Decision support model for weekly operation of hydroelectric reservoirs by stochastic nonlinear optimization

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- Introduction
- System modeling
- Model description
- Case study
- Conclusions

Renaissance of hydro scheduling models

- Nowadays, under a deregulated framework electric companies manage their own generation resources and need detailed operation planning tools
- In the next future, high penetration of intermittent generation is going to force the electric system operation
- Hydro and storage hydro plants are going to play a much more important role due to their flexibility and complementary use with intermittent generation

Medium term model (i)

- Hydroelectric model deals only with hydro plants
- Hydrothermal model manages simultaneously both hydro and thermal plants
- Thermal units considered individually. So rich marginal cost information for guiding hydro scheduling
- No aggregation or disaggregation process for hydro input and output is needed
- It is very difficult to obtain meaningful results for each hydro plant because it requires a huge amount of data and the complexity of hydro subsystems

Medium term model (ii)

- Determines:
  - the optimal yearly operation of all the thermal and hydro power plants
  - taking into account multiple basins and multiple cascaded reservoirs connected among them
- Cost minimization model because the main goal is medium term hydro operation

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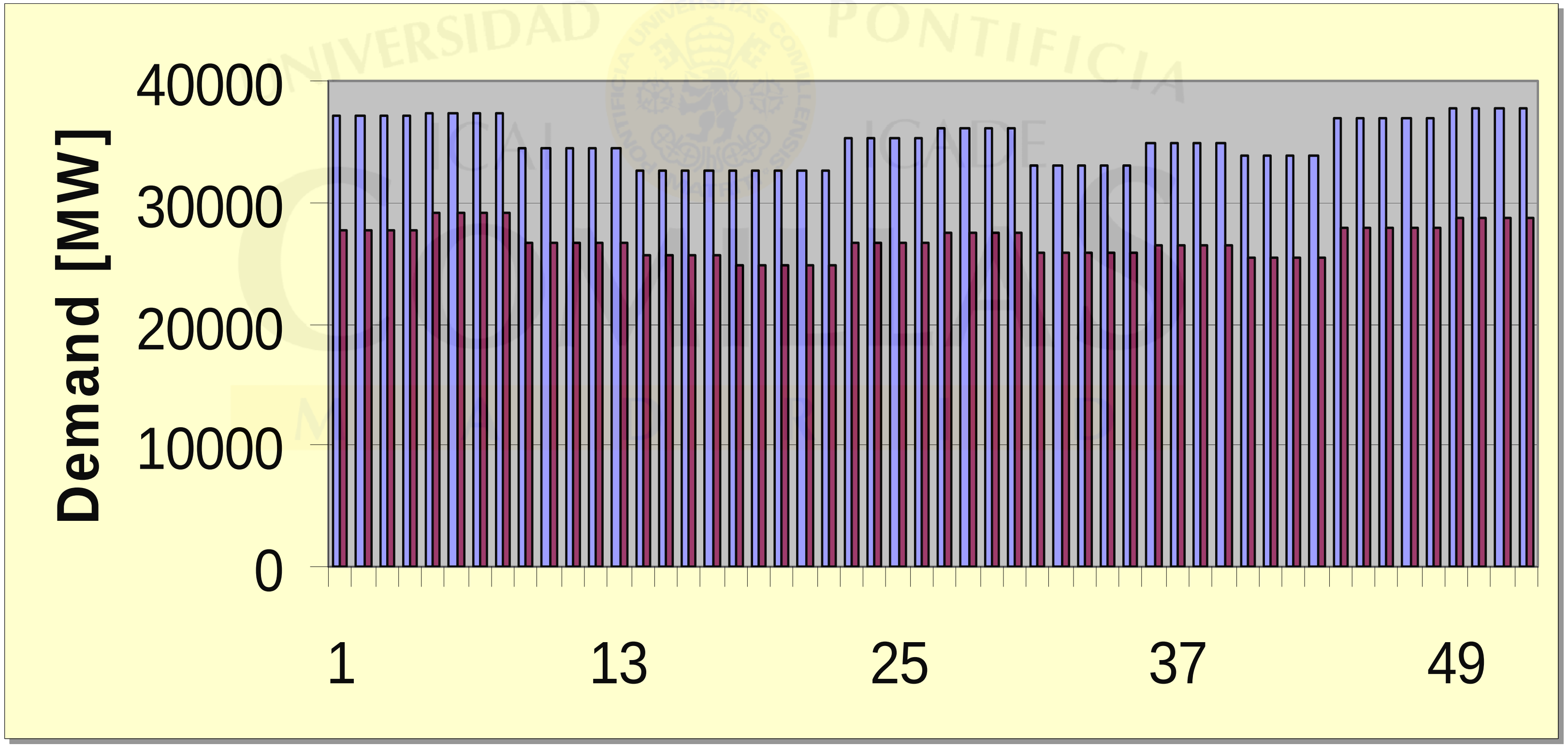
Demand

