

# **Roughness-Stratified NBS Scenarios for Pluvial Flood Attenuation in a Mediterranean Endorheic Detention System: A HEC-RAS 2D Rain-on-Grid Assessment**

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## **ABSTRACT**

This study evaluates roughness-stratified nature-based solution (NBS) scenarios in a dual-cell endorheic detention system at Vignacastri, Puglia, southern Italy. A HEC-RAS 2D rain-on-grid (RoG) model driven by an ERA5-Land reanalysis event from 7 October 2021 (54.0 mm, 25 h) simulates three scenarios modifying Manning's  $n$  and Curve Number (CN) within basin zones: S0 (bare soil,  $n = 0.030$ , CN = 91), S1 (grassland hydroseeding,  $n = 0.035$ , CN = 74), and S2 (shrubland planting,  $n = 0.060$ , CN = 74). To isolate roughness effects, comparing S2 directly to S1 (which share an identical CN) reveals a 0.127 m reduction in Basin 1 peak water surface elevation. In Basin 2, all three scenarios converge within 0.012 m, indicating that stored volume governs peak outcomes once the system approaches design capacity. Mean inundation duration under S1 (15.95 h) and S2 (15.87 h) differs from S0 (15.91 h) by less than 0.05 h. The presented method uses ERA5-Land reanalysis, ESA WorldCover 2020 land-surface parameters, and HEC-RAS RoG as a data stack that requires no local gauge data and is transferable to data-scarce endorheic lowlands across the Mediterranean that are interested in implementing nature-based solutions for flood protection.

*Keywords: Nature-based solutions, Hydrodynamic modeling, Rain-on-grid, Pluvial flooding*

## **INTRODUCTION**

Mediterranean lowlands include a class of endorheic depressions in which runoff accumulates through topographic ponding rather than draining through a channel network. Flood hazard in these settings depends on stored volume, not peak discharge. The Salento plain in Puglia, southern Italy, contains flat terrain with closed depressions classified as high hydraulic hazard under regional flood management plans. This basin typology is absent from most flood risk frameworks, which assume a defined drainage network. Tramblay et al. (2023) show that Mediterranean flood processes are shifting,

with event rainfall intensifying while runoff coefficients decline due to drier antecedent soils.

HEC-RAS 2D rain-on-grid (RoG) applies precipitation directly to the computational mesh, bypassing the need for a separate hydrological model. This makes it suited to catchments where ponding, not channel conveyance, governs the flood response. Alexopoulos et al. (2024) showed that RoG performance depends on terrain resolution, with a KGE of 0.913 at 1 m dropping to 0.577 at 25 m in the Selška Sora watershed, Slovenia. The same approach has been applied to flat, storage-dominated terrain: Alexopoulos et al. (2025a) coupled island-scale and centimeter-scale meshes for pluvial flood risk at the Temple of Apollo on Aegina Island, while Alexopoulos et al. (2025b) reproduced the muted lake-stage response of the Czeszewo Lake basin in Poland, where 46 mm of rainfall produced less than 0.10 m of stage rise. The method is well established for closed or semi-closed basins where water accumulates rather than drains.

Nature-based solutions (NBS) modeling in HEC-RAS has focused on riverine contexts. Sabeti et al. (2026) reviewed 30 studies and found Manning's  $n$  values for 2D afforestation ranging from 0.012 to 0.065 and for increased vegetation from 0.04 to 0.16. Pluvial studies were excluded from that review, and no endorheic system appears among the selected cases. The question of how roughness-based NBS perform in storage-dominated settings, where the basin fills to capacity rather than friction controlling peak water levels, remains open. Chappell and Beven (2024) framed this problem directly: storage features that are already full before the flood peak have no remaining capacity to attenuate inflows.

A prerequisite for transferring such a framework to data-scarce sites is a land surface parameterization that does not rely on local calibration. Cea et al. (2024) assigned Manning's  $n$  values for the Umbeluzi Catchment in Mozambique and validated the resulting model against field water marks and Sentinel-1 flood extent data, all without local parameter tuning. Because ESA WorldCover 2020 uses a consistent global classification, the same parameterization applies to other regions where field data are absent.

