ASSESSING THE WATER-ENERGY-FOOD NEXUS ON THE JUCAR RIVER SYSTEM USING HYDROMETEOROLOGICAL FORECASTING AND STOCHASTIC HYDRO-ECONOMIC PROGRAMMING

Hector Macian-Sorribes[1], Patricia Marcos-Garcia[1], Ilias Pechlivanidis[2], Louise Crochemore[3] and Manuel Pulido-Velazquez[1]

[1] Universitat Politècnica de València, Research Institute of Water and Environmental Engineering (IIAMA), [2] Swedish Meteorological and Hydrological Institute (SMHI), Hydrology Research Unit, [3] INRAE, UR Riverly

INTRODUCTION

FACT

- Multipurpose water systems are subject to complex trade-offs among users
- Interlinkages between users in water allocation should be properly identified

NEED

- Assess the outputs of hydrometeorological forecasting within a sectoral context (urban, agriculture, energy)
- Compare the impact of water allocation for each sector using a common unit

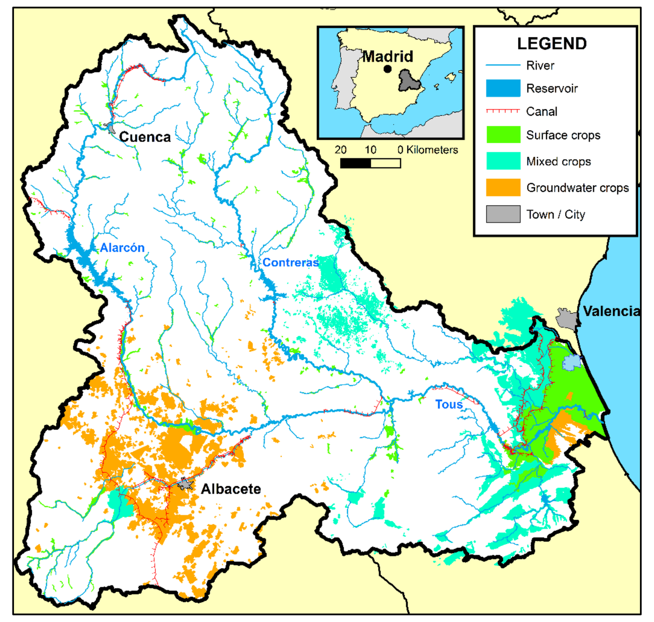
GOAL & APPROACH

GOAL: analyse the economic impacts posed by the implementation of forecast-based allocation rules on the Jucar river system (Spain)

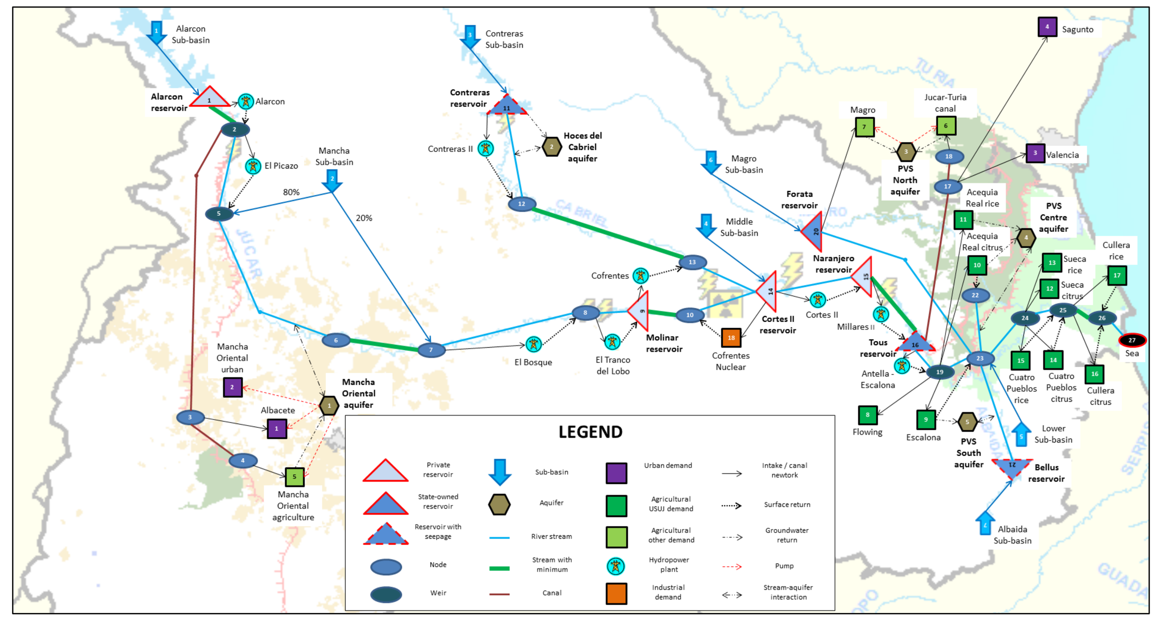
APPROACH: combine hydro-economic Stochastic Dual Dynamic Programming (SDDP) with Model Predictive Control (MPC)

