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Evolutionary Multi-Objective Optimization Algorithms

To Environmental Management and Planning With Water Resources Case Studies

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- **Introduction: Fuzzy multi-objective optimization** by using the niched Pareto genetic algorithm (NPGA).
- **I.** Multi-objective optimization **to water resource management** in China: the Shiyang River Basin in NE and the Hai River Basin in NW. The reference to the study of Three-Gorges reservoir on Yangtze River.
- **II.** A **water resource example problem** by using GAs: the Badra one-reservoir system in India, with two objectives.
- **III.** A **water resource case study** by using NPGA in a fuzzy environment: the Godavari multireservoir multiobjective management problem in India, with two fuzzified objectives.

Contents

● Introduction: multiobjective optimization programming (MOP) problem

- the vector decision variables **x** optimizes a vector of *r* objective functions.
- the *r* objective functions are subjected to *p* inequalities ,*m-p* equality constraints and to *2n* variables bounds, restricting each decision variable in a closed interval . All the constraints define the decision space.
- A feasible solution satisfies both the *m* constraints and the *2n* bounds

$$\left.\begin{aligned} \underset{\mathbf{x}\in\mathbb{R}^n}{\text{minimize}}\ \mathbf{f}(\mathbf{x}) = \left(f_1(\mathbf{x}),\ldots,f_r(\mathbf{x})\right)^T \\ \text{subject to :} \\ g_i(\mathbf{x}) \le 0,\ i=1,\ldots,p \\ h_i(\mathbf{x}) = 0,\ \ i=p+1,\ldots,m \\ x_i \in \left[\underline{x}_i, \overline{x}_i\right],\ i=1,\ldots,n \end{aligned}\right]$$

• Let the conventional multi-objective linear programming problem:

maximize $\mathbf{z} = \mathbf{Cx} = \left(\mathbf{C}_1\mathbf{x}, \mathbf{C}_2\mathbf{x}, \ldots, \mathbf{C}_r\mathbf{x}\right)^T$
subject to
$\mathbf{Ax} \le \mathbf{b}$,
$\mathbf{x} \ge \mathbf{0}$.

where r linear objective functions are maximized simultaneously, subject to m linear constraints for the n decision variables $\mathbf{x}$. The coefficients are the $r \times n$ matrix $\mathbf{C}$, the $r \times n$ matrix $\mathbf{A}$ and the $m \times 1$ vector $\mathbf{b}$. $\mathbf{C}_1$ is the first line of the matrix $\mathbf{C}$. Suppose that the objectives are in an imprecise and uncertain situation and can be represented by fuzzy set.

• The fuzzification of all the objectives associates membership functions, defined by

$$\mu_i(\mathbf{x}) = \begin{cases} 0, & \text{for } z_i \le \underline{z}_i \\ \left(\dfrac{z_i - \underline{z}_i}{\overline{z}_i - \underline{z}_i}\right)^{\beta}, & \text{for } z_i \in \left[\underline{z}_i, \overline{z}_i\right],\ i = 1, \ldots, r \\ 1, & \text{for } z_i \ge \overline{z}_i \end{cases}$$

where $\mu_i(\mathbf{x})$ denotes the degree to which $\mathbf{x}$ fulfills the fuzzy inequality $\mathbf{C}_i\mathbf{x} \le z_i$, where $\overline{z}_i$ is the aspiration level of the objective function i, $\underline{z}_i$ the lowest acceptable level of the objective i, β giving the desired shape of the membership function. The membership of the fuzzy set decision model is then defined by
$\mu_D(\mathbf{x}) = \min_i \left\{\mu_i(\mathbf{x})\right\},\ i = 1, 2, \ldots, r$.

• The programming problem is

maximize $\min_i \left\{\mu_i(\mathbf{x})\right\}$
subject to
$\mathbf{Ax} \le \mathbf{b},\quad \mathbf{x} \ge 0$.

