Integrated water and renewable energy management: the Acheloos-Peneios region case study (1)

EGU General Assembly 2015, Vienna, Austria, 12-17 April 2015

Session ERE3.8/HS5.6: *Harnessing the resources offered by sun, wind and water: control and optimization*

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1. Abstract

Within the ongoing research project "*Combined Renewable Systems for Sustainable Energy Development*" (CRESSENDO), we have developed a novel stochastic simulation framework for optimal planning and management of large-scale hybrid renewable energy systems, in which hydropower plays the dominant role. The methodology and associated computer tools are tested in two major adjacent river basins in Greece (Acheloos, Peneios) extending over 15 500 km^2 (12% of Greek territory). River Acheloos is characterized by very high runoff and holds ~40% of the installed hydropower capacity of Greece. On the other hand, the Thessaly plain drained by Peneios – a key agricultural region for the national economy – usually suffers from water scarcity and systematic environmental degradation. The two basins are interconnected through diversion projects, existing and planned, thus formulating a unique large-scale hydrosystem whose future has been the subject of controversy. The study area is viewed as a hypothetically closed, energy-autonomous, system, in order to evaluate the perspectives for sustainable development of its water and energy resources. In this context we seek an efficient configuration of the necessary hydraulic and renewable energy projects through integrated modelling of the water and energy balance. We investigate several scenarios of energy demand for domestic, industrial and agricultural use, assuming that part of the demand is fulfilled via wind and solar energy, while the excess or deficit of energy is regulated through large hydroelectric works that are equipped with pumped storage facilities. The overall goal is to examine under which conditions a fully renewable energy system can be technically and economically viable for such large spatial scale.

2. Study area

- Acheloos is the largest river of Greece in terms of flow (mean annual discharge 137 m^3/s) and the second one in terms of length (~220 km).
- In the middle and lower course of Acheloos, four dams and interconnected hydropower stations are already in operation, hosting 43% of the installed hydropower capacity of the country (1300 MW).
- Peneios drains the Thessaly plain, the most intensively cultivated and most productive agricultural region in Greece, yet suffering from water scarcity and extensive environmental degradation.
- To remedy the above problems, it was proposed to transfer water from the upper course of Acheloos; here we consider one of the examined layouts involving a diversion tunnel, four dams and four hydropower plants – the two reversible (this plan has been partially implemented).
- The total capacity of other renewables (small hydroelectric plants, solar and wind parks) over the study area exceeds 300 MW (>260 MW solar).
- The favorable hydrometeorological regime and topography allows for further development of the water and renewable energy sources (hydro, solar, wind), for which a holistic management policy is foreseen.

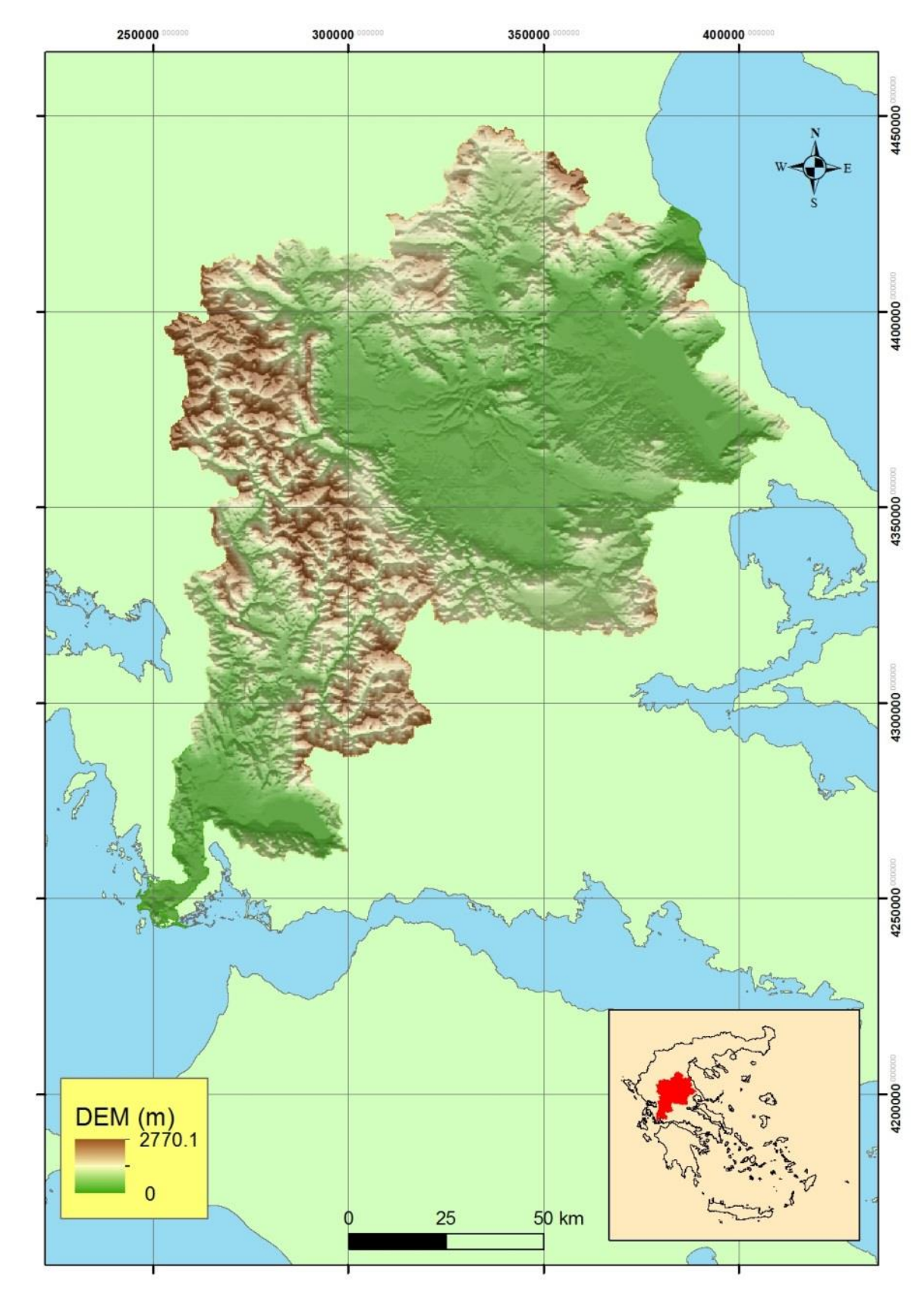


Fig. 1: *Location of interconnected river basins of Acheloos (west) and Peneios (east).*

3. Problem statement, methodology and data

- We consider the future layout of the study area as an **autonomous** system, to investigate its perspectives of sustainable development at a regional scale, merely based on **renewable energy** sources (hydro, solar, wind).
- The optimal management of **water and energy resources** is tackled as a combined problem, where the associated components and fluxes are modelled simultaneously; such an integrated approach is essential due to the **triple role of water** as **energy producer** (hydroelectric plants), **energy consumer** (pumps, boreholes), as well as **energy buffer**, through pumping storage (reverse turbines are activated in the case of over-production of energy from wind and solar parks).
- Seeking a long-term **water-energy planning** of the study area, the following issues are addressed:
    - Which are the water and energy needs of the study area?
    - Which is the optimal management policy of the hydrosystem, ensuring maximization of hydropower production and fulfilment of all water uses and environmental constraints with satisfactory reliability?
    - Which additional renewable energy projects are essential in order to minimize (or eliminate, if possible) the deficits between the electricity demand over the study area and the available energy from local sources (i.e., energy production from hydroelectric stations and current renewables, minus energy consumption by pumps and boreholes)?
- The methodological framework is based on a generalization of the **parameterization-simulation-optimization** (PSO) scheme, allowing conjunctive representation of the **water and energy balance** of the study area.
- Since the driving hydrometeorological processes of the integrated system are inherently **uncertain**, we employ a **stochastic** approach thus using synthetically generated input time series of large length, in order to assess the system performance in terms of **reliability** and **risk**.
- This modelling approach requires multiple types of **data**:
    - Spatial data (DEM, land cover, geology, groundwater bodies, boreholes, canals);
    - Hydrosystem data (layout and properties of major hydraulic structures, water demand for irrigation and domestic use, environmental and operational constraints);
    - Hydrometeorological data (time series of rainfall, runoff, evaporation, wind velocity, and solar radiation);
    - Energy data (solar and wind energy production, domestic, industrial and agricultural energy demand);
    - Economic data (energy production profit, pumping costs, water deficit costs, etc.).

