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# A Medium Term Multireservoir Hydrothermal Coordination Model by Stochastic Programming

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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 used for guiding hydro scheduling
- Hydro plants considered also individually. No aggregation or disaggregation process for hydro input and output is needed
- Obtain a feasible solution for each hydro plant is very difficult because the problem requires a huge amount of data and by 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
- Upper level: stochastic market equilibrium model
- Lower level: daily simulation model

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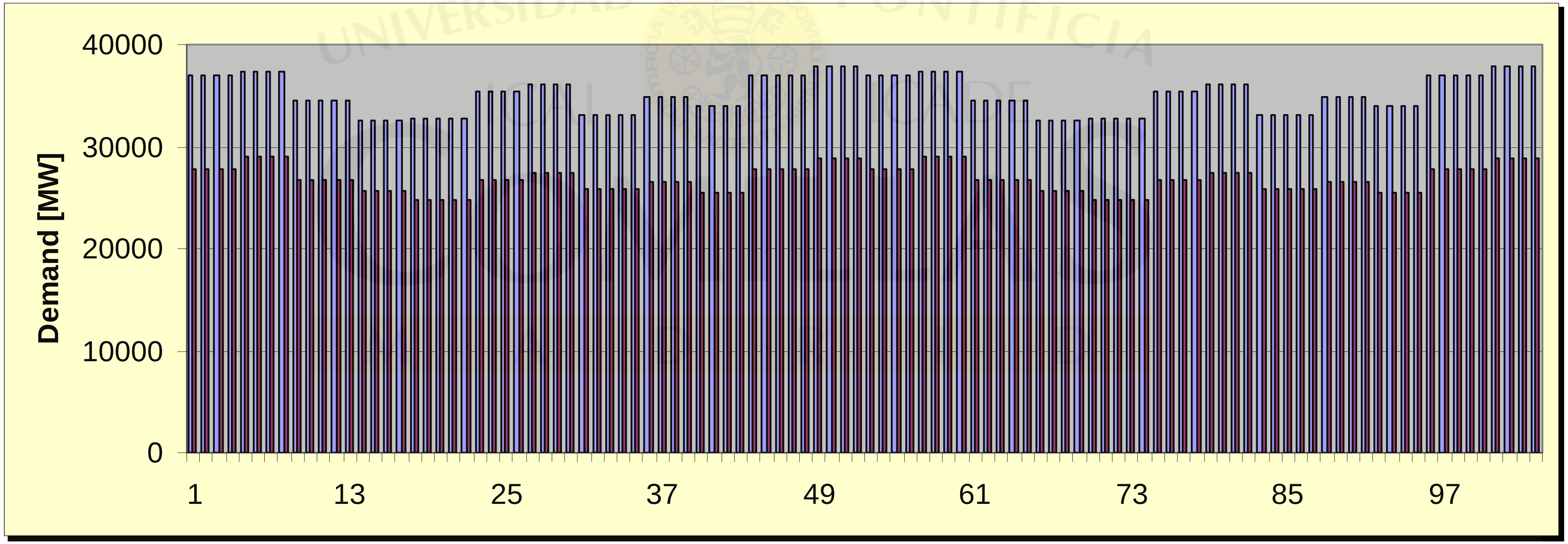
# Demand

- 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 hydro subsystem:
  - Hydro reservoir volumes from 0.15 to 2433 $hm^3$
  - Hydro plant capacities from 1.5 to 934 MW

