basic GA to multiple objectives optimization problem with two additional genetic operators: the Pareto domination ranking and fitness sharing [7,9,10]. The Pareto domination ranking[6] and tournament competitions help for deciding which candidates should go to the next generation. The fitness sharing operator contributes to maintain diversity in the population of solutions. Erickson, *et al*. [7] show a modified flowchart corresponding to the NPGA. Thereafter, the modified algorithm is applied to groundwater quality management problems.

[5] A niche can be viewed as a subspace in the environment that can support different types of life [23].

[6] A design dominates another design if it is at least equal in all the objectives and better than one another in at least one objective. The Pareto domination rank of an individual design is the number of designs that dominate it [7].

2.2 Fuzzy Multiobjective Optimization

2.2.1 Fuzzy LP problem

A fuzzy single objective FLP may be

$$\widetilde{\text{maximize}}\ \mathbf{c}^T\mathbf{x}\ \text{ s.t. }\ \mathbf{A}_i\mathbf{x}\ \mathrm{d}\ b_i\left(i\in\mathbb{N}_m\right),\ \mathbf{x}\geq\mathbf{0},$$

where $\widetilde{\text{maximize}}$ means "improve reaching some aspiration level" and where the fuzzy inequality d means "roughly smaller than''. More generally, we may introduce fuzzy b_i's coefficients, such that we may write:

$$\widetilde{\text{maximize}}\ \mathbf{c}^T\mathbf{x}\ \text{ s.t. }\ \mathbf{A}\,\mathbf{x}\ \mathrm{d}\ \tilde{\mathbf{b}},\ \mathbf{x}\geq\mathbf{0}.$$

2.2.2 Solving a fuzzy multiobjective LP by using crisp equivalent models

Given the fuzzy multi-objective problem

$$\text{maximize }\mathbf{C}\,\mathbf{x}\ \mathrm{t}\ \mathbf{Z}\ \text{ s.t. }\ \mathbf{A}\,\mathbf{x}\leq\mathbf{b},\ \mathbf{x}\geq\mathbf{0}$$

with fuzzy objectives and crisp constraints. The k linear objective functions are maximized simultaneously, subject to m linear constraints for the n decision variables. The coefficients are the $k\times n$ matrix $\mathbf{C}$, the $m\times n$ matrix $\mathbf{A}$ and the $m\times 1$ vector $\mathbf{b}$. The $1\times m$ vector $\mathbf{C}_1$ is the first line of the matrix $\mathbf{C}$. The resolution may consist in solving successive single objective LP's by using each objective:

$$\text{maximize }\mathbf{C}_i\mathbf{x}\ \left(i\in\mathbb{N}_k\right).$$

Using the payoff Table 1, we can obtain lower and upper bounds L_i's and U_i's such that

$$L_i=\min\left\{z_1\left(\hat{\mathbf{x}}^i\right),z_2\left(\hat{\mathbf{x}}^i\right),\ldots,z_k\left(\hat{\mathbf{x}}^i\right)\right\},$$
$$U_i=\max\left\{z_1\left(\hat{\mathbf{x}}^i\right),z_2\left(\hat{\mathbf{x}}^i\right),\ldots,z_k\left(\hat{\mathbf{x}}^i\right)\right\}.$$

Table 1: Payoff table with *k* objectives

Solution	*Objective value*			
	$z_1(\mathbf{x})$	$z_2(\mathbf{x})$	$\cdots$	$z_k(\mathbf{x})$
$\hat{\mathbf{x}}^1$	$z_1(\hat{\mathbf{x}}^1)$	$z_2(\hat{\mathbf{x}}^1)$	$\cdots$	$z_k(\hat{\mathbf{x}}^1)$
$\hat{\mathbf{x}}^2$	$z_1(\hat{\mathbf{x}}^2)$	$z_2(\hat{\mathbf{x}}^2)$	$\cdots$	$z_k(\hat{\mathbf{x}}^2)$

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$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
$\hat{\mathbf{x}}^k$	$z_1\left(\hat{\mathbf{x}}^k\right)$	$z_2\left(\hat{\mathbf{x}}^k\right)$	$\cdots$	$z_k\left(\hat{\mathbf{x}}^k\right)$