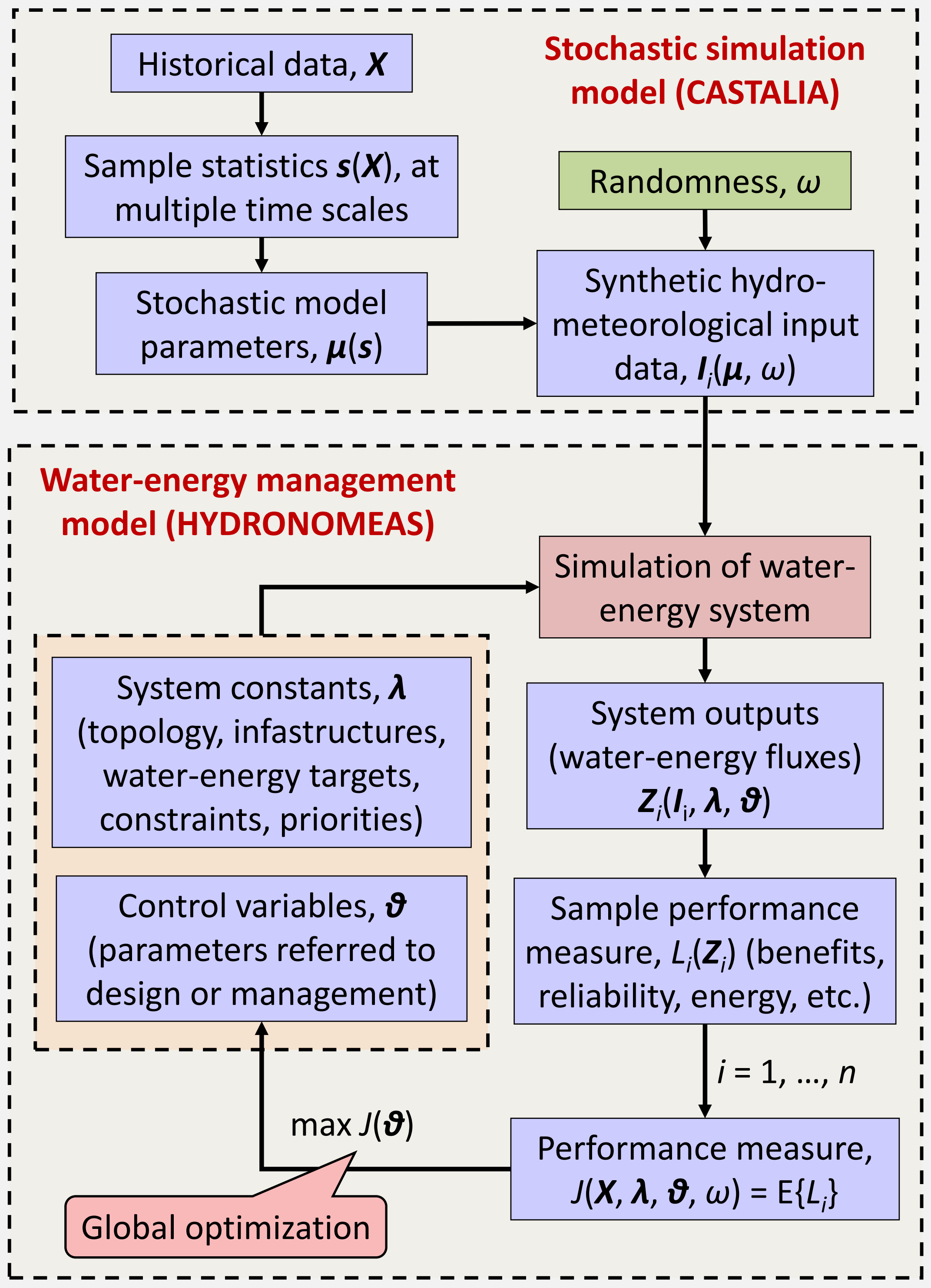
4. Modelling tools

Stochastic simulation of input hydro-meteorological processes (Castalia)

- Multivariate generator of synthetic data employing a three-level disaggregation scheme (annual → monthly → daily);
- Preserves the statistical behavior of the observed data at multiple scales;
- Reproduces the key properties of hydro-meteorological processes, such as the long-term persistence (Hurst–Kolmogorov behavior), periodicity and intermittency.

Simulation and optimization of water-energy system management (Hydronomeas)

- Schematization of water-energy system layout through a network-type representation of real-world components;
- Parameterization of key system controls, in terms of target fluxes or operation rules;
- Simulation of water-energy fluxes through a step-by-step network linear optimization scheme, ensuring physically-consistent description of system dynamics and faithful representation of targets and constraints.
- Optimization of system performance, comprising multiple objectives (safe yield, reliability, hydropower production, benefits, etc.), expressed in probabilistic terms.



Stochastic simulation model (CASTALIA)

Historical data, $\boldsymbol{X}$

Sample statistics $\boldsymbol{s}(\boldsymbol{X})$, at multiple time scales

Stochastic model parameters, $\boldsymbol{\mu}(\boldsymbol{s})$

Randomness, ω

Synthetic hydro-meteorological input data, $\boldsymbol{I}_i(\boldsymbol{\mu}, \omega)$

Water-energy management model (HYDRONOMEAS)

Simulation of water-energy system

System constants, $\boldsymbol{\lambda}$ (topology, infastructures, water-energy targets, constraints, priorities)

Control variables, $\boldsymbol{\vartheta}$ (parameters referred to design or management)

System outputs (water-energy fluxes) $\boldsymbol{Z}_i(\boldsymbol{I}_i, \boldsymbol{\lambda}, \boldsymbol{\vartheta})$

Sample performance measure, $L_i(\boldsymbol{Z}_i)$ (benefits, reliability, energy, etc.)

$i = 1, \ldots, n$

Performance measure, $J(\boldsymbol{X}, \boldsymbol{\lambda}, \boldsymbol{\vartheta}, \omega) = \mathrm{E}\{L_i\}$

max $J(\boldsymbol{\vartheta})$

Global optimization

5. Modelling components and schematic layout of water-energy system

1. **Nodes**
    - River network junctions receiving runoff from their upstream sub-basins;
    - Irrigated areas that are fulfilled by conjunctive surface and groundwater resources (extended areas served by individual boreholes are excluded from the model);
    - Energy-related hydraulic structures (hydropower plants, pumping stations, boreholes).
2. **Storage elements**
    - Reservoirs and lakes (specific types of node with stochastic inflows and regulated outflows).
3. **Water conveyance links**
    - River segments (infinite discharge capacity);
    - Aqueducts (finite discharge capacity).
4. **Targets and constraints (given in priority order)**
    - Water demand for irrigation of water supply;
    - Energy targets assigned to hydropower stations;
    - Water level constraints assigned to reservoirs/lakes;
    - Flow constraints (minimum, maximum) assigned to pumping stations, boreholes and aqueducts;
    - Environmental flows assigned to river segments.

