

# ***Definition of optimal drought-oriented reservoir management policies combining stochastic programming and fuzzy logic***

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**International Conference on DROUGHT:  
Research and Science-Policy Interfacing  
March, 10<sup>th</sup> – 13<sup>th</sup>, 2015 Valencia (Spain)**

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Droughts have hit Europe over the last decades and drought and water scarcity (climate change) will be one of the most important management issues in Europe (DROUGHT R&SPI project)

The most employed ways to confront drought impacts are:

- ❑ Drought early warning (drought indicators)
- ❑ Drought monitoring
- ❑ Drought management plans (programs of measures)
- ❑ Risk-based decision making & operating rules

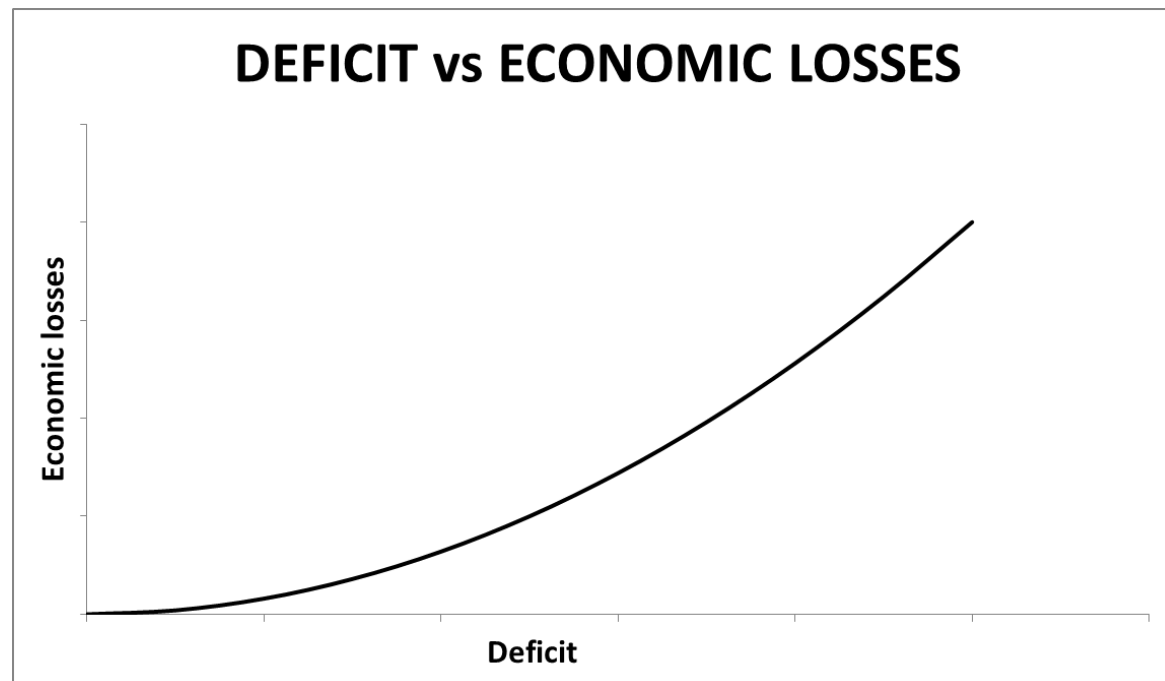
# Economics and droughts

# INTRODUCTION

Droughts might cause significant socio-economic impacts

HOWEVER: economics is often missing in the development of management strategies

Economic losses increase non-linearly with deficits



# Goal & Approach

# INTRODUCTION

## Goal

- ❑ Method to define economically-optimal reservoir operating rules (without perfect foresight of deterministic optimization)

## Approach

- ❑ Economic characterization of demands (demand curves)
- ❑ Stochastic Dynamic Programming algorithm (SDP) to obtain optimal decisions
- ❑ Fuzzy Logic (FRB) to transform optimal decisions into (fuzzy) management rules

# Stochastic Dynamic Programming (SDP)

# METHODS

SDP equation (Bellman's recursive equation)

$$\underbrace{F_t(S_t, Q_t)}_{\text{Total benefits}} = \max_{D_t} \left[ \underbrace{B(S_t, Q_t, D_t)}_{\text{Immediate benefits}} + \sum_q \underbrace{P_{p,q}}_{\text{Markov Chain}} * \underbrace{F_{t+1}(S_{t+1}, Q_{t+1})}_{\text{Future expected benefits}} \right]$$

