

Under the High Patronage of His Majesty King Mohammed VI



XIX WORLD WATER CONGRESS
International Water Resources Association (IWRA)
Marrakech, Morocco | 1-5 December 2025

Kingdom of Morocco



Ministry of
Equipment and Water

AI-Driven Multi-Risk Assessment for Water Quality Under Climate and Land Use Change: Insights for Adaptive River Basin Management

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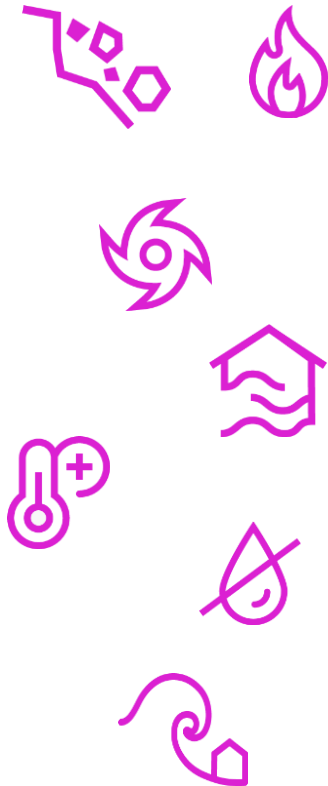
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MULTI-RISKS FOR RIVER WATER QUALITY

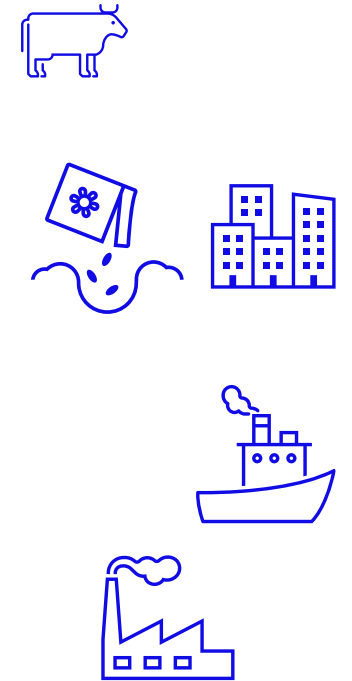


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NATURAL HAZARDS



ANTHROPOGENIC PRESSURES



Some examples...



2022 drought and heatwave in northern Italy:

State of emergency for water crisis driven by compound hot and dry events with wide-reaching environmental and economic impacts

2022 wildfires in Belluno:
Temporally compounding droughts increased the fire risk, amplified by mountain winds, with impacts on transport, biodiversity, air, and water quality



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Severe droughts and heat waves in Europe 2022



Fish Mortality in Oder River

Massive algal bloom in the Gulf of Finland



WATER FRAMEWORK DIRECTIVE AND THE '2027 DEADLINE'