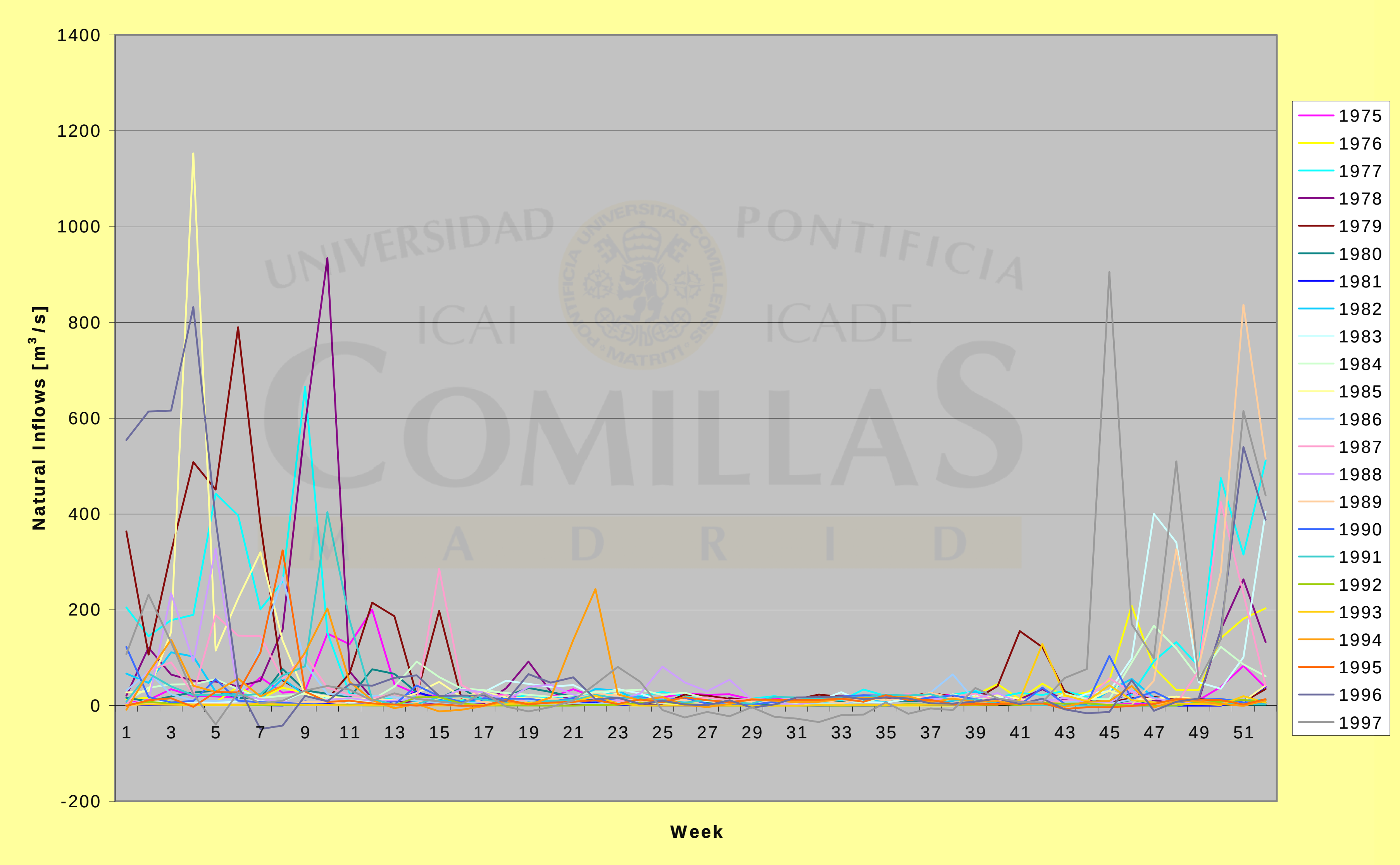
# Stochasticity sources

- 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
  - Seasonal pattern of inflows and
  - Capacity of the reservoir with respect to the inflows