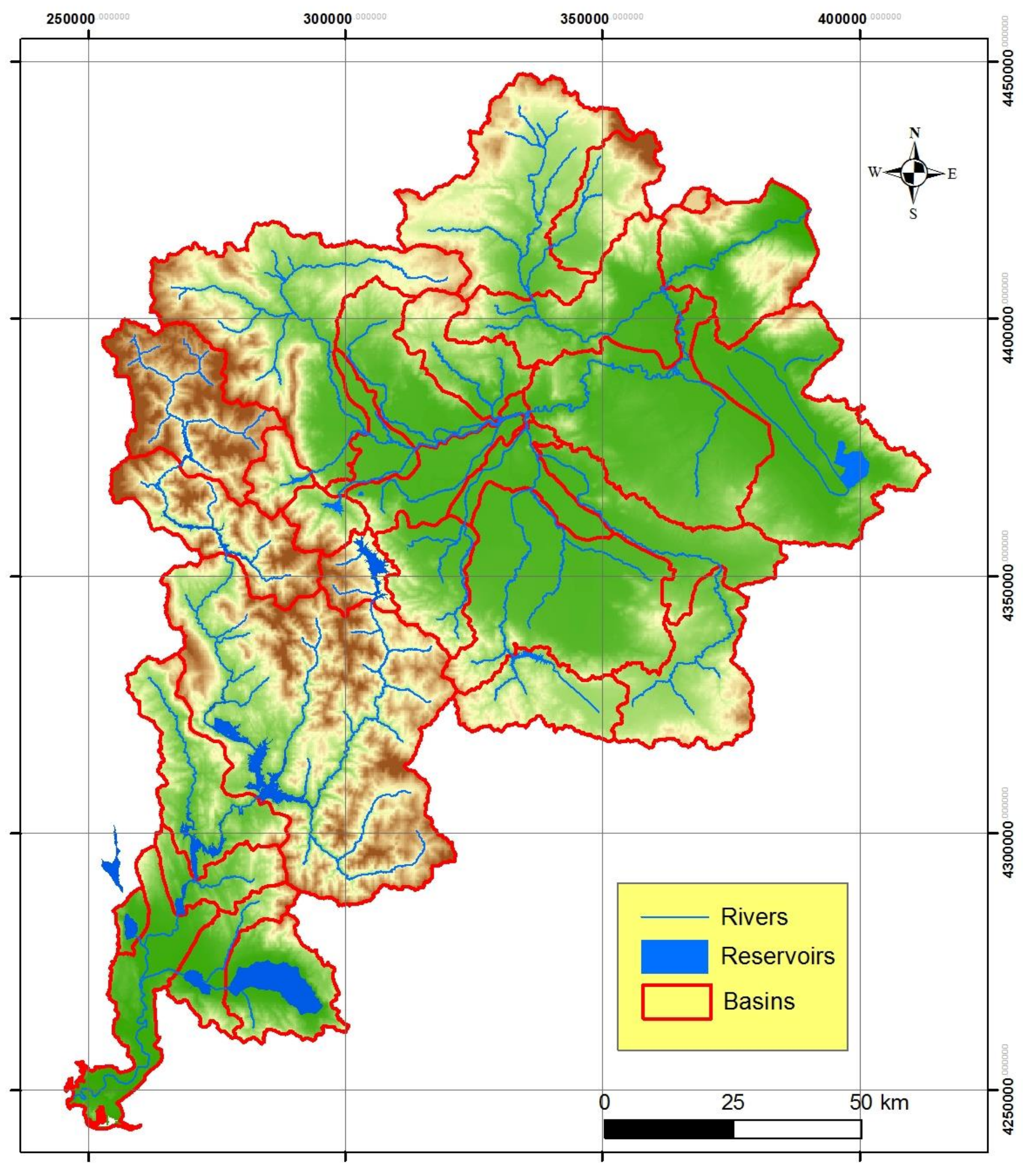


Fig. 2: *Delineation of sub-basins upstream of each point of interest across the main river network (reservoir, water supply node or water abstraction node); system inputs are the runoff time series of each sub-basin, which are synthetically generated via the Castalia model.*

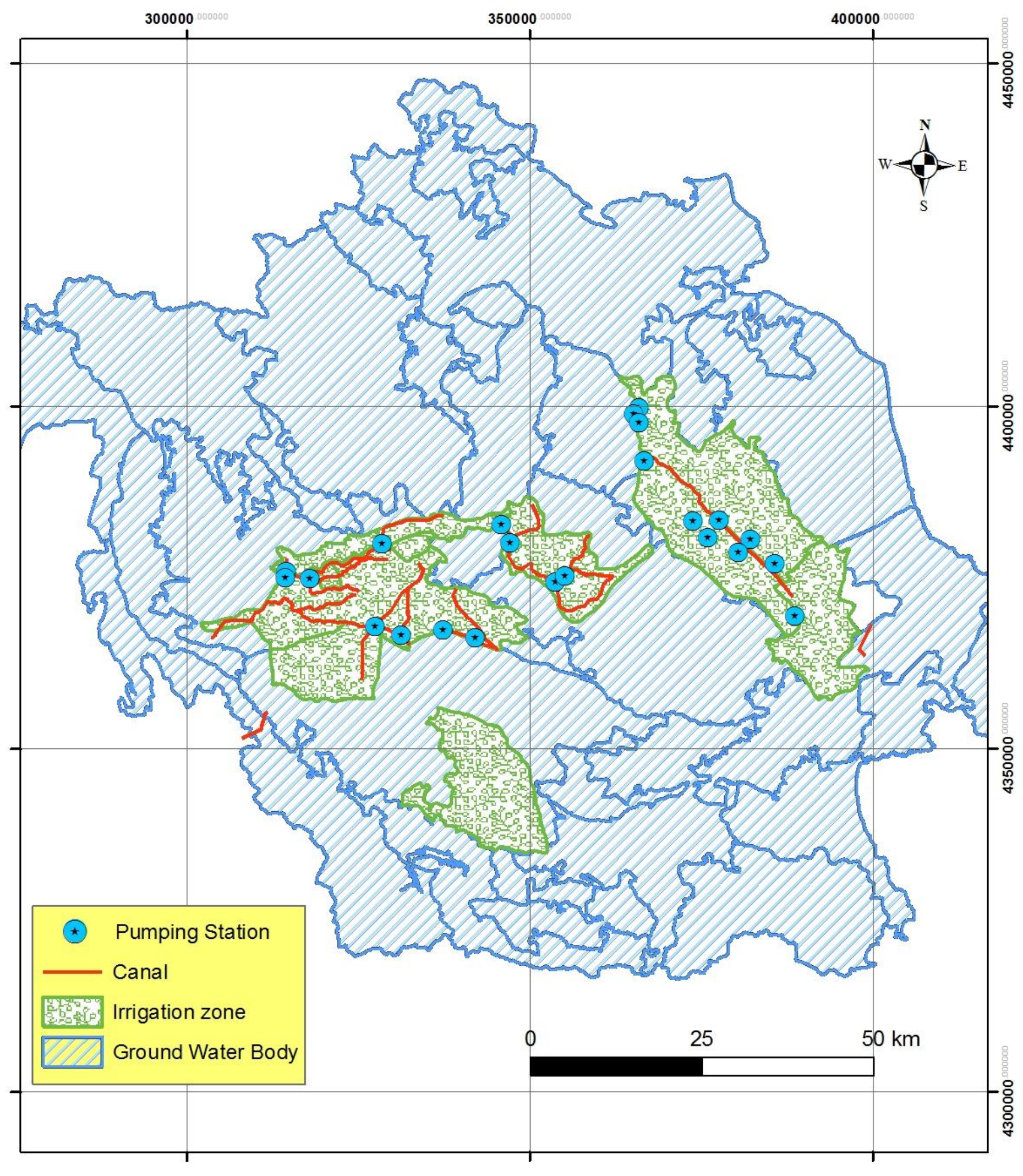


Fig. 3: *Delineation of irrigation zones, each one represented by a conceptual node that accounts the water needs of the zone; nodes are linked with conceptual canals and boreholes, implementing abstractions from surface and groundwater resources, respectively.*