The linear membership functions (MF's) $\mu_{\tilde{G}_i}\ \left(i \in \mathbb{N}_k\right)$ are expressed by

$$\mu_{\tilde{G}_i}\left(\mathbf{x}\right) = \begin{cases} 1, & \mathbf{C}_i\mathbf{x} \geq U_i \\ \left(\mathbf{C}_i\mathbf{x} - L_i\right)/\left(U_i - L_i\right), & \mathbf{C}_i\mathbf{x} \in \left(L_i, U_i\right) \\ 0, & \mathbf{C}_i\mathbf{x} \leq L_i \end{cases}$$

The fuzzy set of the objectives[7] is $G = \bigcap_{i=1}^{k} G_i$ and $\mu_G\left(\mathbf{x}\right) = \wedge_{i=1}^{k} \mu_{G_i}\left(\mathbf{x}\right)$. The decision set is defined by $D = G \bigcap X$. The optimal solution is an efficient solution, which is obtained for the greatest degree α of satisfaction for which the program is

maximize λ s.t. $\left(C_i\mathbf{x} - L_i\right)/\left(U_i - L_i\right) \geq \lambda$,

with $i \in \mathbb{N}_k$, $\mathbf{x} \in X$, $\lambda \in \left(0,1\right]$.

In the constrained method, the problem is transformed to a partially FLP problem with only one of the k objective functions, the remaining $k-1$ fuzzy objectives being placed into the set of constraints. Choosing the first objective and transferring the other objectives yields

$$\begin{aligned} &\text{maximize } z_1\left(\mathbf{x}\right) = \mathbf{C}_1\mathbf{x} \\ &\text{s.t.} \quad \mathbf{C}_j\mathbf{x}\ \text{t}\ z_j^U \left(j \in \mathbb{N}_k \setminus \{1\}\right), \\ &\quad\quad \mathbf{A}\mathbf{x} \leq \mathbf{b}, \\ &\quad\quad \mathbf{x} \geq \mathbf{0}, \end{aligned}$$

where the aspiration level equals the upper value of z_1^U with a tolerance of $z_1^U - z_1^L$. The MF's of the objectives are defined by

$$\mu_{\tilde{G}_i}\left(\mathbf{C}_i\mathbf{x}\right) = \begin{cases} 1, & \mathbf{C}_i\mathbf{x} \geq z_i \\ \left(\mathbf{C}_i\mathbf{x} - z_i^L\right)/\left(z_i^U - z_i^L\right), & \mathbf{C}_i\mathbf{x} \in \left(z_i^L, z_i^U\right) \\ 0, & \mathbf{C}_i\mathbf{x} \leq z_i^L \end{cases}$$

Then we have to solve the parametric programming problem

$$\begin{aligned} &\text{maximize } z_1\left(\mathbf{x}\right) = \mathbf{C}_1\mathbf{x} \\ &\text{s.t.} \quad \mathbf{C}_j\mathbf{x} \geq z_j^U - \lambda\left(z_j^U - z_j^L\right) \left(j \in \mathbb{N}_k \setminus \{1\}\right), \\ &\quad\quad \mathbf{A}\mathbf{x} \leq \mathbf{b}, \quad \mathbf{x} \geq \mathbf{0}. \end{aligned}$$

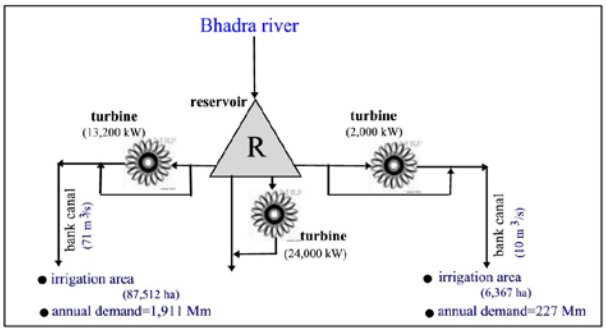
This programming technique will provide a fuzzy decision dependent on the preference parameter λ.

2.2.3 Direct solution method via meta-heuristic algorithms

Baykasoglu and Göçken [1,2] proposed a direct solution method (DSM) for solving fuzzy multi-objective optimization problems to avoid the inconveniences of a transformation into equivalent crisp programs. A ranking method is used for fuzzy numbers to rank the objective values and to determine the feasibility of the constraints. Thereafter, a meta-heuristic algorithm is carried out for searching efficient solutions [25].