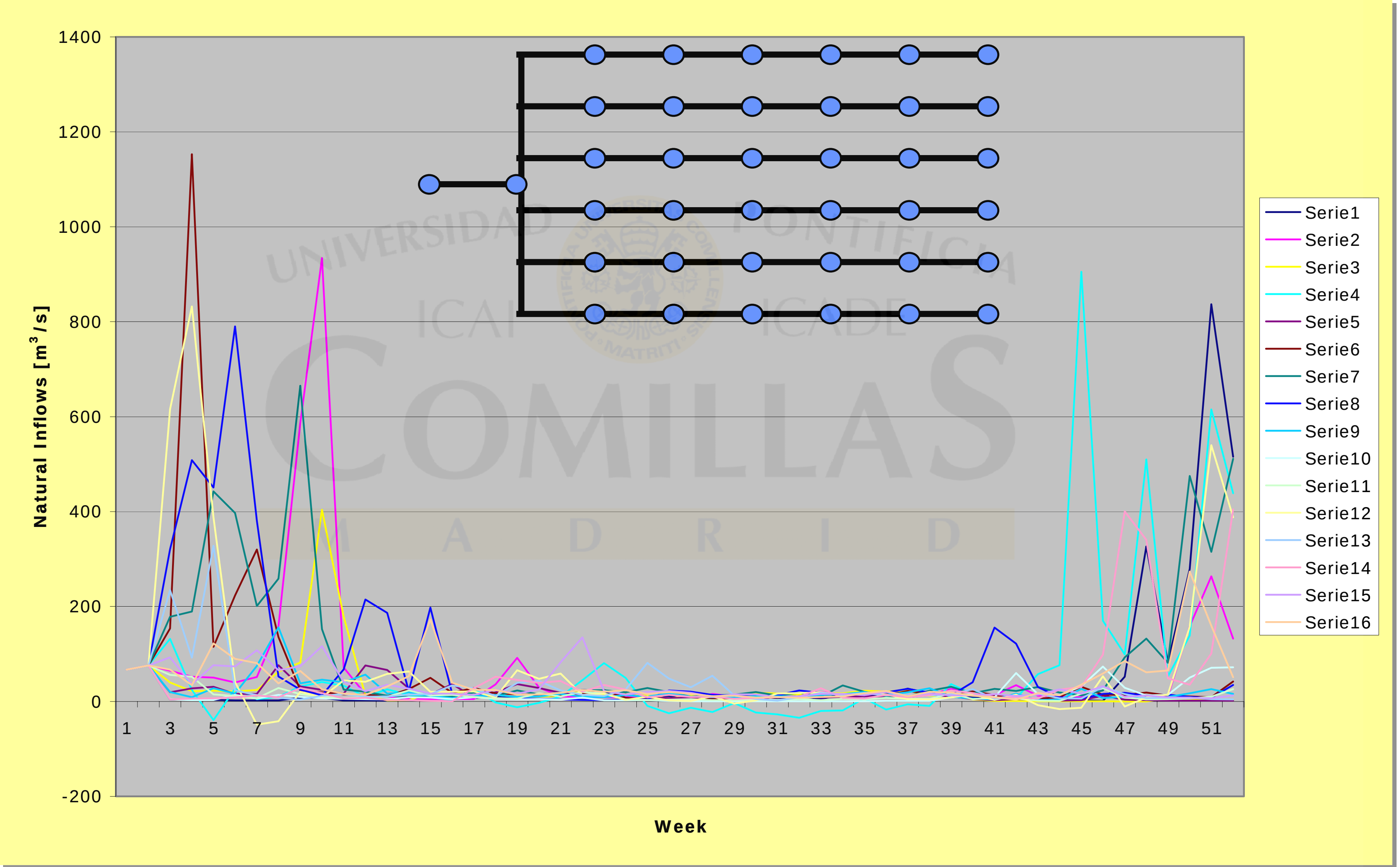
# Historical natural inflows



# 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 medium term operation planning

# Natural inflows: scenario tree



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# Constraints: Generation and load balance

*Generation of thermal units*

*+ Generation of storage hydro units*

*– Consumption of pumped 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

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

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

# Constraints: Water balance for large reservoirs

*Reservoir volume at the beginning of the period*

*+ Natural inflows*

*– Spills from this reservoir*

*+ Spills from upstream reservoirs*

*+ Turbined water from upstream storage hydro plants*

*+ Pumped water from downstream pumped hydro plants*

*– Turbined and pumped water from this reservoir*

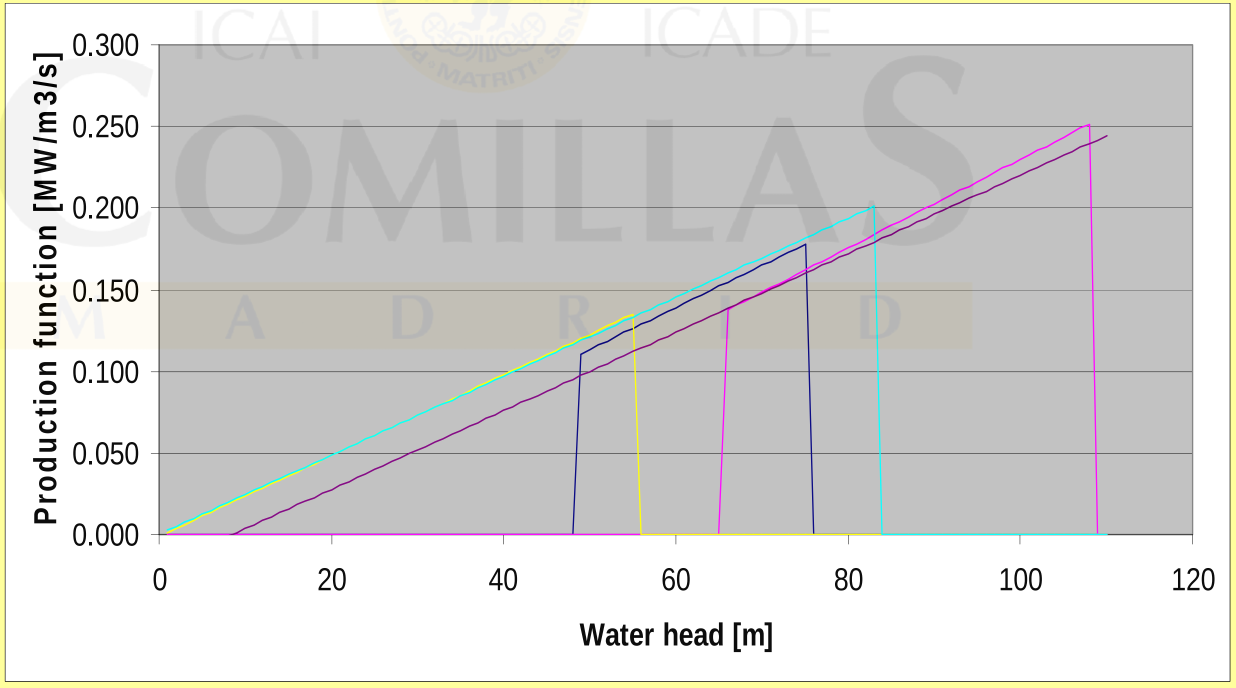
*= Reservoir volume at the end of the period*