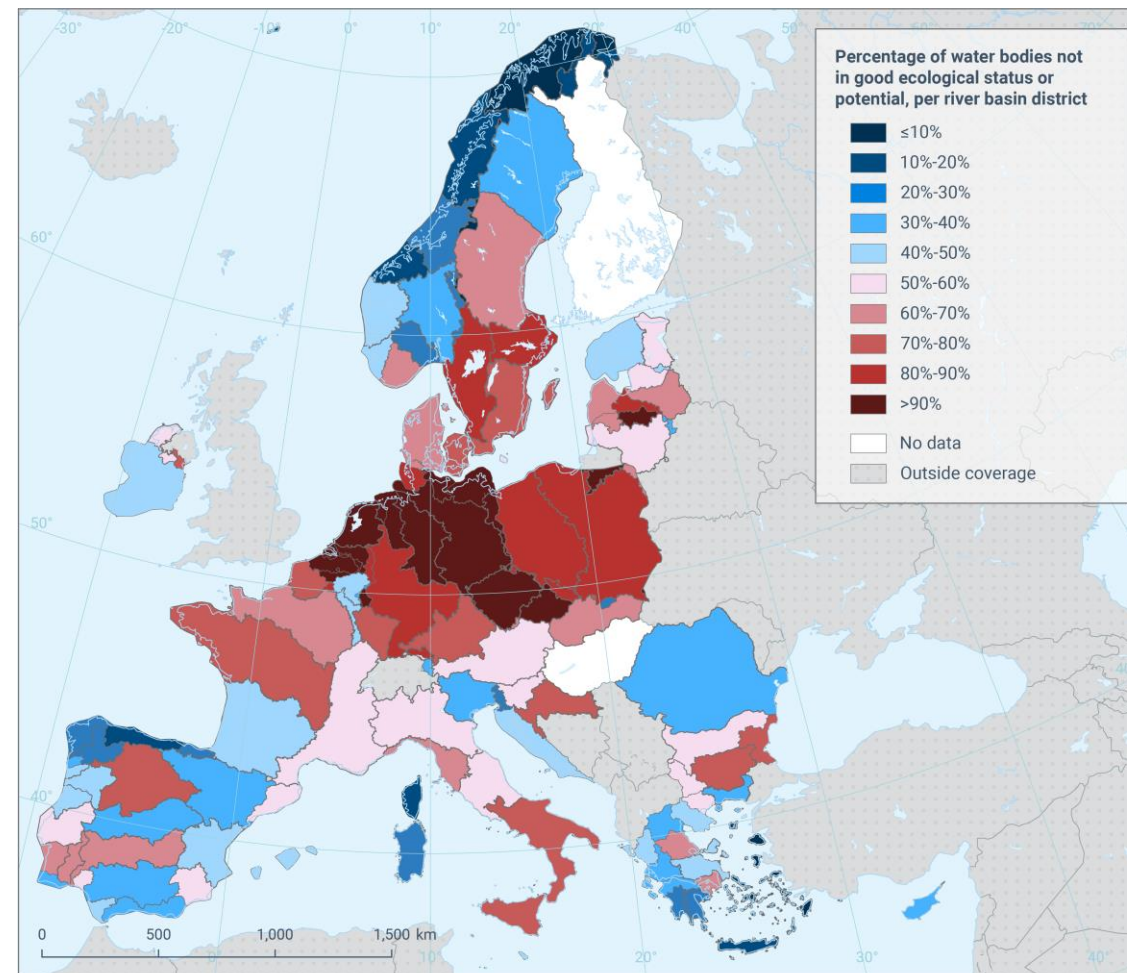
The European Union's Water Framework Directive (WFD) aims to reach good ecological status for all surface waters (rivers, lakes, transitional and coastal waters) across the EU.



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*“The ecological status of European Union surface waters continues to decline, as reported, only **39.6% attained good status in 2021**. Member States must **urgently implement all measures** to achieve a good ecological status to meet the Water Framework Directive’s 2027 deadline.”*

European Environmental Agency (2025)



AI-Driven Multi-Risk Assessment for Water Quality: Case study Veneto region (NE Italy)



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OBJECTIVE:

The research aims to better **understand current impacts and future multi-risks** of single and compound hazards to disturbances in **water quality and riverine ecosystems**, supporting the decision-making process for environmental quality protection and adaptation planning under future changes and uncertainties.

CASE STUDY:

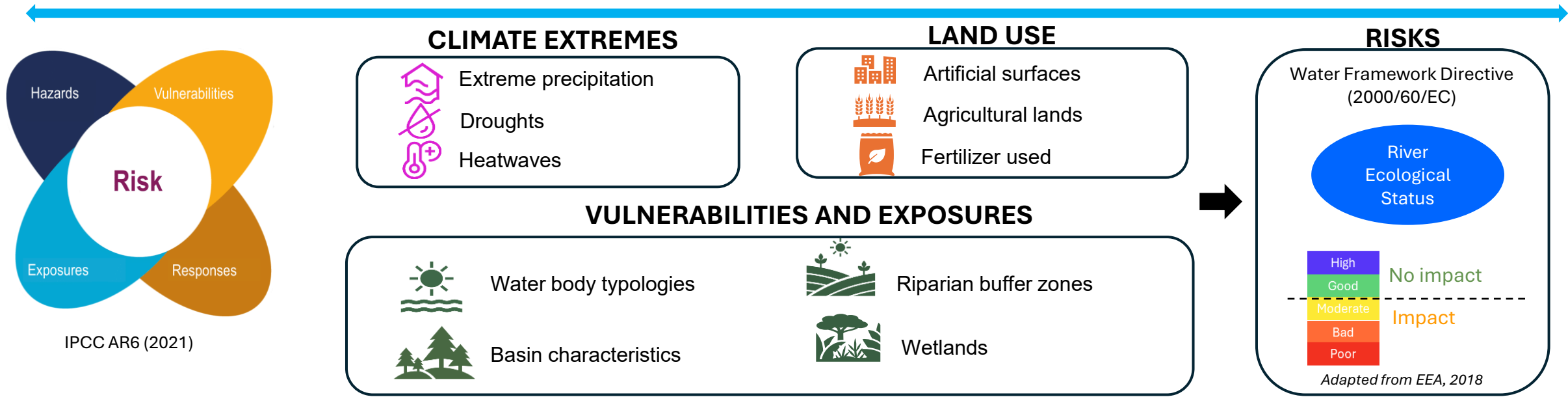
Veneto region (NE Italy) with river water bodies of WFD interests, with diverse landscape from mountains to low plains