2.3 Multi-objective water resource example problem

The following model for water resources management is drawn from Reddy and Kumar (2006) [19][8]. This model is for the Badra dam. It is situated in Chimagalur district of Karnataka State, India. The reservoir is multipurpose, providing for irrigation and for hydropower production. The two irrigation areas are of 87,512 ha and 6,367 ha, respectively. There are three hydropower turbines. One turbine is at the bed of the dam. Fig. 1 shows the flowchart of the reservoir system.



(adapted from Reddy and Kumar, 2006)

Fig. 1: The Badra multipurpose reservoir system in India.

The model formulation consists in three objectives and six constraints [19]. There are two conflicting objectives which consist in minimizing the deviation of releases from demands and in maximizing the total production of energy. Physical

[7] Other real-valued functions have been proposed in the literature : a weighted sum of objectives $\sum_{i=1}^{k} \alpha_i \left(z_i\left(\mathbf{x}\right)^{\beta_i}\right)$, $\alpha_i, \beta_i > 0$ or a product of objectives $\prod_{i=1}^{k} \alpha_i\left(z_i\right)$. This aggregation may also be based on the DM's preferences with utility functions.

[8] The formulation of a water pollution control problem was presented by Sakawa and Seo, 1980 [22], with application to Osaka City, Japan. (See also, Lai and Huang, 1994 [13], pp. 119-123).

and environmental constraints are imposed on the system: i.e., a storage continuity equation, the storage limits, the maximum power production limits, the canal capacity limits, the irrigation demand limitations and the water quality requirements.

Table 2: Water resource management example problem [19]

Objectives:

- minimize $\sum_{t=1}^{12}\left(D_{1,t}-R_{1,t}\right)^2+\sum_{t=1}^{12}\left(D_{2,t}-R_{2,t}\right)^2 \quad \ldots(1)$
- maximize $\sum_{t=1}^{12} p\left(R_{1,t}H_{1,t}+R_{2,t}H_{2,t}+R_{3,t}H_{3,t}\right) \quad \ldots(2)$

Constraints:

- $S_{t+1}=S_t+I_t-\left(R_{1,t}+R_{2,t}+R_{3,t}+E_t+O_t\right) \quad \ldots(3)$
- $S_t \in \left[S_{\min},S_{\max}\right] \quad \ldots(4)$
- $p\,R_{j,t}H_{j,t} \le E_{j,\max},\ j=1,2,3 \quad \ldots(5)$
- $R_{j,t} \le C_{j,\max},\ j=1,2 \quad \ldots(6)$
- $R_{j,t} \in \left[D_{j,\min},D_{j,\max}\right],\ j=1,2 \quad \ldots(7)$
- $R_{3,t} \ge MDT_t \quad \ldots(8)$

List of parameters:

$\boldsymbol{C}_{\max}$: canal carrying maximum capacity
$\boldsymbol{D}_1,\boldsymbol{D}_2$: irrigation demand
$\boldsymbol{D}_{\min},\boldsymbol{D}_{\max}$: minimum and maximum demands
$\boldsymbol{E}$: evaporation losses
$\boldsymbol{E}_{\max}$: turbine capacity
$\boldsymbol{H}_1,\boldsymbol{H}_2,\boldsymbol{H}_3$: net heads available
$\boldsymbol{I}$: inflow to the reservoir;
$\boldsymbol{MDT}$: minimum release to meet downstream water quality
$\boldsymbol{O}$**:** overflow from the reservoir; **p**: power production coefficient
$\boldsymbol{R}_1,\boldsymbol{R}_2,\boldsymbol{R}_3$: releases into bank canals
$\boldsymbol{S}$: active reservoir storage.

The non-dominated sorting genetic algorithm (NSGA II) is used to derive operating policies for the reservoir operation problem. The parameters used are selected after a sensitivity analysis. The population size is of 200 individuals and the maximum generation number is of 1,000. The trade-off between irrigation and hydropower in the objective space is shown in [19]. At this Pareto front, the decision maker may choose a solution corresponding to his preferences.