CASE STUDY: THE JUCAR RIVER SYSTEM

THE RIVER

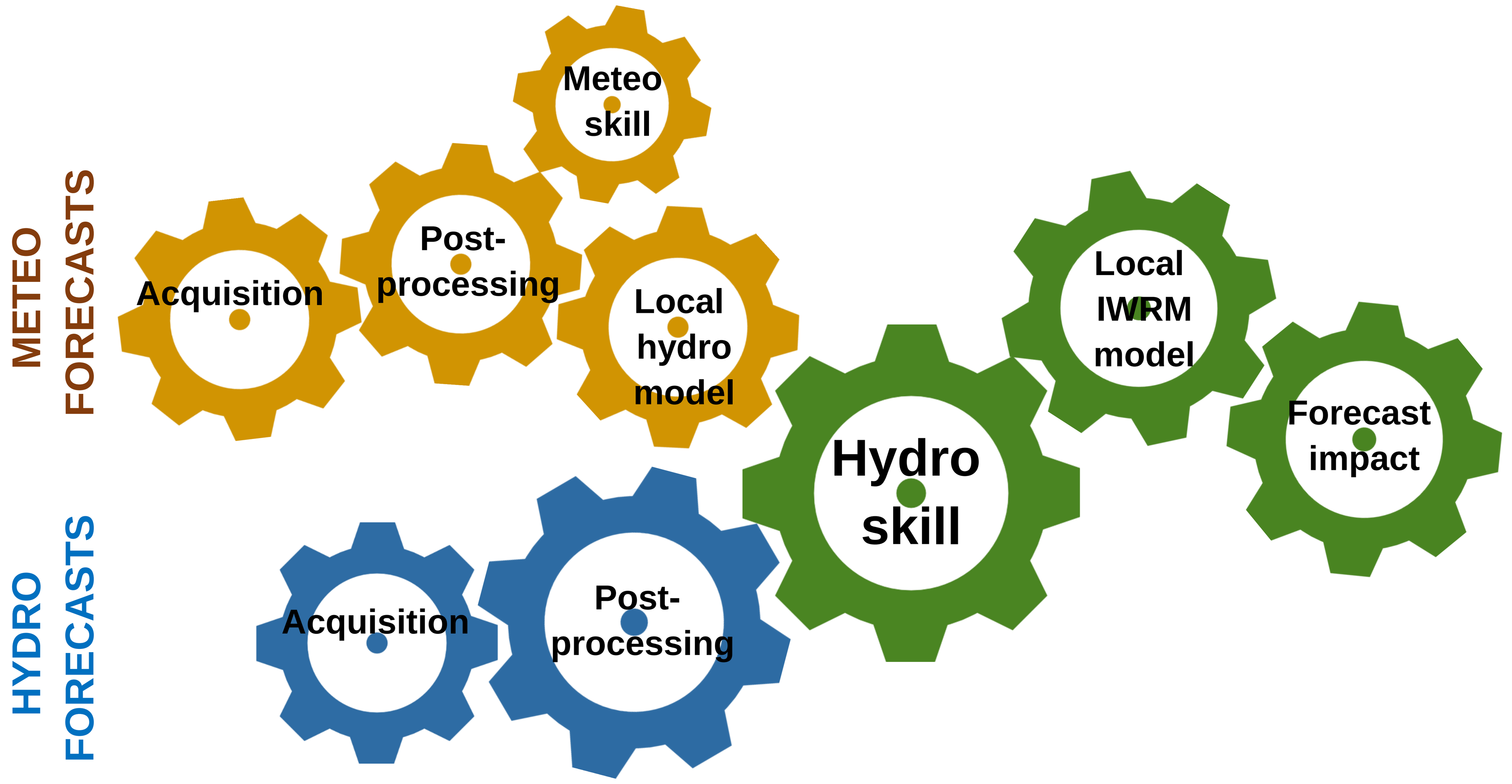


THE MODEL

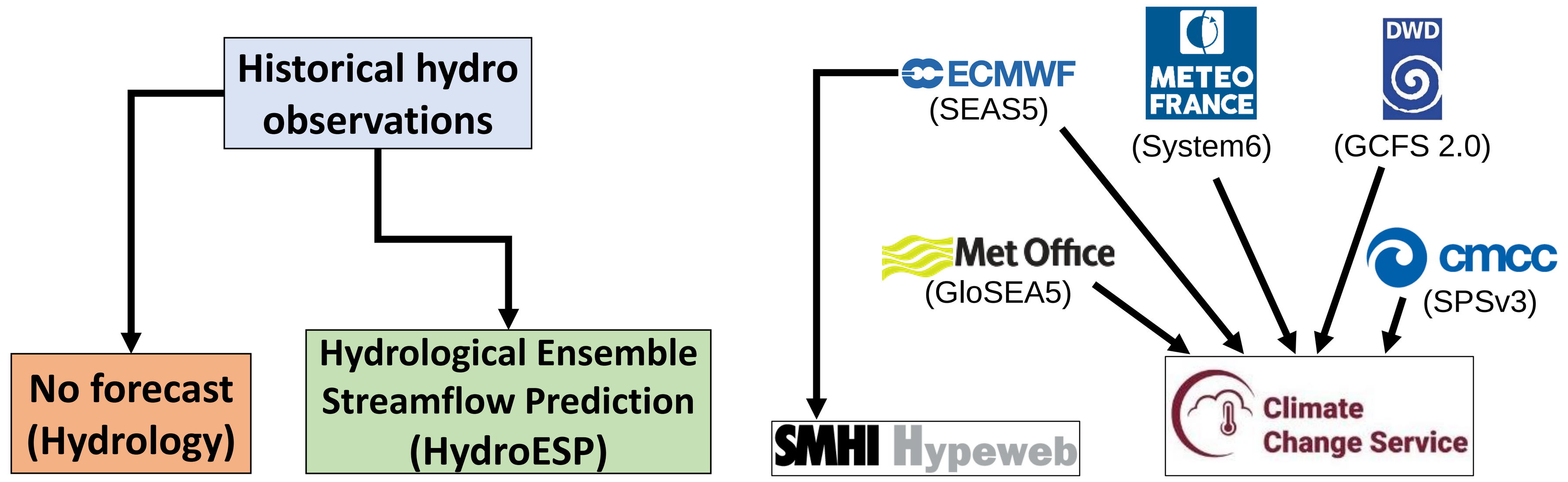


METHODS & MATERIALS

OVERVIEW OF METHODOLOGY



FORECASTING ALTERNATIVES

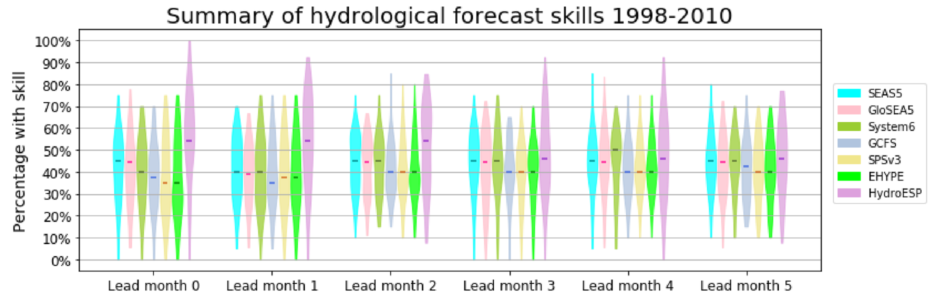


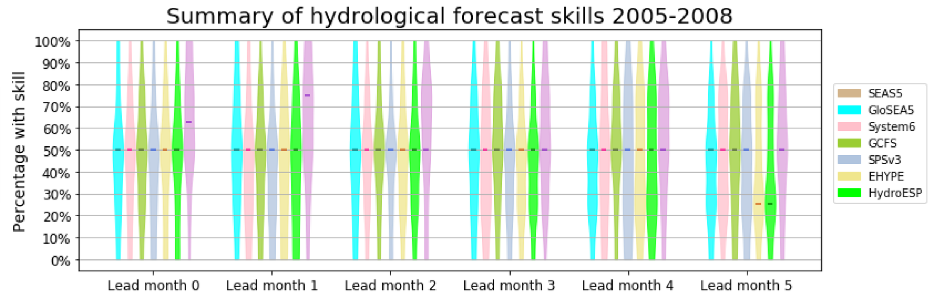
EXPERIMENTAL SETUP

- Analysis period: 1998-2010 (including a major drought in 2005-2008)
- Benchmark for validation of meteorological forecasts: raw forecasts
- Benchmark for skill assessment: no-forecast situation (historical pdfs)
- Benchmark for impact assessment: no-forecast (model forced with the average)

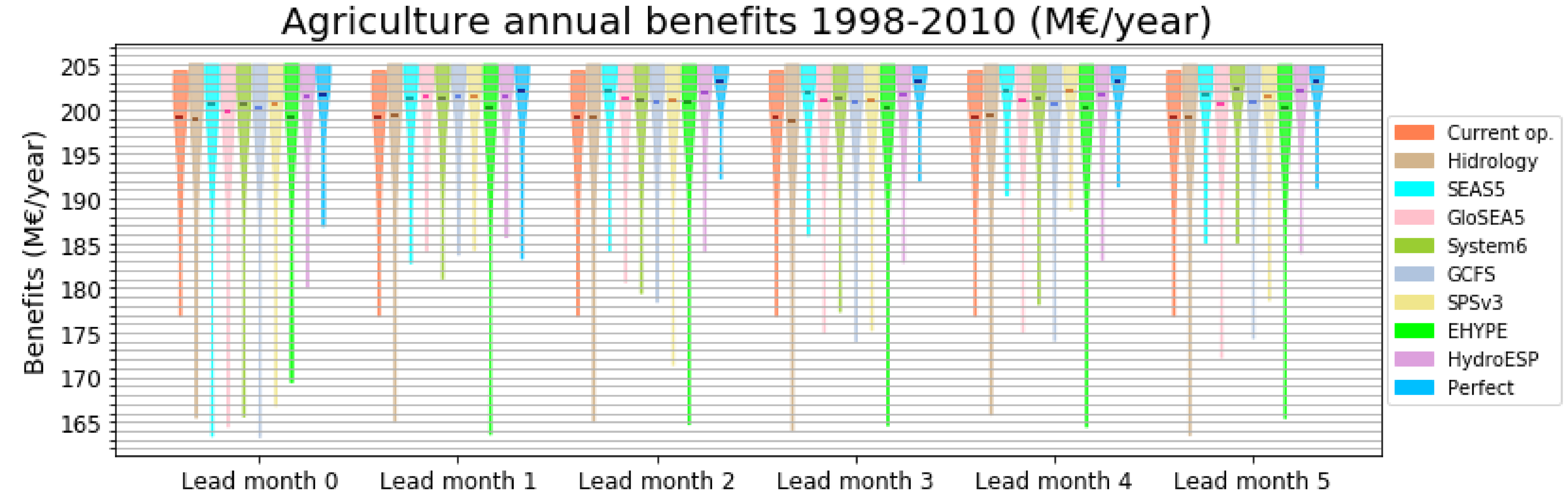
RESULTS AND CONCLUSIONS

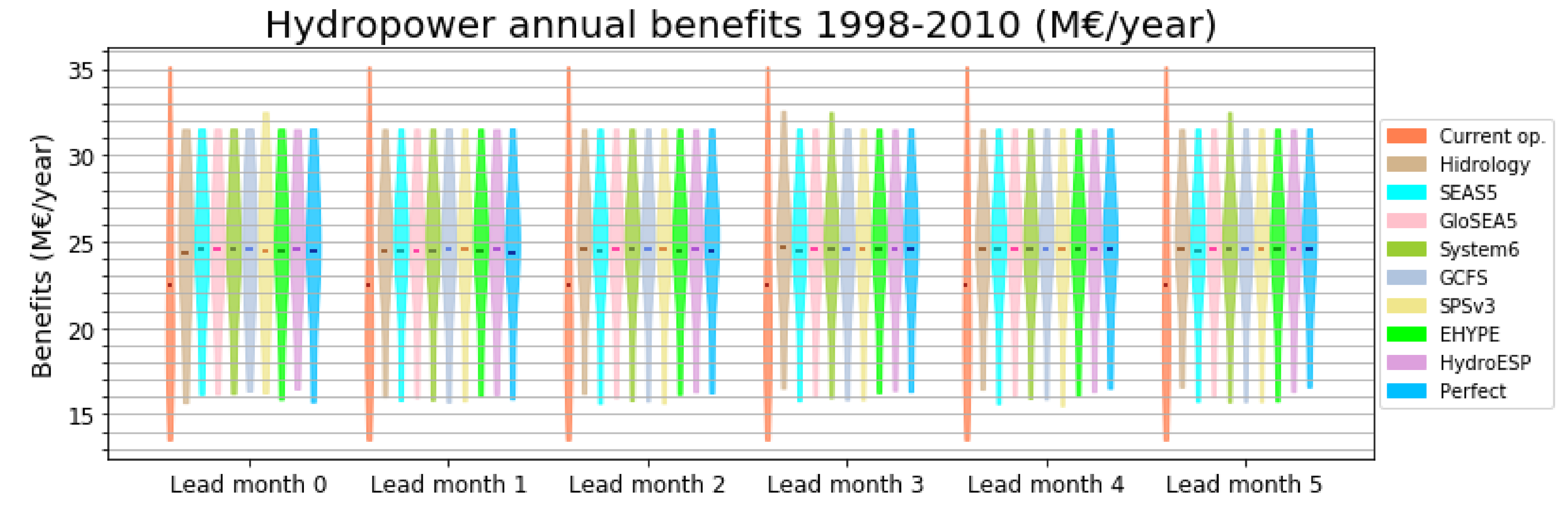
HYDROLOGICAL SKILL ASSESSMENT





FORECAST IMPACT ASSESSMENT





CONCLUSIONS

- All forecasting systems outperform the current operation (with perfect forecast) and the no-forecast situation – **using forecasts results into improved benefits**
- Agriculture: benefits depend on the product used (best: HydroESP and SEAS5)
- Hydropower: all systems show similar benefits – changing operation is the key
- Both improve by adopting forecast-based optimal rules – **room for cooperation**

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Click on figures in sections with red titles for further info