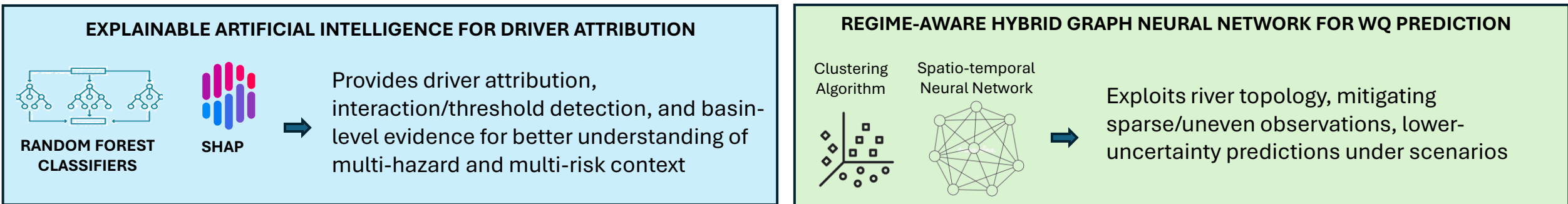


Methodological framework

MULTI-RISK CONCEPTUAL FRAMEWORK



DATA-DRIVEN MODELLING FRAMEWORK





Multi-risk Indicators

CLIMATE EXTREMES



- Extreme precipitation
- Droughts
- Heatwaves

- TXd
- TDd

- PRCPTOT
- R95PTOT
- SPI-12

LAND USE



- Artificial surfaces
- Agricultural lands
- Fertilizer used

- Artificial surface coverage over basin
- Agricultural land coverage over basin
- Nutrient loads from agriculture

VULNERABILITIES AND EXPOSURES



Water body typologies



Riparian buffer zones



Basin characteristics



Wetlands

- Elevation
- Soil skeleton
- Soil permeability
- River typology
- Basin area

- Riparian vegetation coverage
- Riparian vegetation width
- Wetland presence over basin
- Wetland proportion over basin
- Vegetation proportion over basin

RISKS

Water Framework Directive
(2000/60/EC)