▶ Introducing the new variable λ, we may also write and solve the equivalent programming linear problem:

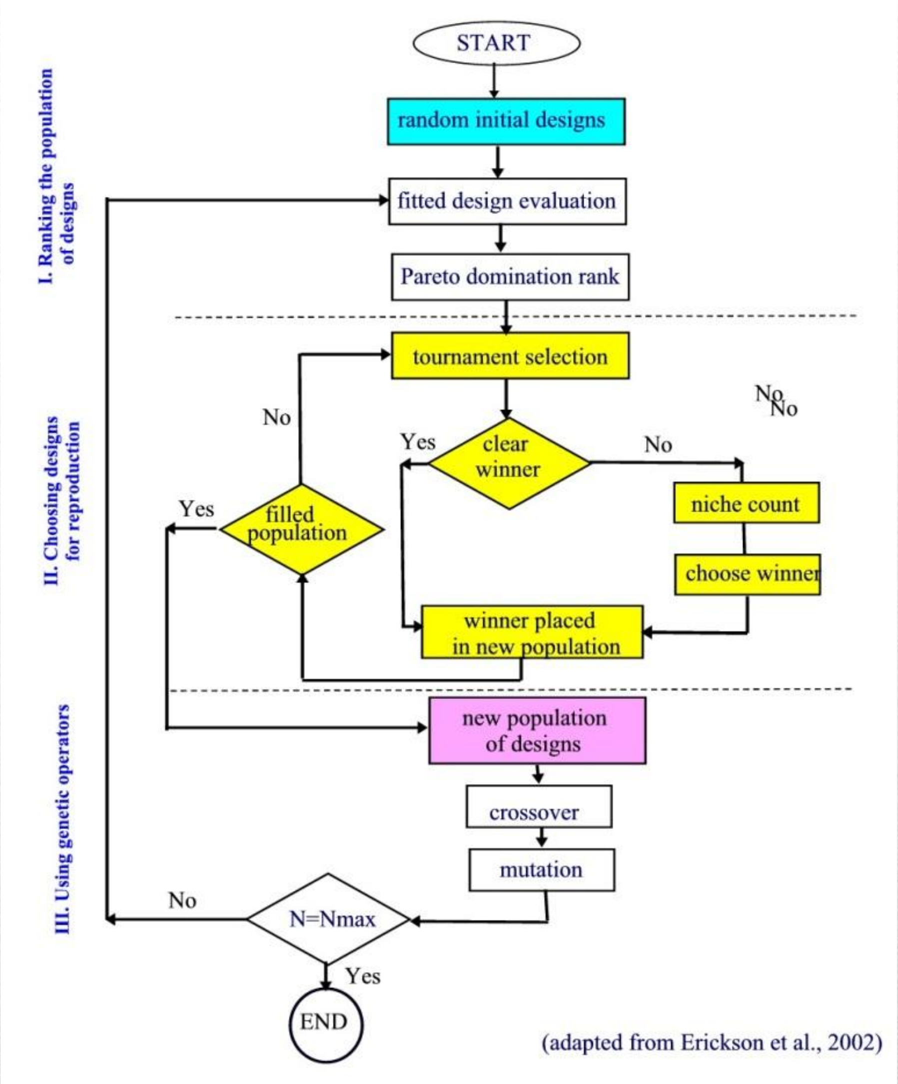
maximize λ
subject to
$\mu_i(\mathbf{x}) \ge \lambda$ for each $i = 1, 2, \ldots, r$
$\mathbf{Ax} \le \mathbf{b}$
$\lambda \in [0, 1], \mathbf{x} \ge \mathbf{0}$.

• Fuzzy multiobjective optimization programming problem

-The **evolutionary** multiobjective optimization algorithm was introduced by Horn et al. (1994).

- The extension of the traditional GA to NPGA involves **two new genetic operators**: the Pareto domination ranking and a continuously updated fitness sharing.

- The **diversity** in the population is then maintained by these two operators.