- Weekly demand with two load levels (peak and off-peak each week)



Hydro subsystem

- Different modeling approach for hydro reservoirs depending on:
  - Owner company
  - Relevance of the reservoir
- Reservoirs belonging to other companies modeled in energy units [GWh]
- Own reservoirs modeled in water units [hm^3, m^3/s]
- Important reservoirs modeled with water head effects
- Very diverse system:
  - Hydro reservoir volumes from 0.15 to 2433 hm^3
  - Hydro plant capacity from 1.5 to 934 MW

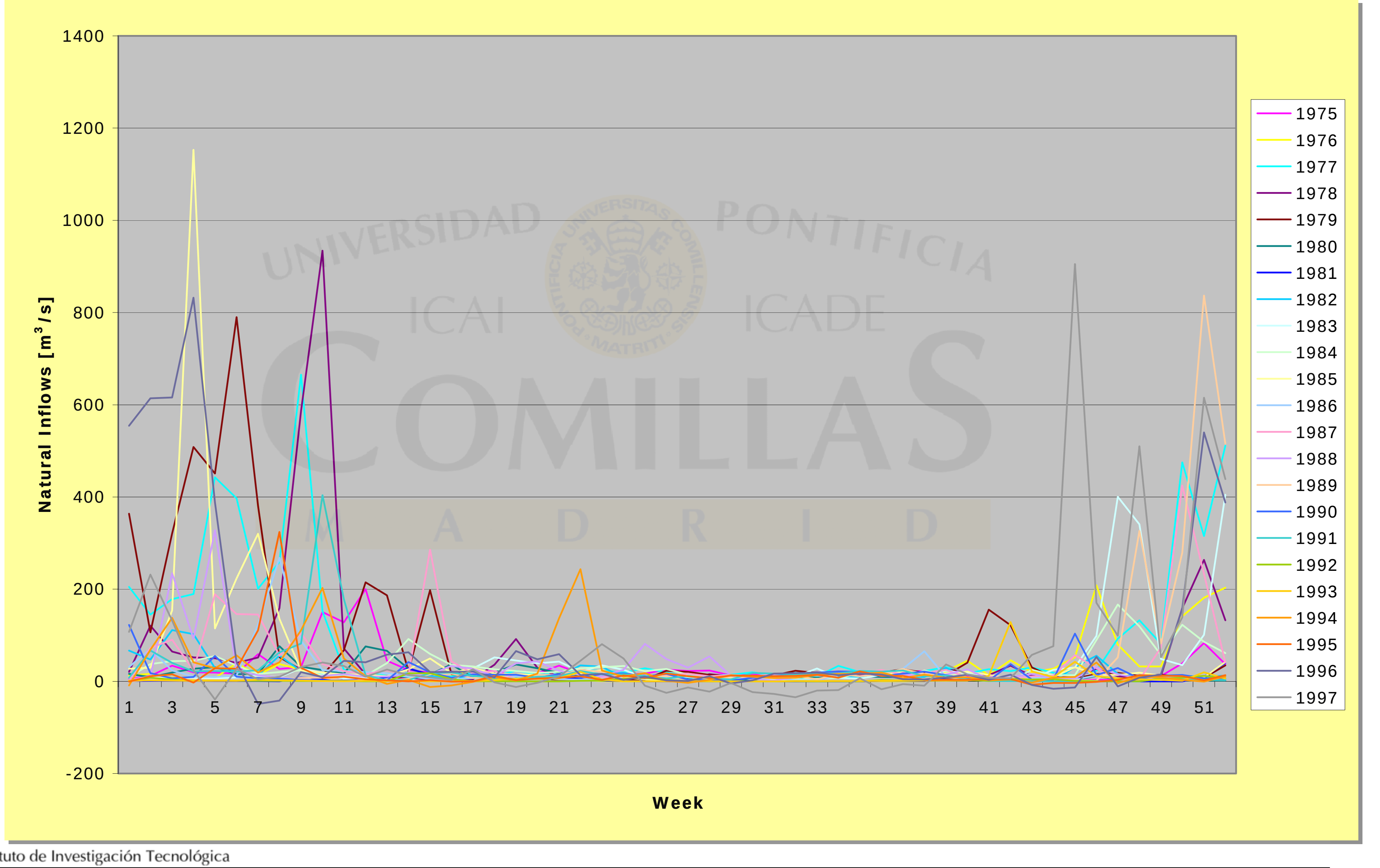
Stochasticity sources

- Natural hydro inflows (clearly the most important factor in Spanish electric system)