## Advantages of SDP

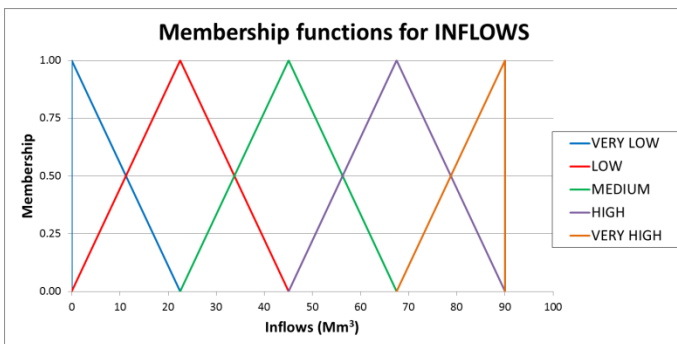
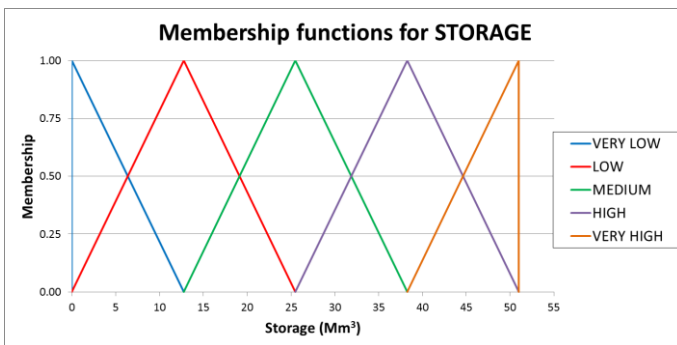
- ❑ Future inflows are forecasted, not known
- ❑ Sequential decision-making process

## Disadvantages of SDP

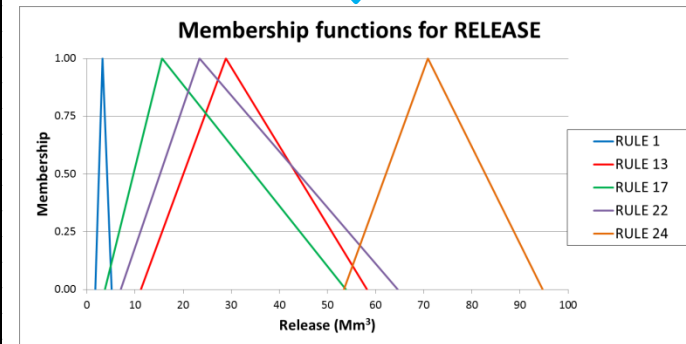
- ❑ Probabilistic description of inflows required (Markov Chain)
- ❑ Curse of dimensionality due to system discretization (although there are alternatives as SDDP, RL, etc.)

## Fuzzy Rule-Based system (FRB)

Mathematical representation of the system operating rules linking the system state (inputs) and the management decisions (outputs), providing a free environment

