



Article

Sensitivity of 2D Hydrologic–Hydrodynamic Simulations to Wet–Dry Tolerance and Hydrological Drying Configurations in Iber

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Abstract

Two-dimensional hydrologic–hydrodynamic models based on shallow water equations require careful specification of wet–dry treatment parameters. However, wet–dry tolerance (depth thresholds) and drying algorithms are often set to defaults without systematic evaluation, particularly in intermittent-flow environments where these settings directly control surface activation and drainage connectivity. This study assesses the sensitivity of discharge estimation, inundation extent, and hydrograph stability to wet–dry tolerance (ε_{wd}) and hydrological drying configurations in the Iber modeling tool, applied to the lower reach of the Riera de la Bisbal (El Vendrell, Catalonia, Spain) under a triangular inflow hydrograph peaking at 586 m³/s, representing an approximate 500-year flood scenario. Four configurations were tested by combining two wet–dry tolerance values ($\varepsilon_{wd} = 1$ mm and $\varepsilon_{wd} = 1$ cm) with hydrological drying enabled or disabled on an unstructured mesh of 15,339 elements. Peak discharge at the outlet varied by only 0.5% across configurations, confirming low sensitivity under high flow conditions. However, local depth behavior differed substantially, with a peak depth difference of approximately 34% in a flood-prone diagnostic cell and flooded areas ranging from 65,687 m² to 69,262 m² depending on configuration. The results indicate that agreement in the outlet hydrograph is not a sufficient criterion for assessing local inundation quality, and that wet–dry configuration choices have operationally relevant consequences for flood-risk mapping and design in urban intermittent streams. Local peak-depth sensitivity was evaluated at five diagnostic cells (zones A–E), with peak-depth ranges across configurations varying from 2.5% to 116.4%; the 34.0% range at Zone A was intermediate within the selected locations.



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Keywords: wetting–drying algorithm; reach-scale modeling; urban flood modeling; Iber model; shallow water equations; 2D hydrodynamic modeling

1. Introduction

Accurate quantification of surface runoff and flow connectivity is critical for water resources planning, especially in data-scarce regions such as many basins in developing countries, where hydrometric networks are sparse and gauges are scattered over vast areas [1,2]. Distributed hydrological and hydrodynamic models are widely used for representing runoff generation, drainage-network activation, and hydrograph response, thereby

informing flood management strategies and water-availability assessment [3–5]. These distributed approaches, however, typically require hydrometric observations for calibration and validation, which can limit their applicability in ungauged or data-scarce basins. Physically based formulations have been shown to perform adequately under such conditions when properly constrained [6]. However, the reliability of these models depends on the appropriate configuration of numerical parameters governing flow activation, particularly in basins with intermittent or shallow-flow conditions.

Two-dimensional hydrologic–hydrodynamic models based on the depth-averaged Saint-Venant equations, also called shallow water equations (SWE) [7,8], allow the joint representation of runoff generation, overland flow, and channel hydraulics, resolving flow depth and velocity over a spatially distributed mesh and thus capturing floodplain inundation patterns and drainage-network activation at the catchment scale [9]. These distributed outputs provide considerable added value over lumped indicators because they resolve flow paths, inundation extent, water depths, discharge fields, and velocity distributions across the domain [10]. However, their application is constrained by demanding data and numerical requirements: reliable simulations depend on high-resolution topography and land-surface information, appropriate parameterization of roughness and boundary conditions, and careful selection of grid resolution, all of which strongly influence model stability and accuracy [11–13]. In addition, 2D schemes must deal with nonlinear dynamics, heterogeneous conditions, and low-depth flows, so that choices in the numerical treatment of wetting and drying can generate instabilities or suppress physically plausible shallow flows [12–14], particularly in shallow or intermittent flow regimes where accurately representing connectivity is most challenging.

In modeling tools based on two-dimensional Saint-Venant equations, wet–dry fronts are the moving interfaces between elements containing water and those treated as dry, and their evolution is controlled by a depth threshold that determines when a computational cell is considered inactive in the hydraulic calculation [15–17]. This threshold has a direct impact on numerical behavior: if it is set too low, sharp transitions between very shallow and dry states can lead to negative depths, spurious oscillations, or loss of stability in finite-volume schemes, whereas overly high thresholds may suppress physically plausible shallow flows and distort the position of the wet–dry interface [18–20]. At the same time, wet–dry tolerance conditions hydrological realism, because in distributed models each cell represents a finite contributing area, so that slight differences in the minimum active depth can modify the simulated extent and duration of surface activation, alter drainage-network connectivity, and affect mass conservation and hydrograph response in intermittent or shallow-flow regimes [20,21].

Numerical treatments of the wet–dry front can be broadly classified into two families. The first family comprises schemes that formally preserve positivity, ensuring that the water depth remains nonnegative; for example, the hydrostatic reconstruction of Audusse et al. [22]. These schemes are widely used because they ensure robustness and stability near wet–dry interfaces. However, several studies have shown that, under certain topographic and hydrological conditions with very shallow flows, positivity-preserving techniques can introduce excessive local corrections and underestimate slope-driven processes, a limitation identified by Delestre et al. [23] and further analyzed by Taccone et al. [24] in the context of rainfall–runoff modeling. A second family comprises schemes that do not formally preserve positivity, such as Roe-type solvers, which generally require introducing a numerical threshold, such as wet–dry tolerance (ϵ_{wd}), to avoid negative water depths and numerical instabilities [25–27]. These schemes have been applied in very shallow flow conditions because they tend to preserve slope-driven effects without the local corrections character-

istic of some positivity-preserving approaches and are comparatively straightforward to implement in operational modeling tools.