Year	Hydro energy Available [TWh]	Index	Probability of being exceeded [%]
2001	32.9	1.13	32
2002	20.9	0.72	87
2003	33.2	1.15	30
2004	22.7	0.79	80
2005	12.9	0.45	100
2006	24.0	0.83	70

- Changes in reservoir volumes are significant because of:
  - stochasticity in hydro inflows
  - chronological pattern of inflows and
  - capacity of the reservoir with respect to the inflows

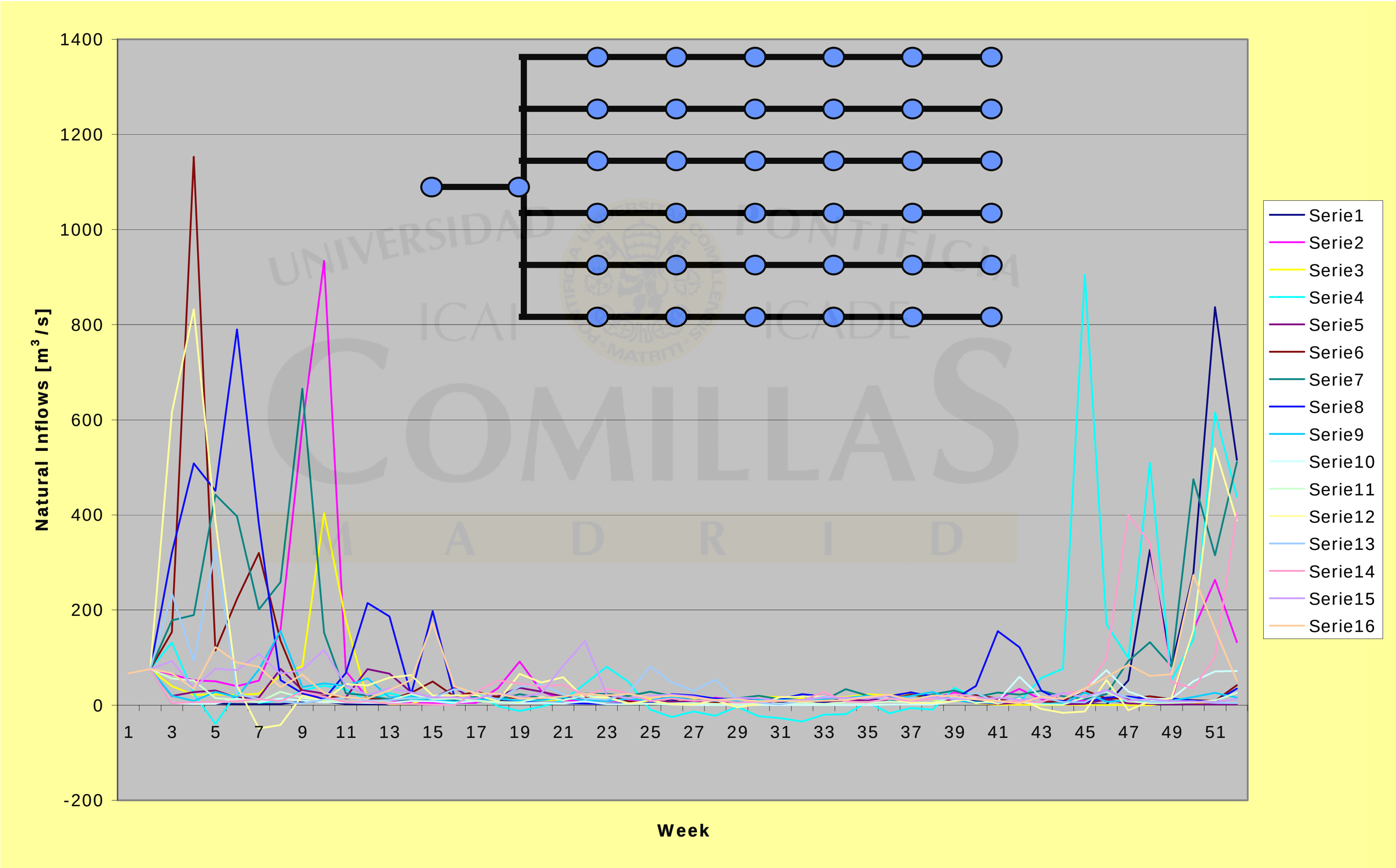
Historical natural inflows



Scenario tree generation

- A multivariate scenario tree is obtained by neural gas clustering technique that simultaneously takes into account the main stochastic series and their spatial and temporal dependencies.
- Very extreme scenarios can be artificially introduced with a very low probability
- Number of scenarios generated enough for yearly operation planning

Natural inflows: scenario tree



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Constraints: Generation and load balance