● NPGA flowchart showing the basic steps

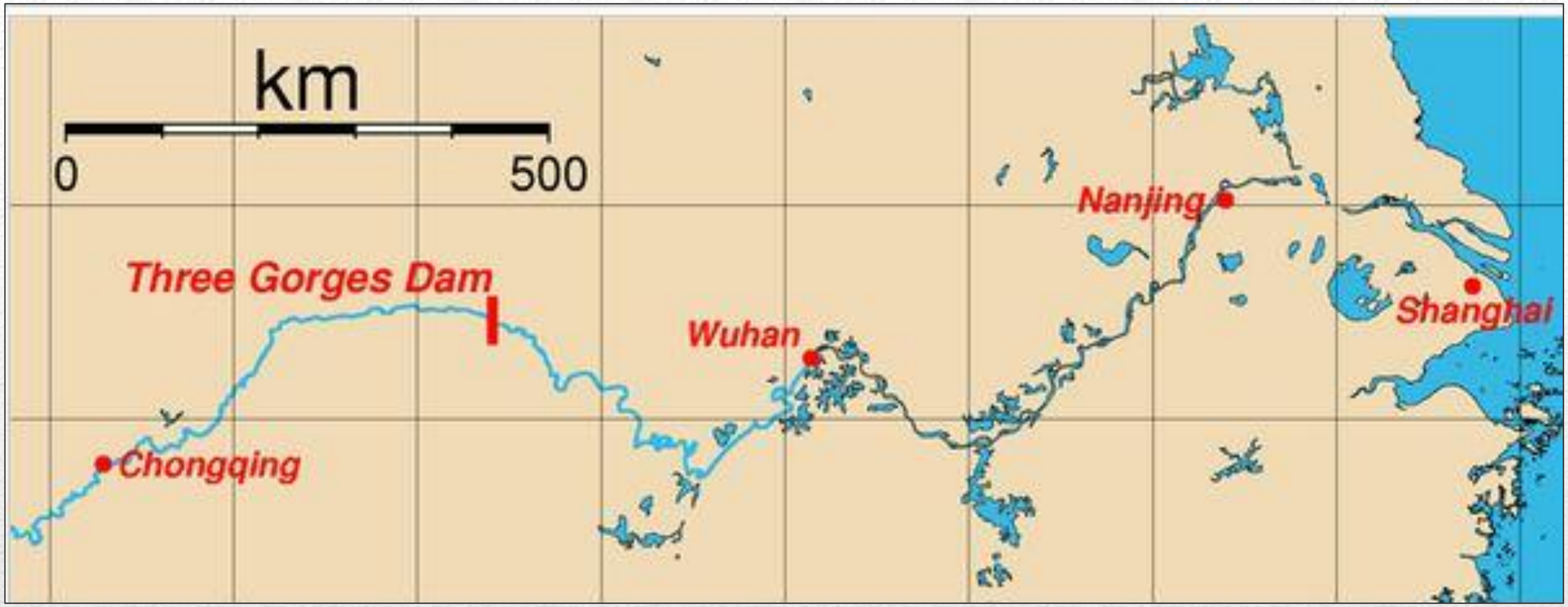
I. MULTIOBJECTIVE OPTIMIZATION TO WATER RESOURCE MANAGEMENT IN CHINA

In this section the methodology of multiobjective optimization problems is applied to water resource management in China. Evolutionary algorithms **in the class of genetic algorithms** may be used.

The main Yangtze River basin in China and two other important river basins in China for this study: the Shiyang River basin and the Hai River basin.

	Shiyang River Basin (Weng, 2005)	Hai River Basin (Yang et al., 2001)
objective functions	▶ **Economic objective** (Regional GDP maximization) ▶ **Environmental objective** (Biological oxygen demand (BOD) discharge minimization) ▶ **Social objective** (Food production maximization)	▶ **Economic objectives:** restrict surface water demand and groundwater pumpage (P1); maximize the economic output of industries in the basin (P6); minimize the investment in water development (P7); satisfy water use of human being and livestock (P2), of industries (P3), of agricultural irrigation (P4), of forestry (P5). ▶ **Environmental objective:** minimize the concentration of total dissolved solids (TDS) increments in groundwater (P9); restrict the groundwater level drawdown (P8).
constraints	• **Economic constraints** (input-output, private and government expenditures, fixed assets and working capital, investment of water projects) • **Planting constraints** (crop area, crop outputs, irrigation water) • **Forestry constraints** (forest area, forest output values, irrigation water) • **Animal husbandry and fishery** constraints (grass area, production of livestock, water needed for animals and fishery) • **Water resource constraint** (water use, wastewater discharge) • **Planting area constraints** (increase in planting area, irrigation area, total planting area) • **BOD discharge constraint**	• Surface water balance constraints • Groundwater balance constraints • Water supply constraints • Water level constraints • Water quality constraints • Economy constraints

Case study	*Location and characteristics*	*Problems and drawbacks*	*Policies and programming method*
Shiyang river Yang, *et al.*, (**2001**) [31]	•**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 Weng, (**2005**) [28]	•**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.