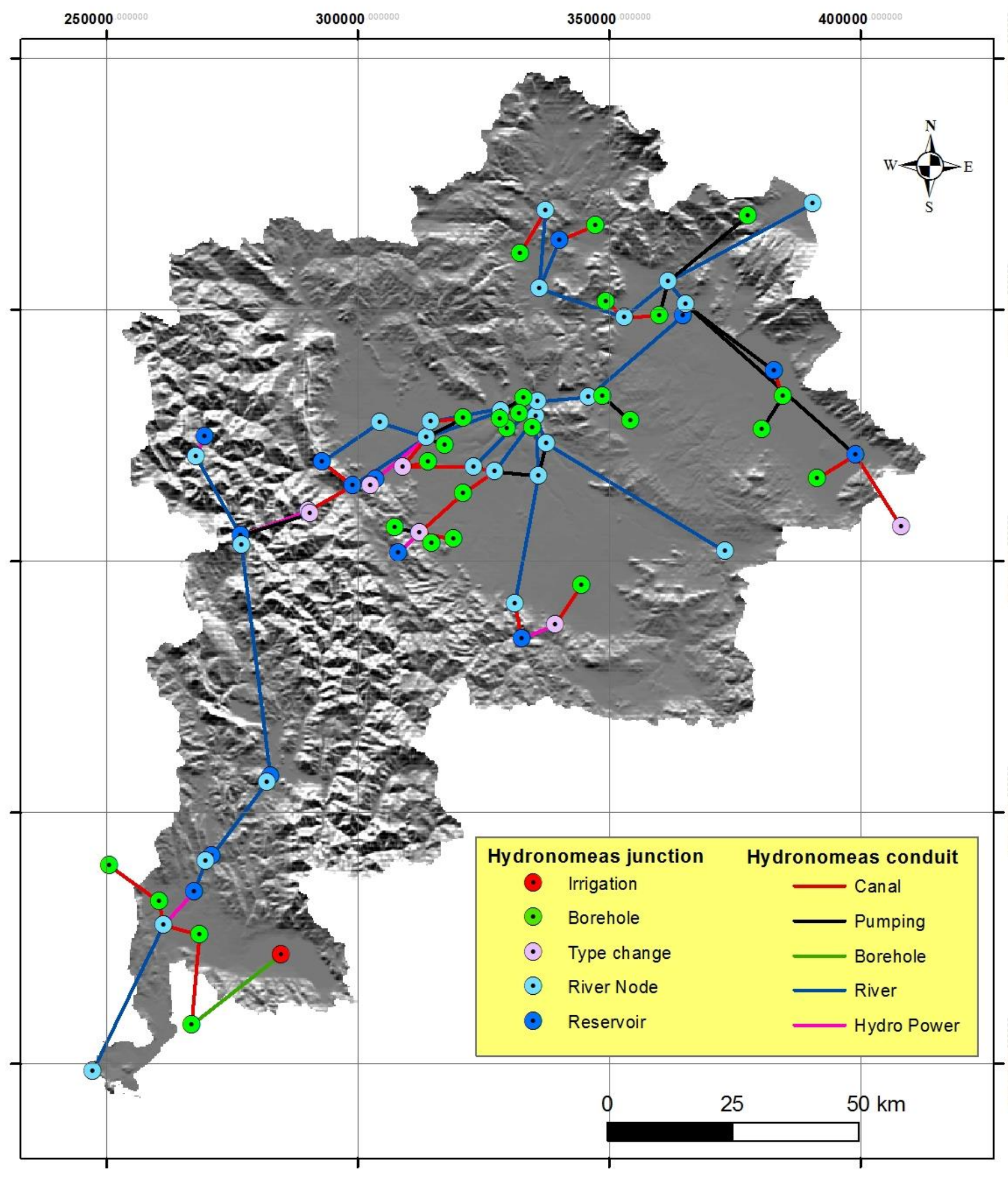


Fig. 4: *Mapping of hydrosystem components by means of junctions and conduits (either real-world or conceptual); the same schematization is considered in the formulation of the water-energy modelling system in the graphical environment of Hydronomeas.*

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6. Graphical representation of water-energy system in Hydronomeas

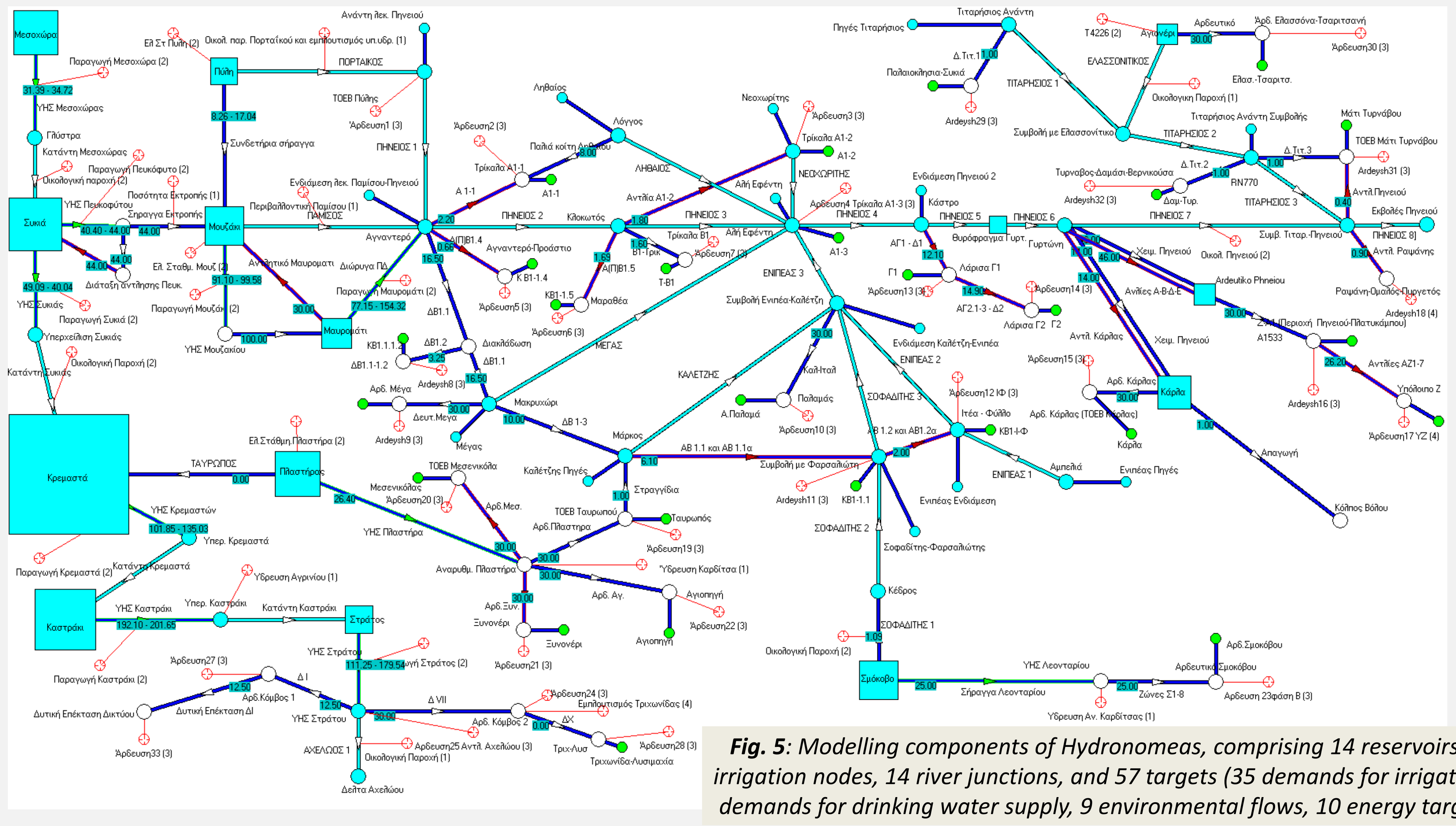

Fig. 5: Modelling components of Hydronomeas, comprising 14 reservoirs, 32 irrigation nodes, 14 river junctions, and 57 targets (35 demands for drinking water supply, 9 environmental flows, 10 energy targets).

7. Generation of synthetic hydrological data

- We retrieved historical time series of monthly inflows at all associated nodes of the model (river junctions, reservoirs, lakes), either based on observed information or by using the semi-distributed hydrological model **Hydrogeios** to reproduce the historical runoff across the sub-basins of interest; the model was calibrated against observed flow and groundwater level data.
- Next we generated 1000 years of monthly synthetic data via multivariate stochastic simulation, using model **Castalia** (26 correlated time series of rainfall and runoff, 10 correlated time series of evaporation).

