Monte Carlo–Based Uncertainty Propagation for Probabilistic Water Masking from Satellite Remote Sensing Reflectance Product

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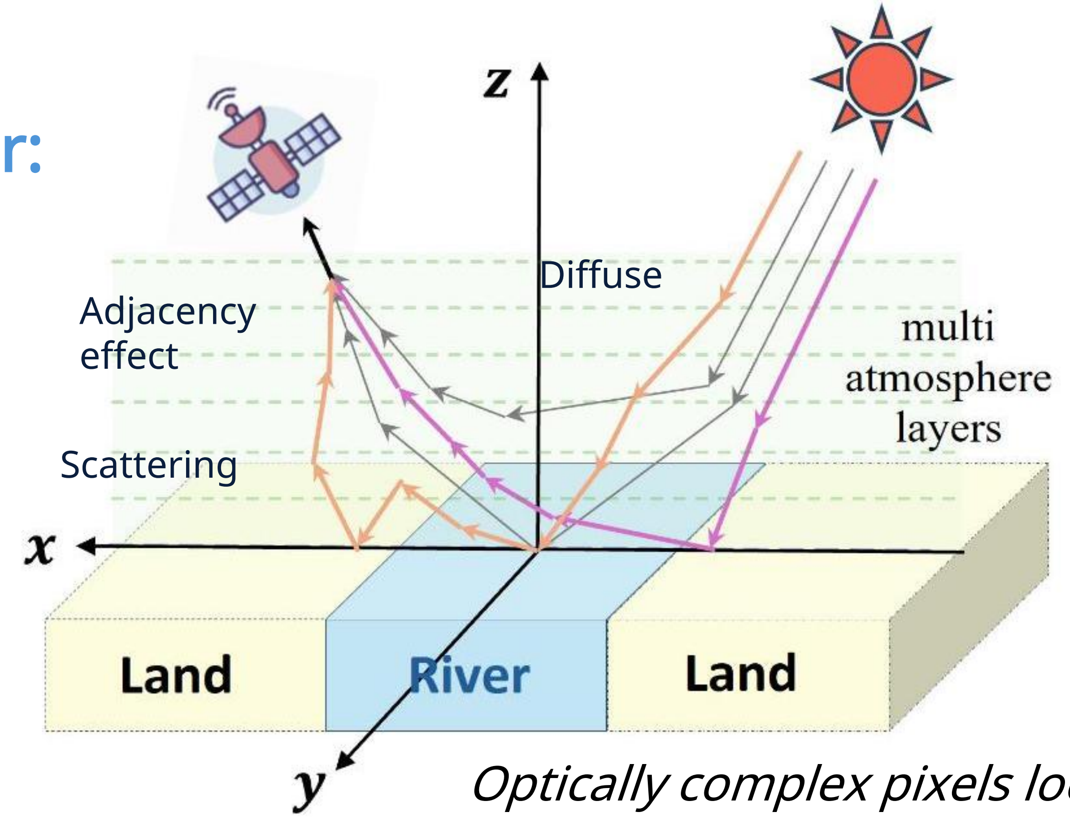
Monte Carlo–Based Uncertainty Propagation for Probabilistic Water Masking from Satellite Remote Sensing Reflectance Product

(Amin et al, 2026)

Problem

Conventional masks fail to account for:

- **Optically complex waters**
  Turbid, mixed, variable Rrs
- **Mixed land-water pixels**
  Riverbanks, bridges, buildings, Ships
- **Shadow contamination**
  Dark surfaces classified as water signal
- **No confidence measure**
  Binary masks hide uncertainty



Optically complex pixels look ambiguous to any single spectral index

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Idea

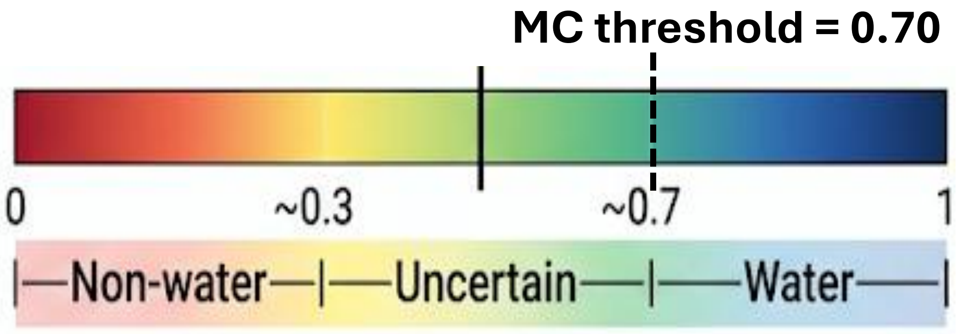
To substitute binary classification with probabilistic water mask