In hydrological scenarios, simulated flow depth is mainly used as an indicator of whether a given grid cell or channel reach is hydraulically active and contributing to runoff at the catchment scale [28,29], whereas in hydraulic scenarios, depth primarily controls local flow resistance, conveyance capacity, and energy gradients in detailed free-surface flow calculations [8,30]. For instance, in a hydraulic application, a dry cell can be considered when the water depth is less than 1 cm, which would be almost negligible for flood-wave propagation; however, in a hydrological scenario, the same 1 cm, interpreted as effective water depth over a discretized contributing area, could represent a considerable storage volume and contribution to streamflow generation depending on the climatic zone. Consequently, in distributed hydrologic–hydrodynamic modeling, the selection of apparently small wet–dry tolerance (for example, 1 mm versus 1 cm) is not a negligible modeling choice, because each active cell represents a finite contributing area, and changes in the minimum depth used to classify a cell as wet can modify the extent of active surface, disrupt or reinforce drainage-network connectivity, and affect the simulated runoff production at the basin scale, including the timing of the rising and falling limbs of the hydrograph [11,19]. Previous applications in urban drainage have shown that flow-activation thresholds strongly influence drainage-network connectivity and water-quality modeling performance, suggesting that threshold treatment is also critical at the watershed scale [31].

Despite the widespread use of 2D hydrologic–hydrodynamic models for assessing watershed response, the influence of wet–dry treatment on model stability and runoff remains insufficiently documented. The algorithms for determining wet–dry fronts are central to numerical performance and the definition of the inundation extent [18,19]; however, depth thresholds (along with other parameters) are commonly set to default values or model-specific recommendations without systematic sensitivity analyses or explicit reporting of the parametrization process [14,19,20,32]. A search in Scopus conducted in May 2026 using TITLE-ABS-KEY ((depth threshold OR depth tolerance) AND (drying)) returned no directly relevant results. A similar search query conducted in Google Scholar confirms that the combined influence of depth thresholds and hydrological drying on both aggregate hydrological outputs and local flood variables has not been systematically evaluated.

For example, technical documentation for hydrodynamic models such as the Flood Modeller [33] or ADCIRC [34] provides generic “reasonable values” for parameters controlling wetting and drying, with the latter explicitly stating that the optimal choice varies across applications. In particular, there is limited guidance on how threshold selection affects drainage connectivity and flow representation in intermittent or data-scarce environments, where activation thresholds control flow generation and validation data are sparse. Addressing this gap is relevant because configurations that produce similar outlet responses may generate operationally significant differences in local inundation depth and extent, with direct consequences for flood-risk mapping and water resources planning in intermittent or shallow-flow systems.

In this context, the present study uses the Iber modeling tool as the computational framework to evaluate different wet–dry configurations at the reach scale. Iber is a two-dimensional hydrologic–hydrodynamic modeling tool developed by GEAMA (University of A Coruña) and the Flumen Institute (UPC/CIMNE) to simulate free-surface flows and transport processes in both urban and fluvial domains [32,35]. The Iber modeling tool is based on the numerical solution of the depth-averaged Saint-Venant equations using a Roe-type finite-volume scheme, and incorporates a configurable wet–dry treatment based on a user-defined ε_{wd} value and a hydrological drying option, which has been reported as stable and mass-conservative in applications with complex topography [7,32,36].

Since Iber belongs to a non-positivity-preserving, threshold-based class of shallow-water solvers, the sensitivity to ε_{wd} and hydrological drying analyzed in this study should be interpreted within that numerical framework rather than as a universal property of all wet–dry treatments. Its configurable tolerance, combined with the documented variability of the recommended ε_{wd} values across Newtonian and non-Newtonian applications, makes Iber well-suited for evaluating this parameter.

This study assesses the effects of wet–dry tolerance configurations on 2D hydrologic–hydrodynamic modeling using the Iber modeling tool, with the objective of examining how ε_{wd} selection influences discharge estimation, end-of-event inundation extent, and hydrograph stability at the reach scale under a triangular peak-flow inflow in an intermittent channel. By evaluating alternative ε_{wd} under shallow and intermittent flow conditions, the analysis characterizes the sensitivity of peak discharge and flooded area to wet–dry tolerance, and discusses the implications for reach-scale simulations, particularly in regions where intermittent flow regimes dominate.

Compared with previous work on wet–dry front algorithms and wet–dry tolerance sensitivity, the novelty of this study lies in jointly evaluating, at the reach-scale and under an intermittent Mediterranean flow regime, how the combination of the ε_{wd} tolerance and the hydrological drying option in Iber affects peak discharge, inundation extent, and local water-depth dynamics simultaneously, to assess whether aggregated indicators such as the outlet hydrograph can mask substantial local differences directly relevant to flood-risk assessment and water resources planning.