3 Modeling Environmental management Problems

In this study, the management and planning problems are illustrated for two main environmental areas: water resources and forest [11,28,30].

3.1 Model formulation

The standard formulation of the model concerns the variables (or parameters), the multiple objectives and the constraints. A distinction is made between the state and the decision variables. The set of the state variables (state vector) for a given system aims at describing the system and all its elements (e.g., area of forest land, machinery, plant species, labor force, budget, etc.) [33]. The variable decisions are under the control of the DM's and can influence the system. This set of feasible parameters is constrained by budget limits, available labor force and machinery, etc. The multiple objectives for water resources and forest management are described in Table 3. Different types of objectives are considered: the economic objectives (e.g., output of groundwater, benefits and costs, labor employment, hydropower production in water resources, timber production in forestry); physical objectives (e.g., irrigation releases); environmental and ecological objectives (e.g., aquifer yield, BOD discharge, TDS concentration, groundwater salinity in water resources, wildlife habitat condition, in forest management; social health and education objectives (e.g., food production, employment possibilities, health risk, environmental awareness). The constraints are inequalities and equalities that determine the set of the admissible decisions. The constraints can be divides into physical, economic and environmental constraints as in Table 3. Thus, the physical constraints are limitations such as water level, turbine releases for multi-reservoir systems.

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Table 3: Objectives and constraints in water resources and forest management problems

Literature	*Objectives*	*Constraints*
	Water resources management problem	
Onta, *et al*. (**1991**) [17] ; Makowski & Somlyody (**2000**) [15]; Yang, *et al*. (**2001**) [32]; Ericksson, *et al*. (**2002**) [7]; Cohon (**2003**) [4]; Raju & Duckstein (**2003**) [18]; Weng (**2005**) [29]; Dawoud (**2006**) [5]; Reddy & Kumar (**2006**) [19]	●**Economic objectives** : **1)** maximize economic output of groundwater use ; **2)** maximize economic output of industries; **3)** maximize GDP; **4)** maximize benefits from hydropower generation; **5)** maximize net benefits from agricultural; **6)** maximize the ratio benefits to costs; **7)** maximize employment of labour; **8)** maximize food grains production; **9)** minimize cost; **10)** minimize investment in water development; **11)** minimize net value of groundwater depletion mitigation cost. ●**Physical objectives** (in multi-reservoir systems): **1)** maximize irrigation releases; **2)** maximize hydropower production; **3)** maximize the irrigated cropped area; **4)** minimize the irrigation deficit. ●**Environmental objectives**: **1)** maximize aquifer yield; **2)** maximize cleanup time; **3)** minimize BOD (biological oxygen demand) discharge; **4)** minimize concentration (in total dissolved solids (TDS)) increment in groundwater; **5)** minimize the air pollution (total amount of SO_2); **6)** minimize the water pollution (dissolved oxygen (DO) and ammonia (NH_4) concentrations); **7)** minimize groundwater salinity. ●**Social, health and educational objectives**: **1)** maximize food production; **2)** minimize health risk.	●**Physical constraints**: **1)** water level; **2)** water resources; **3)** maximum surface availability; **4)** maximum groundwater availability; **5)** crop water requirement; **6)** maximum area availability; **7)** crop area continuity; **8)** forestry; **9)** drawdown; **10)** surface water balance; **11)** turbine release (for multi-reservoir system); **12)** irrigation release; **13)** reservoir storage; **14)** hydrologic continuity for all reservoirs. ●**Economic constraints**: **1)** water demand; **2)** microeconomic constraints; **3)** expenditures; **4)** agricultural production requirement. ●**Environmental constraints**: **1)** animal husbandry and fishery; **2)** BOD discharge; **3)** water quality.
	Forest management problem	
Steuer & Schuler, (**1979**) [24] ; Mendoza, *et al*. (**1993**) [16] ;Tecle, *et al*. (**1998**) [26] ; Raju & Duckstein (**2003**) [18] ;Weintraub & Romero (**2006**) [27] ; Zadnik Stirn (**2006**) [33]; Kennedy, *et al*. (**2008**) [12]	●**Economic objectives** : **1)** maximize net present value ; **2)** maximize timber production ; **3)** maximize on-site merchandable timber volume ; **4)** maximize forage production ; **5)** maximize herbage production ; ●**Environmental objectives** : **1)** maximize water yield ; **2)** maximize wild life habitat condition ; **3)** minimize sediment yield. ●**Social and educational objectives**: **1)** promotion of environmental awareness; **2)** education about flora and fauna.	●**Physical constraints**: **1)** acreage limitations; **2)** timber harvesting yield. ●**Economic constraints**: **1)** budget limitation. ●**Environmental constraints**: **1)** bird habitat; **2)** land; **3)** sediment yield; **4)** fire danger.

