Event-scale nutrient transport revealed by integrated runoff monitoring and time-lapse imagery

Giulia Mancini[1], Chiara Iavarone[1], Raffaele Pelorosso[1], Albert Nkwasa[2], Alessio Patriarca[1], Fabio Recanatesi[1], and Maria Nicolina Ripa[1]

[1]University of Tuscia, Department of Agriculture and Forest Sciences (DAFNE), Via San Camillo de Lellis, Viterbo (01100), Italy

[2]Water Security Research Group, Biodiversity and Natural Resources Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria

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1. Background and Objective

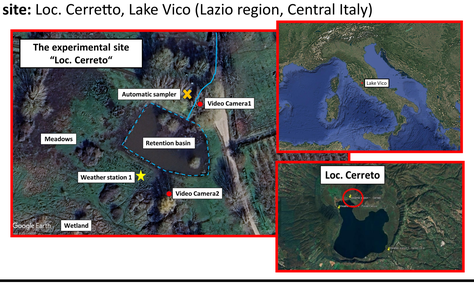
Surface runoff plays a key role in hillslope sediment and nutrient transport and represents a major pathway controlling lake water quality within the **EUROLakes monitoring framework**. However, continuous detection of runoff activation at high temporal resolution remains difficult in poorly instrumented sites.

Time-lapse imagery enables low-cost hydrological monitoring in intermittent environments (Tauro et al., 2022; Noto et al., 2022), but automated runoff detection is still limited by radiometric variability and seasonal transferability issues.

This study aims to:

- develop a workflow for automatic runoff detection using ROI-based features
- evaluate seasonal classifier transferability through cross-month validation
- identify rainfall thresholds controlling runoff activation at hourly, daily, and event scales

Study site: Loc. Cerretto, Lake Vico (Lazio region, Central Italy)



2. Dataset and Monitoring Setup

Runoff events were monitored using a **Reolink Go Ranger PT** time-lapse camera (4K resolution) acquiring **RGB daytime and NIR nighttime** images every **30 minutes**. The monitoring setup also includes an automatic sampler for event-scale water quality characterization.

Two partially independent datasets were used:

1) Classification dataset (model development)

Selected months representing different seasonal conditions:

- October 2025 → training
- November and December 2025 → independent validation
- February 2026 → domain-shift assessment and seasonal retraining

2) Rainfall–runoff dataset (hydrological analysis)

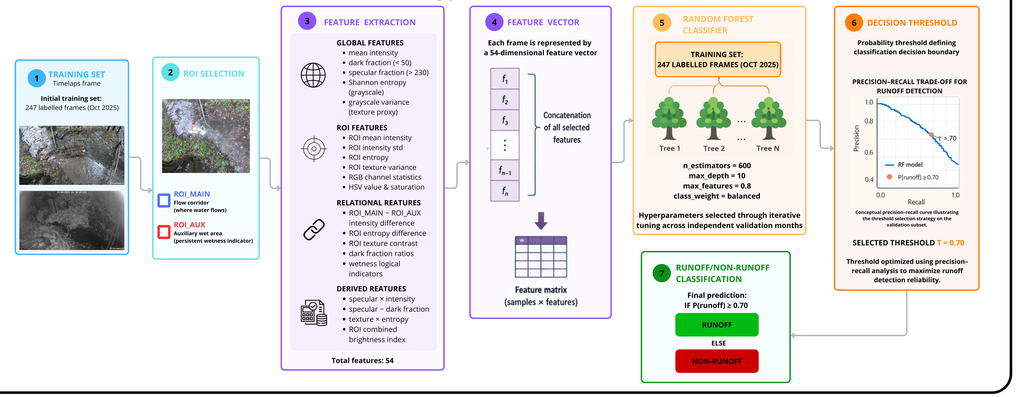
Manual frame-by-frame annotation:

- 5,530 images total
- 401 runoff frames
- 5,129 non-runoff frames

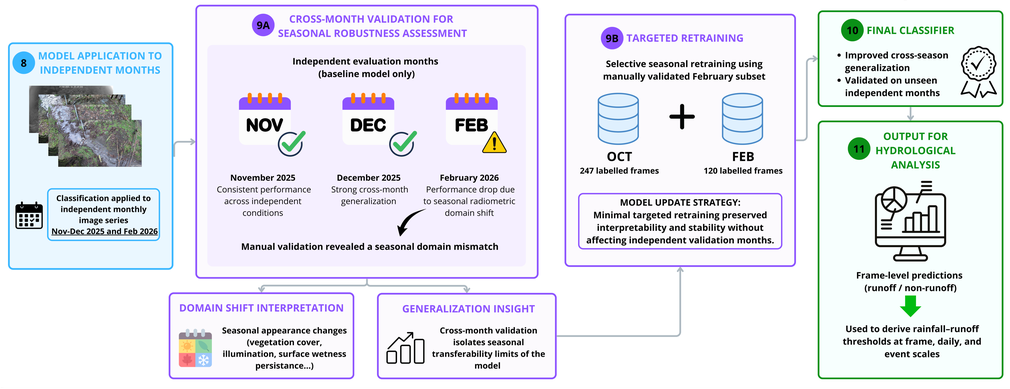
Rainfall data were synchronised with image timestamps to compute antecedent precipitation accumulated over multiple temporal windows (1–72 h) for threshold analysis.