2. Materials and Methods

2.1. Study Area

The study area corresponds to the lower reach of the Riera de la Bisbal as it crosses the urban area of El Vendrell (Baix Penedès, Catalonia, Spain), with outlet coordinates close to 41.183455° N, 1.548232° E. The Riera de la Bisbal is a small Mediterranean stream with an intermittent (ephemeral) flow regime. In its lower reach, the stream crosses the urban area of El Vendrell, where municipal projects such as RENAT3R and related planning documents explicitly address the renaturalization of the Riera de la Bisbal and its integration into the town's urban and peri-urban green–blue infrastructure [37]. Like other coastal “rieres” in Catalonia, the Riera de la Bisbal exhibits a torrential Mediterranean regime, with long dry periods and sudden flood peaks generated by short, intense rainfall events, as reflected in regional descriptions of litoral streams and in the documented flash-flood impacts of June 2000 in this area [38,39]. The simulation conditions were defined for this lower reach using 15,339 unstructured mesh elements with finer cells along the main channel and adjacent contributing areas, two wet–dry tolerance values ($\varepsilon_{wd} = 1$ mm and 1 cm), with hydrological drying enabled or disabled, and a triangular inflow hydrograph peaking at 586 m³/s during the total simulation time, representing an approximate 500-year flood scenario according to regional flood-hazard information provided by the Catalan Water Agency (ACA) [40]. Rainfall and infiltration were not simulated. The total simulation time was 3600 s. The study area location is shown in Figure 1.

The final reach of the Riera de la Bisbal near its coastal outlet was modeled for this scenario, spanning approximately 735 m around coordinates 41.183455° N, 1.548232° E. A 1 m resolution digital elevation model (topographic survey) from May 2022 was used. Five distinct zones were considered, each with its own type of land cover (Manning roughness, n) and a different grid (See Figure 2). A finer grid was applied to residential land cover to assess the extent of the hydrological drying process's impact. Specifically, the rural area was modeled with a cell size of 15 m, the river and beach area with a cell size of

6 m, and the residential area with a cell size of 4 m. The polygon under consideration has an extent of 33.2 ha.

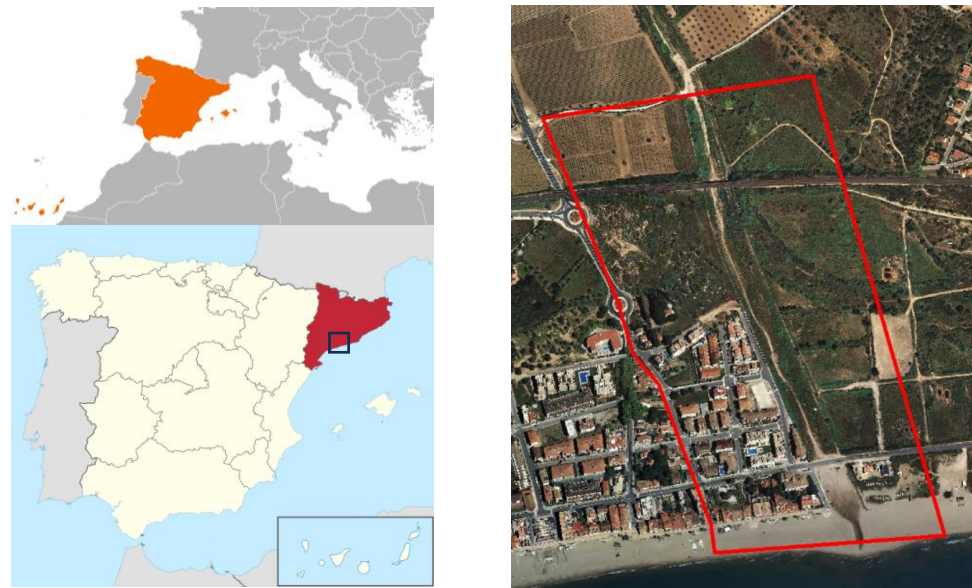


Figure 1. Location of the study area.

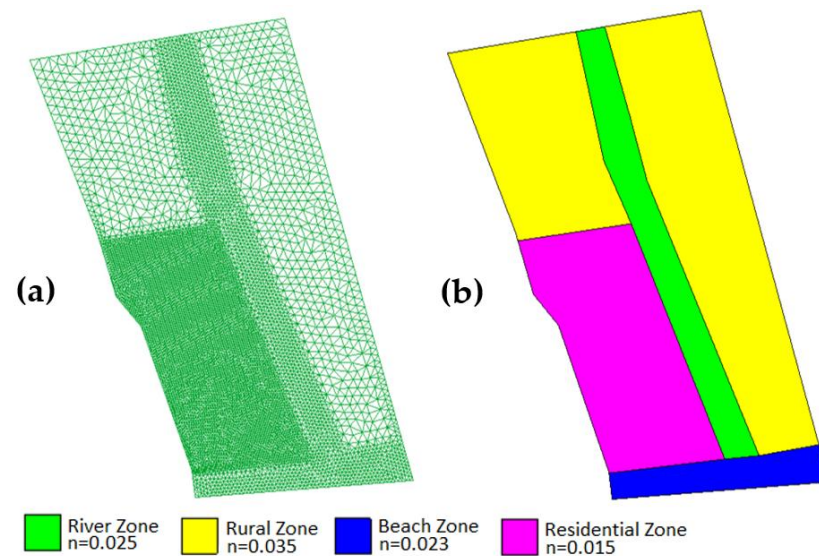


Figure 2. Study area characteristics employed in the Iber modeling tool: (a) meshing and (b) distribution of zones by roughness type.