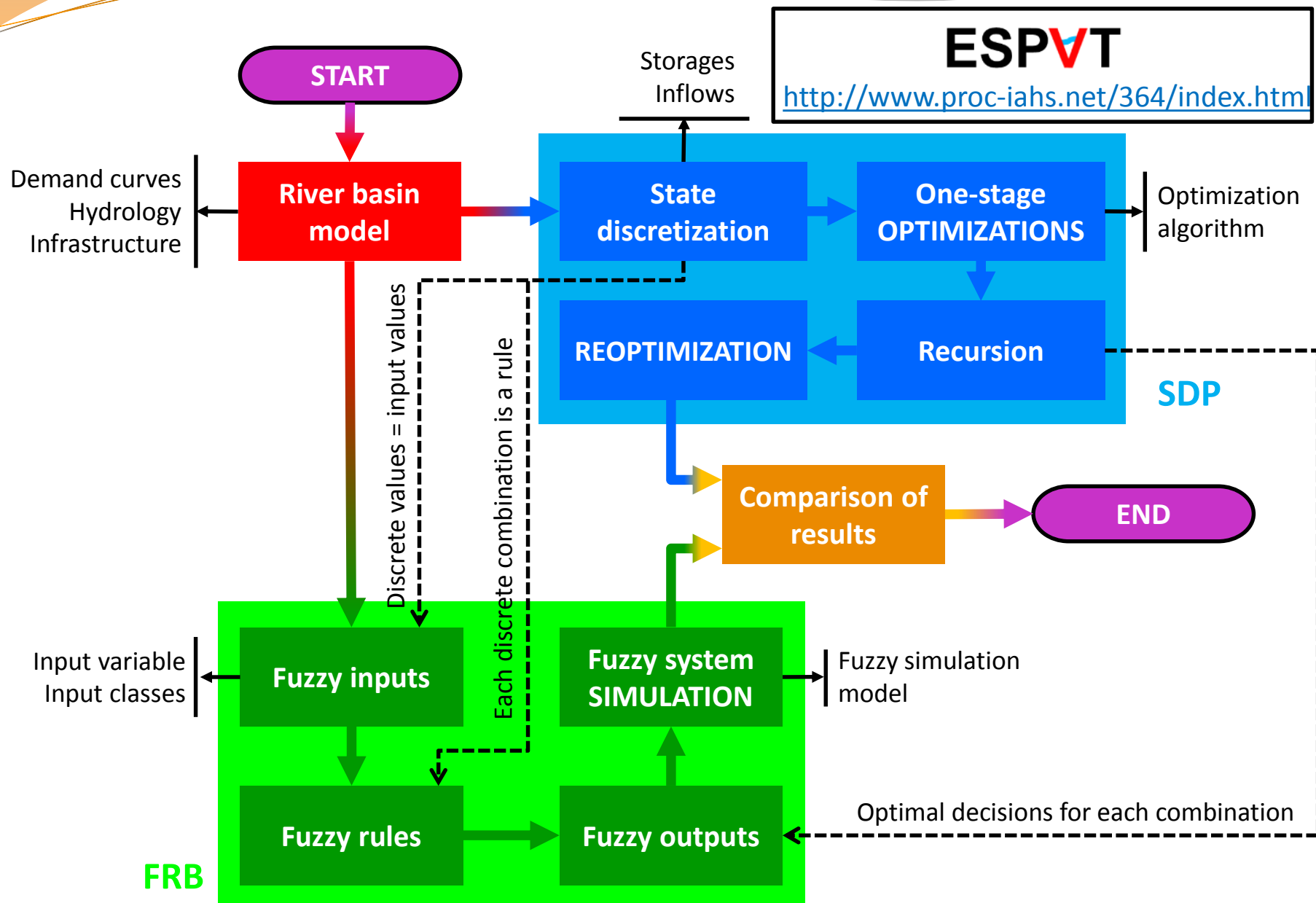


RULE NUMBER	INPUTS		OUTPUTS		
	STORAGE	INFLOWS	RELEASE		
			A	M	B
1	VERY LOW	VERY LOW	1.70	3.29	5.10
2	VERY LOW	LOW	1.53	3.35	10.80
3	VERY LOW	MEDIUM	4.40	5.50	6.60
4	VERY LOW	HIGH	4.40	5.50	6.60
5	VERY LOW	VERY HIGH	4.40	5.50	6.60
6	LOW	VERY LOW	1.36	3.44	7.36
7	LOW	LOW	1.36	3.64	11.12
8	LOW	MEDIUM	4.40	5.50	6.60
9	LOW	HIGH	4.40	5.50	6.60
10	LOW	VERY HIGH	4.40	5.50	6.60
11	MEDIUM	VERY LOW	2.31	5.50	16.24
12	MEDIUM	LOW	2.00	5.68	26.08
13	MEDIUM	MEDIUM	11.20	28.85	58.20
14	MEDIUM	HIGH	46.10	59.20	71.90
15	MEDIUM	VERY HIGH	74.76	81.08	86.28
16	HIGH	VERY LOW	1.73	5.50	15.55
17	HIGH	LOW	3.75	15.65	53.85
18	HIGH	MEDIUM	15.07	35.70	64.46
19	HIGH	HIGH	50.71	67.04	94.71
20	HIGH	VERY HIGH	74.76	86.64	99.32
21	VERY HIGH	VERY LOW	7.02	16.92	40.50
22	VERY HIGH	LOW	7.02	23.41	64.62
23	VERY HIGH	MEDIUM	24.97	37.01	64.46
24	VERY HIGH	HIGH	53.46	70.88	94.71
25	VERY HIGH	VERY HIGH	94.71	94.71	94.71