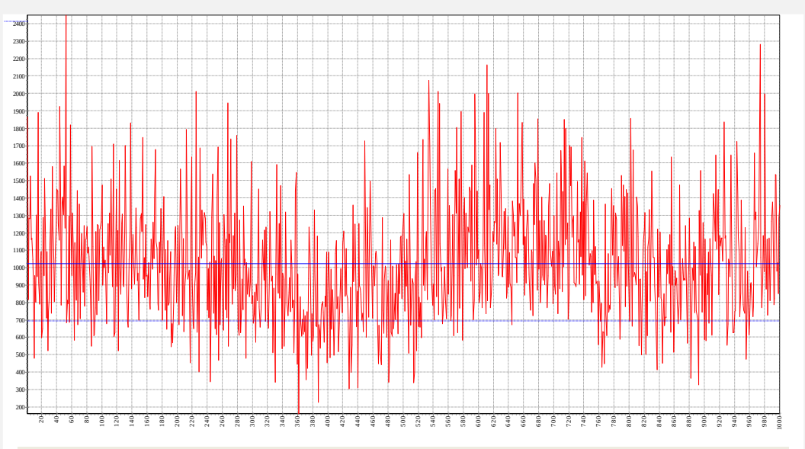

Fig. 7: Synthetic time series of annual runoff generated through Castalia, exhibiting significant persistence (Hurst-Kolmogorov behavior).

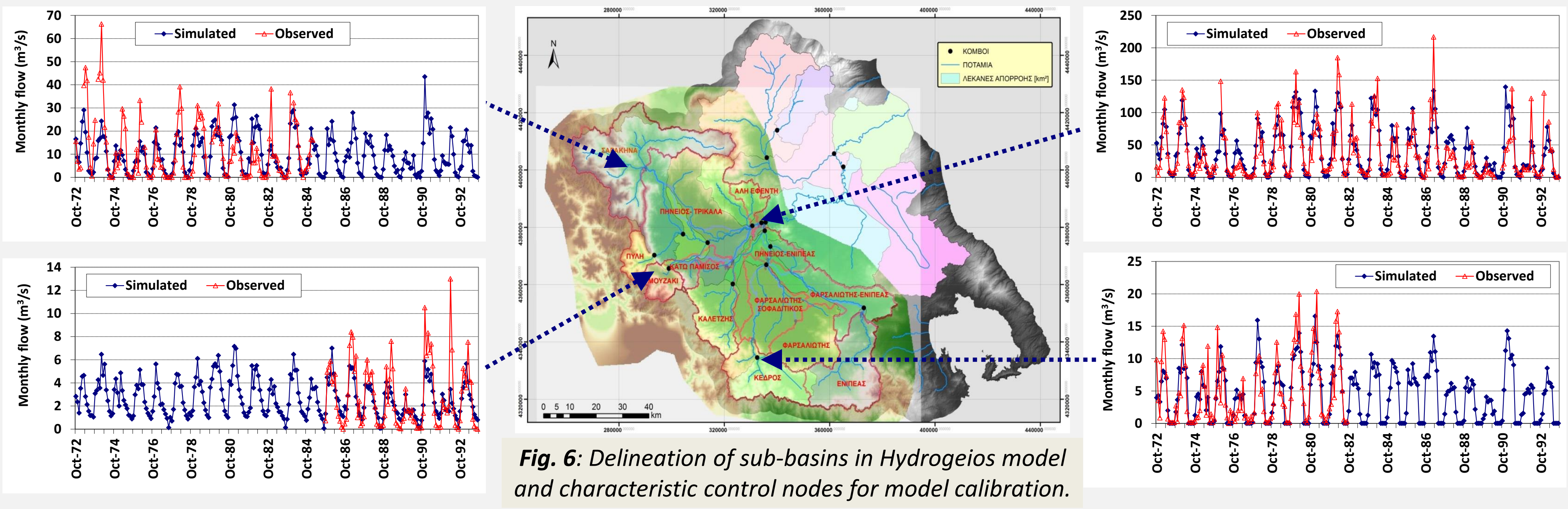

Fig. 6: Delineation of sub-basins in Hydrogeios model and characteristic control nodes for model calibration.

8. Multiobjective analysis: peak energy production vs. irrigation deficit

Statement of optimization problem

- Control variables = energy generation targets assigned to all hydropower stations (10 variables, in total);
- Objective function = weighted sum of peak energy and failure probability of selected irrigation targets.

Key assumptions

- Peak energy is defined as the minimum value of monthly energy generated by all power stations, which is available in 99% of time (11 880 months);
- Failure probability is empirically estimated in terms of frequency of annual deficits (i.e. number of deficits divided by the number of simulated years);
- Since the two criteria are conflicting, a Pareto front is drawn solving the problem several times with different weights;
- Apart from failure probability, mean annual irrigation deficits are also accounted for, resulting to a 3D Pareto front;
- The Pareto front has an irregular shape, formulating an almost right angle, which indicates significant sensitivity of the water management policy against each pair of criteria;
- This particular shape allows the detecting of the best compromise solution (upper left corner of the front).

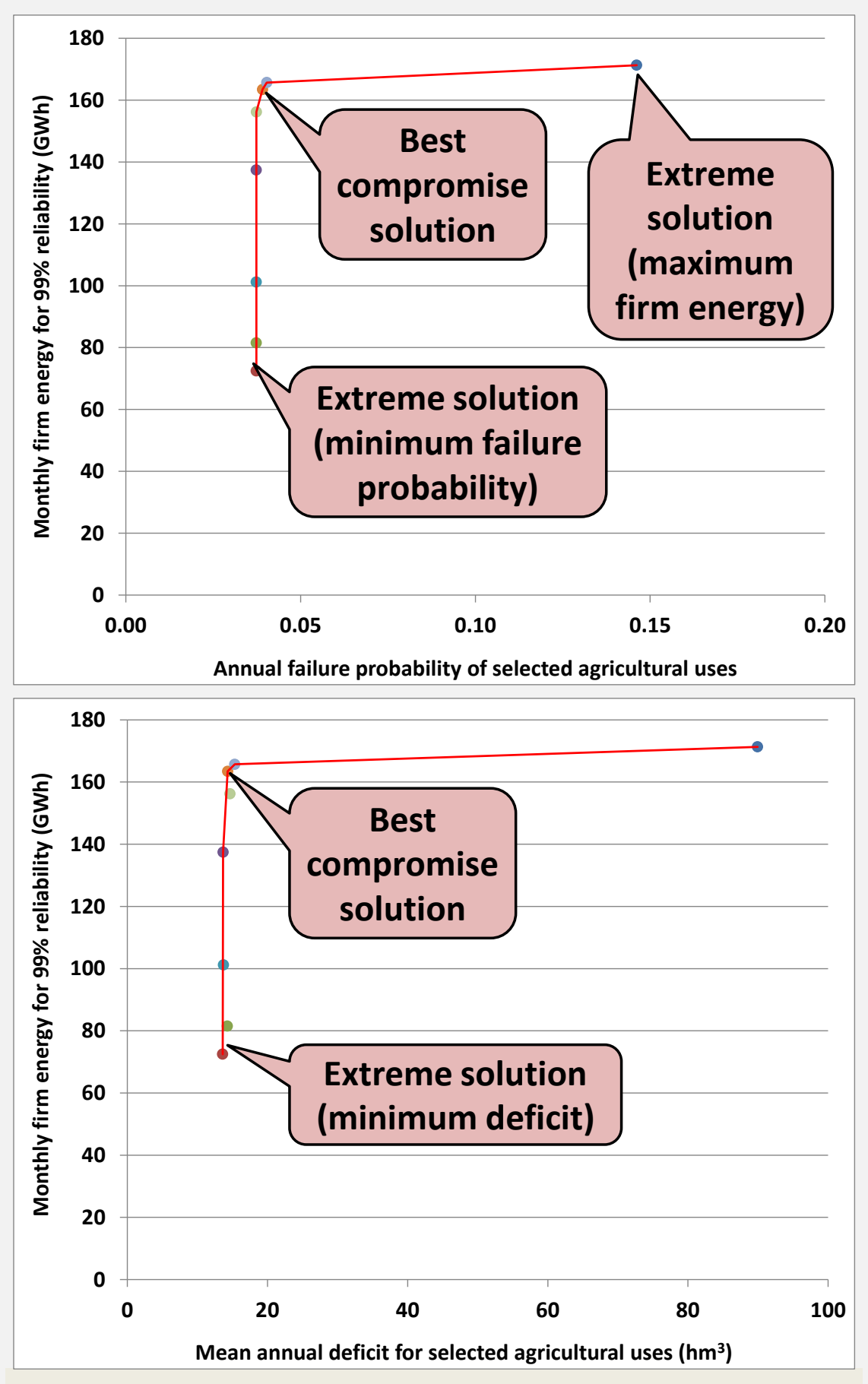

Fig. 8: Monthly peak energy vs. annual failure probability (up); peak energy vs. mean annual irrigation deficit (down).