# 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 plant water head

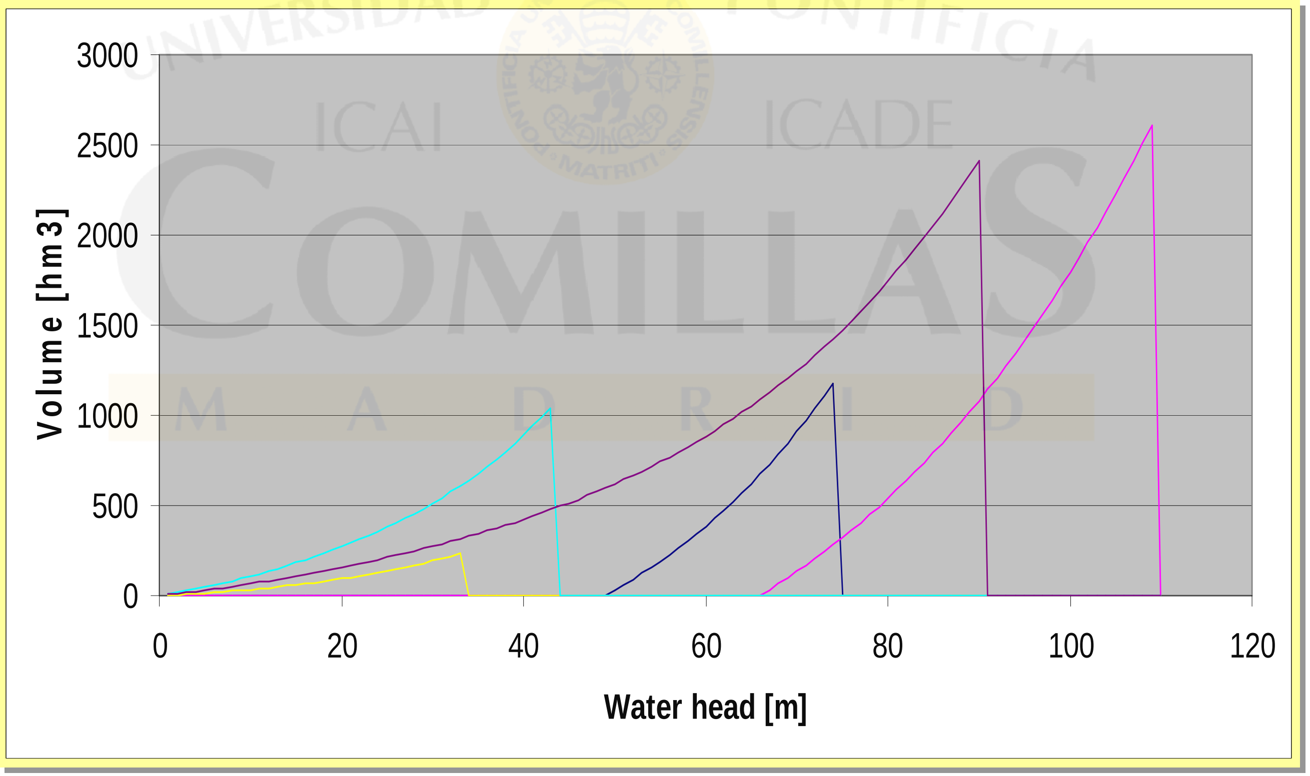
$$PF = \alpha H_p$$



# Constraint: Volume as a function of the head

- Reservoir volume depends quadratically (nonlinearly) on reservoir 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