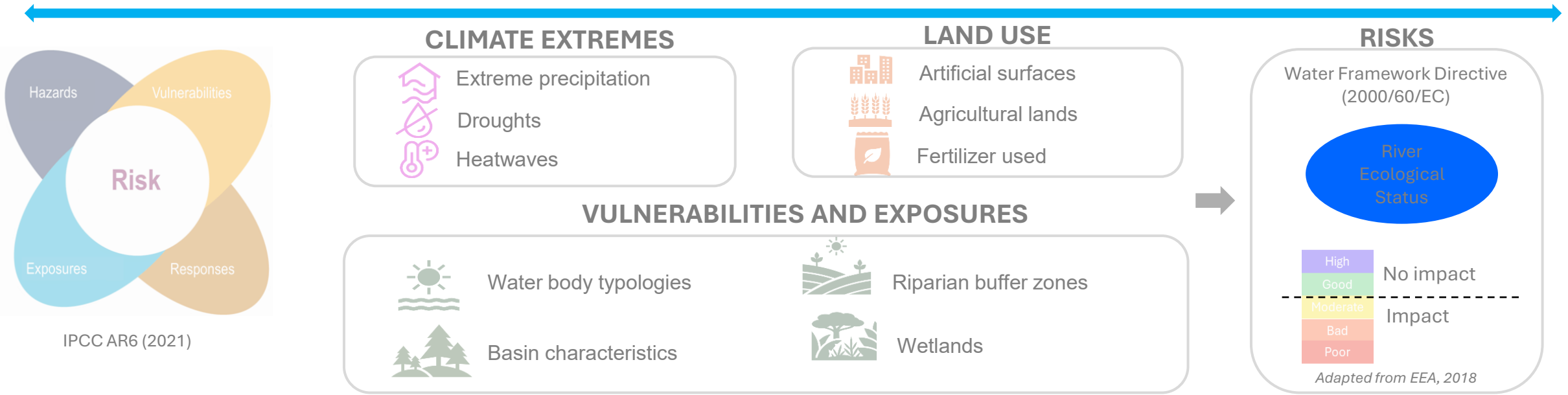
Adapted from EEA, 2018



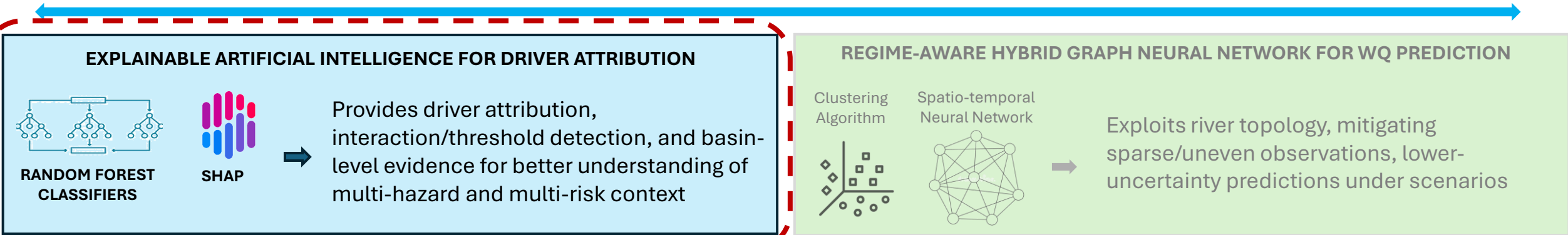


Methodological framework

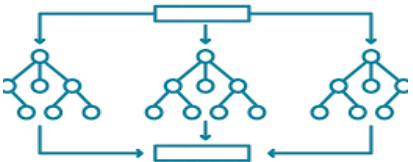
MULTI-RISK CONCEPTUAL FRAMEWORK



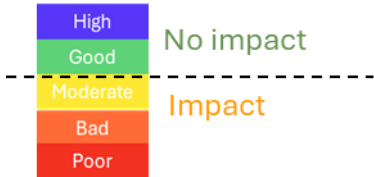
DATA-DRIVEN MODELLING FRAMEWORK



Explainable artificial intelligence for driver attribution



RANDOM FOREST CLASSIFIERS



Adapted from EEA, 2018



SHAP

Annual layers of hazards and vulnerability/exposure are assembled for elemental basins

A Random Forest classifier predicts ecological status and splits outcomes into **No-impact** vs. **Impact** classes

SHAP provides local/global attributions to identify the most **influential drivers** and **interaction regimes**

SHAP dependence reveals thresholds and synergies among drivers.

- Capturing **non-linear interactions** between extreme climate events, vulnerabilities, and exposures.
- Yielding **insight into which factors most shift predicted impacts**, clarifies **regime boundaries** for intervention design and targeted adaptation planning.



Explainable artificial intelligence for driver attribution



Synergistic effects of heat stress and drought conditions with a threshold effect when temperature > ~22°C

Anthropogenic land use amplified the negative effects, especially when exceeding certain thresholds.