Generation of thermal units

+ Generation of hydro units

– Consumption of storage hydro units

= Demand

Constraints: Minimum and maximum operating hours of thermal units

- Introduced to model:
  - Unavailability of thermal units
  - Domestic coal subsidies
  - CO2 Emission allowances
  - Capacity payments
- They are not separable by period

$$minimum \leq \textit{Yearly operation hours of each thermal unit for each scenario} \leq maximum$$

$$minimum \leq \textit{Average yearly operation hours of each thermal unit} \leq maximum$$

Constraints: Water balance

Reservoir volume at the beginning of the period

+ Natural inflows

– Spills from the own reservoir

+ Spills from upstream reservoirs

+ Turbined water from upstream hydro plants

+ Pumped water from downstream hydro storage plants

– Turbined and pumped water from the own reservoir

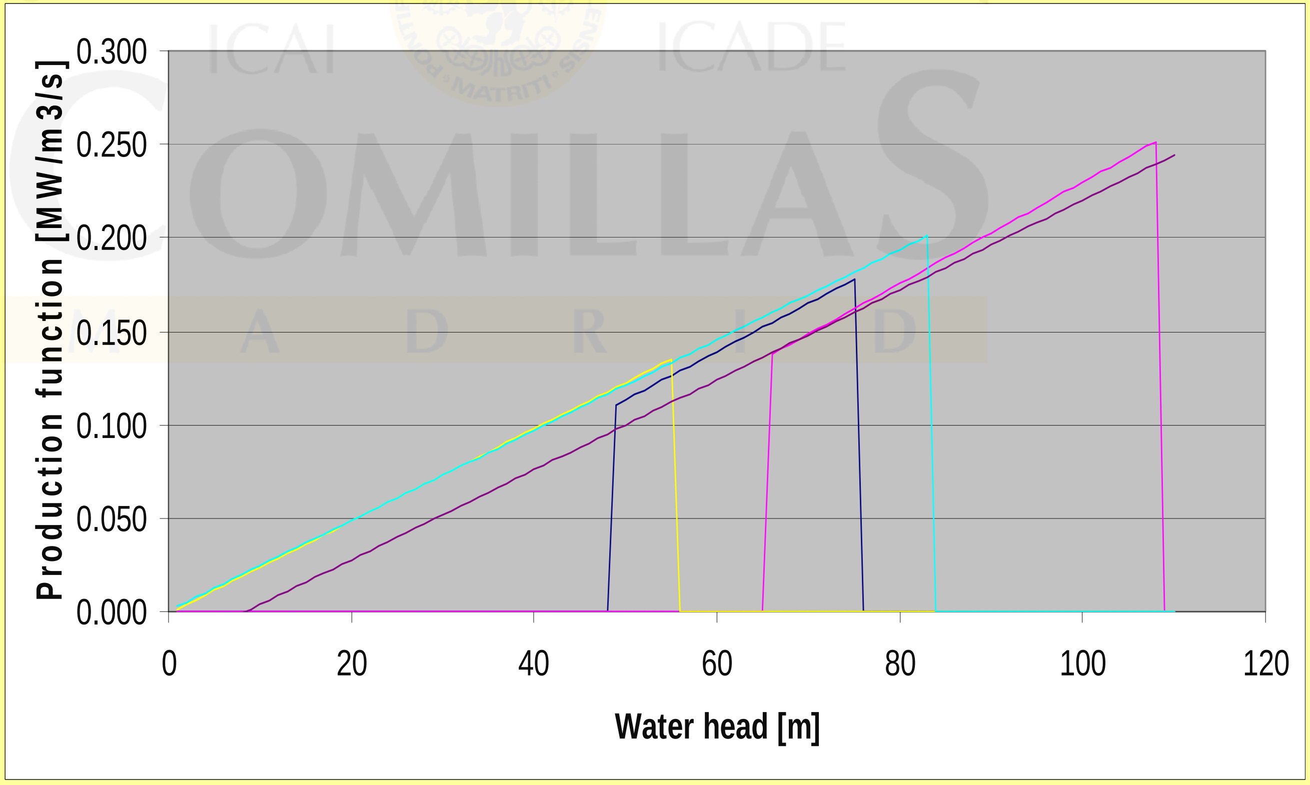
= Reservoir volume at the end of the period

Constraint: Water head effects

- Power generation is the product (nonlinear function) of the flow and the production function $P = Q \times PF$