# Model results

- Results for each period and load block and for each scenario
  - Storage hydro, pumped hydro and thermal plant operation
  - Reservoir management
  - Basin and river production
  - Marginal costs

- Byproduct
  - Optimal water release tables for different stochastic natural inflows and reservoir levels (obtained by stochastic nested Benders' decomposition) used by a lower level daily simulation model

# 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, Lagrangian Relaxation, Stochastic Dual Dynamic Programming)
  - Stochastic Nonlinear Programming

# Solution algorithm

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

- Very careful implementation
  - Natural 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 (CONOPT 3.14)

# Model implementation

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

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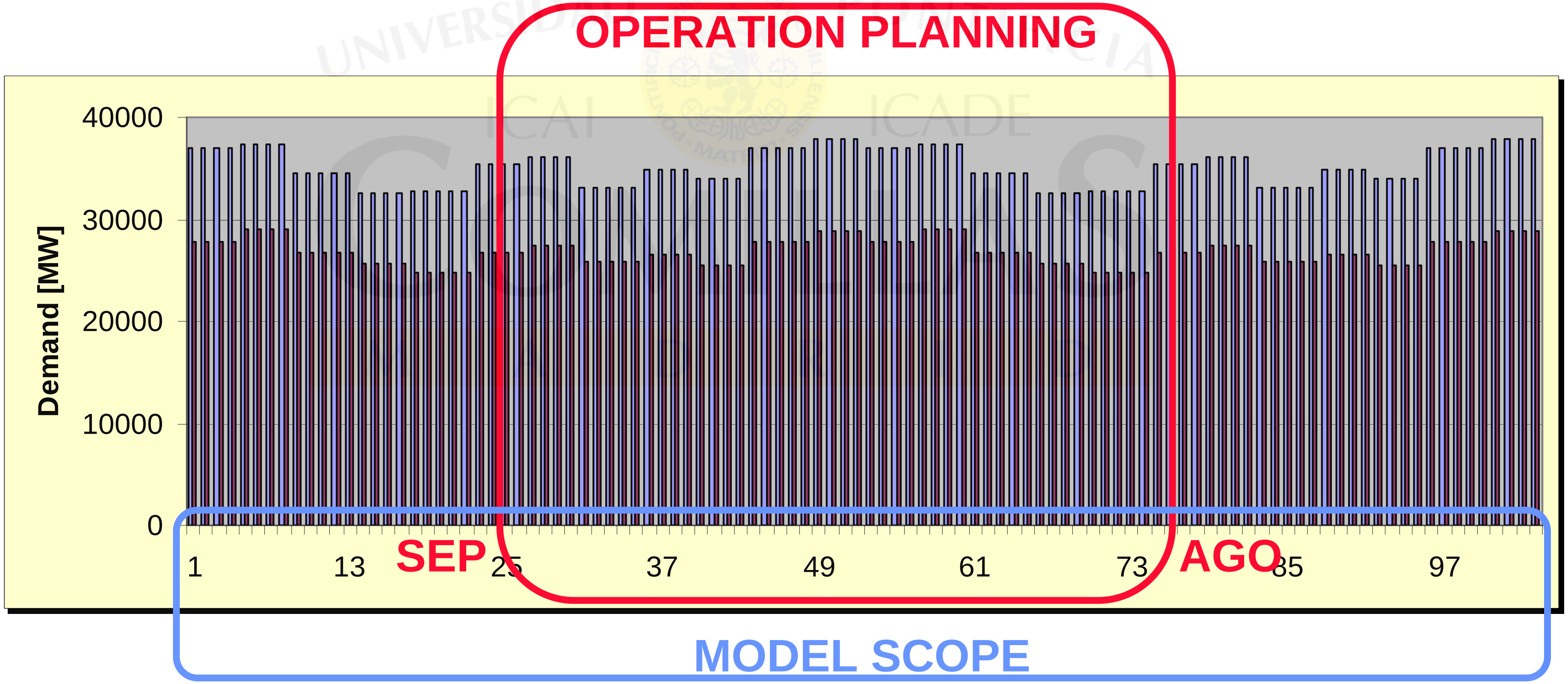
# Model use for operation planning

- Two-year long scope for one year operation planning
- Avoid initial and terminal effects