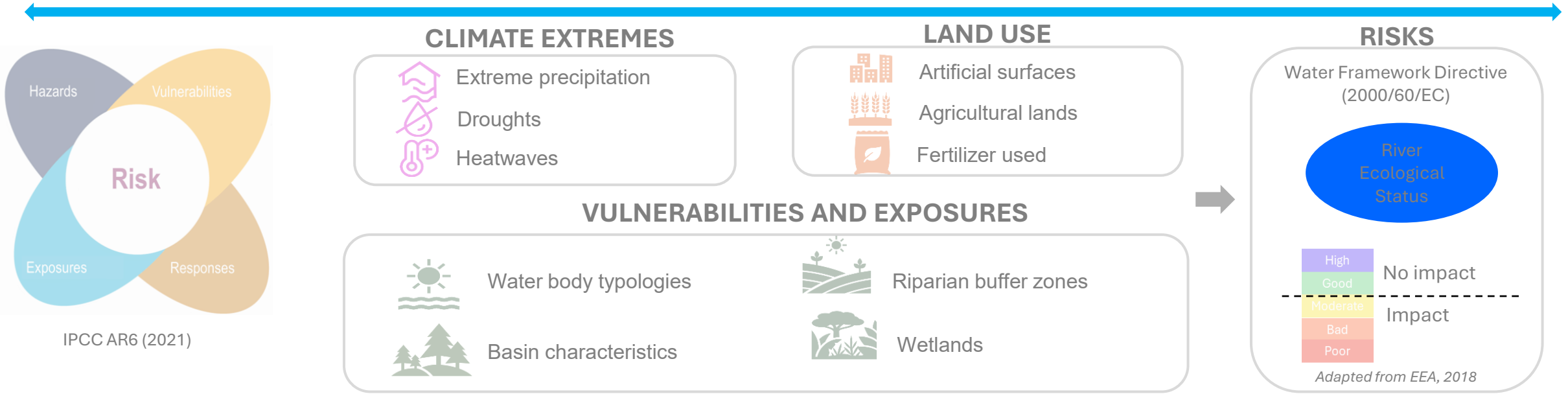
Each point is an observation with its feature value on the x-axis and SHAP contribution to predicted impact on the y-axis; color encodes an interacting driver. Curves and dashed guides are added post-hoc to aid threshold and interaction identification.