● Q. Li, J. Ren and M. Yu (2011). ‘*’Genetic algorithms based hydropower optimization of the Three-Gorges reservoir operation under two reservoir storing water schemes*’’. Oxford: IAHS Press.

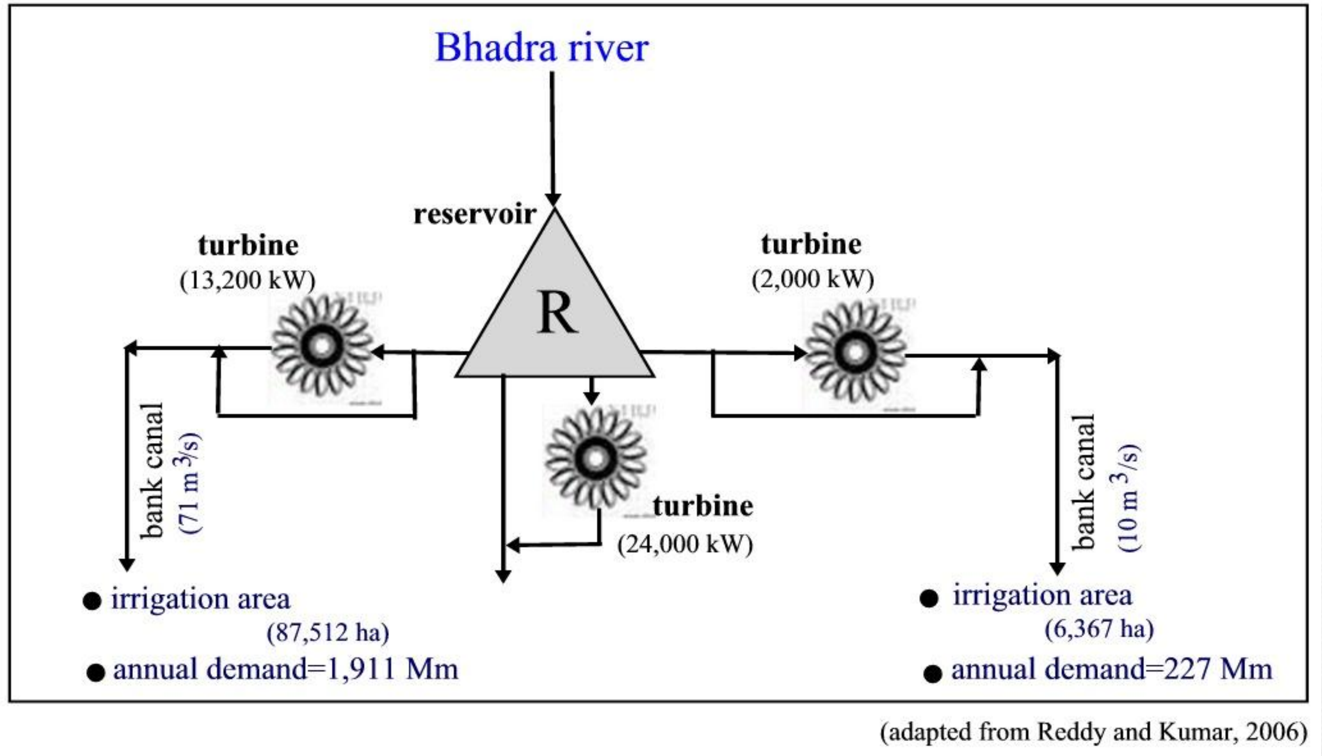
► A case study by **Hohai University** (HHU) in Nanjing to explore the hydropower optimization problem by using genetic algorithms with daily time series over the period 1950-2002.

II. WATER RESOURCES EXAMPLE PROBLEM

In this section, an one-reservoir example problem is shown: a **two objectives one-reservoir** problem. For this example a brief description is given with the flowchart of the system, the formulation of the model and the results. For this problems the basic **multiobjective genetic algorithm** (MOGA) is used for solving the programming system. This example problem is drawn from the literature and adapted for this study.