3. Classification Strategy

- A Random Forest classifier was initially trained on **54 radiometric and texture features** extracted from two hydrologically meaningful ROIs using **247 labelled frames from October 2025**.
- The feature set combined **literature-based radiometric descriptors** with **relational features** capturing contrasts between the flow corridor and persistent wet areas.
- **Cross-month validation** assessed temporal transferability across independent months.
- The final classification threshold **(P ≥ 0.70)** was selected by **maximizing the F1-score of the runoff class** on an independent validation subset.



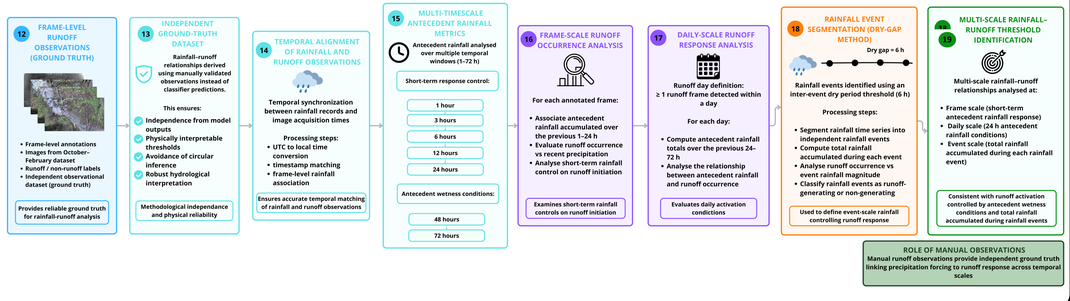
4. Cross-Month Validation and Seasonal Model Adaptation



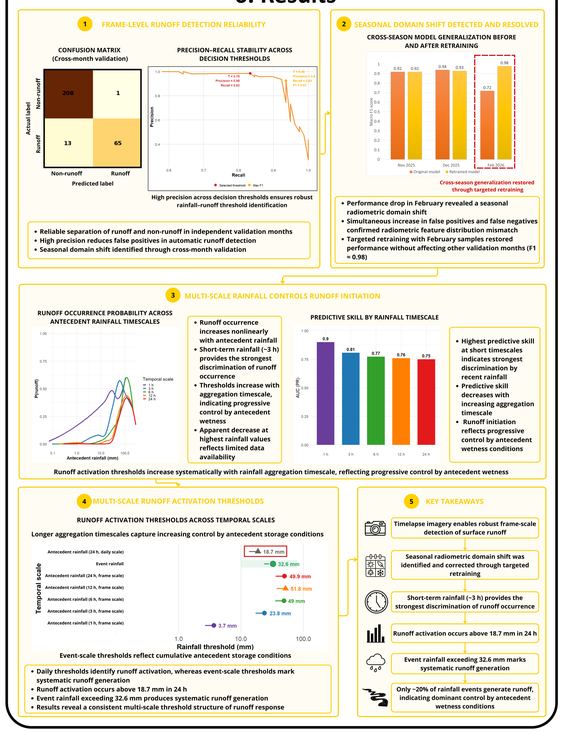
- **Cross-month validation** revealed a seasonal radiometric domain shift affecting winter performance;
- A targeted **retraining strategy** using a manually validated **February subset (120 labelled frames)** corrected this seasonal mismatch;
- The **updated classifier** achieved stable cross-month generalization and supports rainfall–runoff analysis across multiple temporal scales.

5. Identification of multi-scale rainfall thresholds for runoff activation

- **Manual runoff** observations provided independent ground truth for **rainfall–runoff analysis** across temporal scales;
- **Antecedent rainfall** was evaluated over multiple windows **(1–72 h)** at frame- and daily-scale resolutions, while event-scale analysis considered total rainfall accumulated during each rainfall event;
- **Event-scale segmentation** enabled robust identification of hierarchical runoff activation thresholds.



6. Results



7. Conclusion

- Runoff activation reflects the interaction between recent rainfall and antecedent wetness conditions, **consistent with previously reported rainfall-intensity and soil-moisture controls in the Lake Vico catchment.**
- **Multi-scale rainfall** thresholds reveal a hierarchical hydrological response across hourly, daily, and event timescales, **providing quantitative support through automated image-based monitoring.**
- Identified thresholds distinguish **daily runoff activation conditions** from **systematic runoff generation at the event scale**.
- **Seasonal radiometric variability** affects **classifier transferability** and requires **seasonally representative training datasets**.

8. Future work

- Runoff detection currently relies on visual observations; future work will explore the potential of image sequences to derive **quantitative runoff metrics** (e.g. **runoff duration** and **peak-flow proxies**) for improved characterization of **hillslope hydrological response**.
- Integrated analysis of **climatic conditions** and **soil properties** will further constrain **rainfall–runoff threshold controls** at the monitored site.
- The approach and monitoring activities will be extended to **additional Lake Vico sub-catchments within the EUROLakes framework** to assess and verify **threshold transferability** and derive representative **basin-scale runoff-generation thresholds**, while hydrochemical observations collected during runoff events will help interpret **runoff sources** and support **hydrological model calibration**.