2.2. Governing Equations

The Iber modeling tool solves the two-dimensional depth-averaged SWE using a finite-volume scheme on unstructured meshes composed of triangular or quadrilateral elements [41]. The conservative vector form of the SWE is:

$$\frac{\partial}{\partial t} \mathbf{U} + \nabla \cdot \mathbf{F} = \mathbf{H}, \quad (1)$$

where $\mathbf{U}$ is the vector of conserved variables (mass and momentum per unit area), $\nabla \cdot \mathbf{F}$ is the divergence of the flux tensor representing the net convective transport of mass and momentum through the boundaries of each control volume, and $\mathbf{H}$ is the source term

vector accounting for bed slope, friction, and, when applicable, rainfall and infiltration contributions [42]. The conserved variables, fluxes, and source terms are defined as:

$$\mathbf{U} = \begin{pmatrix} h \\ hu \\ hv \end{pmatrix}, \quad (2)$$

$$\mathbf{F} = \begin{pmatrix} hu & hv \\ hu^2 + g\frac{h^2}{2} & huv \\ huv & hv^2 + g\frac{h^2}{2} \end{pmatrix}, \quad (3)$$

$$\mathbf{H} = \begin{pmatrix} I - L \\ gh(S_{ox} - S_{fx}) \\ gh(S_{oy} - S_{fy}) \end{pmatrix}, \quad (4)$$

where h is the water depth, u and v are the depth-averaged velocity components, g is the gravitational acceleration, S_{ox} and S_{oy} are the bed slope components, S_{fx} and S_{fy} are the friction slope components, I represents rainfall intensity, and L represents infiltration losses. In the present application, no rainfall or infiltration processes were simulated ($I = 0$, $L = 0$), so the source term $\mathbf{H}$ reduces to the bed slope and friction contributions. In applications where these processes are represented, the rainfall and infiltration terms are commonly obtained through coupling with infiltration models such as the Green–Ampt formulation or 1D/3D Richards-based approaches [43,44].

The inviscid fluxes at cell interfaces are computed using a Roe-type approximate Riemann solver [45]. The spatial discretization uses a first-order upwind scheme on an unstructured finite-volume mesh, where each element stores the mean values of the conserved variables. The Courant–Friedrichs–Lewy (CFL) condition rules the time step [32]:

$$\Delta t \leq \frac{\Delta X}{Vel + \sqrt{gh}}, \quad (5)$$

where ΔX is the characteristic cell size (width), Vel is the flow velocity, and h is the local water depth. The numerical scheme was first-order; the CFL (Courant–Friedrichs–Lewy) number used in the simulations was 0.45, and turbulence was not considered. The CFL number controlled the adaptive time step in the explicit solution scheme and was kept constant across all configurations to isolate the effects of ε_{wd} and hydrological drying. Iber's finite-volume formulation is locally and globally mass-conservative [41,46], and the hydrological drying procedure limits the outflow from elements approaching dry conditions. These properties concern numerical stability and mass conservation; they do not establish numerical convergence. No mesh-refinement or time-step/CFL sensitivity analysis was performed. The reported sensitivity to ε_{wd} and hydrological drying is therefore conditional on the adopted mesh resolution and CFL = 0.45, and does not establish mesh- or time-step-independent estimates of outlet discharge, flood extent, or local water depth.

2.3. Wet–Dry Front Treatment

The treatment of wet–dry fronts used in Iber is stable, conservative, and non-diffusive, including for high bed slopes in river channels and contributing areas [47]. A wet–dry tolerance ε_{wd} is defined such that if the water depth in a cell is less than ε_{wd} , the cell is considered dry and is excluded from the calculation. A cell with no water is classified as dry (Figure 3a); a cell that is dry but adjacent to wet cells and therefore subject to potential inflow is considered wettable (Figure 3b); and a cell whose depth exceeds ε_{wd} is wet and actively participates in the computation (Figure 3c). The wet–dry tolerance ε_{wd} represents

the minimum depth threshold separating dry from wet states (Figure 3d). The water height is never forced to zero to avoid mass loss within the computational domain [41,46].

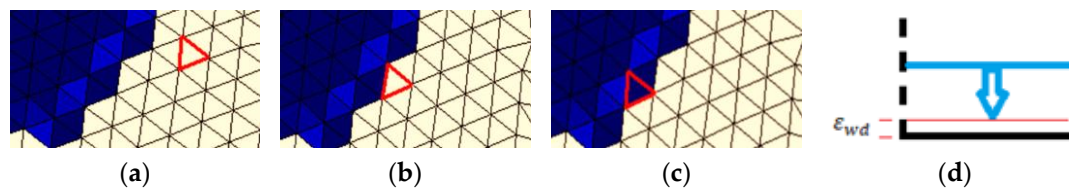


Figure 3. Combination of cell drying or wetting options and representation of the dry–wet tolerance ϵ_{wd} . For the cell outlined in red: (a) Dry cell, (b) wettable cell, (c) wet cell, and (d) schematic of ϵ_{wd} .