- Instead of deterministic decision of **water / non-water** from single index
- Estimate Probability ***P(water)*** per pixel

  A value between 0 and 1. Prob = 0.87 means "water in 87 of 100 simulations"
- Capture uncertainty explicitly

  High P → confident water; Low P → confident non-water; P ≈ 0.5 → genuinely ambiguous pixel

In urban river like the Seine, boundary is not as simple as it looks.



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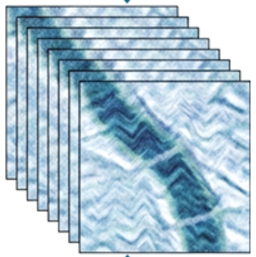
Method

NDWI, MNDWI, AWEI, and MBWI were computed independently per iteration. At least 2 of 4 must vote 'water' to reduces false positives from any single index.

Sentinel-2 **Input: Rrs (B,G,R,NIR,SWIR1,SWIR2)**



RadCor
A generalized physics-based correction for adjacency effects

ACOLITE v20250402.0

S2B_MSI_20241024110725T31UDQ

Per-band uncertainty σ(b)

σ=1.5%

N=100

Gaussian noise

N Perturbed Rrs
(Random noise added based on uncertainty)

NDWI
MNDWI
AWEI
MBWI

Voting-Based Fusion & Spectral constrains
(NIR/SWIR, Low-Signal Filter)

NIR < 0.030
SWIR1 < 0.018
SWIR2 < 0.014

Decision Logic

(Feyisa et al. 2014; Wang et al. 2018)

Probability Map
P(water) per-pixel

P=hits/*N*

Per-pixel probability = fraction of iterations classifying as water

Final mask
(prob ≥ 0.7)

Accuracy
Shp: openwater/ Bridges

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Study Area

- Seine River, Paris
- Urban, narrow, turbid, optically complex
- Sentinel-2 ACOLITE L2W Rrs (atmospherically corrected)
- The Seine hosts Olympic-standard open-water swimming since 2024, requiring reliable real-time water quality monitoring at spatial scale.
- Water masking is the critical first step in the WQ retrieval chain.

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Spatial Probability Patterns

Main river channel:
High-confidence water dominates (mean P ≥ 0.9; >97% pixels high confidence)

Riverbanks & bridges:
Intermediate probabilities concentrated here

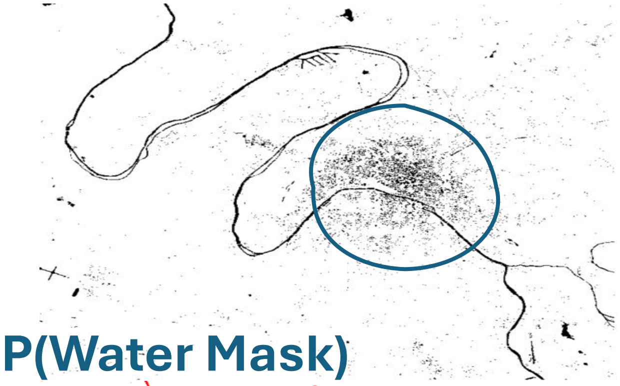
Narrow tributaries:
Mixed probabilities reflecting optical complexity

Shadows & dark surfaces:
Suppressed by NIR/SWIR physical gates

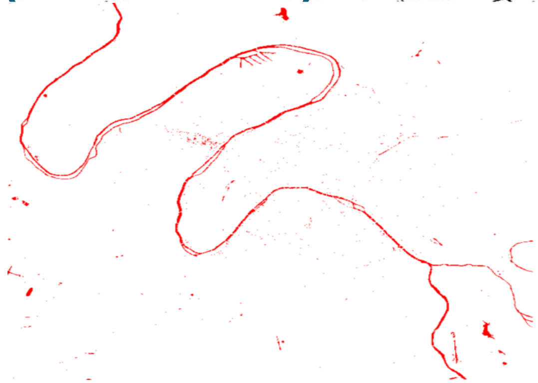
Transition zones:
P 0.3–<0.7 spatially confined to water-land edges

MC result: P ≥ 0.70 extracts only confirmed open water.