Table 4: Environmental selected case studies in water resources management

Case study	*Location and characteristics*	*Problems and drawbacks*	*Policies and programming method*
Shiyang River, <u>China</u> Yang, *et al.*, (**2001**) [32]	●**Location**: northwestern China ●**Characteristics**: **1)** a sediment fillen graben of 30,000 km^2 area; **2)** annual average precipitation of 100-250 mm; **3)** potential evaporation of 2000-3000 mm; **4)** about 65% of water coming from the precipitation and 35% from groundwater.	●**Problems**: **1)** Extensive water uses begin in the 1950s; **2)** overexploitation of groundwater ●**Drawbacks**: **1)** conflicts between water supply and water demand; **2)** continuous drawdown of the groundwater level; **3)** deterioration of water quality; **4)** withering of vegetation; **5)** soil desertification and salinization.	●**Policies**: **1)** maintain the current water utilization; **2)** perform a conjunctive management of groundwater and surface water; **3)** minimize the groundwater deterioration; **4)** meet the increasing water demand of human, livestock, industry and forestry users; **5)** achieve economic, best social and ecological values of water uses. ●**Programming method**: multi-objective optimization model
Hai River, <u>China</u> Weng, (**2005**) [29]	●**Location**: northern part of China ●**Characteristics**: **1)** basin area of 189,000 km^2; **2)** semi-humid climate with uneven rainfall distribution (average precipitation of about 550 mm) ; **3)** about 10% of China grain output, a center of various industrial activities, a population of 110 millions in 1994.	●**Problems**: **1)** rapid economic growth wide variety of industries; **2)** substantial changes in the water demand; **3)** few water treatment facilities ●**Drawbacks**: **1)** water deficit; **2)** scarce of water resources; **3)** increase in of water area; **4)** competition of other uses; **5)** water pollution (urban population growth and industry); **6)** wastewater discharged to the river.	●**Policies**: **1)** water saving policy (controlling, leakage, promoting re-use of water, etc.); **2)** protection of water resources (reducing water pollution, building waste water infrastructure, charging rational prices); **3)** South-north water transfer project ●**Programming method**: **1)** microeconomic multiobjective water resource model; **2)** multiobjective optimization component; **3)** a stepwise multiobjective programming algorithm; **4)** scenarios.
Godavari River, <u>India</u> Regulwar & Raj, (**2008**) [20]	●**Location**: Maharashtra State, in India. ●**Characteristics:** The physical water system consists of five reservoirs (one is a barrage): the Jayakwadi project stages I and II, the Yeldari project, the Siddheshwar project and the Vishnupuri project.	●**Problems**: **1)** scarcity of water for irrigation and hydropower production, industrial requirement and domestic purposes; **2)** increasing water demands; **3)** the complexity of water resources domains, of river basin planning under uncertainty. ●**Drawbacks**: **1)** water quality deterioration; **2)** water deficit; **3)** competition between uses.	●**Policies**: **1)** maximize the irrigation releases; **2)** maximize the hydropower production; **3)** consider other increase alternatives for irrigation and hydropower demands. ●**Programming method**: multi-objective optimization by using genetic algorithms with fuzzified objectives. Solution surface covering the whale range of policies for different levels of satisfaction.

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3.2 Environmental water resources case studies

Environmental case studies in water resources have been selected for this introductory approach: two are river basins northern of China and the other case study is a multireservoir system on the Godavari river in India. In Table 4, the characteristics of the case studies are compared. The main problems and drawbacks are mentioned. The chosen policies by authorities result with some details.