Each finite volume in Iber has an associated bed level. Schematically, the river bed or contributing area can be represented in profile relative to the mesh elements, and between two adjacent volumes with different bed elevations, three situations can occur (Figure 4): (a) both volumes contain water, so no wet–dry front is present; (b) only one volume contains water, but the free surface elevation of the wet element remains below the bed level of the dry element; and (c) a wet–dry front exists, and the free-surface elevation of the wet element is above the bed level of the neighboring dry element. Cases (b) and (c) correspond to wet–dry interfaces, but only in case (c) is differential treatment necessary, consisting of redefining the bed slope and imposing a reflection condition at the front.

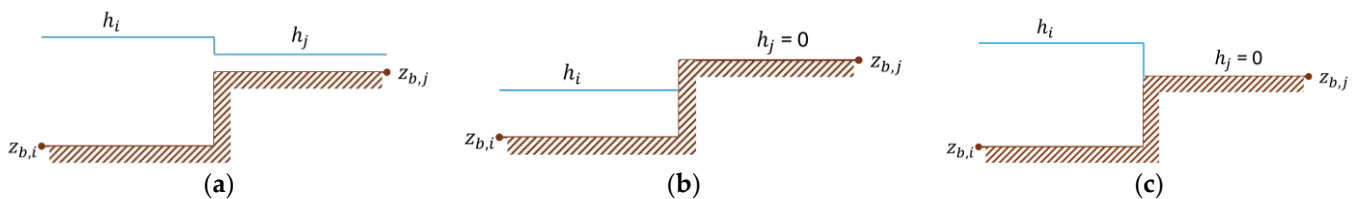


Figure 4. Wet–dry front configurations between two adjacent finite volumes: (a) both cells are wet; (b) the free surface of the wet cell lies below the bed of the dry cell; (c) the free surface of the wet cell exceeds the bed of the dry cell.

According to Cea et al. [46], the contribution of the bed slope at the wet–dry front is treated as follows:

$$\Delta z_{b,ij} = \begin{cases} h_i - h_j & \text{if } h_j \leq z_{b,j} - z_{b,i} \\ z_{b,j} - z_{b,i} & \text{if } h_j > z_{b,j} - z_{b,i} \end{cases} \quad (6)$$

The reflection condition is imposed as:

$$q_{n,ij} = q_{x,ij}n_{x,ij} + q_{y,ij}n_{y,ij} = 0, \quad (7)$$

where $q_{x,ij}$ and $q_{y,ij}$ are the unit discharge components at the interface between finite volumes i and j , and $n_{x,ij}$ and $n_{y,ij}$ are the components of the outward unit normal vector to that interface. This condition enforces zero normal flux across the wet–dry front, effectively treating it as a reflective boundary. This treatment provides a well-balanced hydrostatic solution for any bathymetry, without extending the front or generating non-smooth local variations in the free surface [46,47].

For the drying process, an alternative method, hydrological drying, is used. At each simulation time step, a check is made to determine whether the outflow from an element can cause it to dry, excluding the inflow. If this is the case, the outlet flow rate is decreased by a factor equal to V_{out}/V , where V is the volume of water in the element and V_{out} is the outlet flow multiplied by the time increment. This method reduces drying instabilities

when the water level is low by limiting the outflow from near-dry elements, without increasing the total simulation time [45,48].

The user can set ε_{wd} to approach zero; however, in problems with irregular bathymetry, values in the range of 0.1–1 mm have been adopted in Newtonian flow applications to increase stability without compromising precision [48,49]. For non-Newtonian shallow flows, Sanz-Ramos et al. [32] used a higher threshold of 1 cm and noted that further investigation is needed to fully understand the role of this parameter. These variations across applications underscore the need for a systematic assessment of wet–dry tolerance effects, which is the focus of the present study.

In this study, we selected ε_{wd} values of 1 mm and 1 cm to bracket the range between the conservative thresholds typically adopted for Newtonian shallow-flow applications [48,49] and the more permissive values reported for non-Newtonian shallow flows in Iber [32], allowing a conservative threshold to be contrasted with a more permissive one within the range documented in the literature. It is worth mentioning that two ε_{wd} values cannot fully characterize threshold response across its entire range; additional ε_{wd} values (e.g., 10^{-4} m and 10^{-5} m) would provide a more complete description of the threshold-response pattern and are identified as future research, particularly in combination with benchmark test cases or actual flood scenarios.

2.4. Simulation Setup and Tested Configurations

The computational domain was discretized with an unstructured mesh of 15,339 elements, with finer elements along the main channel. A triangular inflow hydrograph was imposed at the upstream boundary, rising linearly from 0 m³/s at $t = 0$ s to a peak discharge of 586 m³/s at $t = 1800$ s and receding linearly to 0 m³/s at $t = 3600$ s. The downstream boundary condition was a free outlet with no outlet structure, and the initial condition assumed a dry riverbed (initial water level = 0). The symmetric triangular hydrograph was used as an idealized transient boundary condition that includes flood rise, peak, and recession phases relevant to wet–dry-front dynamics. The peak discharge was selected for comparison with the approximate 500-year flood-hazard scenario mapped in [40].