NDWI



P(Water Mask)



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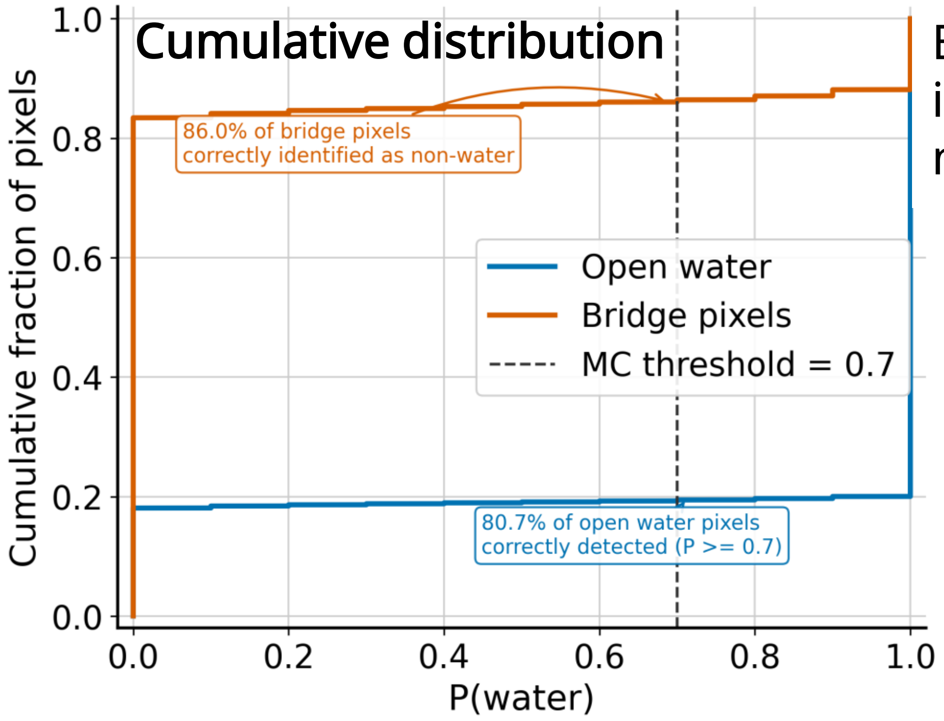
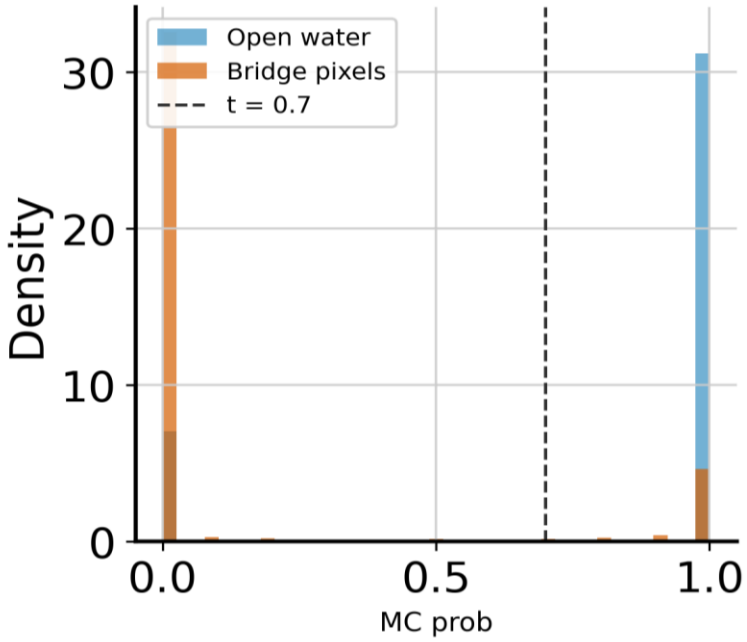