Three contributions distinguish this work from the state of the art and from the authors' prior rain-on-grid studies. First, it provides the first rain-on-grid assessment of vegetation-based NBS in a designed dual-cell endorheic detention basin, a configuration absent from the Sabeti et al. (2026) review and from the riverine NBS literature. Second, it extends the rain-on-grid framework developed by Alexopoulos et al. (2024, 2025a, 2025b) for storage-dominated watersheds, cultural heritage sites, and lacustrine basins into a setting with engineered hydraulic structures (embanked basins, overflow notch, concrete inlet channel). Third, it introduces a roughness-only isolation framework: by holding Curve Number constant between the grassland and shrubland scenarios, the friction contribution to peak attenuation is separated from the infiltration contribution, quantifying each independently. The scenario stack uses ERA5-Land reanalysis, ESA WorldCover 2020, and HEC-RAS rain-on-grid, and requires no local gauge data.

## **METHODOLOGY**

The Vignacastrisi detention system serves a localized morphological depression within a larger 50 km<sup>2</sup> endorheic region of flat karstic terrain, meaning only a fraction of this broader area contributes runoff to the specific hydraulic works. The hydraulic works consist of two series-sequential embanked detention basins with a total design storage of 4,475 m<sup>3</sup>, designed for the 200-year return period pluvial event. Infrastructure includes a reinforced concrete box inlet channel (260 m), a microtunnel crossing under

Via Circonvallazione, and gabion wall retaining foundations. The site forms part of the ARIANNA Interreg ADRION project, Activity 2.1, coordinated by LP-ASSET (Province of Lecce).

The NBS intervention targets revegetation of basin bottoms (Zone 1A: 367.3 m<sup>2</sup>, Zone 1B: 369.4 m<sup>2</sup>, Zone 2A: 371.4 m<sup>2</sup>, Zone 2B: 326.2 m<sup>2</sup>), slopes between the bottoms and the perimeter berms (1,456.8 m<sup>2</sup>), and the perimeter berms themselves (580.9 m<sup>2</sup>) with native Mediterranean species, totaling 3,472 m<sup>2</sup> of intervention area. Figure 1 shows the catchment boundary (A), the ERA5-Land forcing event (B), and the detailed layout of basin zones and connecting hydraulic structures (C).

## Terrain and Computational Mesh

The DEM was processed in HEC-RAS RAS Mapper from topographic survey data. To ensure consistent routing pathways across all scenarios, a single post-intervention terrain was used, featuring a modified connection between Basin 1 and Basin 2 across the central embankment via an overflow notch. The computational mesh uses a 20 m global cell size with 2 m refinement within basin zones. Breaklines and refinement regions were enforced along the inlet channel, the embankment crests and the overflow notch alignment.

## Hydrological Forcing

The precipitation forcing is an ERA5-Land reanalysis event recorded on 7 October 2021. Alexopoulos et al. (2023) demonstrated that ERA5-Land underestimates extreme rainfall by a median relative error of −35% across return periods of 1–50 years in Slovenia, but model recalibration to ERA5-Land forcing maintains KGE values above 0.6 across catchments. The event totals 54.0 mm over 25 h, with peak hourly accumulation of 21.0 mm (Figure 1B). Precipitation is applied as spatially uniform. Infiltration uses the SCS Curve Number (CN) method. CN is assigned spatially from ESA WorldCover 2020 (Zanaga et al., 2022) at Hydrologic Soil Group C (Vertisol/clay soils, Salento). While the CN look-up table values remain globally constant, changing the land cover in the basin zones from bare soil to vegetation inherently lowers the localized CN from 91 in S0 to 74 in S1/S2. However, CN is held strictly constant at 74 between S1 and S2 to isolate Manning's  $n$  as the sole independent variable governing attenuation. The depth threshold for inundation mapping is 0.10 m, applied to exclude numerical artifacts at wet-dry boundaries, consistent with standard practice in high-resolution pluvial flood modeling.

## Land Surface Parameterization

Manning's  $n$  values follow Cea et al. (2024) by ESA WorldCover 2020 class. CN values follow the suggestions of the United States Department of Agriculture (USDA, 1986). Table 1 presents the full parameterization.