9. Results for best compromise water-energy policy

Model variables (annual time scale)	Value
Annual demand for irrigation (hm³)	1245.7
Annual demand for water supply (hm³)	36.5
Mean annual abstractions from surface water resources (hm³)	1128.7
Mean annual abstractions from groundwater resources (hm³)	112.1
Mean annual agricultural deficit (hm³)	41.2
Mean annual deficit for water supply (hm³)	0.2
Mean annual runoff at the outlet of Acheloos river (hm³)	3380.1
Mean annual runoff at the outlet of Peneios river (hm³)	1544.1
Mean annual energy production (GWh)	3257.5
Firm energy production (GWh)	1961.3
Mean annual energy consumption from pumps (GWh)	28.6
Mean annual energy consumption from boreholes (GWh)	537.4
Mean annual energy consumption from reverse turbines (GWh)	350.5
Annual failure probability for water supply (%)	7.9
Annual failure probability for irrigation (%)	14.6
Relative annual deficit for environmental uses (%)	0.4

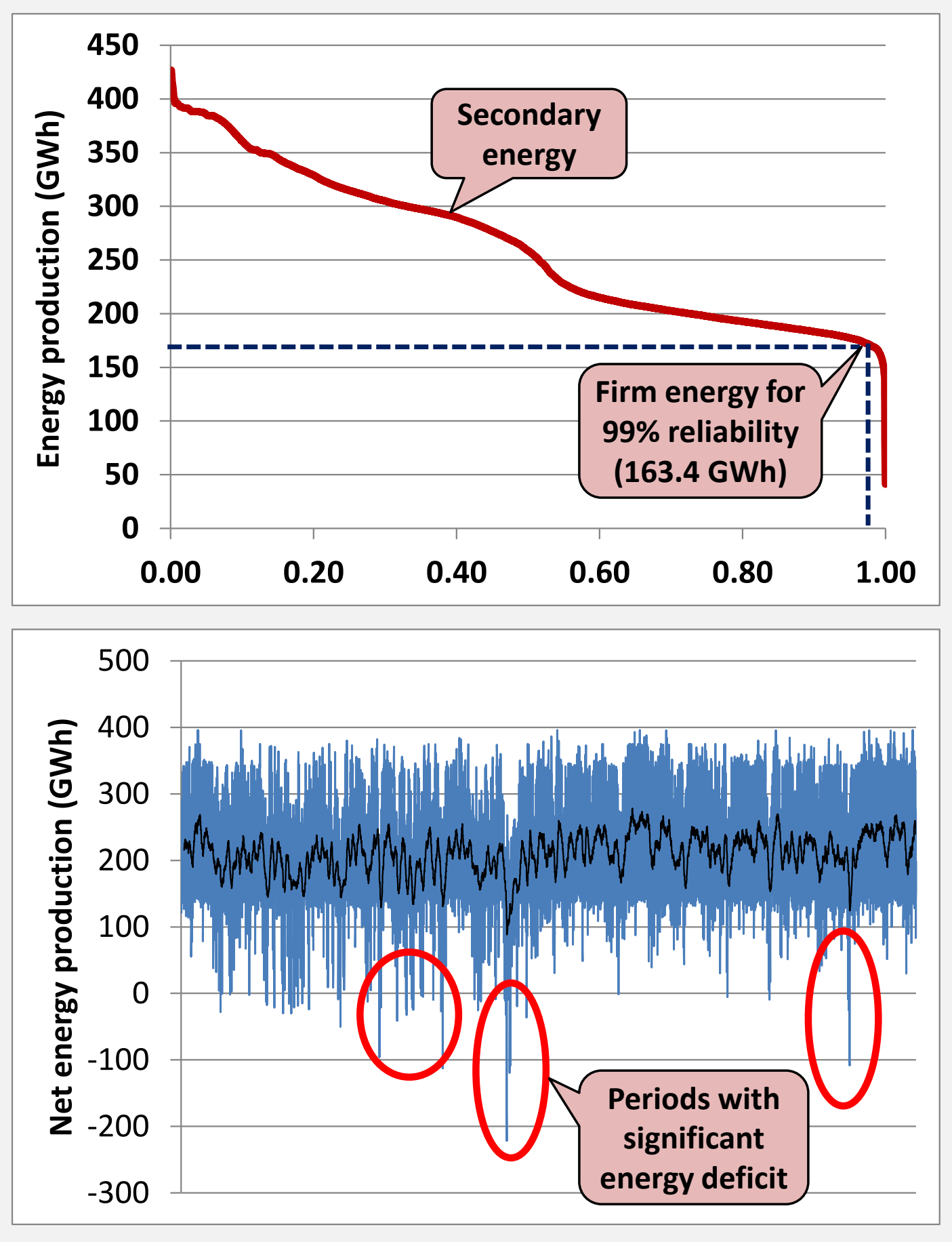

Fig. 9: Empirical cdf of monthly energy production and firm energy level for 99% probability (up); net energy (= production – consumption) and moving average for 12 000 simulated months (down).

10. Analysis of electricity demand in Thessaly

- We considered the Prefecture of Thessaly, significant part of which is covered by the river basin of Peneios.
- We analyzed the electricity demand of years 2002 to 2012, initially exhibiting an increasing trend (until 2008) and then a declining one, due to the major economic crisis in Greece.
- This scaling behavior can also be represented through a Hurst-Kolmogorov process; in this context, we used Castalia to generate 1000 years of energy demand data.