Bridge identified as non-water: **86%**

River pixels identified as water: **80.7%**

Δμ = 0.665
highest class separation



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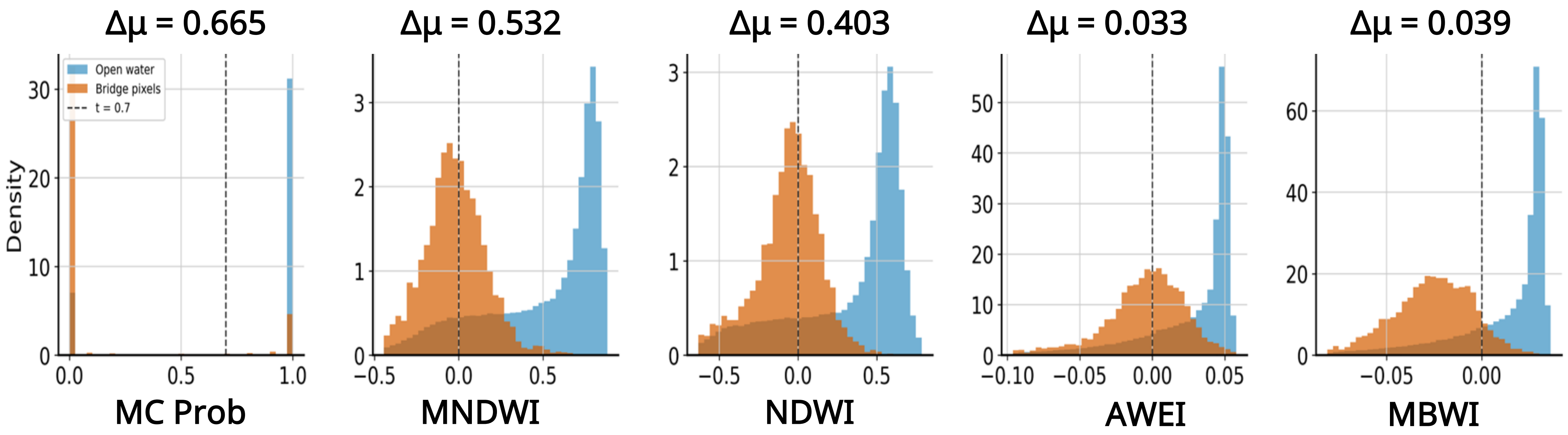
Higher Δμ = better separation of water pixels from bridges.



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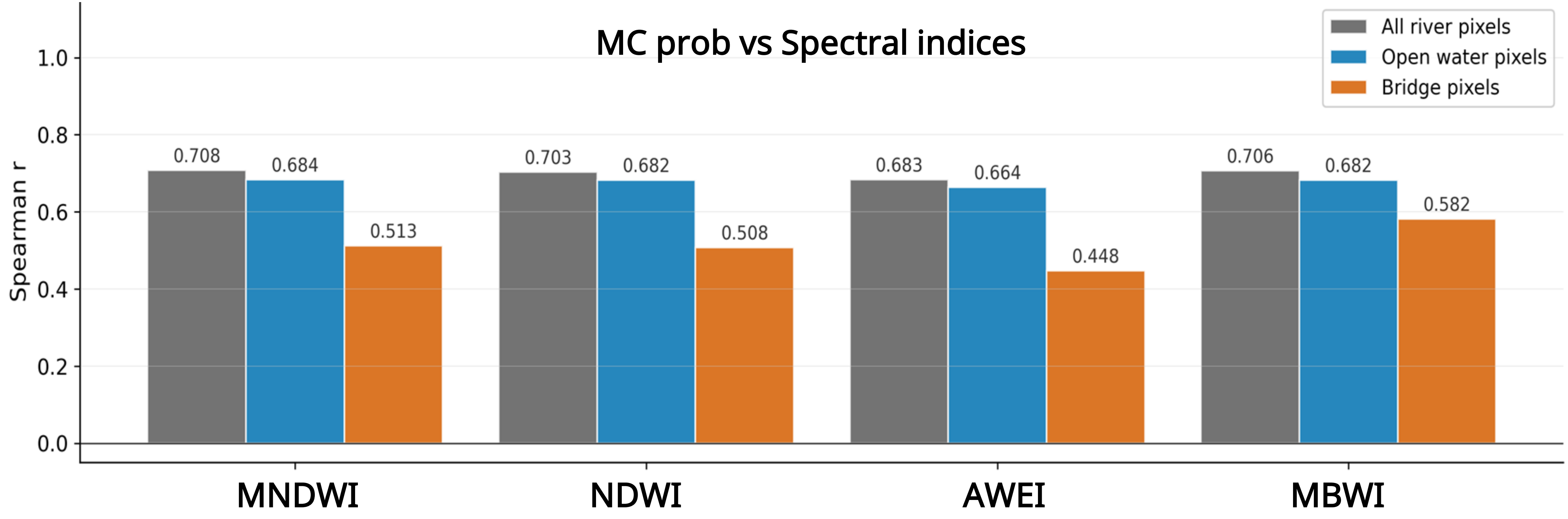