- An example problem due to **Reddy and Kumar (2006)**, in *Water Resources Management*, 20, pages 861-878.
- The **Bhadra project** is multipurpose, providing for irrigation and for hydropower production.
- The mathematical formulation includes **two conflicting objectives** such as minimization of irrigation deficits and maximization of hydropower production. The **contraints** are the storage continuity equation, storage limits, power capacity limits, canal capacity limits, irrigation demands and water quality requirements.
- The **multiobjective GA** is applied to derive operating policies. It is possible to generate a large number of alternatives. After arriving at the Pareto front (the transformation curve between the objectives), subjective judgments are required from the decision maker.
- The flowchart of the system, the mathematical formulation , the implementation and optimal solutions in the objective space are shown below.

● Example problem 1: presentation



● The **Bhadra dam** is situated in Chimagalur district of Karnataka state, India. The reservoir provides water for irrigation of 87,512 ha and 6,367 ha. There are three Hydropower turbines. One turbine is at the bed of the dam. Data of monthly inflows were notably collected over a period of 69 years.

● Example problem : the Badra reservoir system in India

$C_{\max}$	Canal carrying maximum capacity
D_1, D_2	Irrigation demand
$D_{\min}, D_{\max}$	Minimum and maximum irrigation demands for the
E	Evaporation losses
$E_{\max}$	Turbine capacity
H_1, H_2, H_3	Net heads available
I	Inflow to the reservoir
MDT	Minimum release to meet downstream water qual
O	Overflow from the reservoir
p	Power production coefficient
R_1, R_2, R_3	Releases into bank canals
S	Active reservoir storage

● Example problem : notations of the model

minimize $\sum_{t=1}^{12}\left(D_{1,t}-R_{1,t}\right)^2+\sum_{t=1}^{12}\left(D_{2,t}-R_{2,t}\right)^2$ ... deviation of releases from demands

maximize $\sum_{t=1}^{12} p\left(R_{1,t}H_{1,t}+R_{2,t}H_{2,t}+R_{3,t}H_{3,t}\right)$ ... total production of energy

subject to

- storage continuity

  $S_{t+1}=S_t+I_t-\left(R_{1,t}+R_{2,t}+R_{3,t}+E_t+O_t\right)$
- storage limits

  $S_t\in\left[S_{\min},S_{\max}\right]$
- maximum power production limits

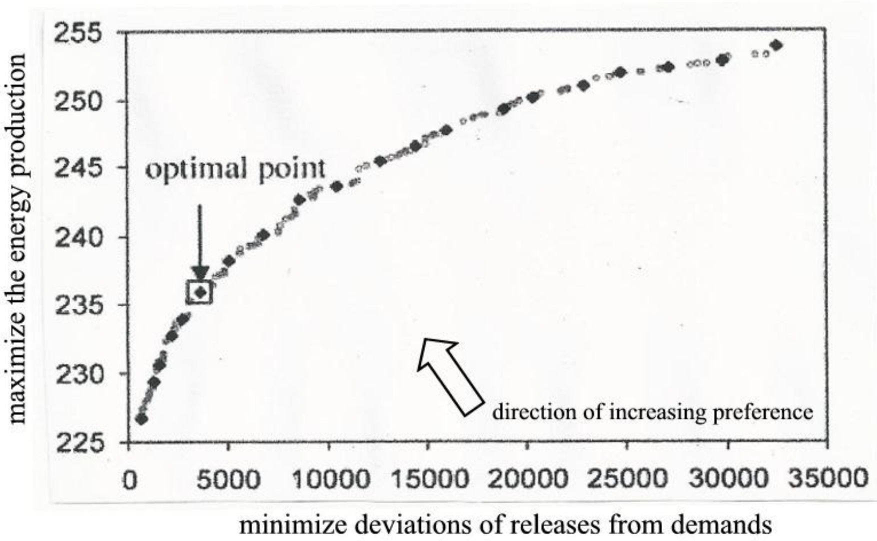
  $pR_{j,t}H_{j,t}\le E_{j,\max},\ j=1,2,3$
- canal capacity limits

  $R_{j,t}\le C_{j,\max},\ j=1,2$
- irrigation demands

  $R_{j,t}\in\left[D_{j,\min},D_{j,\max}\right],\ j=1,2$
- water quality requirements

  $R_{3,t}\ge MDT_t$

● Example problem : Equations of the model



The non-dominated sorting genetic algorithm (**NSGA II**) principle is used for the reservoir operation problem to derive operating policies. The parameters used are selected after a sensitivity analysis. The population size is of 200 and the maximum generation number is of 1000. The crossover probability is 0.9 and the mutation probability is 0.03. The figure shows the **trade-off between irrigation and hydropower**. After arriving at the Pareto front, the decision maker chooses a solution corresponding to his preferences.