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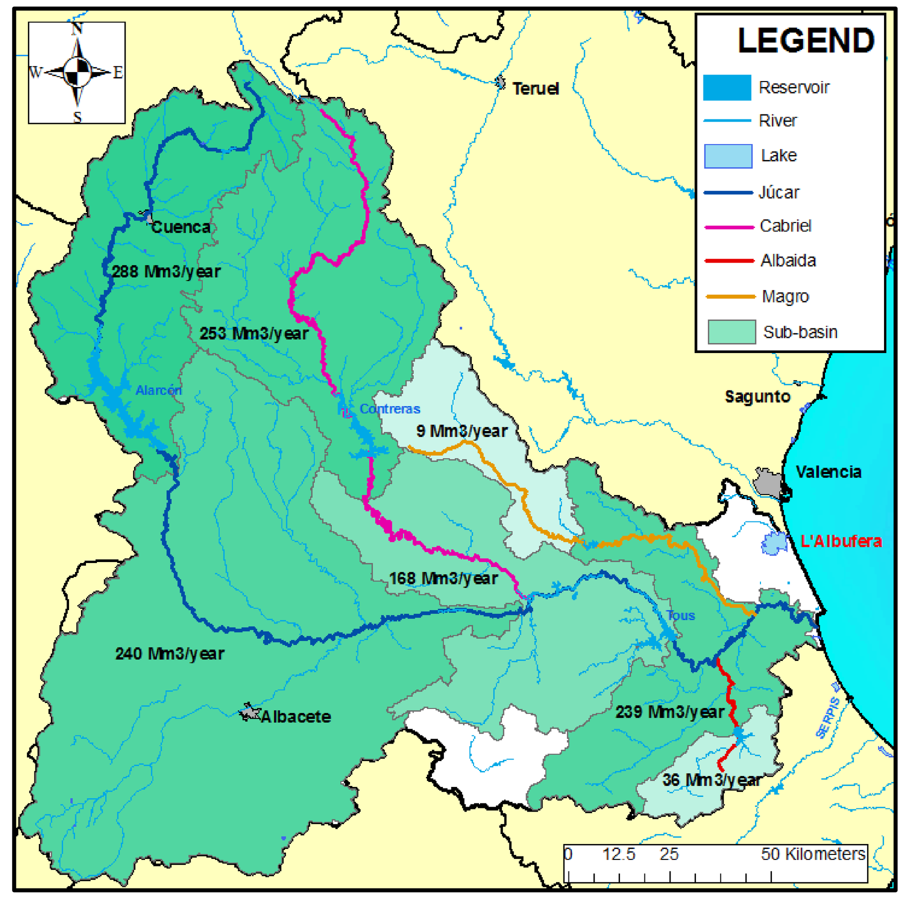
THE JUCAR RIVER BASIN

WATER RESOURCES

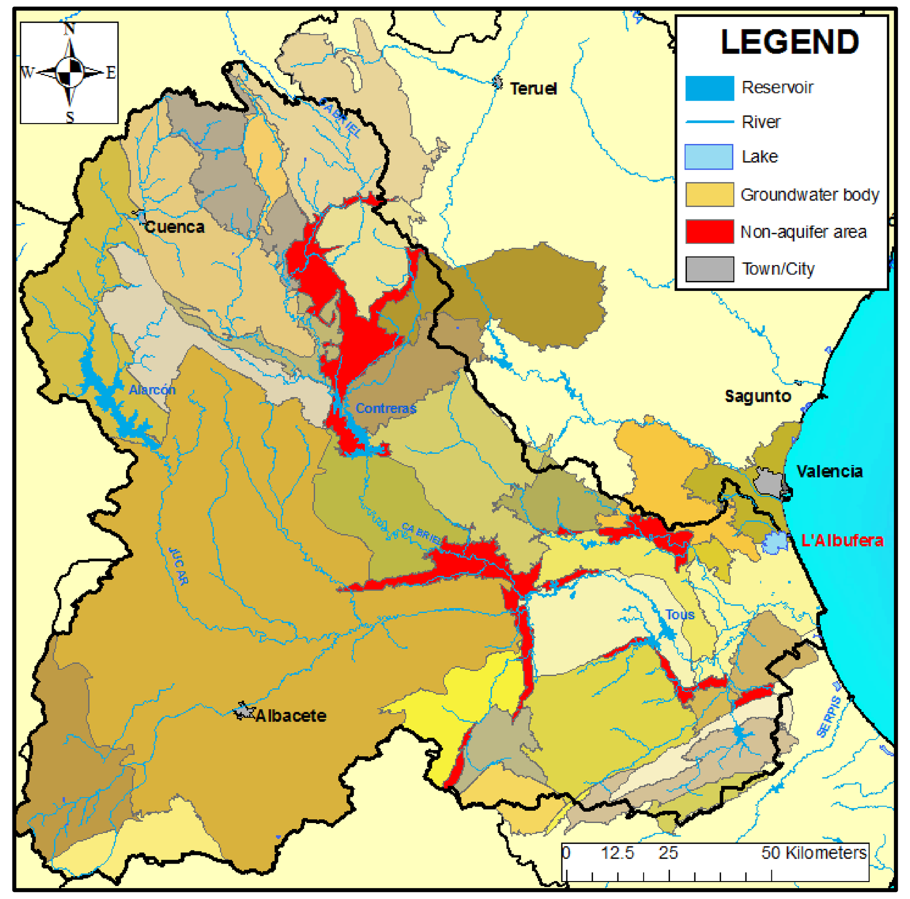


SURFACE WATER

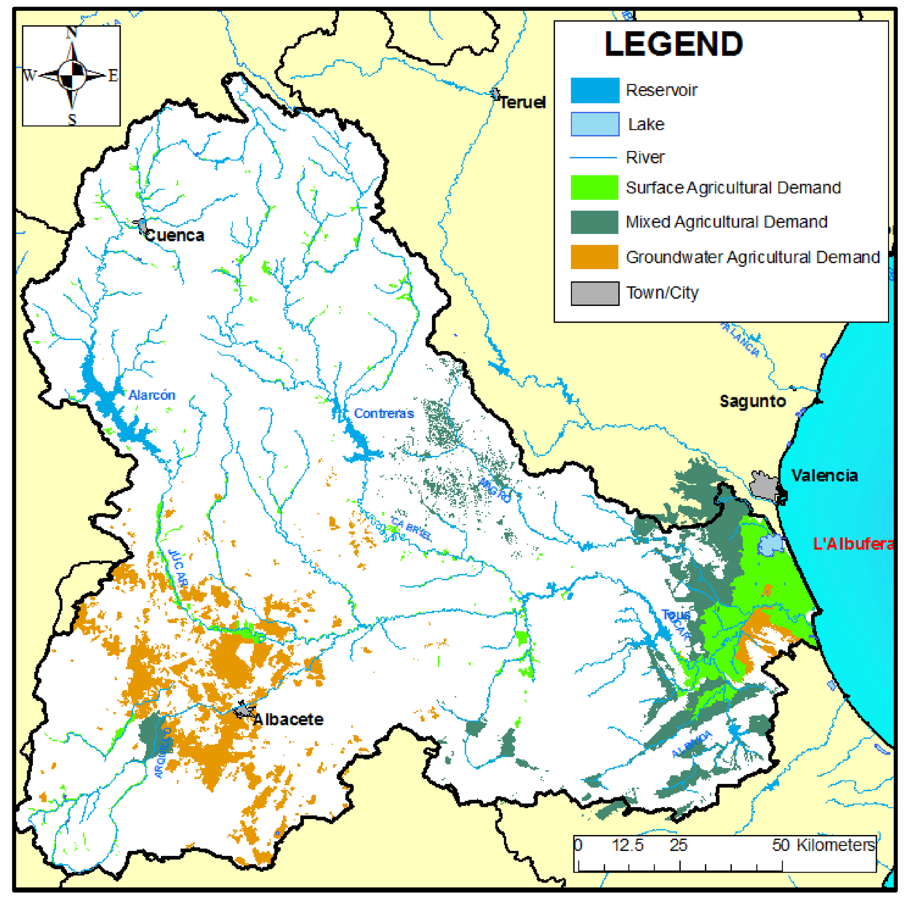
- ❑ 7 main sub-basins
- ❑ Average resource: 1,605 Mm^3/year
- ❑ Mediterranean hydrology (peaks at Autumn, low flows during summer)
- ❑ Multi-annual droughts
- ❑ Strong regulation and modification
- ❑ Distinct stream-aquifer interactions

GROUNDWATER

- ❑ 27 groundwater bodies
- ❑ Available resource to be pumped: 1,439 Mm^3/year (although depletion will cause a reduction of surface resources)
- ❑ 5 of them show piezometric decline
- ❑ 10 of them are heavily committed (pumping > 30% of available resource) and 6 are overexploited (pumping higher than available resource)