Example: Sorbe river in central Spain (Macian-Sorribes, 2012)

## Framework used



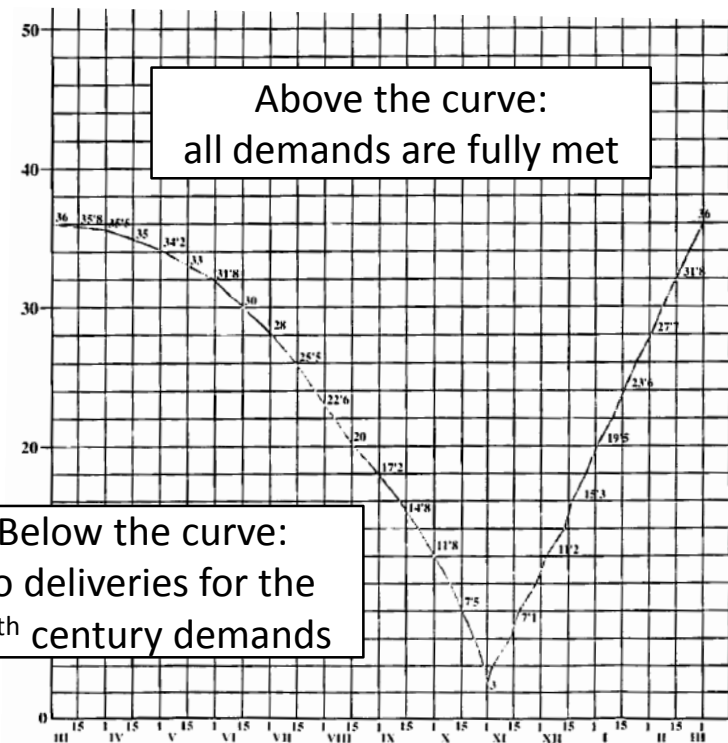


## Mijares River Basin



### Current management rule:

- ☐ Zone-based policy
- ☐ Established in 1970 for Sichar
- ☐ Now applied to total storage



NAME	CAPACITY	START	MAIN USE	DEMAND
Arenós	93 Mm <sup>3</sup>	1980	Agricultural	120 Mm <sup>3</sup>
Sichar	49 Mm <sup>3</sup>	1959	Agricultural	
MEAN ANUAL INFLOW (1980-2009)				196 Mm <sup>3</sup>