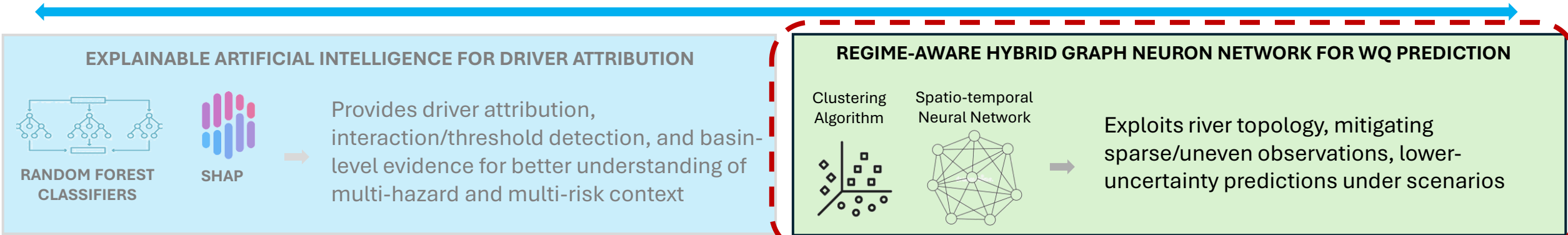


Methodological framework

MULTI-RISK CONCEPTUAL FRAMEWORK



DATA-DRIVEN MODELLING FRAMEWORK

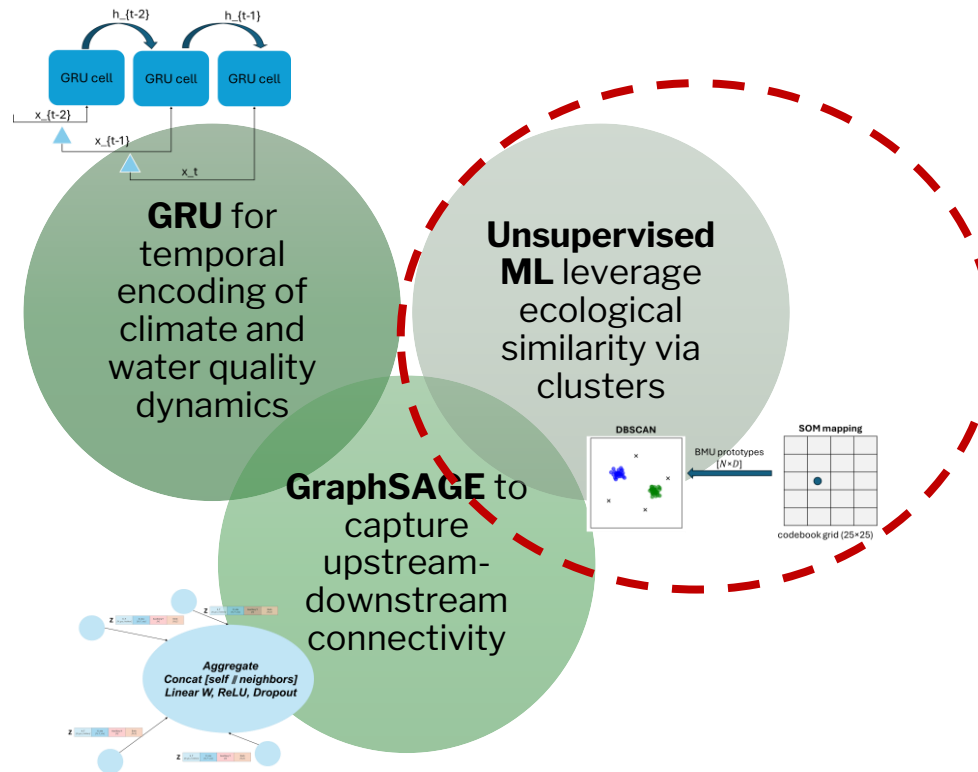


Regime-aware hybrid graph neural network for WQ prediction



From sparse observations to graph learning: A heterogeneous river system with missing observation is recast as **a directed, clustered graph.**

This topology lets the model propagate signals along hydrological connections and learn status patterns despite missing data.





Regime-aware hybrid graph neural network for WQ prediction

Self-Organizing Maps and DBSCAN yield 10 clusters plus a noise group

When summarized by **climate and land-based gradients**, these regimes coalesce into three interpretable macro profiles:

- **cool/wet, natural basins**
 - occupy higher elevations with extensive vegetation and limited artificial cover
- **hot/dry, strongly modified basins**
 - aligns with lowland agriculture/urban areas with stronger pressure signals
- **mixed-climate, wetland-rich basins**
 - concentrates where wetland extent is prominent.


→ Embedded in Hybrid-GNN, letting the model to learn not only from upstream neighbours but also from ecological group (cluster)



Hybrid-GNN performance on test set (15%) and comparisons with benchmark models (GNN, XGBoost, MLP)

Hybrid-GNN outperforms benchmark models:

- RMSE=0.028, MAE=0.02, $R^2=0.98$
- Across calibration and residual plots, Hybrid-GNN variants lie closest to the 1:1 line with the narrowest 95% bands, indicating the best calibration and precision.
- Residuals stay centered near zero over most of the range, unlike GNN, XGBoost, and MLP, which show range compression (overpredict low, underpredict high) and larger uncertainty.

- 
- ✓ Address missing observation by leverage regime knowledge to extrapolate insights from monitored to unmonitored segments with similar characteristics
 - ✓ Predict changes in WQ under climate and land use change scenario
 - ✓ Suitable for “what-if” scenario analyse to explore interventions by altering input features



Take-home messages



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1. EXPLAINABLE ARTIFICIAL INTELLIGENCE FOR DRIVER ATTRIBUTION

- Using ML and explainable AI as a robust framework for multi-(hazard-)risk assessment, revealing the complex interplay between land use and climate extremes and their compound impacts on water quality.
- Implying the needs to address the amplifying role of human activity and prioritize natural landscape conservation to safeguard water quality under increasing climate extremes.

2. REGIME-AWARE HYBRID GRAPH NEURAL NETWORK FOR WQ PREDICTION

- Spatio-temporal GNN with embedded regime learning from unsupervised ML effectively learns group-specific response patterns instead of over-generalizing across the network, helps the GNN resolve behaviors that network topology alone cannot explain
- Address real-world challenges in water monitoring: data gaps/spatially sparse sensors and hydrologic connectivity across heterogeneous basins
- Contributes a generalizable modeling framework: supports cross-basin management decisions, land and climate scenario assessments, and targeted interventions in riverine systems



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Thank you!

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