- Production function PF depends linearly on water head

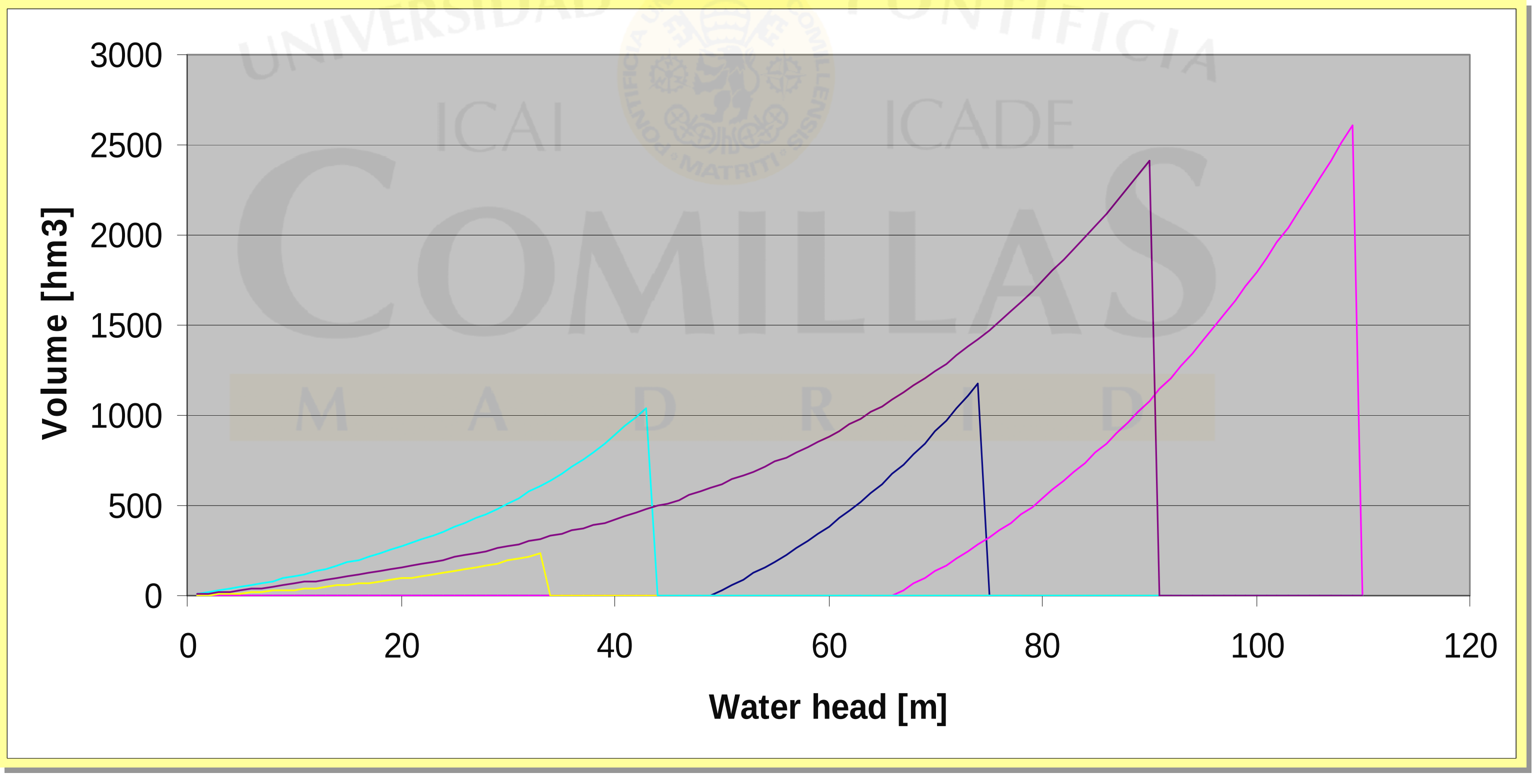
$$PF = \alpha H_p$$



Constraint: Volume as a function of the head

- Reservoir volume depends quadratically (nonlinearly) on water head

$$V = \beta + \beta' H_r + \beta'' H_r^2$$



Constraint: Water heads

Water head of the reservoir = forebay level – reference level

Water head of the plant = forebay level of the reservoir – tailrace level of the plant

Tailrace level of the plant = max [*forebay level of downstream reservoir, reference tailrace level of the plant*]

Constraint: operation limits

Reservoir volumes between limits for each hydro reservoir

Power operation between limits for each unit

Multiobjective function

- Thermal plant variable costs

- Penalties introduced in the objective function for softening several additional constraints:
  - Final reservoir volumes
  - Exceeding operating rule curves (minimum and maximum)
  - Minimum and maximum yearly operation hours of thermal units

Type of optimization problem

- Deterministic approaches:
  - Network Flows
  - LP
  - NLP
  - MILP
    - commitment of thermal or hydro units
    - piecewise linear approximation of water head effects
- Stochastic approaches:
  - Stochastic Dynamic Programming (SDP)
  - Stochastic Linear Programming. Decomposition approaches (Benders, Lagrangean Relaxation, Stochastic Dual Dynamic Programming)
  - Stochastic Nonlinear Programming