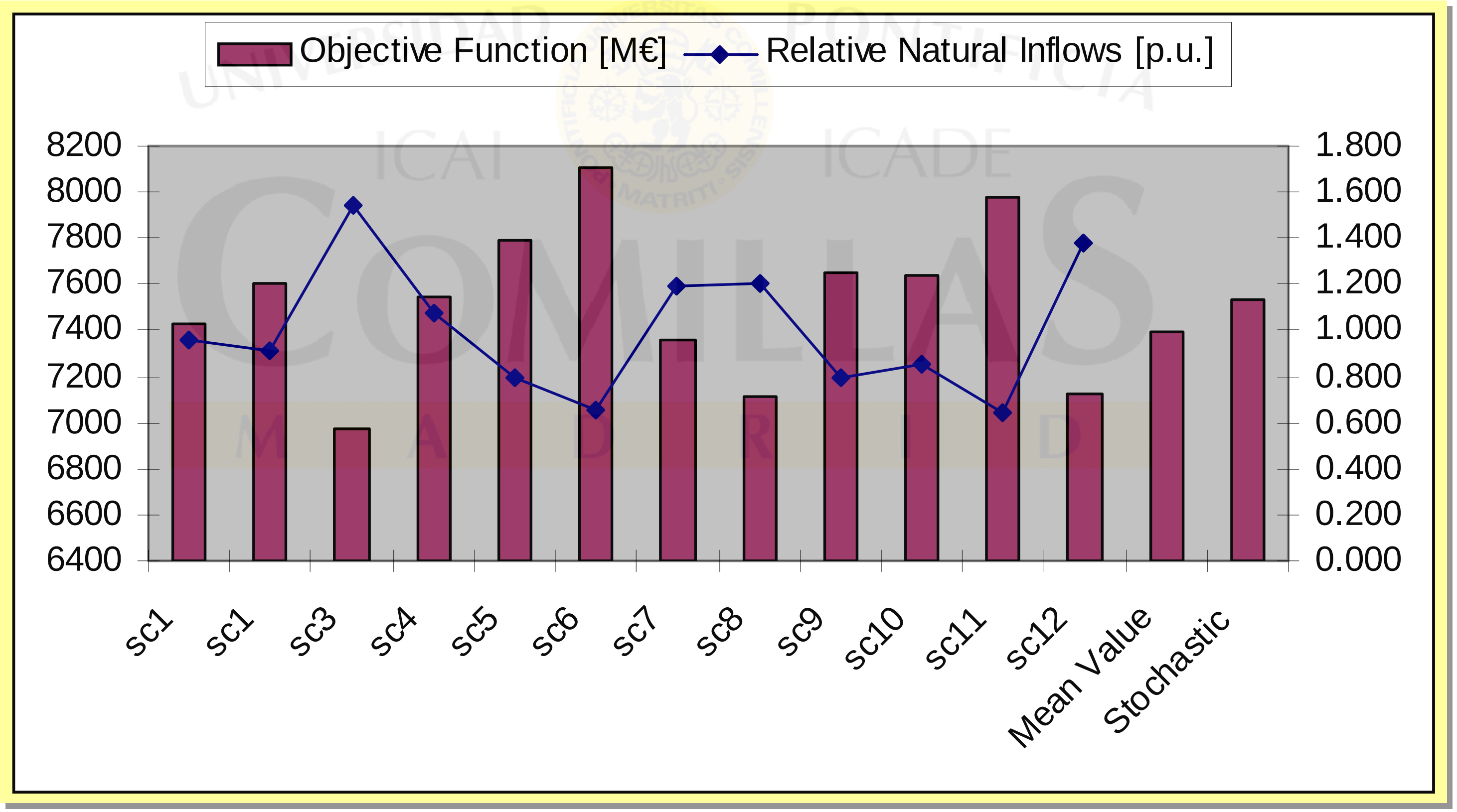


# Two-year long case study

- Spanish electric system
  - 130 thermal units
  - 3 main basins with 50 hydro reservoirs/plants and 2 pumped storage hydro plants
  - 12 scenarios
- Problem size:
  - 297913 constraints
  - 530379 variables
  - 1430949 non zero elements
  - 17904 nonlinear variables
  - 17904 nonlinear constraints