Source: SCRM (1974). Current Mijares operating rule

# SDP Mijares model

# CASE STUDY

## Features

### Physical

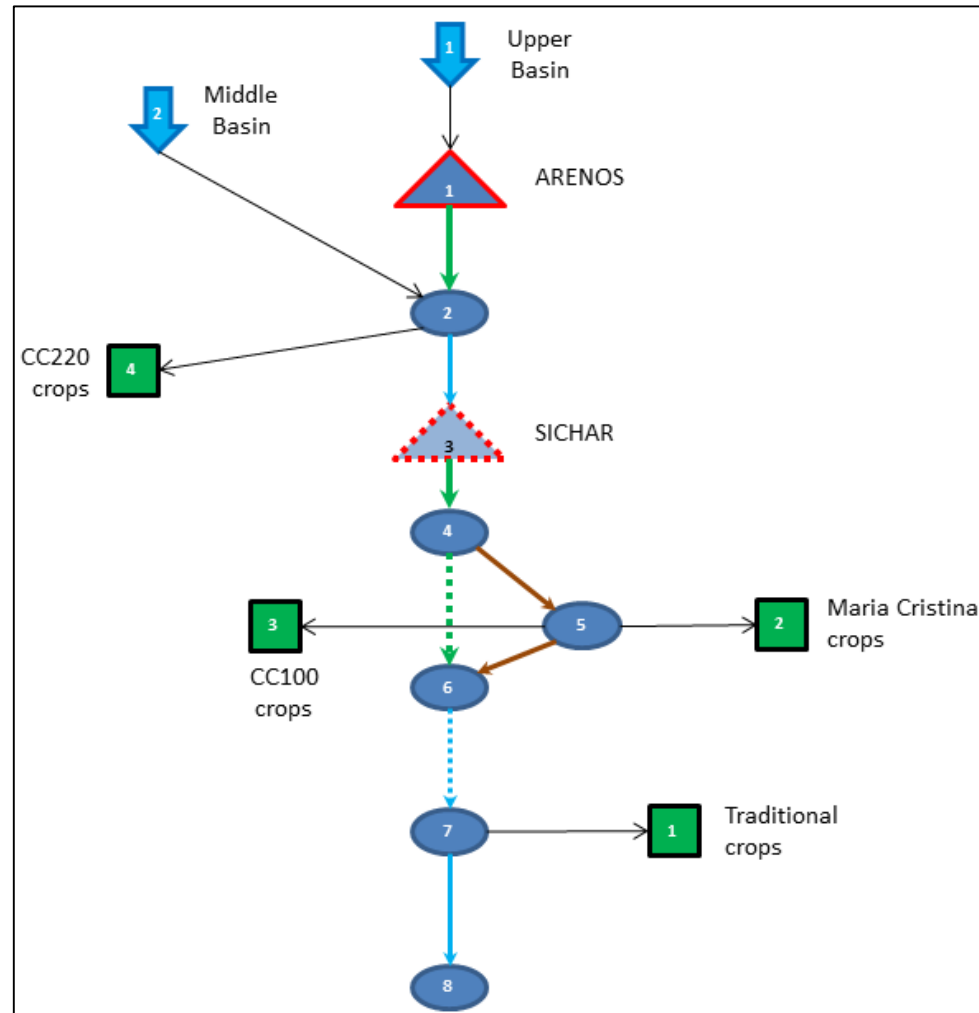
- 2 sub-basins
- 2 reservoirs
- 4 demands
- 3 environmental flows
- 91-point grid storage
- 16-point grid inflow
- Lag-1 Markov Chain

### Economic

- Demand curves obtained from previous studies

## Goal

- Maximize total benefits



# SDP Mijares model

# CASE STUDY

## Results

### □ Mijares model run summary

FIRST CONVERGENCE CRITERIA STATUS	ACHIEVED
SECOND CONVERGENCE CRITERIA STATUS	ACHIEVED
NUMBER OF ITERATIONS DONE	20
ITERATION IN WHICH SECOND CONVERGENCE ACHIEVED	12
FIRST CONVERGENCE ERROR	0.0100
EXPECTED VALUE	63.8000
NUMBER OF NON-NORMAL SOLVER TERMINATIONS	0

### □ Recursion results: optimal policies per discrete point

Stage	ARENOS	SICHAR	UPPER BASIN	MIDDLE BASIN	Imm. Benefits	Fut. Benefits	Total_Benefits
t1	2.00	3.00	5.09	0.00	1.51	44.5	46.01
t1	2.00	3.00	5.09	1.00	2.02	44.74	46.75
t1	2.00	3.00	5.09	2.70	2.93	46.57	49.5
t1	2.00	3.00	5.09	29.88	6.74	56.07	62.82
t1	2.00	3.00	7.66	0.00	2.86	47.33	50.19
t1	2.00	3.00	7.66	1.00	3.41	45.97	49.38
t1	2.00	3.00	7.66	2.70	4.34	48.35	52.69
t1	2.00	3.00	7.66	29.88	6.38	57.29	63.67
t1	2.00	3.00	9.60	0.00	3.93	54.22	58.15