Solution algorithm

- Algorithm:
  - Successive LP
  - Direct solution by a NLP solver

- Very careful implementation
  - Scaling of variables
  - Use of simpler expressions
  - Initial values and bounds for all the nonlinear variables computed from the solution provided by linear solver CPLEX 10.2 IPM
  - Nonlinear solver CONOPT3

Model implementation

- General hydro topology
- Spreadsheet-based graphical interface
- GAMS-based optimization model

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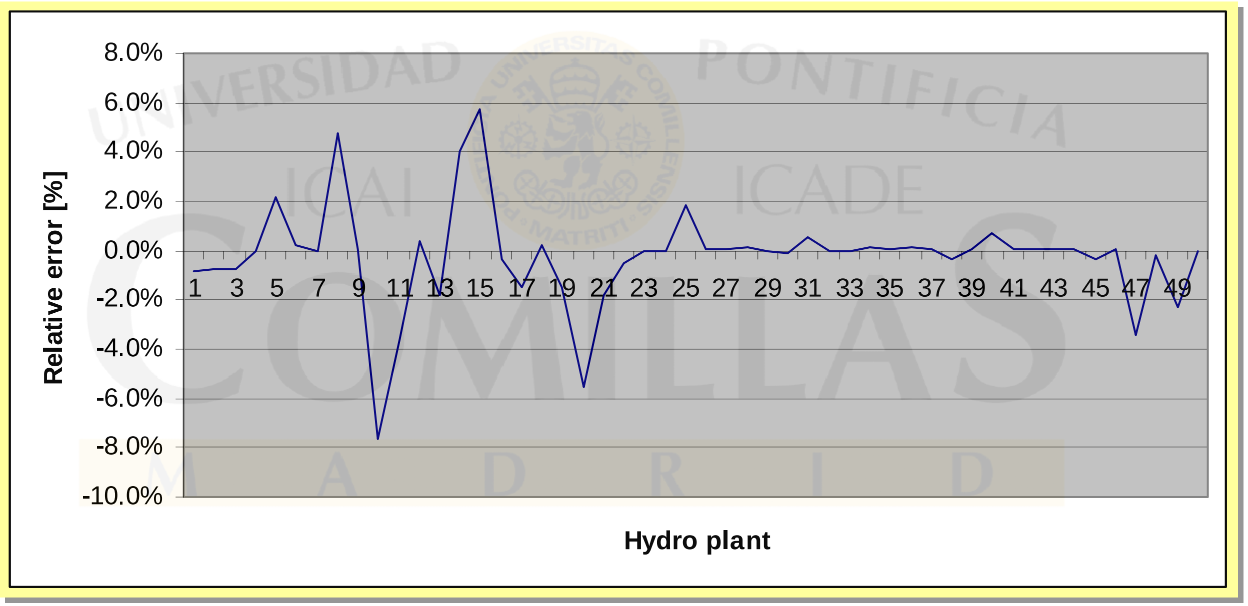
Case study

- Spanish electric system
  - 130 thermal units
  - 3 main basins with 50 hydro reservoirs/plants and 2 pumped storage hydro plants
  - 16 scenarios
- Problem size:
  - 271887 constraints
  - 442239 variables
  - 1611184 non zero elements
  - 12832 nonlinear variables
  - 8020 nonlinear constraints