● Example problem : Solving the example problem by using a multi-objective GA

III. WATER RESOURCE CASE STUDY: A MULTIRESERVOIR MANAGEMENT PROBLEM IN FUZZY ENVIRONMENT

In this section a **real world** water resources case study is presented: a multireservoir management model for the Godavari River sub-basin in India. A multi-objective GA in **fuzzy environment** is used for solving. This case study is drawn from the literature and adapted for this study.

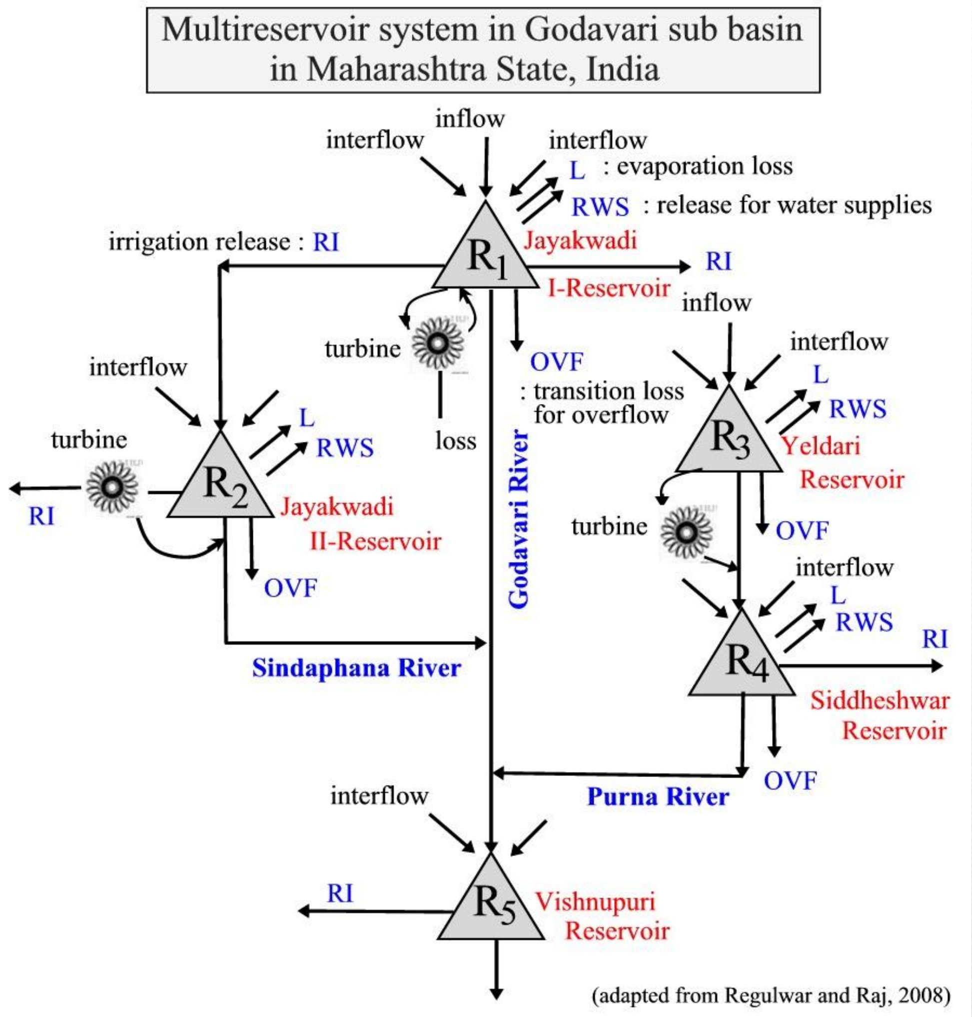
- A real-world case study due to **Regulwar and Raj (2008)** in Water Resource Management, 22, pages 595-610.
- A Multireservoir management problem for **irrigation** and **hydropower production**. The multireservoir system in Godavari River sub basin in Maharashtra State, India consists of four reservoirs and a barrage.
- The decision maker aims at **maximizing two objectives simultaneously**: 1. the irrigation releases and 2. the hydropower production. These two objectives beeing **fuzzified,** a level of satisfaction is maximized in the crisp equivalent version of the programming problem.
- The multiobjective optimization algorithm **NPGA** is used for generating the trade-off curve of the programming problem.