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Conclusion

- MC correctly identifies 86% of bridge pixels as non-water ($P < 0.70$), outperforming all four spectral indices on intra-river structure discrimination.
- MC achieves the highest class separation ($\Delta\mu = 0.665$) between open water and bridge surfaces.
- MC probability is physically consistent with all spectral indices (Spearman $r \approx 0.70$), confirming uncertainty propagation respects the spectral physics.

The MC probabilistic framework does not totally replace spectral indices BUT it integrates them into a calibrated uncertainty estimate that makes the right tradeoff for water quality monitoring: maximum confidence in what we call water, with transparent quantification of where we are uncertain.

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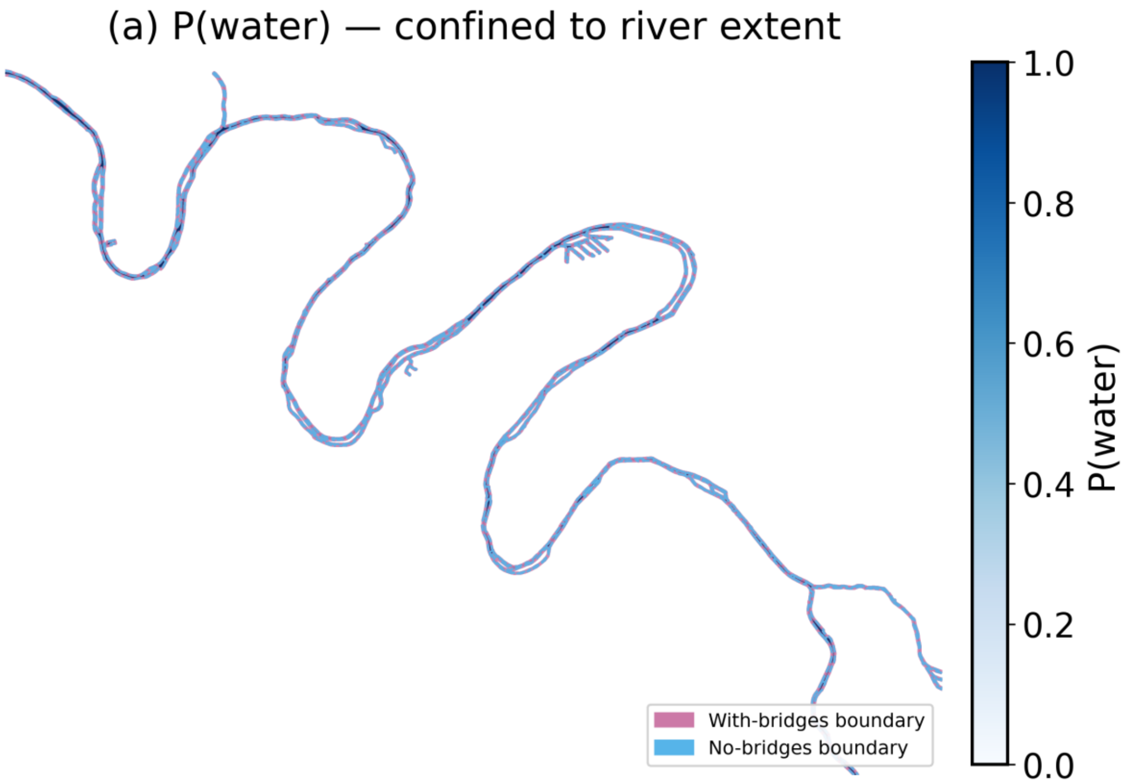