To evaluate the influence of the wet–dry tolerance on the simulation results, four configurations were tested by combining two ε_{wd} values (1 mm and 1 cm) and two drying options (enabled and disabled).

The analyzed outputs were outlet discharge, local water depth, and inundated area at the end of the 3600 s simulation. Simulations were performed using Iber 3.3.1 and executed sequentially on a Windows 11 Pro 64-bit workstation with an Intel Core CPU, 15 GB of RAM, and a 1 TB SSD, using the standard CPU implementation. The mean runtime was approximately 2.5 min per simulation for the mesh resolution and terrain representation used. Five diagnostic cells (named as zones A–E) were selected at different locations within the modeled reach for local water-depth analysis. Zone A is located in the urbanized area, whereas zones B–E provide additional local comparisons across the modeled reach. Water-depth hydrographs were extracted at each cell for all four wet–dry configurations, and peak water depth, time to peak, maximum observed local fluctuation, and peak-depth range across configurations were evaluated.

For completeness, a cell was considered part of the flooded area when its simulated water depth exceeded ε_{wd} of the corresponding configuration, consistent with the wet/dry classification described in Section 2.3. Manning’s roughness coefficients for each land-cover zone are reported in Figure 2. The hydrological drying option in Iber 3.3.1 reduces, at each time step, the outflow of near-dry elements by a factor proportional to the ratio between the outgoing volume and the available water volume in the element [45], which limits drying-

induced instabilities without altering global mass balance. Other numerical parameters (mesh resolution, terrain representation, and time step/CFL criteria) were kept fixed across configurations to isolate the effects of ε_{wd} and hydrological drying.

3. Results

The results for the four wet–dry configurations (C1–C4) are presented below for outlet discharge, inundation extent at the end of the simulation, and local depth dynamics in a shallow sector of the domain. The analysis evaluates the sensitivity of these outputs to the wet–dry tolerance ($\varepsilon_{wd} = 1$ mm or 1 cm) and to the activation of hydrological drying. Table 1 summarizes the peak discharge and time to peak at the outlet for the four configurations. Peak discharge ranges from 470 m³/s (C2) to 473 m³/s (C1), a spread of 3 m³/s representing approximately 0.5% of the imposed inflow of 586 m³/s. Time to peak varies between 1938 s (C3) and 1968 s (C2), a range of 30 s over the 3600 s simulation. The outlet hydrographs for C1–C4 are visually nearly identical and are therefore not reproduced individually; the key quantitative indicators are shown in Table 1.

Table 1. Implemented scenarios of hydrological drying and wet–dry tolerance, and hydrograph characteristics at the outlet.

Condition	Hydrological Drying	Wet–Dry Tolerance	Time to Peak Discharge (s)	Peak Discharge (m ³ /s)	Total Flooded Area (m ²)
C1	YES	1 mm	1950	473	65,687
C2	YES	1 cm	1968	470	69,262
C3	NO	1 cm	1938	471	65,688
C4	NO	1 mm	1959	471	68,429

Within configurations with hydrological drying enabled (C1–C2), reducing ε_{wd} from 1 cm to 1 mm increases peak discharge by 3 m³/s and shifts the peak 18 s earlier. Without hydrological drying (C3–C4), the same change in ε_{wd} produces no difference in peak discharge (471 m³/s for both) and shifts the peak 21 s earlier. These results indicate that, at the outlet scale, the sensitivity of peak discharge to ε_{wd} and hydrological drying is small under the high-flow conditions tested.

Regarding the floodplain within the study area and under the conditions considered, the distribution of depth ranges is very similar for all four configurations (C1–C4), as shown in the stacked column plot in Figure 5, and the spatial extent of inundation for case C2 in Figure 6.

In all configurations, flooded cells account for approximately 20% of the model domain. The shallow band ($h < 0.31$ m) and the deep band ($h > 1.27$ m) each account for roughly 4% of the total domain and a range of 8–10%, respectively, with only small differences across C1–C4. The most noticeable differences occur in the deepest band ($h > 1.27$ m), which reaches its maximum in C4 and minimum in C1, indicating a slightly higher concentration of water in the deepest parts of the floodplain when hydrological drying is disabled and $\varepsilon_{wd} = 1$ cm.

However, the nearly identical depth distributions at the floodplain scale do not capture the spatial variability of local depth sensitivity. Local water–depth hydrographs were extracted at five diagnostic cells (zones A–E; Figure 6) for the four wet–dry configurations. The local water hydrographs for Zone A (1.5467940° E, 41.1848470° N), located in the urbanized area, are presented in Figure 7 as a detailed example; hydrographs for zones B–E are provided in Supplementary Figures S1–S4. Table 2 summarizes peak water depth, time to peak, observed local fluctuations, and peak–depth range across configurations for all five diagnostic cells.