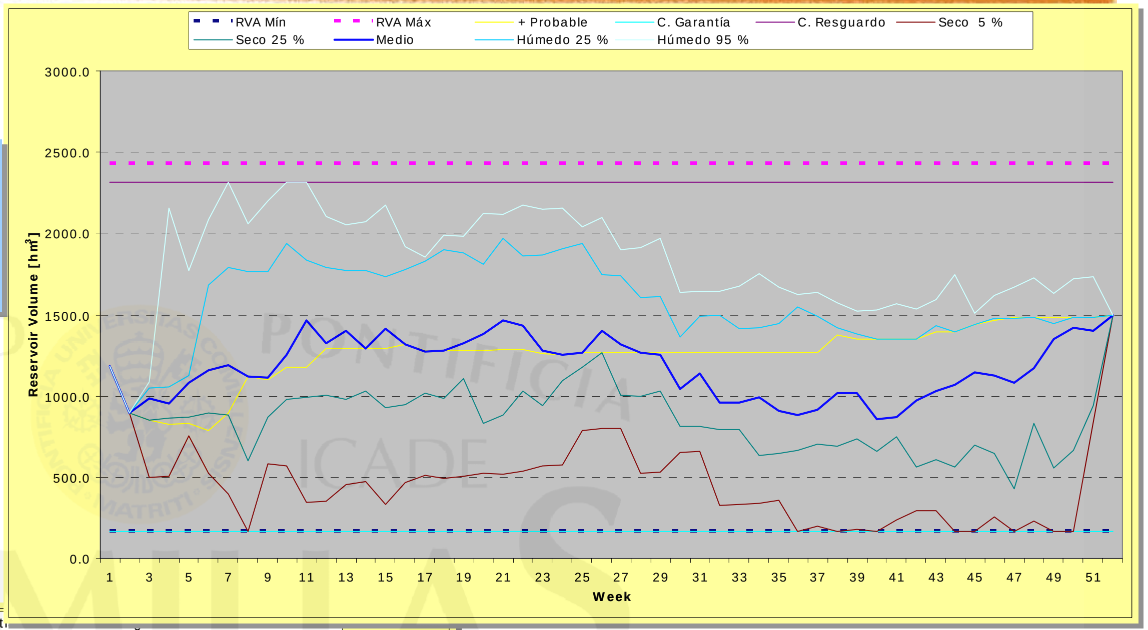
Hydro plant operation

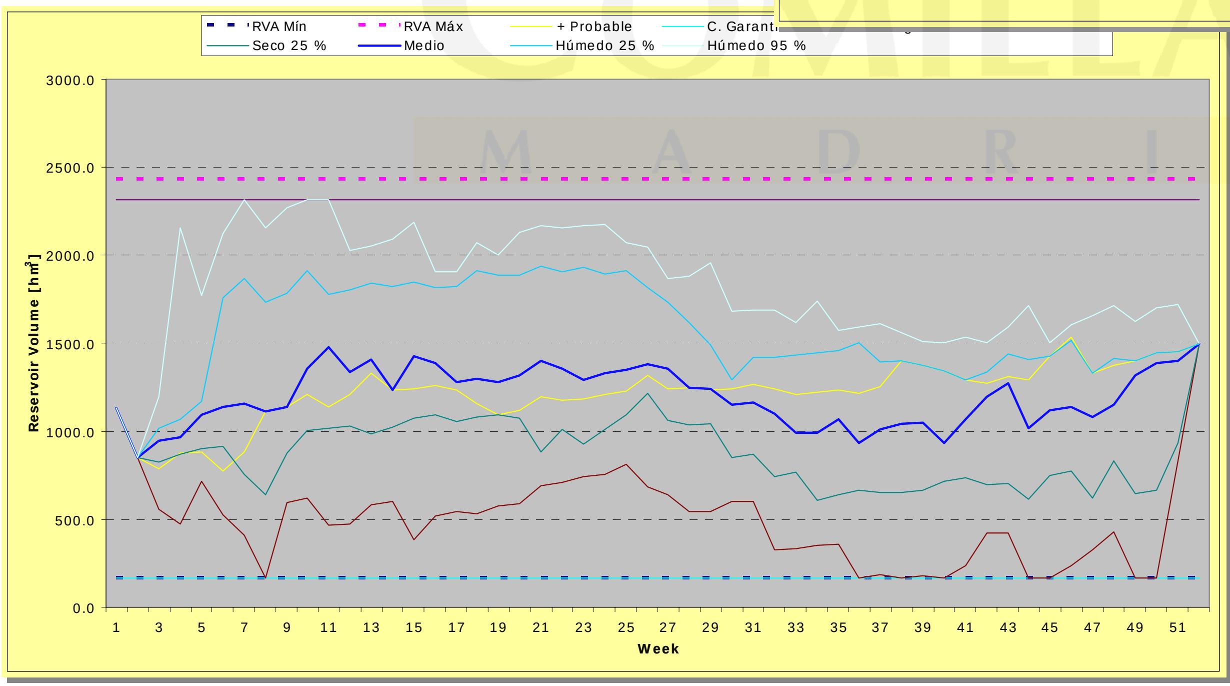
- Relative error in the energy generated for each hydro plant between LP and NLP approaches



Hydro reservoir operation (i)