### □ Reoptimization results: optimal decisions for the 1940-2009 historical inflows

# FRB reproducing optimal policies

# CASE STUDY

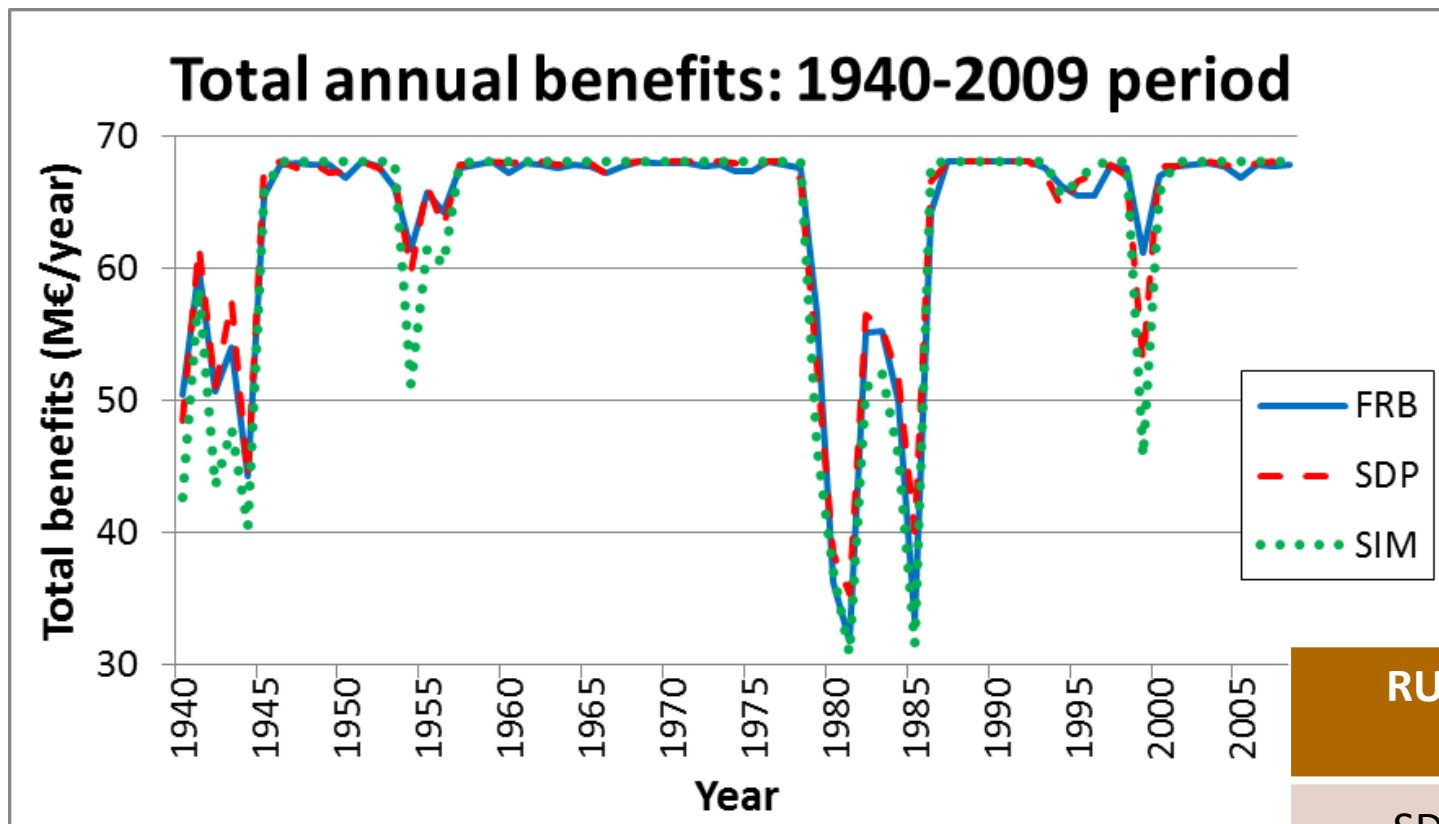
The FRB features are conditioned by the SDP

- ❑ Inputs: same as SDP
  - ❑ Time (month of the year)
  - ❑ Storages (Arenos and Sichar)
  - ❑ Inflows (Upper and Middle Basin)
- ❑ Rules: initially one rule per discrete point, then the rules with equal outputs were merged into one
- ❑ Outputs: same as historical rules
  - ❑ Deliveries to Traditional Crops
  - ❑ Deliveries to the rest of agricultural demands