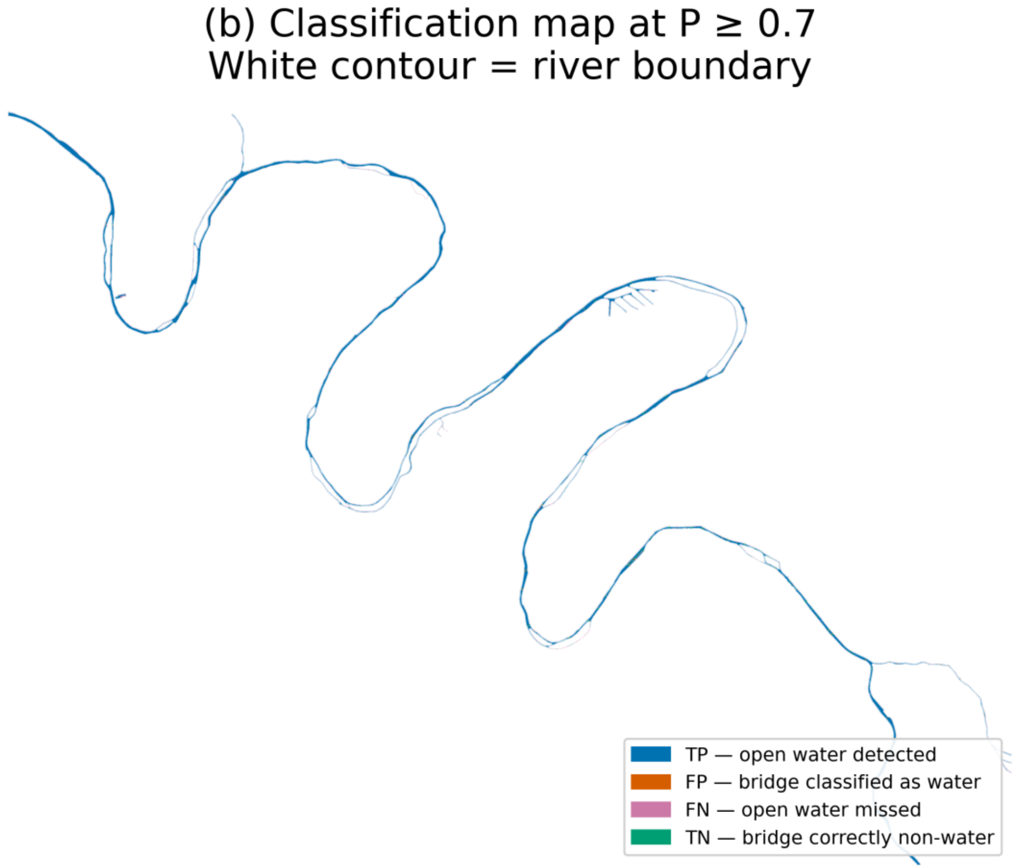

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NDWI - Normalised Difference Water Index (Green - NIR) / (Green + NIR)
MNDWI - Modified Normalised Difference Water Index (Green - SWIR1) / (Green + SWIR1)
AWEI - Automated Water Extraction Index, shadow-corrected variant AWEIsh (Feyisa et al. 2014)
MBWI - Multi-Band Water Index (Wang et al. 2018)

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References

Wang, Xiaobiao, et al. "A robust Multi-Band Water Index (MBWI) for automated extraction of surface water from Landsat 8 OLI imagery." *International Journal of Applied Earth Observation and Geoinformation* 68 (2018): 73-91.

Feyisa, Gudina L., et al. "Automated Water Extraction Index: A new technique for surface water mapping using Landsat imagery." *Remote sensing of environment* 140 (2014): 23-35.