● Multireservoir management : presentation

- The **two objectives** are to maximize the irrigation releases, to maximize the hydro-power distribution.
- Only the objectives are supposed to be **fuzzy**, all other parameters being **crisp** in nature.
- 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 the reservoirs.

2. Multireservoir management : programming problem

- **Each reservoir** of the system is described in terms of gross storage, live storage, installed capacity for power generation. The irrigable area is defined.
- Monthly historical flow **data** is collected over several tens of years.
- The irrigation demand and inflow are **given** for all the reservoirs.



● Multireservoir physical system

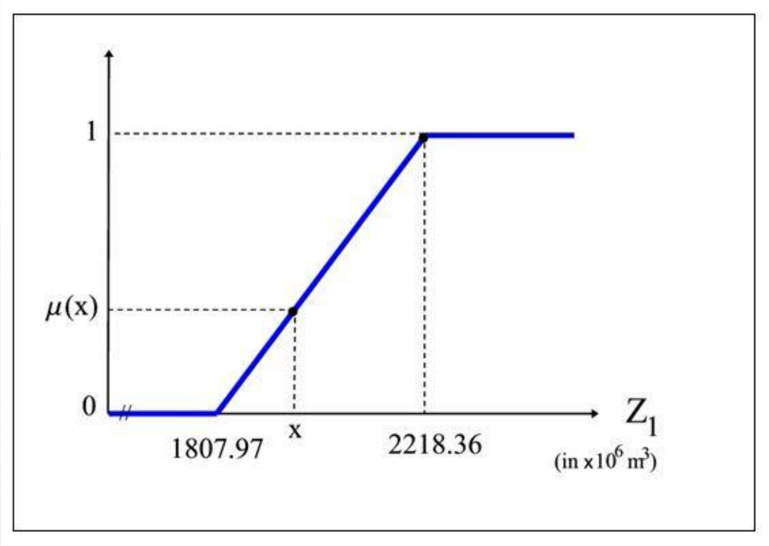
- **Step 1**: Determining the best and worst values for both objectives by considering one objective at a time and ignoring the others. Thus, when Z1 is maximized, the corresponding value of Z2 is considered to be the worst and vice versa.
- **Step 2**: Fuzzifying both irrigation releases and hydropower production objectives by considering linear membership functions.
- **Step 3**: A modified optimization problem is formulated for which the single objective to be maximized is the level of satisfaction, the both initial constraints being placed into the constraints.
- **Step 4**: The programming problem is solved by using the NPGA evolutionnary algorithm.
- **Step 5**: Results are obtained for 500 generations. Simulations are realized for different rates of increased demand.

● Different steps for solving the fuzzy multiobjective optimization problem

Objective function	Existing demand	
	Best value	Worst value
Irrigation releases Objective 1 (in 10^6 m^3)	2,218.36	1,807.97
Hydro-power production Objective 2 (in 10^4 kWh)	11,739.5	8,559.2

► Step 1: Best and worst values for the objectives

Membership function (MF)



MF's linear formulation

$$\mu_{Z_1} = \begin{cases} 0, & \text{if } Z_1 \leq 1807.97 \\ \dfrac{Z_1 - 1807.97}{2218.36 - 1807.97}, & \text{if } Z_1 \in [1807.97, 2218.36] \\ 1, & \text{if } Z_1 \geq 2218.36 \end{cases}$$