**Table 1.** Manning's  $n$  and CN values by ESA WorldCover 2020 class.

| ESA Code | Land Cover Class | Manning $n$ (s m <sup>-1/3</sup> ) | CN (HSG C) |
|----------|------------------|------------------------------------|------------|
| 10       | Tree cover       | 0.070                              | 70         |
| 20       | Shrubland        | 0.060                              | 74         |
| 30       | Grassland        | 0.035                              | 74         |
| 40       | Cropland         | 0.050                              | 85         |

|    |                        |       |    |
|----|------------------------|-------|----|
| 50 | Built-up areas         | 0.100 | 98 |
| 60 | Bare/sparse vegetation | 0.030 | 91 |
| 80 | Permanent water bodies | 0.025 | 99 |
| 90 | Herbaceous wetland     | 0.040 | 78 |
| —  | Concrete channel       | 0.013 | 98 |
| —  | Gabion walls           | 0.035 | 91 |

Manning  $n$ : Cea et al. (2024); concrete channel: Chow (1959). CN: USDA (1986).

## NBS Scenario Framework

Three scenarios differ only in Manning's  $n$  and CN within basin zones (bottoms, slopes, perimeter). All other domain cells retain background values.

S0 (Baseline): bare/sparse vegetation in basin zones ( $n = 0.030$ , CN = 91). This isolates the baseline roughness conditions prior to planting.

S1 (Grassland NBS): native grassland hydroseeding in all basin zones ( $n = 0.035$ , CN = 74). This corresponds to the initial phase of the ARIANNA planned intervention.

S2 (Shrubland NBS): native shrubland in all basin zones ( $n = 0.060$ , CN = 74). This represents mature NBS consistent with shrub planting densities in the ARIANNA technical plan.

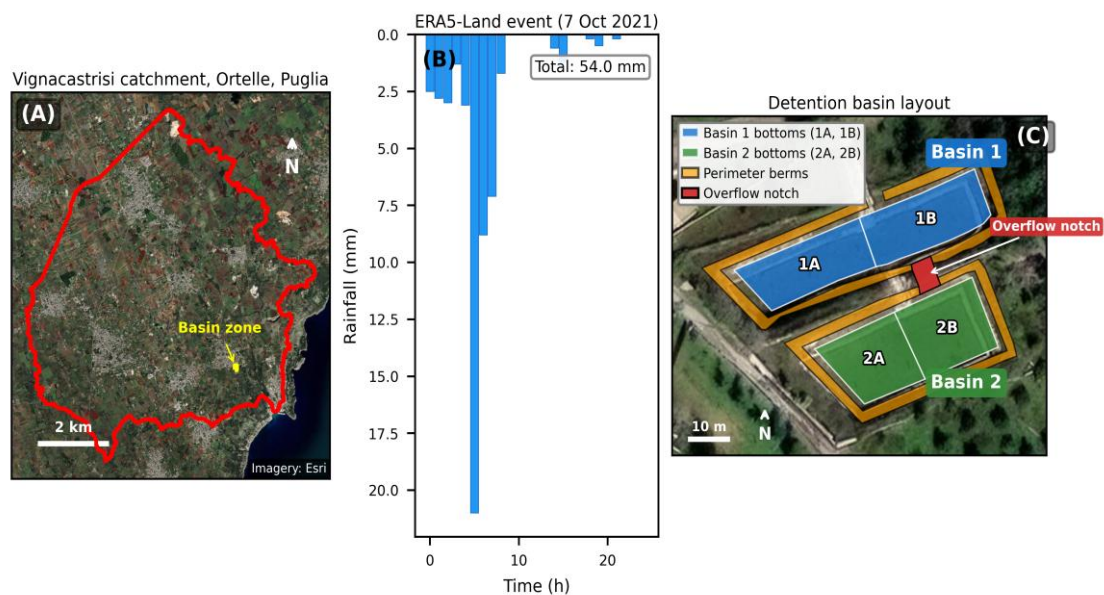


**Figure 1.** (A) Vignacastrisi catchment boundary (Province of Lecce, Puglia) with basin zone location. (B) ERA5-Land reanalysis precipitation event of 7 October 2021 used as model forcing. (C) Detailed layout of the dual-cell detention system showing basin bottoms (1A, 1B, 2A, 2B), perimeter berms, and the overflow notch connecting Basin 1 to Basin 2.