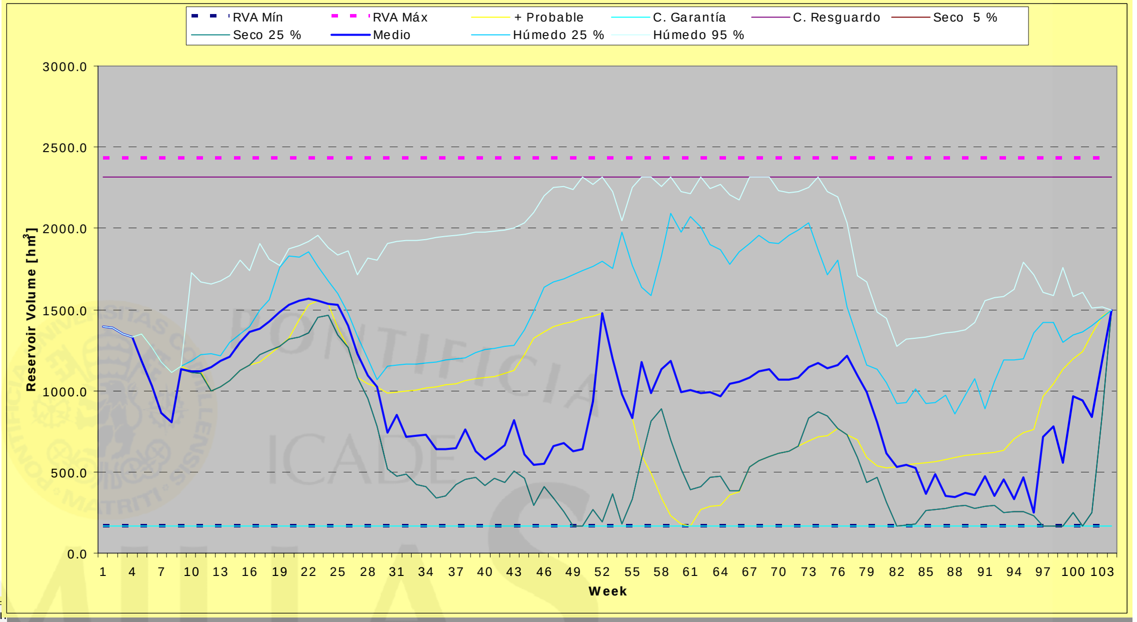
# Scenario analysis and stochastic measures

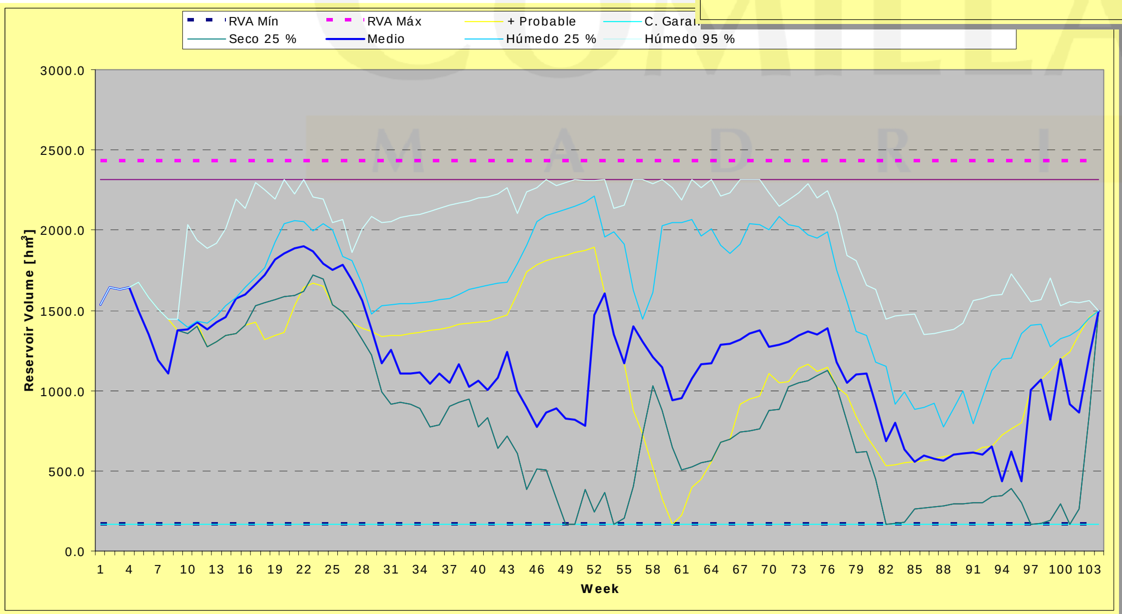
- Value of the stochastic solution (VSS) = 133 M€
- Expected value with perfect information (EVWPI) = 7526 M€