WATER DEMANDS

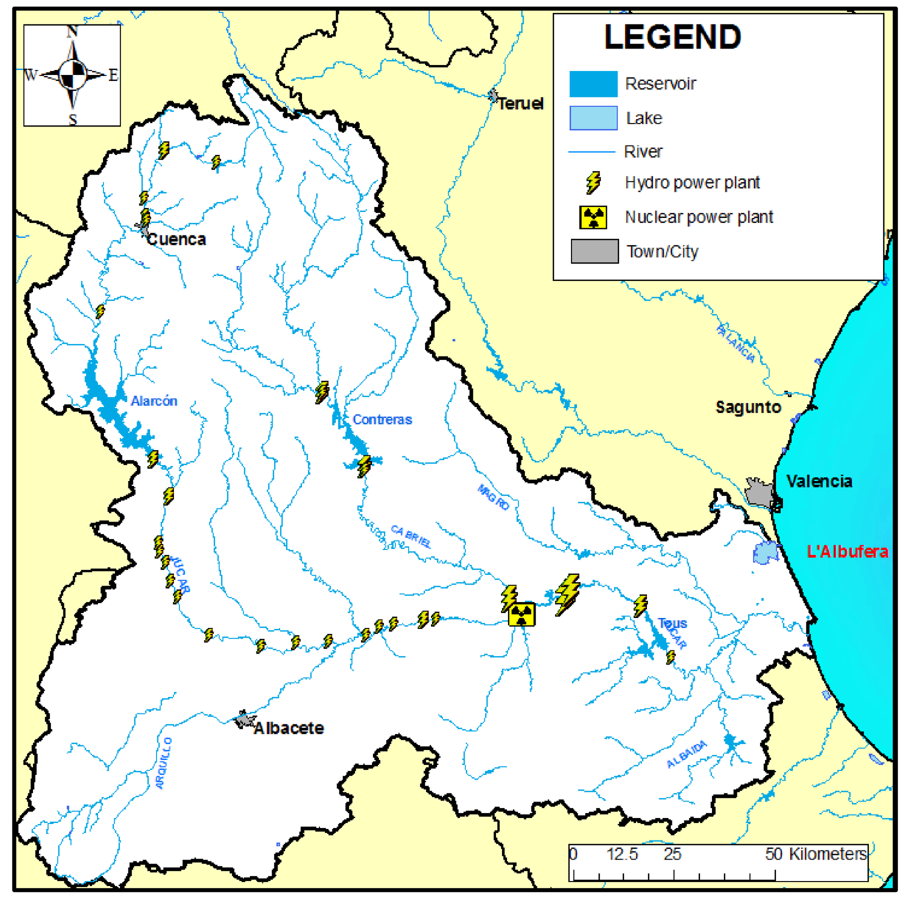


CONSUMPTIVE DEMANDS

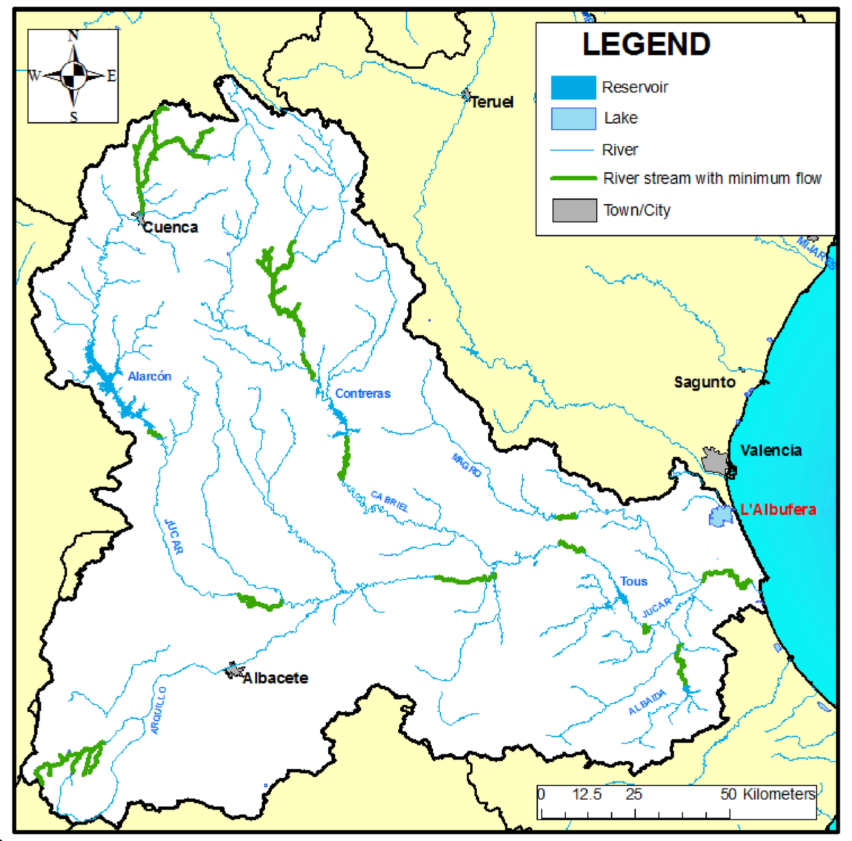
- ❑ Urban demands
  - ➢ 36 demands
  - ➢ 119.9 Mm^3/year in total
- ❑ Agricultural demands
  - ➢ 10 demand units
  - ➢ 1,402.9 Mm^3/year in total
- ❑ Industrial demands
  - ➢ 4 demand units
  - ➢ 28.6 Mm^3/year in total

ENERGY GENERATION

- ❑ 1 nuclear power plant (Cofrentes) plus 31 hydropower plants
- ❑ Hydropower plant installed capacities range between 0.2 MW to 628.35 MW
- ❑ Aggregated installed capacity equal to 1,271.88 MW
- ❑ The main facilities (La Muela de Cortes, Cortes II and Millares II) are located in its middle basin



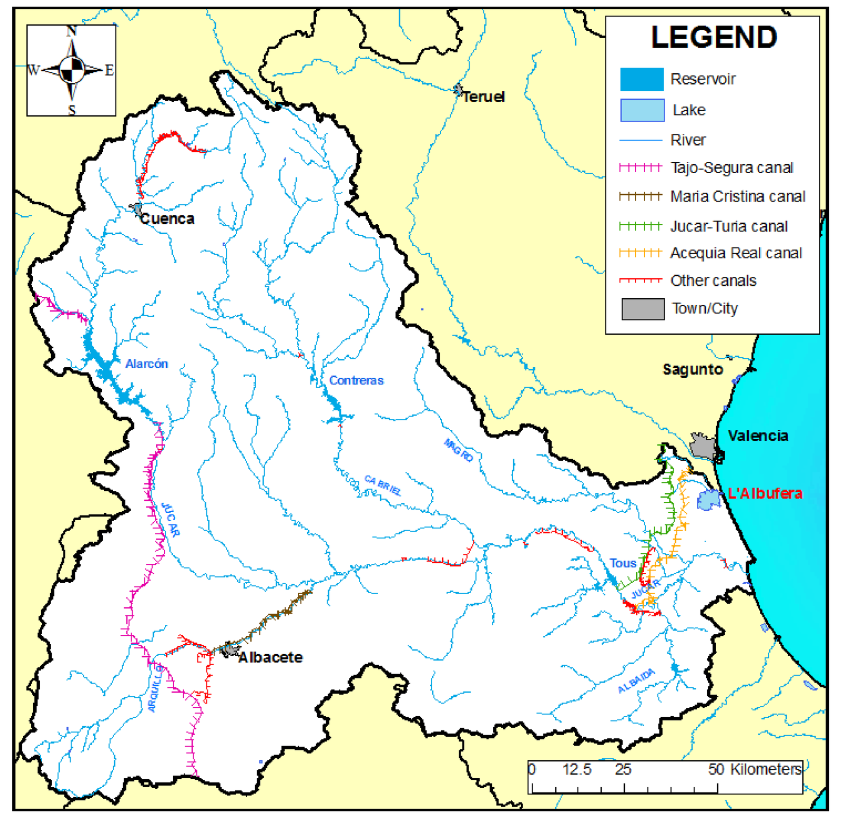
ENVIRONMENTAL FLOWS



- ❑ 18 Jucar River Basin streams have currently a minimum environmental flow
- ❑ Minimum environmental requirements are also set for the l'Albufera lake protected area (167 Mm^3 for the whole year and 148 Mm^3 for the September-April period)
- ❑ Environmental restrictions are likely to be tougher in the future

INFRASTRUCTURE

- ❑ 11 reservoirs with more than 1 Mm^3 of capacity, ranging between 1,118 Mm^3 (Alarcon) and 4.3 Mm^3 (Molinar)
- ❑ Reservoir ownership: farmers (1), state (5), and energy companies (5)
- ❑ Main reservoir uses: consumptive, hydropower and flood protection
- ❑ 4 main water distribution canals devoted to consumptive demand conveyance (3) and lagoon drainage (1)



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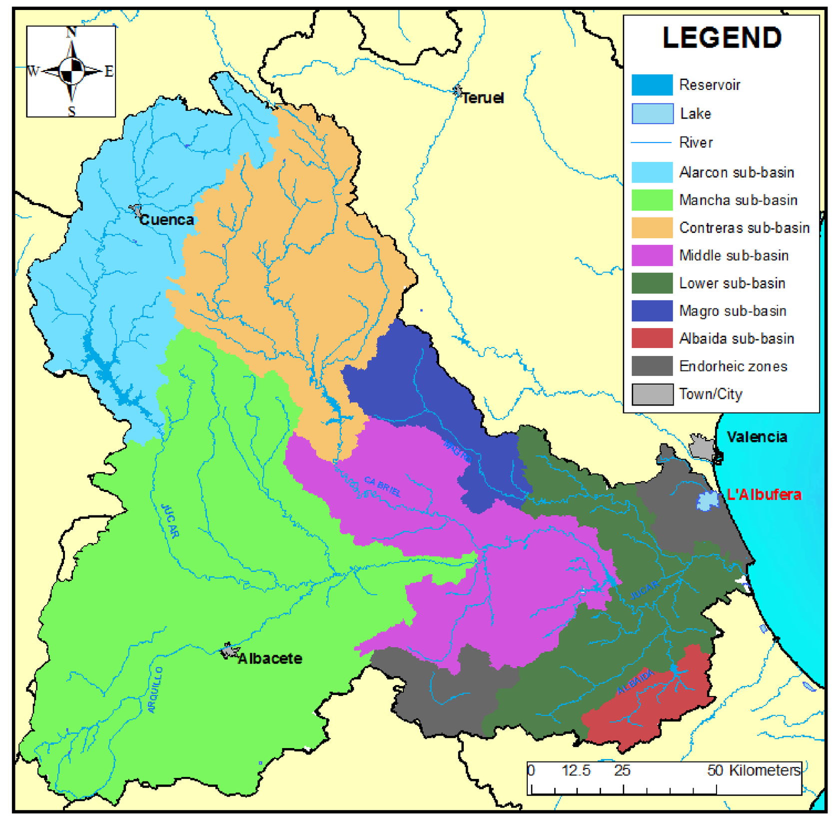
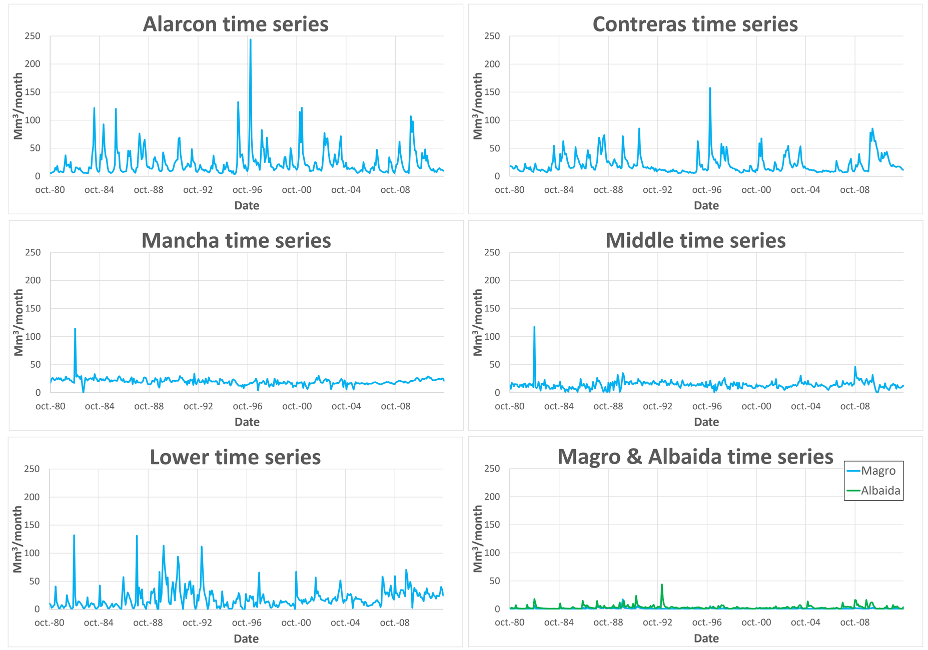
WATER MANAGEMENT MODEL OF THE JUCAR RIVER SYSTEM