## RESULTS

Figure 2 shows the maximum inundation depth for the baseline scenario and the per-cell depth change relative to the baseline for S1 and S2. S0 produces a maximum depth of 1.791 m. S1 yields 1.784 m (0.44% reduction). S2 produces 1.822 m (1.72% increase). The inundated area above the 0.10 m threshold is 9,822 m<sup>2</sup> under S0, 10,111

m<sup>2</sup> under S1 (+2.9%), and 9,442 m<sup>2</sup> under S2 (−3.9%). Mean depth within the inundated area is 0.468 m (S0), 0.465 m (S1), and 0.442 m (S2). The S2 difference map (relative to baseline) illustrates the combined effect of altered infiltration and maximum roughness, showing a depth reduction of up to 0.27 m (blue) in Basin 1 and a localized depth increase of up to 0.24 m (red) in the lower catchment area. S1 differences are an order of magnitude smaller, confirming minimal combined hydraulic impact from the grassland intervention.

Figure 3 presents the longitudinal profile of maximum water surface elevation (WSE) and velocity along the inlet channel to Basin 2 centerline. In Basin 1, peak WSE is 88.252 m a.s.l. (S0), 88.253 m a.s.l. (S1), and 88.126 m a.s.l. (S2). The S2 scenario reduces Basin 1 peak WSE by 0.126 m relative to S0, while S1 produces no measurable change. In Basin 2, the three scenarios converge: peak WSE is 84.980 m (S0), 84.987 m (S1), and 84.975 m (S2), a total range of 0.012 m.

At the inter-basin transfer zone (station 297 m), WSE drops from 85.440 m (S0), 85.555 m (S1), and 85.350 m (S2) to approximately 84.98 m within 2 m of longitudinal distance. The velocity spike at this location reaches 8.447 m/s (S0), 8.679 m/s (S1), and 7.430 m/s (S2). S2 reduces notch velocity by 14.4% relative to S1, isolating the kinematic damping effect of the shrubland roughness. The maximum velocity along the full profile is 10.207 m/s (S0), 10.822 m/s (S1), and 12.284 m/s (S2).

Figure 4 shows inundation duration for the baseline scenario and per-cell duration change relative to baseline for S1 and S2, computed as the fraction of the 24-hour simulation period during which water depth exceeds 0.10 m. Maximum duration is 22.01 h for all three scenarios. Mean duration within the inundated area is 15.91 h (S0), 15.95 h (S1), and 15.87 h (S2). The number of cells with duration data is 4,132 (S0), 4,125 (S1), and 3,954 (S2). The S2 difference map (relative to baseline) maps the total intervention impact, revealing duration reductions of up to 6 h in the lower catchment area and along the inlet channel, while basin interiors remain near-saturated. S1 shows marginal changes below 1 h.