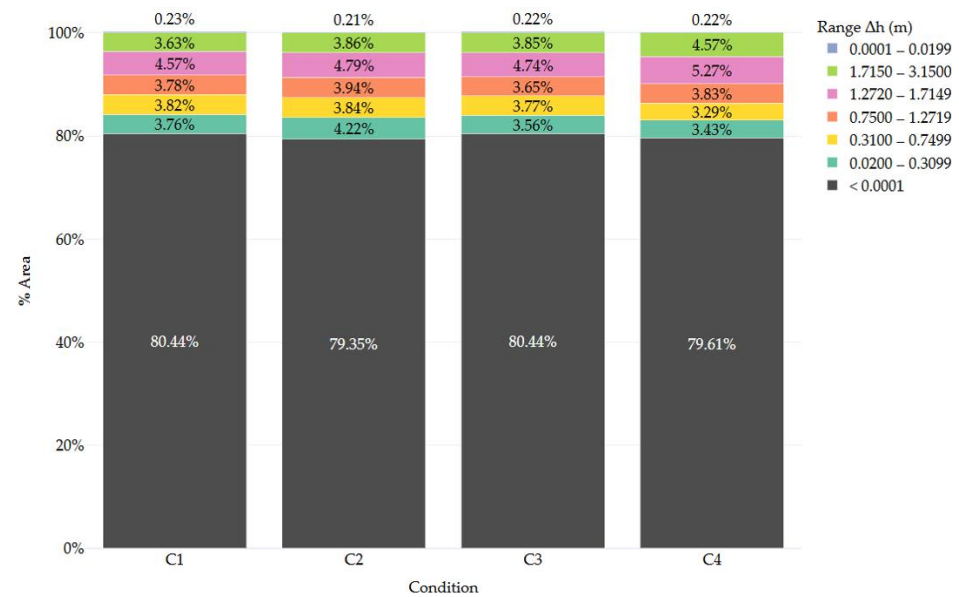


Figure 5. Percentages of flooded area by depth range in the study area. C1: with hydrological drying, $\epsilon_{wd} = 1$ mm; C2: with hydrological drying, $\epsilon_{wd} = 1$ cm; C3: no hydrological drying, $\epsilon_{wd} = 1$ cm; C4: no hydrological drying, $\epsilon_{wd} = 1$ mm.

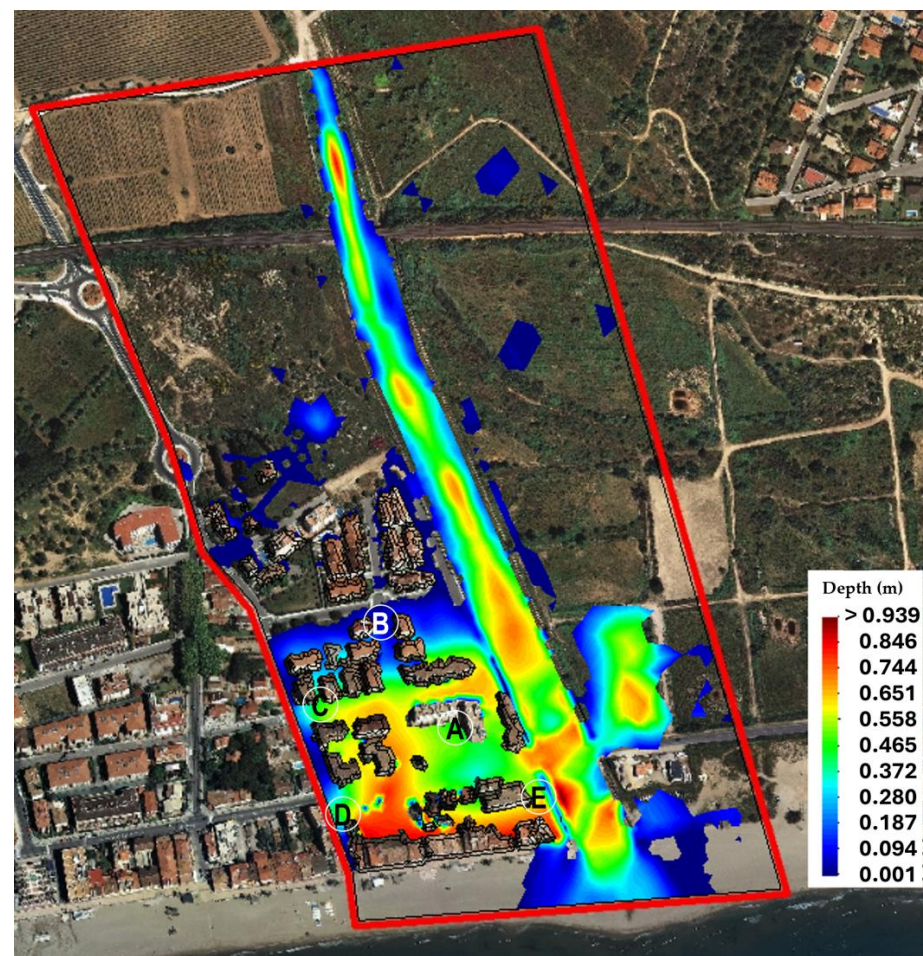


Figure 6. Simulated water depth at $t = 3600$ s for configuration C2 ($\epsilon_{wd} = 1$ cm, hydrological drying enabled). Circles identify the five diagnostic cells used for local water-depth analysis: Zone A (1.5467940° E, 41.1848470° N), Zone B (1.546240° E, 41.185498° N), Zone C (1.545339° E, 41.185103° N), Zone D (1.545923° E, 41.184000° N), and Zone E (1.547794° E, 41.184083° N). Local hydrographs for Zone A are shown in Figure 7; those for Zones B–E are provided in Supplementary Figures S1–S4.