INFLOWS



- Datasets restored to natural regimen by the Jucar River Basin Agency (CHJ)



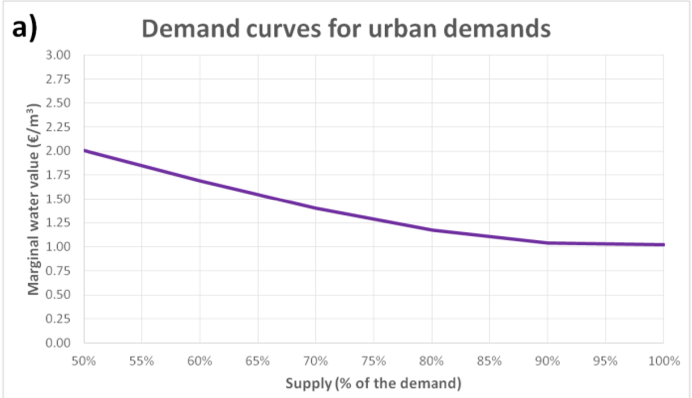
CONSUMPTIVE DEMANDS

- Urban demands in Mm³/year (below) of Albacete, Mancha Oriental, Valencia and Sagunto)
- Agricultural demands in Mm³/year (right) in the middle and lower streams of the Jucar

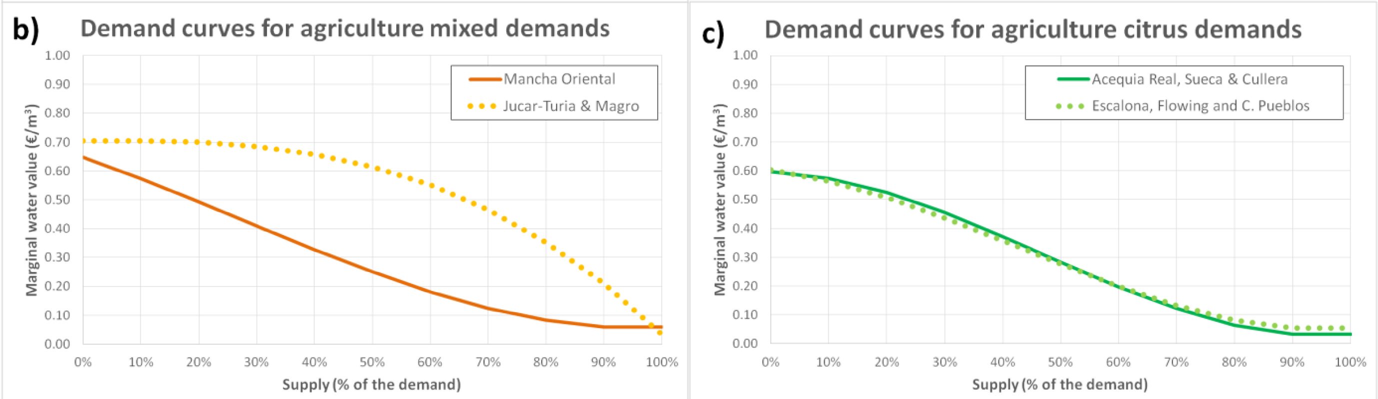
Demand	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Albacete	1.45	1.39	1.45	1.45	1.29	1.45	1.39	1.45	1.39	1.45	1.45	1.41
Mancha Oriental urban	1.14	1.10	1.13	1.13	1.02	1.14	1.11	1.14	1.10	1.14	1.15	1.11
Valencia	9.08	8.76	9.08	8.97	8.12	9.08	8.76	9.08	8.76	9.08	9.18	8.86
Sagunto	0.64	0.62	0.62	0.62	0.57	0.65	0.64	0.64	0.64	0.70	0.72	0.64

Demand	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Mancha Oriental agriculture	14.6	0.0	0.0	0.0	0.0	20.9	24.6	34.2	46.5	76.5	79.1	35.9
Jucar-Turia	5.7	1.3	2.5	1.2	1.9	5.8	5.0	8.8	15.7	20.6	16.3	9.6
Magro	0.6	0.1	0.2	0.1	0.1	0.4	0.4	0.6	1.4	1.9	1.6	1.0
Flowing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	3.9	4.0	4.0	3.9
Escalona	3.1	0.8	1.3	0.6	1.1	3.1	2.4	3.4	6.6	8.4	6.9	4.6
Acequia Real citrus	8.8	2.3	3.7	1.8	3.0	8.6	6.9	9.5	18.8	23.8	19.2	12.7
Acequia Real rice	0.0	0.0	0.0	0.0	0.0	0.9	0.7	23.2	14.7	21.8	9.9	4.8
Sueca citrus	1.1	0.3	0.5	0.2	0.4	1.1	0.9	1.2	2.4	3.0	2.4	1.6
Sueca rice	11.2	16.4	15.5	9.5	1.9	3.9	4.6	21.4	22.0	28.1	26.6	5.4
Cuatro Pueblos citrus	0.5	0.1	0.2	0.1	0.2	0.5	0.4	0.6	1.1	1.4	1.1	0.8
Cuatro Pueblos rice	0.3	1.5	0.9	0.7	0.4	0.0	0.3	4.5	3.4	3.6	4.1	0.6
Cullera citrus	2.8	0.7	1.2	0.6	1.0	2.7	2.2	3.0	6.0	7.6	6.1	4.1
Cullera rice	4.3	9.1	8.2	4.8	3.8	3.1	2.7	13.2	11.6	11.3	11.8	2.1

ECONOMIC EVALUATION



- Consumptive demands: demand functions derived from historical observations and theoretical assumptions:
  - ➢Urban demands: point expansion method
  - ➢Agriculture: producer's theory



- Energy: use of energy prices for the 1998-2012 period

RESERVOIRS

- Maximum monthly levels in Mm³ (excl. flood pool)

Reservoir	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Alarcon	1118	1118	1118	1118	1118	1118	1118	1118	1118	1118	1118	1118
Molinar	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3
Contreras	444	444	444	444	444	444	444	444	444	444	444	444
Cortes II	118	118	118	118	118	118	118	118	118	118	118	118
Naranjero	26.25	26.25	26.25	26.25	26.25	26.25	26.25	26.25	26.25	26.25	26.25	26.25
Tous	72	72	126	195	170	216	240	217	194	171	148	126
Forata	15.9	15.9	25.1	26.6	28.4	28.4	28.4	26.5	26.5	31	21	20.2
Bellus	18.3	18.4	18.3	28.6	28.6	28.6	28.6	28.6	28.6	28.6	28.6	18.3

- Minimum allowed storages (Mm³)

Reservoir	Alarcon	Molinar	Contreras	Cortes II	Naranjero	Tous	Forata	Bellus
Minimum	30	0.5	15	75	16	10	1	1

NON-CONSUMPTIVE USE

Location	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Jucar in Alarcon	2.00	2.00	2.00	2.40	2.40	2.40	2.40	2.40	2.00	2.00	2.00	2.00
Jucar in Mancha	0.60	0.60	0.60	0.72	0.72	0.72	0.72	0.72	0.60	0.60	0.60	0.60
Jucar in Molinar	1.70	1.70	1.70	2.04	2.04	1.70	1.70	1.70	1.70	1.70	1.70	1.70
Cabriel in Contreras	0.80	0.80	0.80	0.96	0.96	0.96	0.96	0.96	0.80	0.80	0.80	0.80
Jucar in Naranjero	1.60	1.60	1.60	1.92	1.92	1.60	1.60	1.60	1.60	1.60	1.60	1.60
Jucar in Cullera	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50