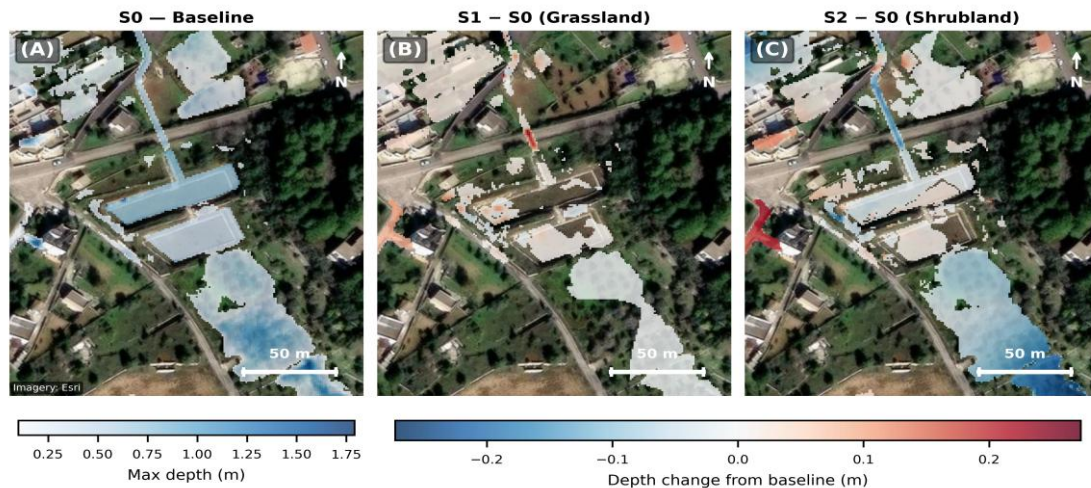


**Figure 2.** Maximum inundation depth for the S0 baseline (left), and the per-cell difference maps showing the combined depth change relative to baseline for the S1 grassland (center) and S2 shrubland (right) interventions. Depth threshold: 0.10 m.

## DISCUSSION

The WSE profile (Figure 3) confirms that Basin 1 fills and reaches the overflow notch invert (84.85 m a.s.l.) before Basin 2 activates. The WSE gradient at station 297 m shows a drop of approximately 0.5 m within 2 m of horizontal distance, with a

corresponding velocity spike exceeding 8 m/s under S0 and S1. This confirms that the overflow notch at 84.85 m a.s.l. acts as the hydraulic control governing inter-basin transfer. S2 attenuates the velocity at this location by 14.4% relative to S1, indicating that higher roughness in the upstream basin slows the approach flow to the notch.

Because both scenarios share an identical DEM and Curve Number ( $CN = 74$ ), the 0.127 m peak WSE reduction in Basin 1 between S2 and S1 isolates the pure hydraulic impact of the shrubland's higher Manning's  $n$  (0.060 vs. 0.035). In Basin 2, all scenarios converge within 0.012 m. Enu et al. (2025) report peak flow reductions of 14–24.4% for their restoration ambitious scenario in the Aboabo basin, with the combined floodplain-wetland scenario achieving 16–19% reductions in prolonged storms. The dispersed landscape scenario in the same study yields only 1–3% reductions, comparable to the marginal differences observed between S0 and S1 in this study. Bril et al. (2026) find that retention pond storage expansion from 0.7 to 1.7 million  $m^3$  reduces flood extent by only 3% for a 1-in-25-year event, because the storage is insufficient relative to rainfall volumes (30–54 million  $m^3$ ).