The first **fuzzified objective** is taken as an illustrative example of a linear membership Function (MF). The **membership function** (or characteristic function or or degree of truth) is an essential component of a fuzzy set. Formally, we have $\mu(x) : \mathcal{U} \longrightarrow [0,1]$. For any element x of the universum $\mathcal{U}$. The <u>second fuzzified objective</u> for this study is **similar.**

►Step 2: Fuzzification of the objectives

a	$=0.5A_a e$
A_a	Reservoir water spread area per unit value of active storage volume
A_0	Reservoir water spread area per unit value of dead storage volume
$DSIN$	Downstream inflow
$DSREQ$	Downstream requirement
e	Evaporation rate
FCR	Transition loss for canal feeder release
ID	Irrigation demand
IR	Inflow into reservoirs
OVF	Transition loss for overflow
RI	Release into canals for irrigation
RP	Release into turbines for power production
RWS	Release for water supply
S	Storage in the reservoirs
S_{min}	Minimum storage capacity
SC	Maximum storage capacity
TC	Flow through turbine capacities
λ	Level of satisfaction

maximize λ

subject to

- fuzzified objectives

$$\frac{Z_1 - 1807.97}{2218.36 - 1807.97} \geq \lambda$$

$$\frac{Z_2 - 8559.2}{11739.5 - 8559.2} \geq \lambda$$

- turbine release - capacity constraints

$$RP_{i,t} \leq TC_i$$

$$RP_{i,t} \geq FP_i$$

- irrigation release - demand constraints

$$RI_{i,t} \leq ID_{i,t}$$

$$RI_{i,t} \geq ID_{i,t}^{min}$$

- reservoir storage - capacity constraints

$$S_{i,t} \leq SC_i$$

$$S_{i,t} \geq S_i^{min}$$

- hydrologic continuity constraints

$$\left(1+a_{1,t}\right)S_{1,t+1} = \left(1-a_{1,t}\right)S_{1,t} + IN_{1,t} - RP_{1,t} - RI_{1,t} - OVF_{1,t} - RWS_{1,t} - FCR_{1,t} + \alpha_1 RP_{1,t} - A_0 e_{1,t} \quad \text{... reservoir 1}$$

$$\left(1+a_{2,t}\right)S_{2,t+1} = \left(1-a_{2,t}\right)S_{2,t} + IN_{2,t} - RP_{2,t} - RI_{2,t} - OVF_{2,t} - RWS_{2,t} + \alpha_2 FCR_{1,t} - A_0 e_{2,t} \quad \text{... reservoir 2}$$

$$\left(1+a_{3,t}\right)S_{3,t+1} = \left(1-a_{3,t}\right)S_{3,t} + IN_{3,t} - RP_{3,t} - OVF_{3,t} - RWS_{2,t} - A_0 e_{3,t} \quad \text{... reservoir 3}$$

$$\left(1+a_{4,t}\right)S_{4,t+1} = \left(1-a_{4,t}\right)S_{4,t} + IN_{4,t} + \alpha_4 RP_{3,t} - RI_{4,t} - OVF_{4,t} - \alpha_3 OVF_{3,t} - RWS_{4,t} + \alpha_4 RP_{3,t} - A_0 e_{4,t} \quad \text{... reservoir 4}$$

$$DSREQ_t = C_1 \times OVF_{1,t} + C_2 \times OVF_{2,t} + C_3 \times OVF_{4,t} + DSIN_t + \alpha_5 RP_{2,t} \quad \text{.. reservoir 5}$$

$$S_{i,1} = S_{i,13}$$

►Step 3: Crisp equivalent optimization problem

- The **genetic operators** are: a stochastic remainder selection, a one point crossover, a binary mutation.
- The **crossover probability** is 0.7 for maximizing the irrigation releases and 0.9 for maximizing hydropower production. In both cases, the **mutation probability** is set to 0.1.
- The **parameter values** are: a population size of 130 and 500 generations,

►Step 4: solving by using NPGA

Existing demand		Demand evolutions	
		Increase of 10%	Increase of 20%
Level of satisfaction (in %)	60	52	47
Irrigation releases Objective 1 (in 10^6 m^3)	2,054.22	2,195.34	2,342.94
Hydropower production Objective 2 (in 10^4 Kwh)	1,4750	11,026	11625

►Step 5: Results for different demand evolutions

THANK YOU FOR YOUR ATTENTION !