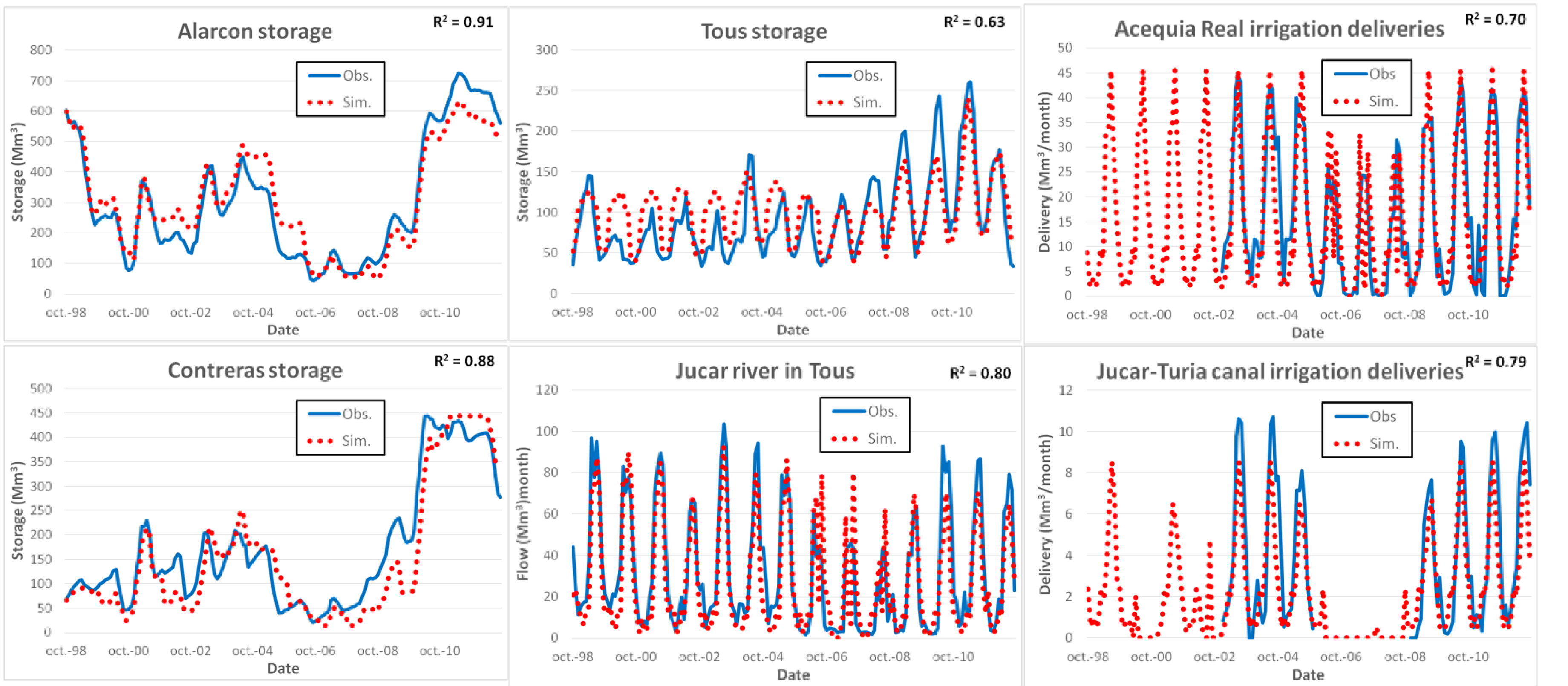
- Minimum streamflows (Mm³/month) prescribed in 6 key locations of the Jucar river

- 9 hydropower plants introduced (facilities with less than 3.5 MW of installed capacity were discarded)

Name	Type	Installed capacity (MW)	Net head (m)	Turbine capacity (m³/s)	Efficiency
Alarcon	Impoundment	16.4	56.0	40.0	0.75
El Picazo[1]	Impoundment	18.0	49.0	46.0	0.81
El Bosque	Run-of-river	8.0	21.5	40.0	0.95
El Tranco del Lobo	Run-of-river	3.8	12.5	42.0	0.75
Cofrentes	Impoundment	124.2	141.6	108.3	0.83
Contreras II	Impoundment	52.5	102.0	80.0	0.66
Cortes II	Impoundment	280.0	96.0	326.0	0.91
Millares II	Impoundment	67.1	137.3	55.0	0.91
Antella-Escalona	Run-of-river	3.6	6.6	40.0	1.00

[1] Associated reservoir not modeled (negligible live storage), so it works as run-of-river in the model

MODEL CALIBRATION



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METHODOLOGY

METEO FORECAST POST-PROCESSING

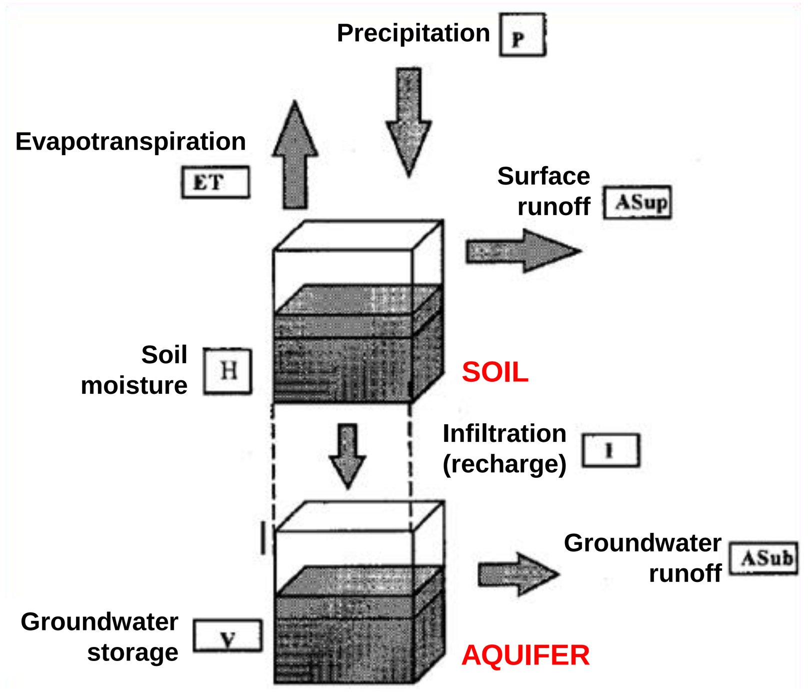
- Reference dataset: Spain02 v5 (available at http://www.meteo.unican.es/datasets/spain02)
- Method: month-dependent linear scaling (Crochemore et al., 2016)

$$Post - processed = a + b * raw$$

- Adjustment of linear scaling coefficients: Non-linear programming using Python (scipy optimize library)
- Validation of post-processing: comparing the skill of forecasts before and after post-processing

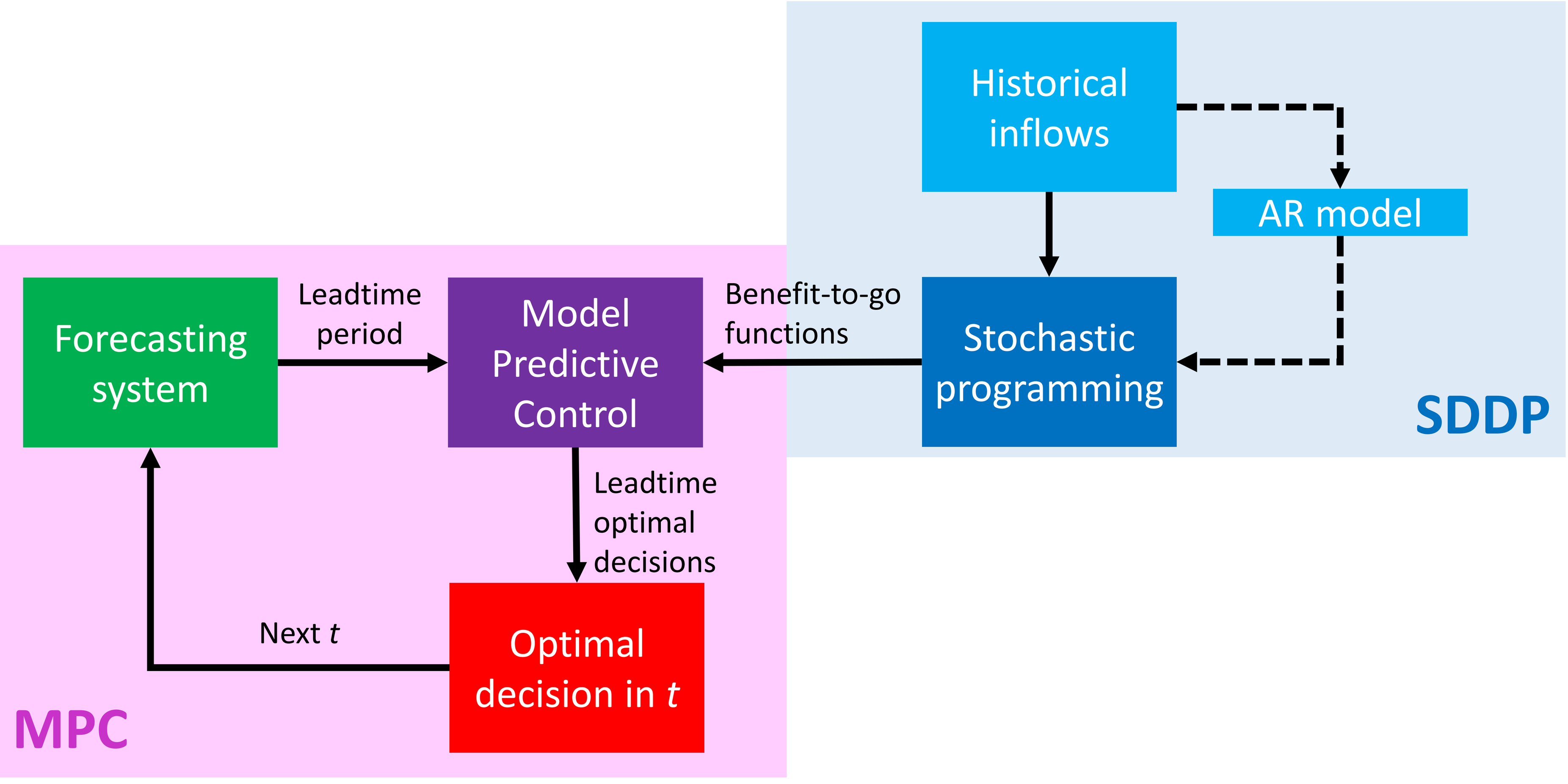
LOCAL HYDROLOGICAL MODEL

- Lumped pseudo-distributed conceptual Temez model
- Conceptually simple but suited to the Mediterranean hydrological regime
- Reference dataset for calibration: historical hydrological discharges from the Jucar River Basin Agency
- Calibrated models obtained from Marcos-Garcia (2019)



FORECAST IMPACT ASSESSMENT

- Combination of hydro-economic Stochastic Dual Dynamic Programming (SDDP) with Model Predictive Control (MPC)



- Objective function: maximize systemwide benefits (summation of all uses)

$$\max_i \left[\sum_{t=1}^{t=L} B_{t,i}(s_{t,i}, r_{t,i}, q_{t,i}) + F_{L+1} \right]$$

Forecast dependent (MPC) — Common (SDDP)

i: ensemble member
L: leadtime
$B_{t,i}$: revenus
$s_{t,i}$: storages
$r_{t,i}$: release decisions
$q_{t,i}$: hydrological forecasts
F_{L+1}: future benefits
n: ensemble members