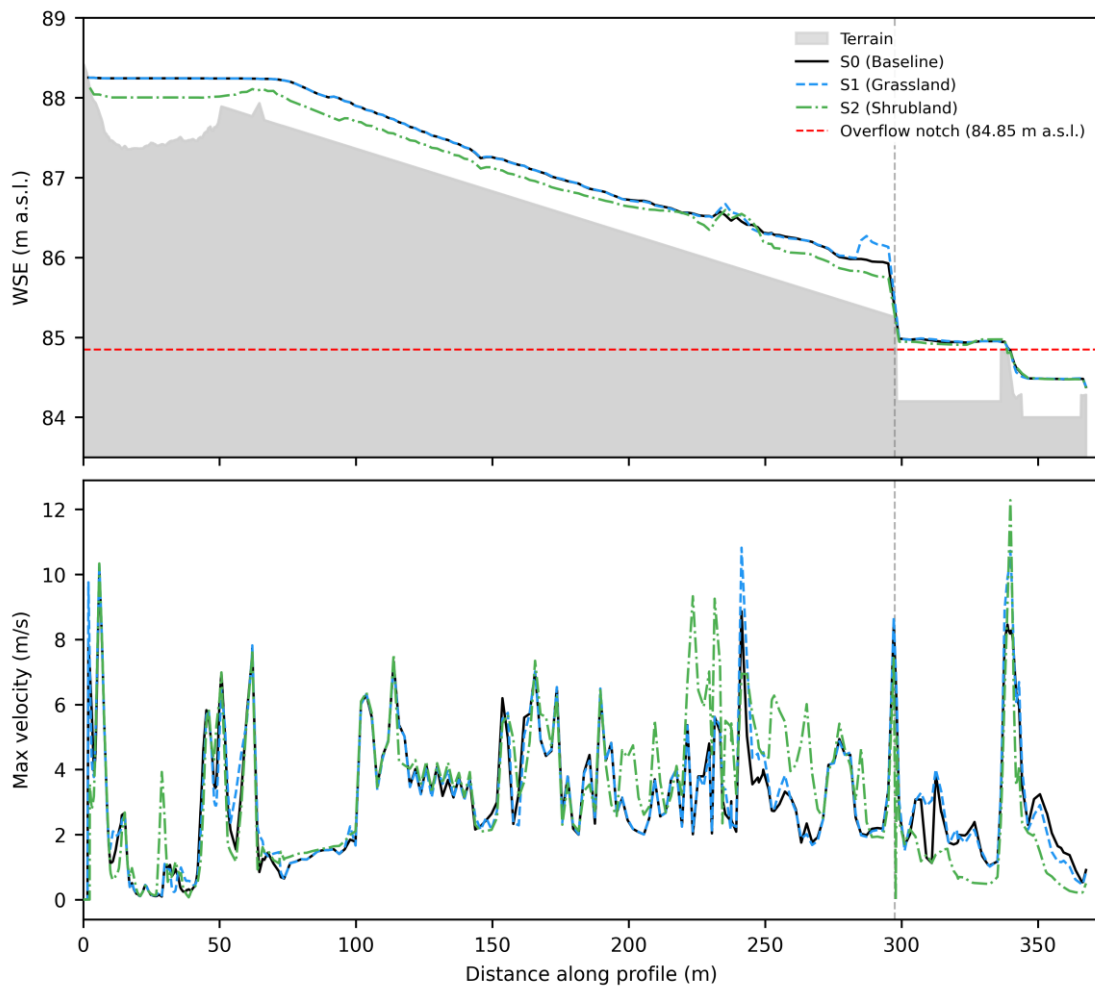


**Figure 3.** Longitudinal profile of maximum water surface elevation (top) and maximum velocity (bottom) along the inlet channel to Basin 2 centerline for S0, S1, and S2. Dashed vertical line indicates overflow notch position.

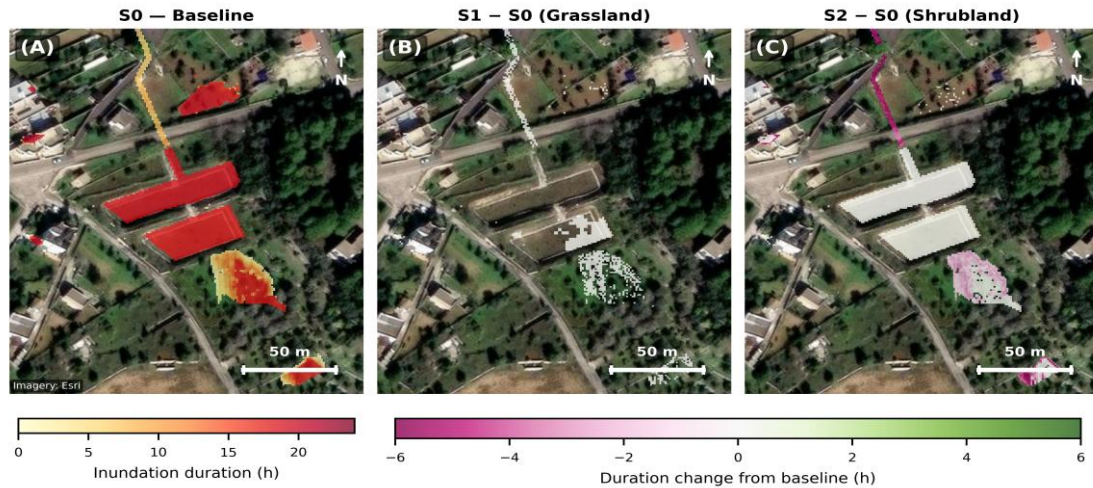


**Figure 4.** Inundation duration (hours) for the S0 baseline, and the per-cell duration change relative to baseline for the S1 and S2 interventions. Depth threshold: 0.10 m. Longer duration indicates an extended hydroperiod.