# Hydro reservoir operation (i)

LP solution

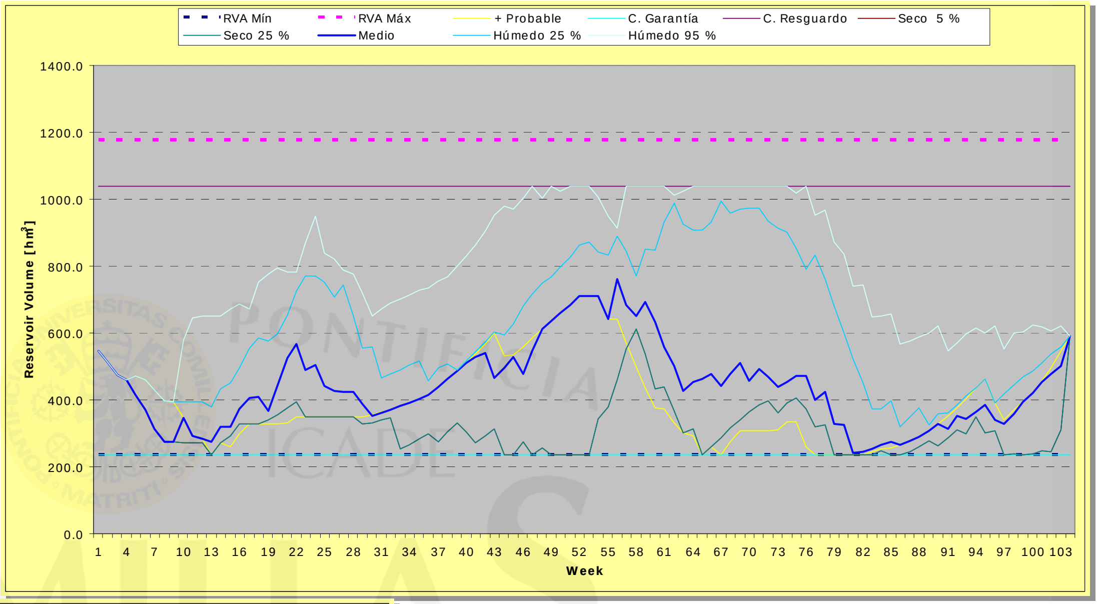


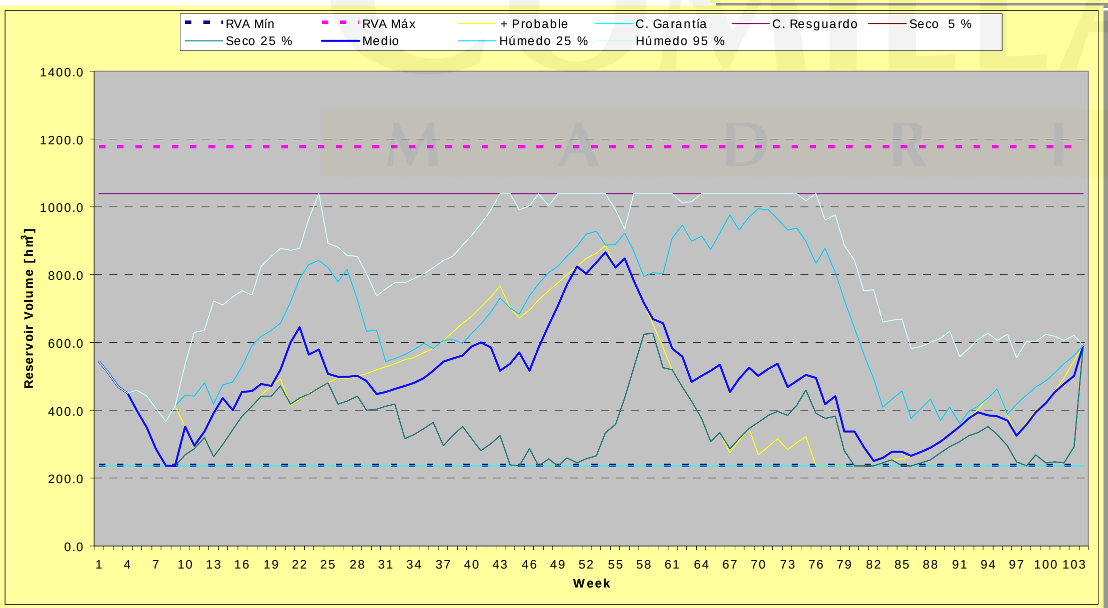




NLP solution

# Hydro reservoir operation (ii)

LP solution




NLP solution

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# Conclusions

- Medium term stochastic hydrothermal model for a complex multi-reservoir and multi-cascaded hydro subsystem
- Nonlinear water head effects modeled for large 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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