HYDRO FORECAST POST-PROCESSING

- Method: mapping observations in sub-basins to modelled discharges in related E-HYPE catchments using artificial intelligence (fuzzy logic)
- Reference dataset: historical hydrological discharges from the Basin Agency
- Fuzzy logic systems developed and trained with Python (scipy optimize library)
- Validation of post-processing: comparing the skill of forecasts before and after post-processing
- More details in Macian-Sorribes et al. (2020)

FORECAST SKILL ASSESSMENT

- Index: Mean Absolute Error (MAE)

$$MAE_t = \frac{1}{N} \sum_{i=1}^{N} \left| F_{t,i} - O_t \right|$$

- t: time step
- i: ensemble member
- N: ensemble size
- F: forecast
- O: observation

- Skill score: Mean Absolute Error Skill Score (MAESS)

$$MAESS_t = 1 - \frac{MAE_{F,t}}{MAE_{B,t}}$$

- F: given forecasting system
- B: benchmark forecast

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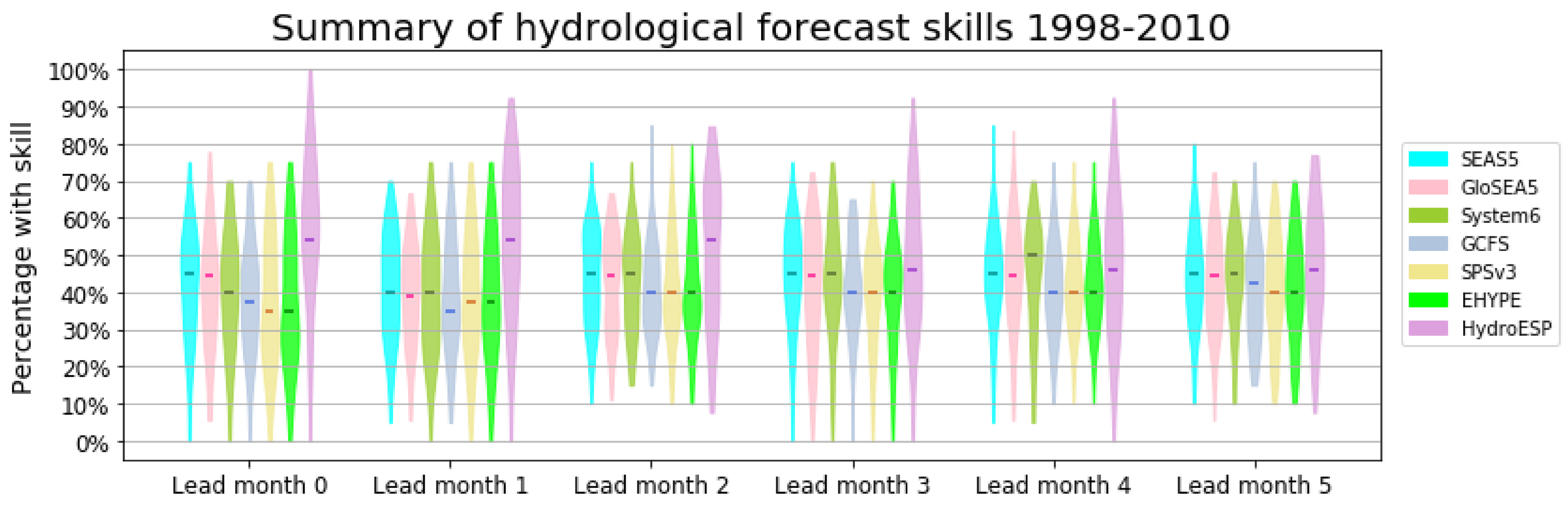
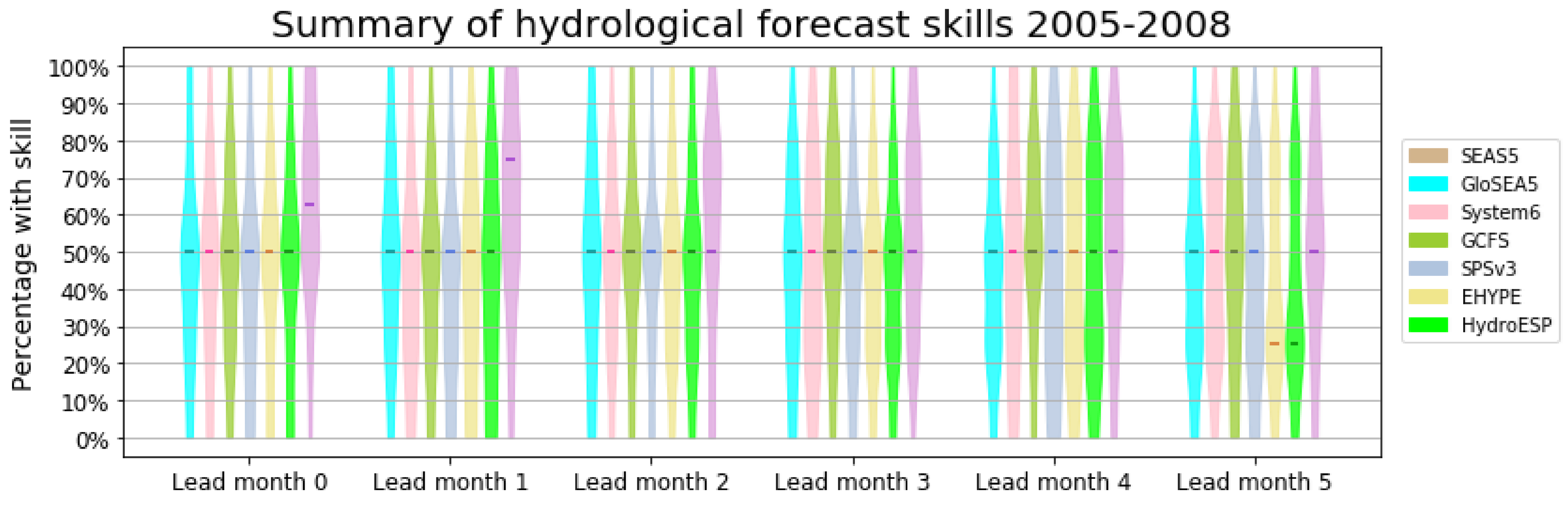
SUMMARY OF SKILLS

WHOLE PERIOD



- ❑ Low skill for hydrological forecasts on a broader view
- ❑ HydroESP offers the most skillful forecasts
- ❑ SEAS5 and GloSEA5 forecasts are, in general, above the rest of hydrological forecasts based on meteorological forecasts and local hydrological models

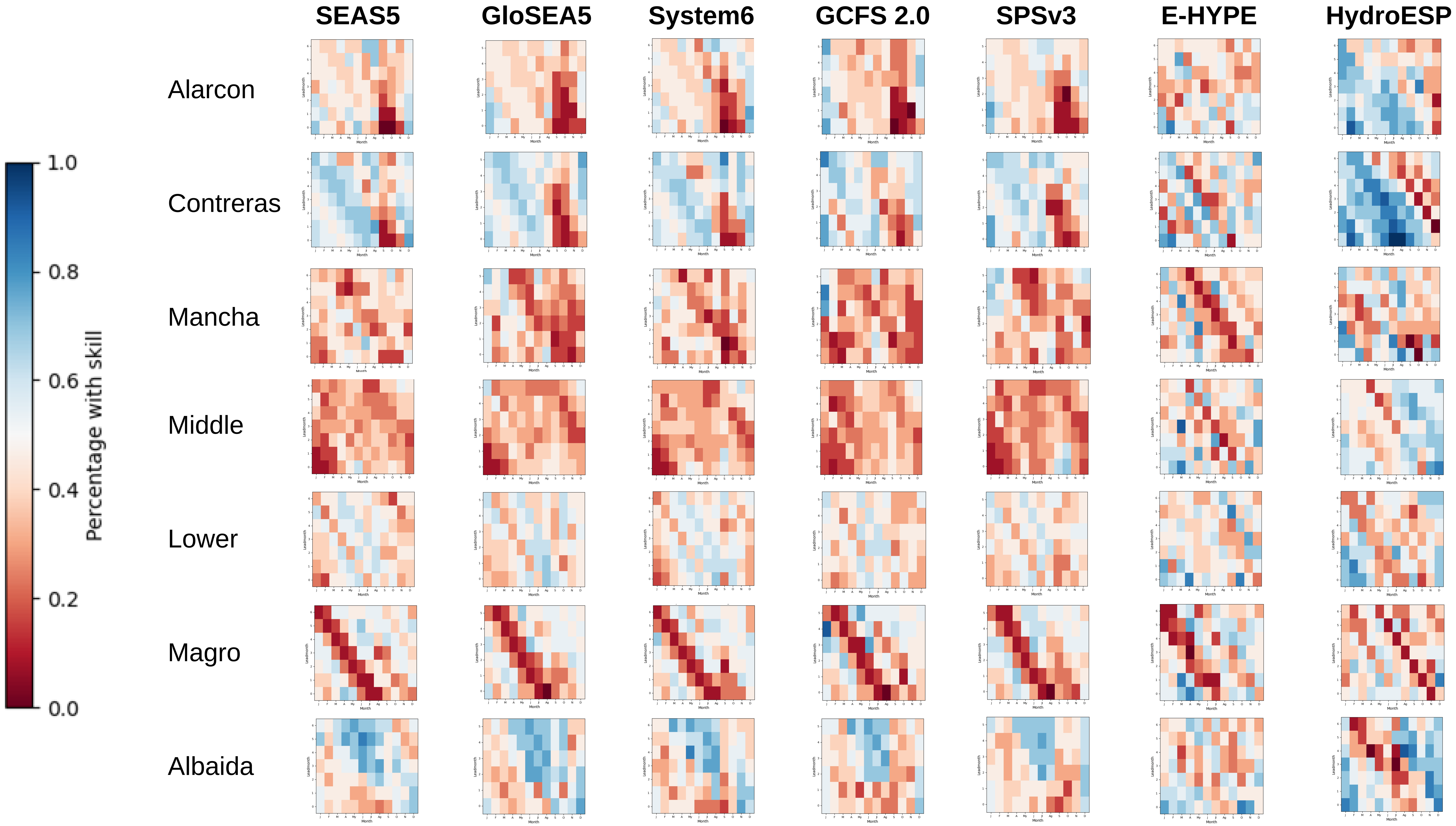
DROUGHT



- ❑ Forecasts perform slightly better during dry periods
- ❑ HydroESP offers again the best performance