The limited sensitivity of peak outcomes between S1 ( $n = 0.035$ ) and S2 ( $n = 0.060$ ) under this event reflects a storage-dominated regime. When the basin approaches its 4,475 m<sup>3</sup> design capacity, the volume threshold governs the maximum WSE regardless of surface friction. As framed earlier by Chappell and Beven (2024), this mechanism is fundamental: volume exhaustion neutralizes any residual attenuation capacity. The convergence of Basin 2 WSE across all three scenarios (within 0.012 m) is consistent with this exhaustion effect: once the inter-basin transfer volume exceeds the downstream storage capacity, roughness differences upstream produce negligible additional attenuation at the final cell.

S1 and S2 show mean inundation durations of 15.95 h and 15.87 h, compared to 15.91 h under S0. The differences are small ( $< 0.05$  h) at this return period. Extended hydroperiod, where it occurs, increases the potential for evapotranspiration and supports the ecological objectives of the ARIANNA pilot: enhancement of basin water retention capacity, integration with the surrounding terrain, and suppression of invasive species. Chappell and Beven (2024) distinguish between the hydraulic attenuation function of NBS features and their ecological function, noting that ponds permanently holding water "for ecological benefit" serve a different role than features designed for peak flow reduction. In the present context, the NBS revegetation serves both functions: the increase in roughness delays flow transit, while the vegetation itself provides the ecological services targeted by the ARIANNA intervention.

The modeling framework uses ERA5-Land, ESA WorldCover 2020, and HEC-RAS RoG as a fully open-data stack. ERA5-Land underestimates extreme rainfall by approximately 35% (Alexopoulos et al., 2023), which means the 54.0 mm event may underrepresent the magnitude of a 200-year recurrence. Model recalibration to ERA5-Land forcing maintains acceptable performance ( $KGE > 0.6$ ) across diverse catchments (Alexopoulos et al., 2023). The ESA WorldCover Manning parameterization from Cea et al. (2024) was validated against 20 field water marks in the Umbeluzi Catchment (Mozambique), with depths ranging from 0.6 to 4.3 m, and against Sentinel-1 flood extent data. The stack applies to data-scarce endorheic systems across the Mediterranean without requiring local gauge infrastructure.

The study has several limitations. (a) Spatially uniform rainfall: spatial variability in extreme events can alter inter-basin transfer timing. (b) No calibration data: future monitoring of the ARIANNA pilot will enable validation. (c) Reliance on standard tabular CN: Both grassland (S1) and shrubland (S2) share a CN of 74 under standard USDA

classifications for this soil group. However, Chappell and Beven (2024) note that storage features with sufficient freeboard can retain floodwater beyond what static land-cover parameters predict, meaning true attenuation could be greater than reported here. (d) Single event: a multi-event analysis spanning different return periods (50, 100, 200-year) would characterize the full performance curve. Bril et al. (2026) show NBS effectiveness diminishes with event severity, with damage reduction declining from 39% at 1-in-25-year to 35% at 1-in-1,000-year. (e) Trambly et al. (2023) document shifting flood generation mechanisms (runoff coefficient decline of 14.62%, flood date advance of 22 days), and non-stationary intensity-duration-frequency forcing warrants assessment in future work.

## CONCLUSIONS

2D hydrodynamic RoG modeling reproduces series-sequential detention dynamics in a Mediterranean endorheic system, with Basin 1 filling to notch invert before Basin 2 activates. NBS revegetation modifies the flow regime: isolating surface friction by holding CN constant reveals that shrubland (S2) reduces Basin 1 peak WSE by 0.127 m and notch velocity by 14.4% relative to grassland (S1).

Under the ERA5-Land event forcing, the difference in peak WSE in Basin 2 between S1 and S2 is 0.012 m, because storage volume governs peak outcomes once the system approaches design capacity. The ERA5-Land + ESA WorldCover 2020 + HEC-RAS RoG data stack requires no local gauge data and is transferable to data-scarce endorheic lowlands.

Results support the ARIANNA pilot NBS intervention design and provide quantitative evidence for NBS integration in Mediterranean detention infrastructure management.

Ultimately, these findings confirm that while NBS in endorheic systems provide marginal peak attenuation once storage is exhausted, they can be reliably modeled across data-scarce regions to extend hydroperiods and deliver targeted ecological benefits without compromising hydraulic safety.