# Simulation and results

# CASE STUDY

1940-2009 period results



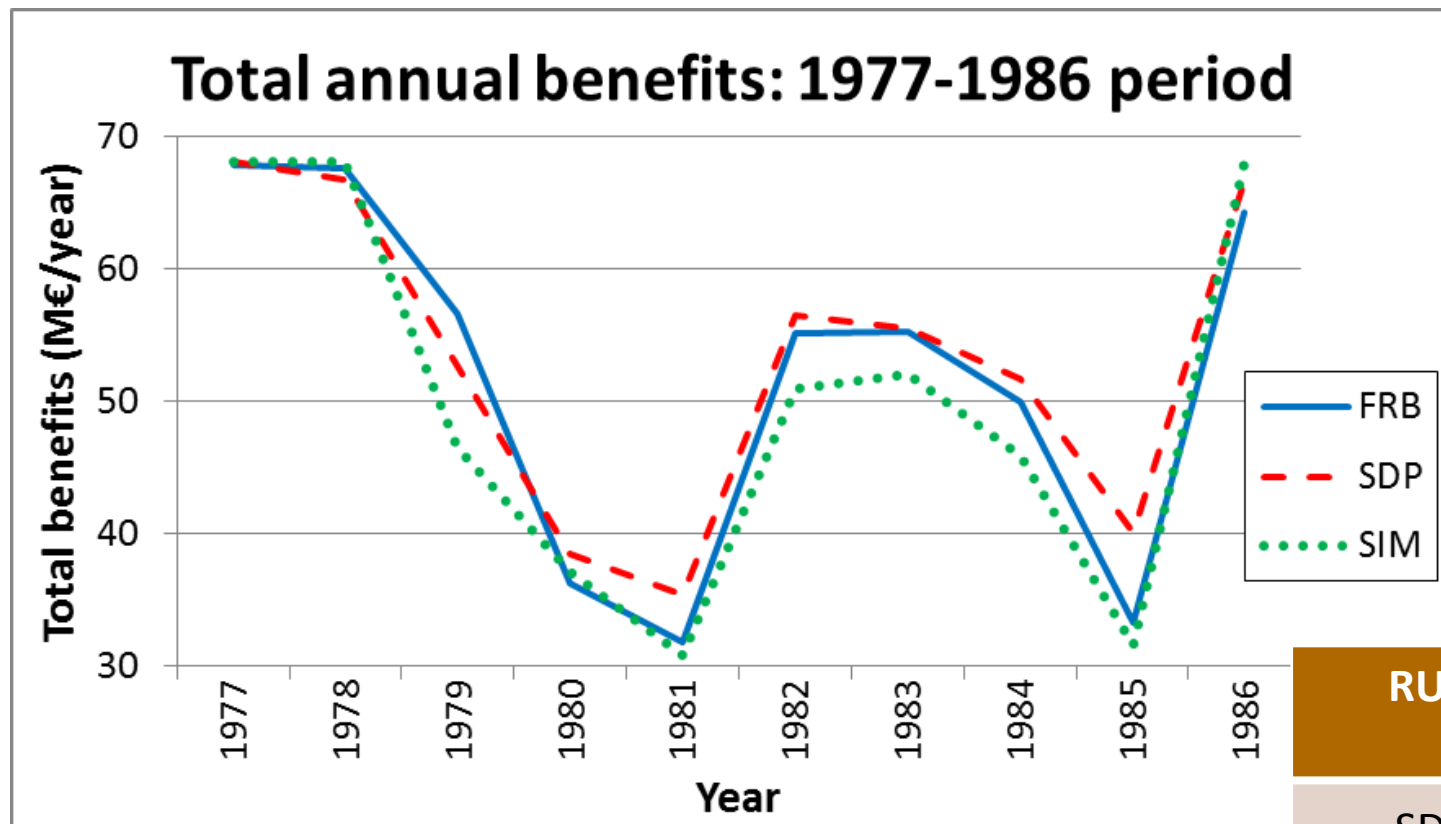
- SDP: reoptimization from SDP algorithm
- FRB: fuzzy rule-based operating rules
- SIM: current system operating rules

RUN	BENEFITS (M€/year)
SDP	64.16
FRB	63.94
SIM	63.06

# Simulation and results

# CASE STUDY

1977-1986 period results



- SDP: reoptimization from SDP algorithm
- FRB: fuzzy rule-based operating rules
- SIM: current system operating rules

RUN	BENEFITS (M€/year)
SDP	53.19
FRB	51.84
SIM	49.93

## Simulation and results

## CONCLUSIONS

- ❑ Drought economic impacts can be reduced by the adoption of improved operating policies based on stochastic programming (avoiding the perfect foresight)
- ❑ Fuzzy logic provides a flexible environment to define improved operating policies able to cope with droughts
- ❑ The methodology does not require the use of massive optimization runs. Constrained to the use of SDP but could be extended to other stochastic programming approaches
- ❑ Although the rules are defined to reduce the impacts of droughts, they are applicable in normal situations



# THANK YOU FOR YOUR ATTENTION

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