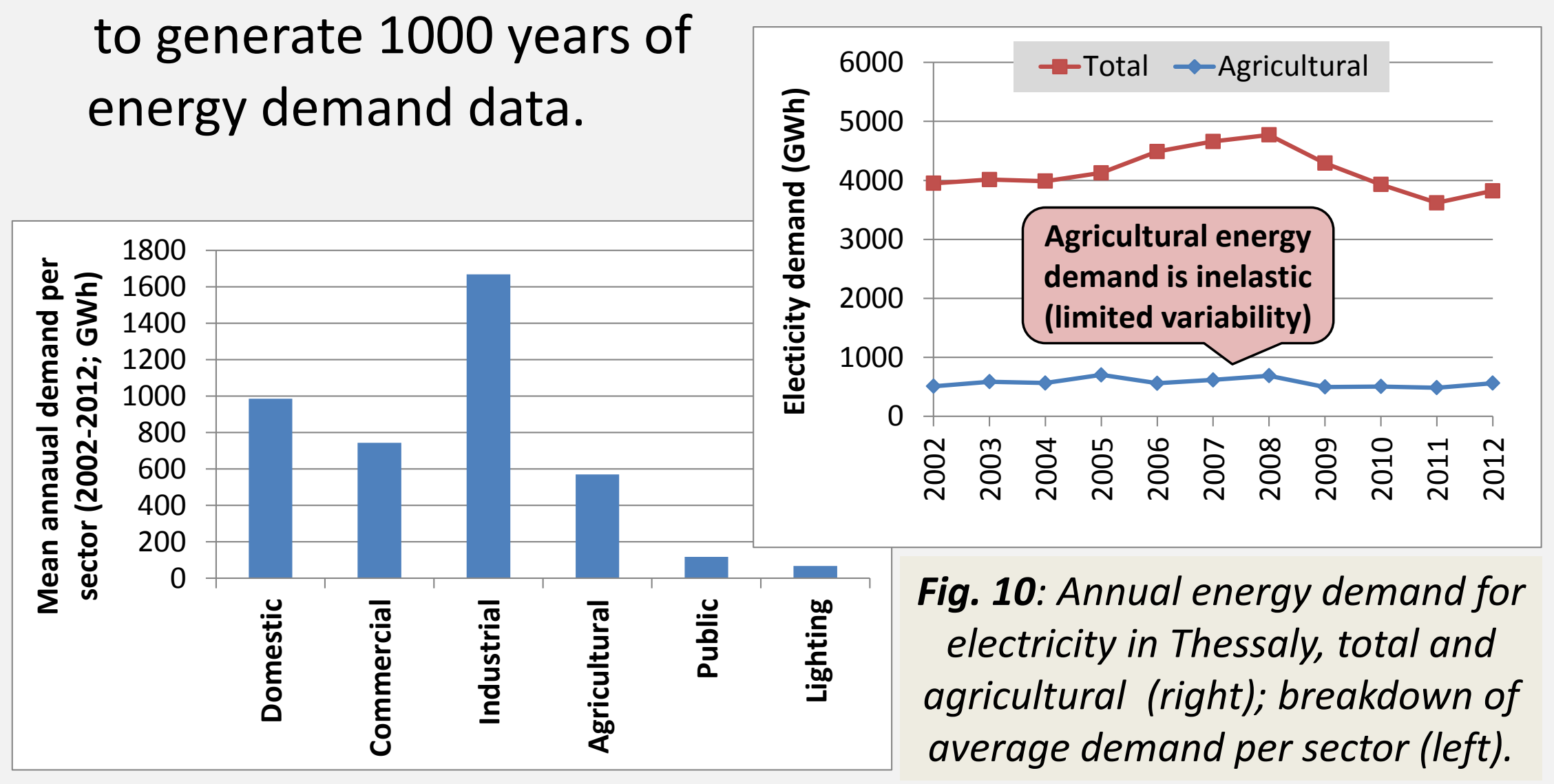

Fig. 10: Annual energy demand for electricity in Thessaly, total and agricultural (right); breakdown of average demand per sector (left).

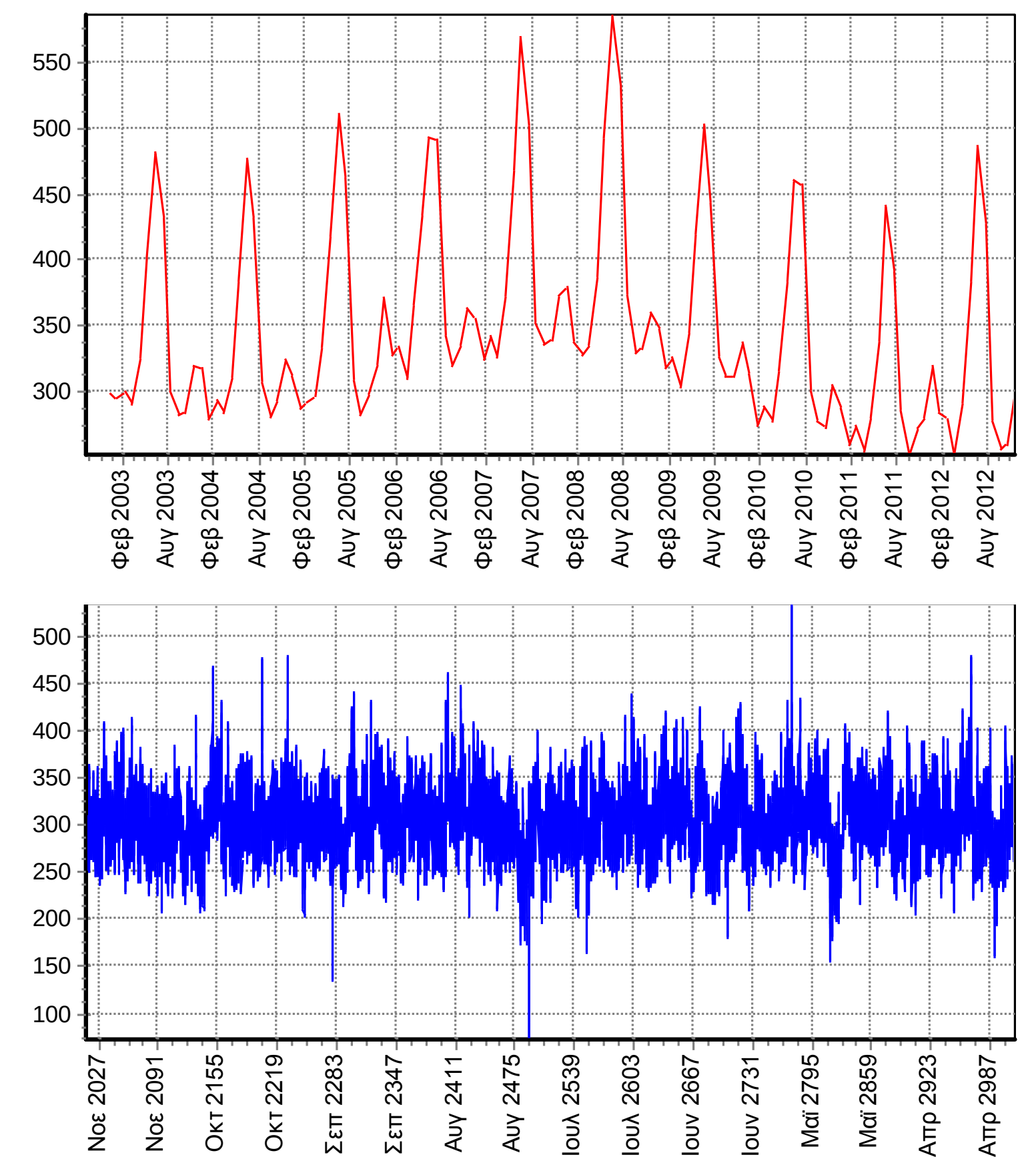

Fig. 11: Time series of monthly energy demand for electricity in Thessaly region (up); simulated demand data generated through Castalia model (down).

11. Investigation of potential renewable energy sources in Thessaly (solar & wind)

Station	U24 (m/s)	max KWh
Agia	1.171	128.0
Volos (NOA)	1.007	81.5
Volos (UTH)	1.247	154.6
Gardiki	0.775	37.2
Zagora	0.849	48.8
Kalampaka	1.059	94.6
Karditsa	1.097	105.3
Koniskos	1.102	106.8
Larissa	0.374	4.2

Station	U24 (m/s)	max KWh
Lafkos	1.343	193.0
Plastiras	2.643	1472.0
Makrinitsa	2.788	1728.8
Moni Paou	2.106	745.4
Pertouli	0.866	51.7
Trikala	0.786	38.7
Portaria	1.651	359.2
Volos (NOA)	1.007	81.5
Volos (UTH)	1.247	154.6

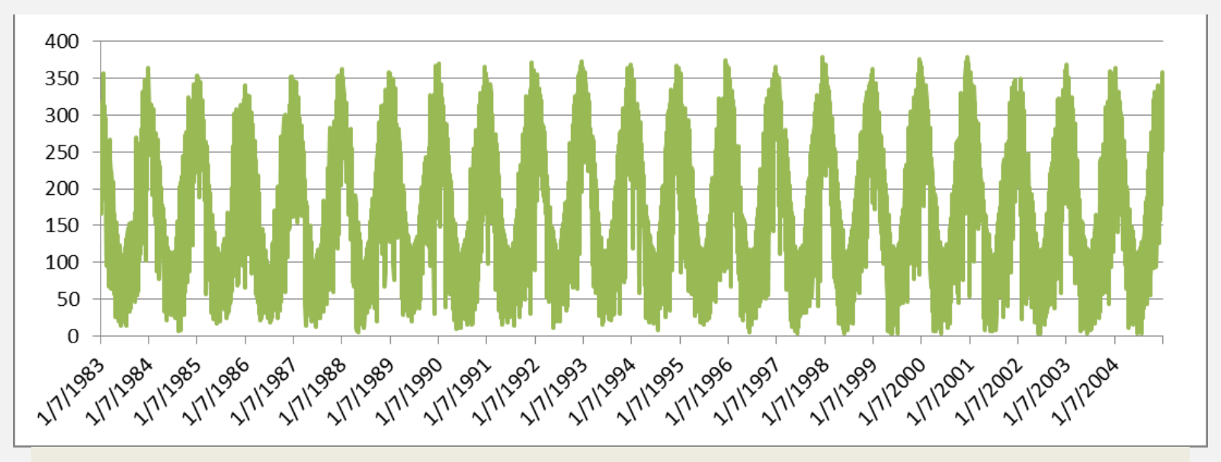

Fig. 12: Daily time series of global solar radiation received by Thessaly from 1/7/1981 to 30/6/2005 (Wh/m²).