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## REFERENCES

- Alexopoulos, M. J., Dimitriadis, P., Iliopoulou, T., Bezak, N., Kobold, M., & Koutsoyiannis, D. (2024). Effects of digital elevation model resolution on rain-on-grid simulations: a case study in a Slovenian watershed. *Hydrological Sciences Journal*, 69(11), 1468-1485. <https://doi.org/10.1080/02626667.2024.2378487>
- Alexopoulos, M. J., Iliopoulou, T., Modé, P., Istrati, D., Spyarakos, C. C., Soile, S., Verykokou, S., Ioannidis, C., & Koutsoyiannis, D. (2025a). A novel and scalable flood risk assessment framework for cultural heritage based on unmanned aerial vehicle photogrammetry and multi-scale rain-on-grid hydraulic modeling. *Science of The Total Environment*, 998, Article 180256. <https://doi.org/10.1016/j.scitotenv.2025.180256>
- Alexopoulos, M. J., Iliopoulou, T., Modé, P., Istrati, D., Koutsoyiannis, D., Królewicz, S., Graf, R., Kaczmarek, L., & Rączkowski, W. (2025b). Flood risk assessment of cultural heritage sites near lakes via advanced hydrodynamic modeling and digital technologies. *Results in Engineering*, 28, Article 107977. <https://doi.org/10.1016/j.rineng.2025.107977>

Alexopoulos, M. J., Müller-Thomy, H., Nistahl, P., Šraj, M., & Bezak, N. (2023). Validation of precipitation reanalysis products for rainfall-runoff modeling in Slovenia. *Hydrology and Earth System Sciences*, 27(13), 2559-2578. <https://doi.org/10.5194/hess-27-2559-2023>

Bril, V. C., de Bruijn, J., de Moel, H., Sadana, T., Busker, T., Botzen, W. J. W., & Aerts, J. C. J. H. (2026). Assessing the effectiveness of nature-based solutions and building-level flood risk reduction measures: An open-source coupled model. *Water Resources Research*. <https://doi.org/10.1029/2025WR041436>

Cea, L., Álvarez, M., & Puertas, J. (2024). Using integrated hydrological-hydraulic modeling and global data sources to analyse the February 2023 floods in the Umbeluzi Catchment (Mozambique). *Natural Hazards and Earth System Sciences*, 24(1), 225-243. <https://doi.org/10.5194/nhess-24-225-2024>

Chappell, N. A., & Beven, K. J. (2024). Nature-based solutions for effective flood mitigation: potential design criteria. *Environmental Research Letters*, 19(7), Article 074006. <https://doi.org/10.1088/1748-9326/ad4fa2>

Chow, V. T. (1959). *Open-Channel Hydraulics*. McGraw-Hill.

Enu, K. B., Merk, F., Su, H., Rauch, M., Zingraff-Hamed, A., Broich, K., Förster, K., Pauleit, S., & Disse, M. (2025). A scenario-based analysis of wetlands as nature-based solutions for flood risk mitigation using the TELEMAC-2D model. *Nature-Based Solutions*, 7, Article 100236. <https://doi.org/10.1016/j.nbsj.2025.100236>

Sabeti, R., Kjeldsen, T. R., Chambers, M., Moftakhari, H., Partida, L., Stamataki, I., Simmonds, S., Lee, R., Hankin, B., Hoskings, M., Dixon, K., Molloy, J., & Narayanaswamy, M. (2026). Modeling nature-based solutions in HEC-RAS. *Water Resources Management*, 40, Article 89. <https://doi.org/10.1007/s11269-025-04379-0>

Tramblay, Y., Arnaud, P., Artigue, G., Lang, M., Paquet, E., Neppel, L., & Sauquet, E. (2023). Changes in Mediterranean flood processes and seasonality. *Hydrology and Earth System Sciences*, 27(15), 2973-2987. <https://doi.org/10.5194/hess-27-2973-2023>

United States Department of Agriculture. (1986). *Urban Hydrology for Small Watersheds* (Technical Release 55). Natural Resources Conservation Service.

Zanaga, D., Van De Kerchove, R., Daems, D., De Keersmaecker, W., Brockmann, C., Kirches, G., & Smets, B. (2022). *ESA WorldCover 10 m 2021 v200*. <https://doi.org/10.5281/zenodo.7254221>