LP solution

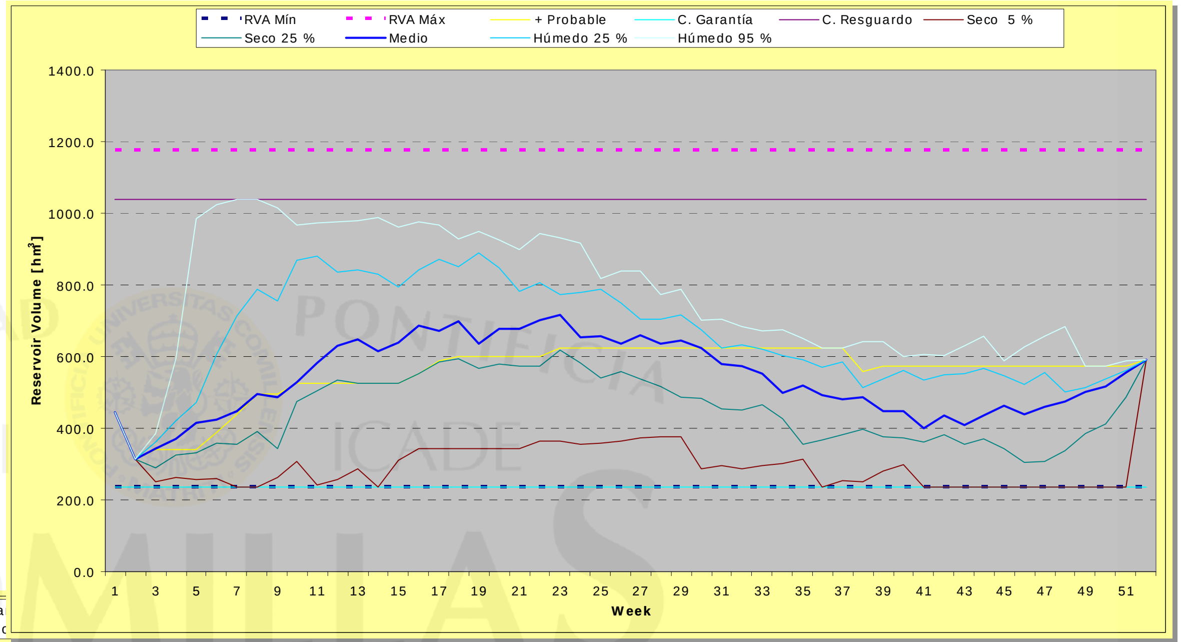


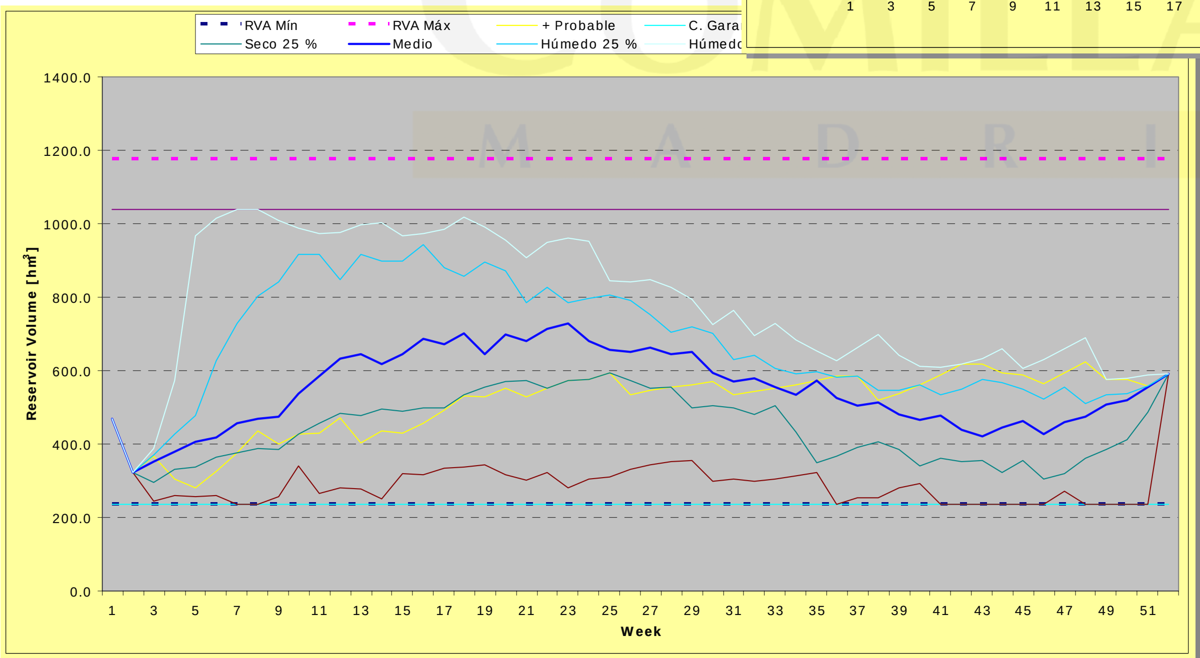


NLP solution

Hydro reservoir operation (ii)

LP solution





NLP solution

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Summary

- Medium term hydrothermal model
- Nonlinear water head effects modeled for relevant reservoirs
- Stochastic nonlinear optimization problem solved directed by a nonlinear solver given a close initial solution provided by a linear solver

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