SKILL PER SUB-BASIN AND ALTERNATIVE

row: issue month   column: lead month



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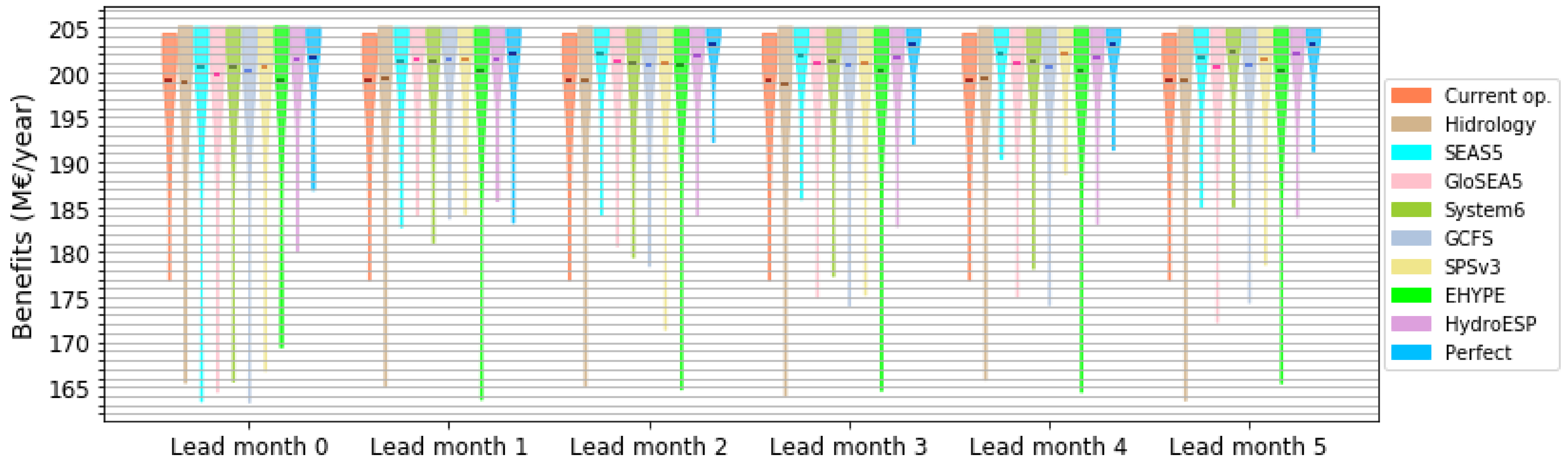
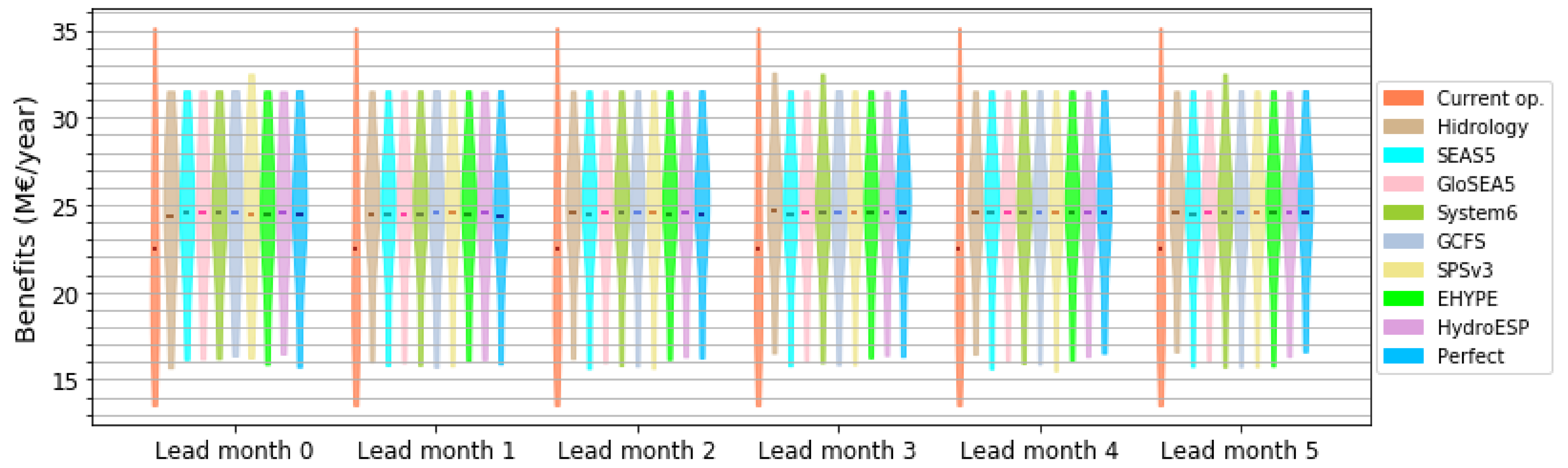
SUMMARY OF BENEFITS

AGRICULTURE



- ❑ All forecast products outperform current operation and hydrology – no forecasts (up to 3 M€/year) - forecast products show value
- ❑ Revenues depend on product (HydroESP and SEAS5 offer the highest benefits)
- ❑ HydroESP is both the most skillful forecast and the most valuable one
- ❑ In general, there is no direct link between average skill and revenues
- ❑ E-HYPE adds value but shows the lowest benefits (challenging local hydrology)

HYDROPOWER

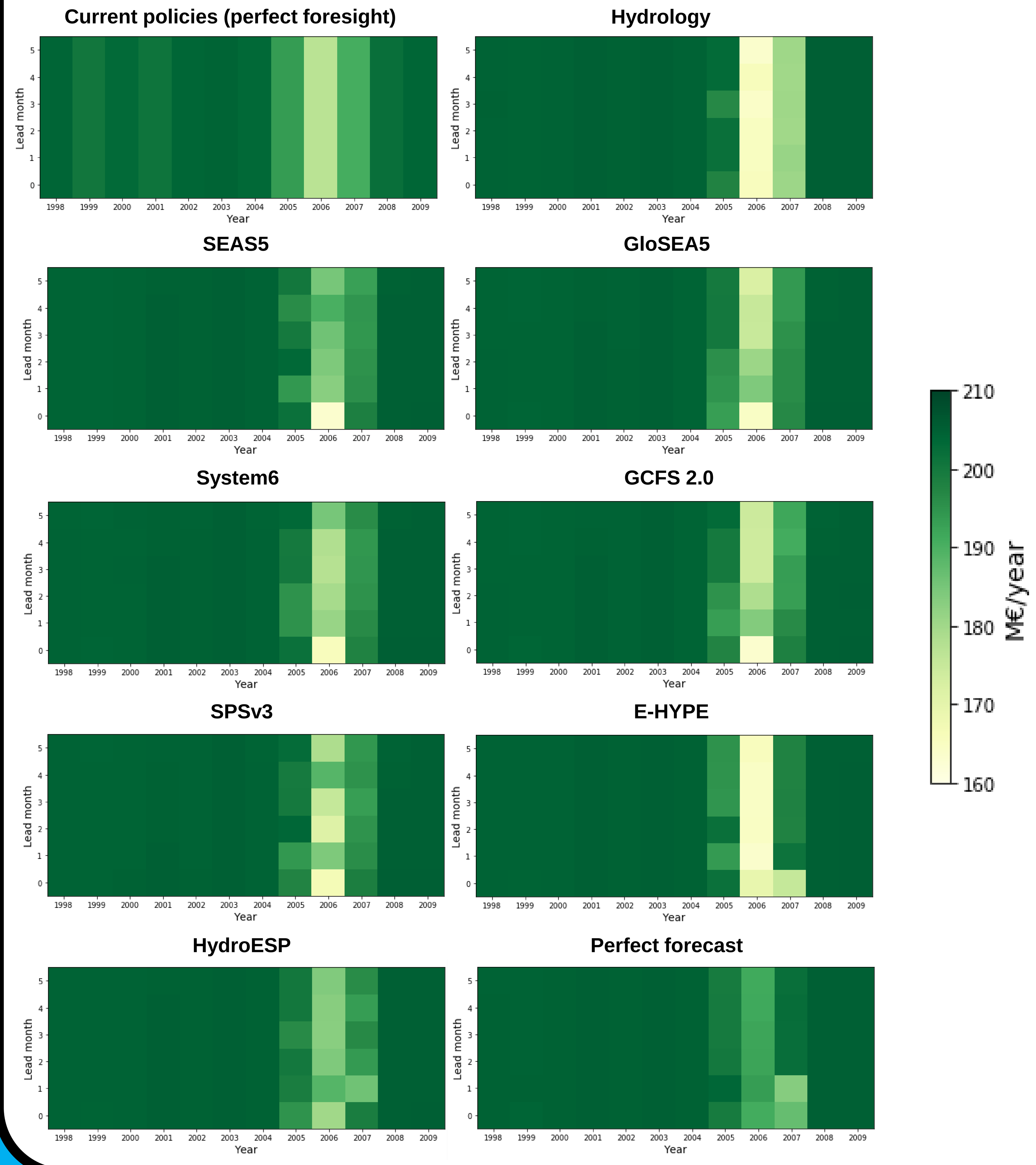


- ❑ Benefits increase for forecast-based optimal allocation (around 2 M€/year)
- ❑ All forecasts show similar revenue levels (from hydrology to perfect forecasts)
- ❑ Room for cooperation between both uses (agriculture's main benefit source is the forecast product to choose, while hydropower's is adopting improved rules)

BENEFITS PER LEAD MONTH AND ALTERNATIVE

row: year column: lead month

AGRICULTURE



HYDROPOWER