3.3 Multireservoir Case Study in Maharashtra Sub Basin

The real-world case study by Regulwar and Raj (2008, 2009) [20,21] illustrates a multireservoir management problem for irrigation and hydropower production. The physical system is shown in Fig. 2 which has been adapted from [21]. It consists of four reservoirs and a barrage. Each reservoir is described in terms of gross storage, live storage, installed capacity for power generation[9]. The irrigable area is also defined. The monthly irrigation demand and inflow are given for all the reservoirs.

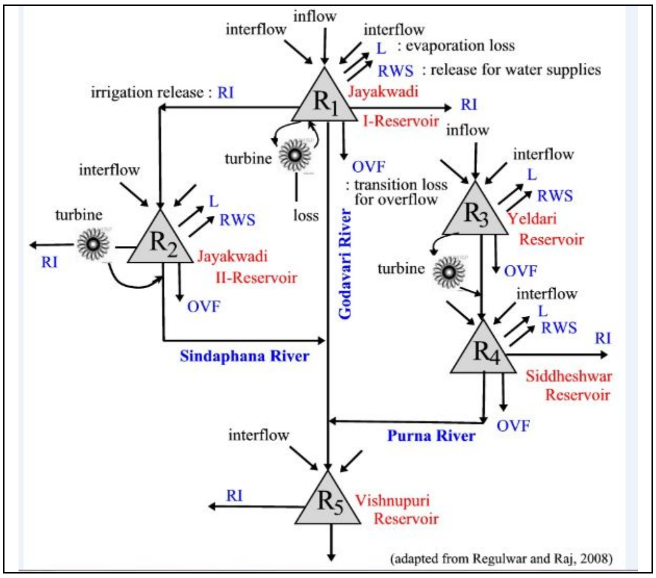

Fig. 2. Multireservoir system in Godavari sub basin in Mahharashtra State, India.

[9] All the data are given in [21]. The reservoir R_1 is the largest reservoir with a gross storage of $2,909 \times 10^6\,\mathrm{m}^3$, an installed capacity for power generation of 12.MW and for an irrigable area of $1,416.40\,\mathrm{km}^2$. Considering the gross storage, the reservoir are ranked as $R_5 < R_4 < R_2 < R_3 < R_1$. Monthly historical flow data have been collected over 32 years.

The decision maker aims at maximizing two objectives: the irrigation releases and the hydropower production. The constraints are due to the turbines for power production, to irrigation releases, to the reservoir storage capacities. There are also hydrologic continuity constraints for all reservoirs [21]. Only the two objectives are supposed to be fuzzy, all other parameters being crisp in nature. The membership functions (MFs) of the two objectives are supposed to have a linear formulation, for which the best and worst values are determined for each MF[10].

The two fuzzified objectives are maximized by defining, and then maximizing a level of satisfaction (ranged from 0 to 100%). The resulting crisp equivalent single objective programming problem is solved by using GA. The genetic operators are: a stochastic remainder selection, a one point crossover and a binary mutation. The crossover probability is 0.7 for the first objective and 0.9 for the second. In both cases, the mutation probability is set to 0.1. The parameter values are a population of 130 and 500 generations.

The results for an existing demand[11] are: a level of satisfaction of 60%, irrigation releases (objective 1) of $2,054.22 \times 10^6\,\mathrm{m}^3$ and a hydropower production (objective 2) of $10,475 \times 10^4\,\mathrm{kWh}$ [20].

4 Conclusion

The importance of water resources and forest management is proved by numerous applications in the environmental literature. DM's aim at sustainable solutions. They are faced to long term multi-objective planning problems for which data are imprecise and judgments are vague. Therefore most decision-making systems are based on fuzzy evolutionary multi-objective optimization methods. This introductory study is used adequate methods

[10] For the irrigation releases first objective the worst and best values are respectively $1,807.97$ and $2,218.36 \times 10^6\,\mathrm{m}^3$ respectively. For the hydropower production second objective the worst and best values are respectively $11,739.5$ and $8,559.5 \times 10^4\,\mathrm{kWh}$ respectively [21].

[11] The results for an increased demand of 10 % are the following [21] : a level of satisfaction of 52%, irrigation releases (objective 1) of $2,195.34 \times 10^6\,\mathrm{m}^3$ and a hydropower production of $11,026 \times 10^4\,\mathrm{kWh}$.

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and examples with selected case studies in water resource and forest management.

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