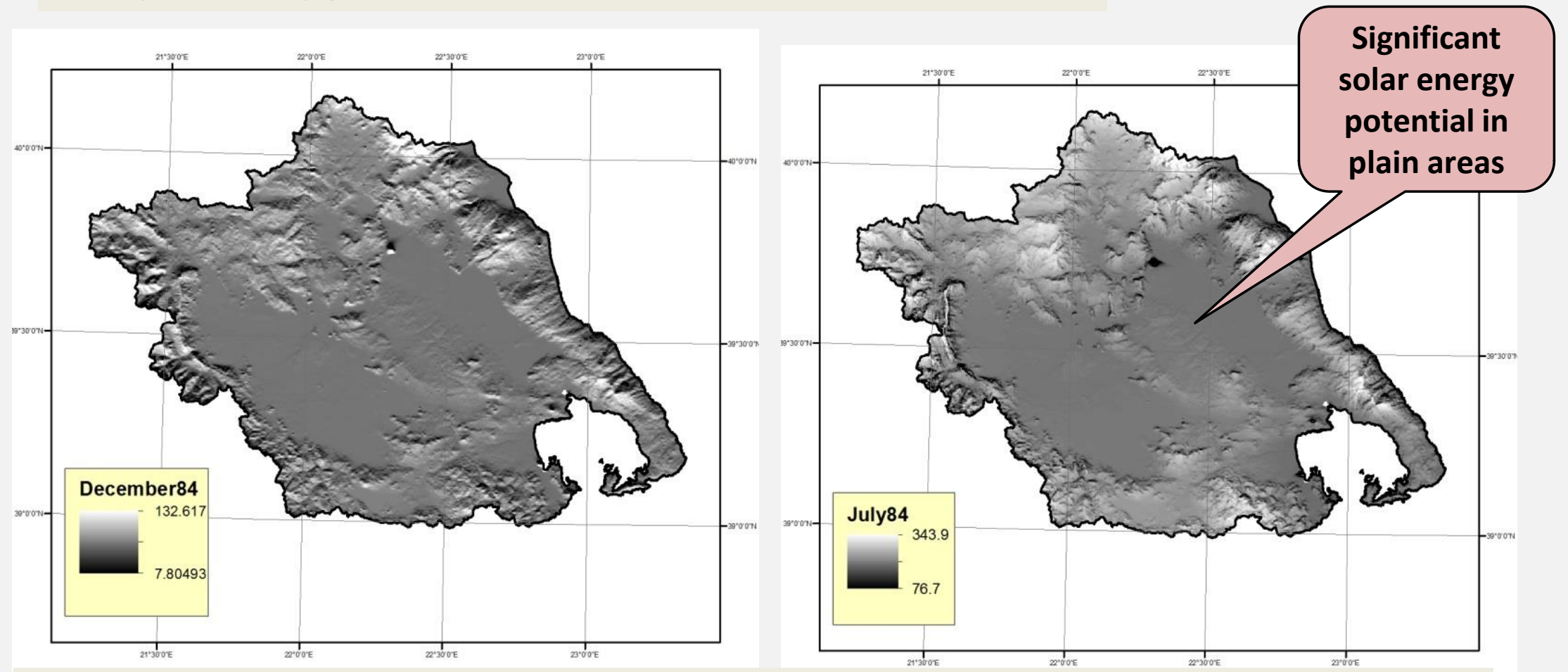

Fig. 13: Spatial distribution of global solar radiation received by Thessaly in December 1984 (left) and July 1984 (right), based on satellite data.

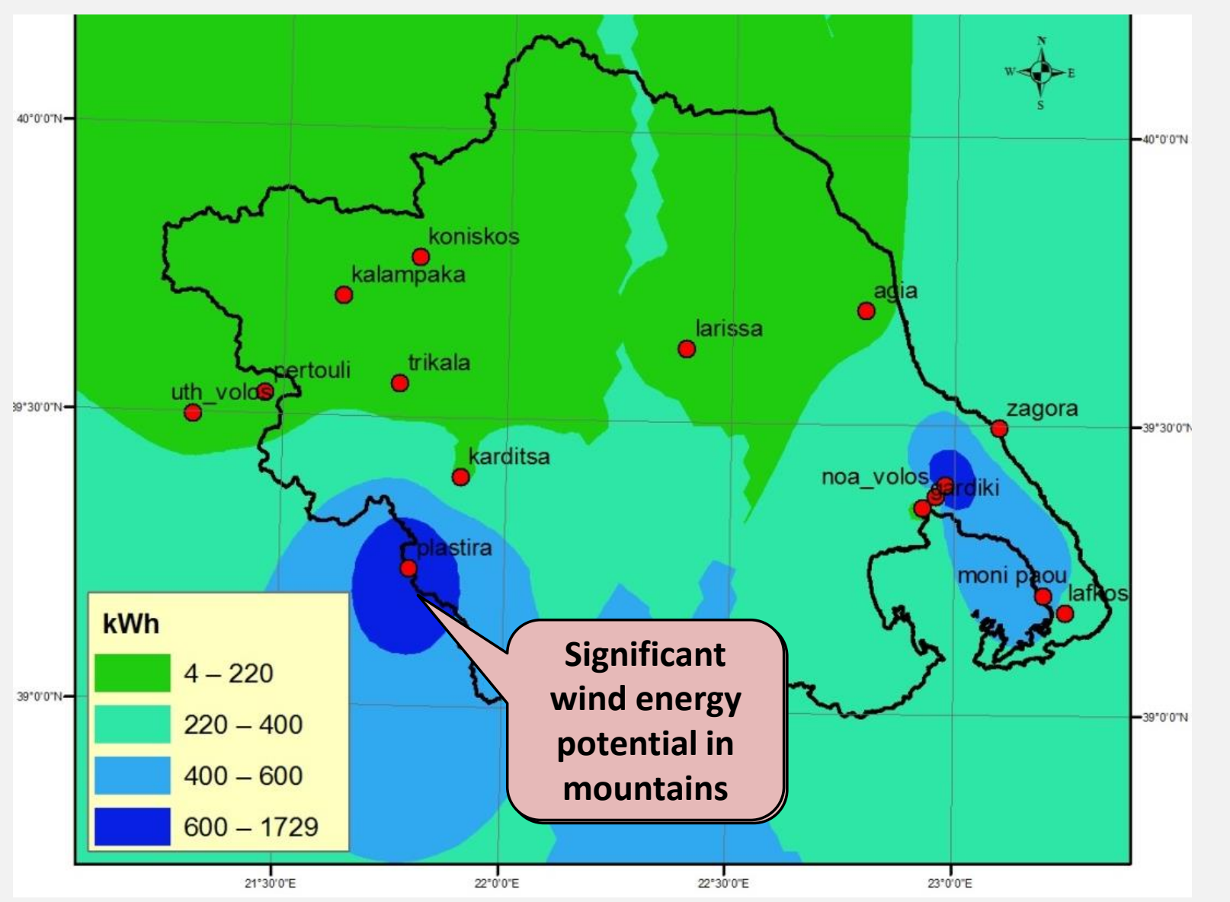

Fig. 14: Wind energy potential estimated through spatial integration of wind station data over Thessaly.

12. Towards integrated modelling of combined water-energy system

- Next research steps involve the estimation of the essential installed capacity of renewable energy sources (allocated to solar and wind parks), based on detailed analysis of the energy balance of the study area.
- For each given configuration of renewables, we will use synthetic time series of hourly solar radiation and wind velocity to estimate the energy ensured by solar and wind parks; we will generate synthetic hourly data of energy demand, for alternative scenarios of socio-economic development.
- For each scenario, we will run Hydronomeas with known energy surplus and/or deficit from renewables, to optimize the management of combined water and energy resources of the study area at the daily scale.

Acknowledgments

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Project web page (including associated publications): http://cressendo.org/

The presentation is available online at http://www.itia.ntua.gr/1524/