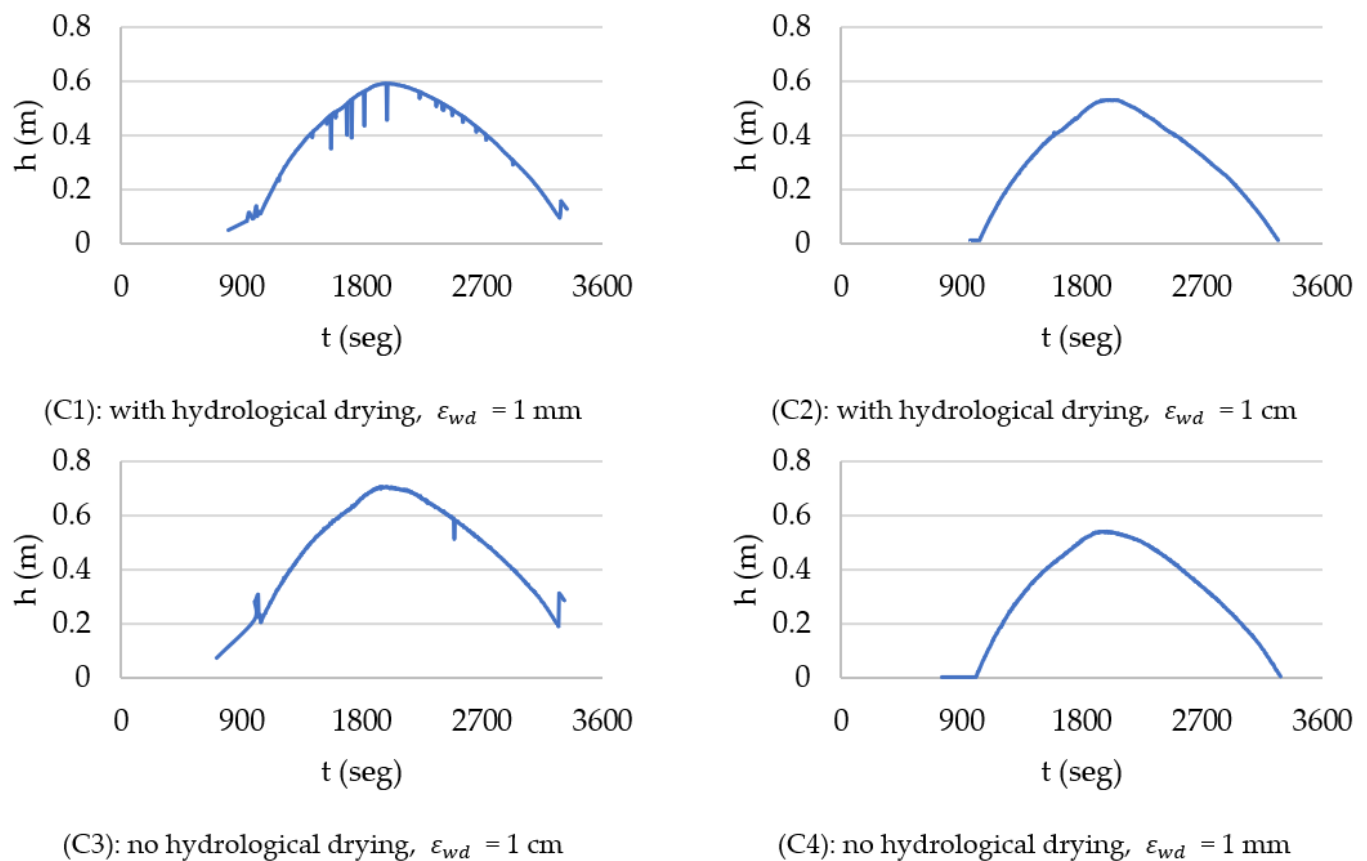


Figure 7. Local water-depth hydrographs at the diagnostic cell for Zone A ($1.5467940^\circ \text{ E}$, $41.1848470^\circ \text{ N}$) for the four wet-dry configurations.

Table 2. Local peak water depth, time to peak, maximum observed local fluctuation, and peak-depth range across the four wet-dry configurations at the five diagnostic cells.

Zone	C1 h (m)	C1 t (s)	C2 h (m)	C2 t (s)	C3 h (m)	C3 t (s)	C4 h (m)	C4 t (s)	Max. Observed Local Fluctuation (m)	* Range C1–C4 (%)
A	0.59	1980	0.53	2005	0.71	1990	0.54	1965	0.14 (C1)	34.0
B	0.78	1995	0.85	1930	0.85	1945	0.84	2015	0.08 (C4)	9.0
C	0.86	1995	0.91	2045	0.99	2130	0.93	1995	0.21 (C3)	15.1
D	0.79	2070	0.81	2100	0.80	2020	0.81	1995	<0.01	2.5
E	0.67	1995	1.43	1940	1.45	1920	1.45	1900	0.04 (C3)	116.4

* Peak-depth range was calculated as $(h_{p,\max} - h_{p,\min}) / h_{p,\min} \times 100$, using the peak depths shown in the table. “Max. observed local fluctuation” denotes the maximum amplitude of a non-smooth variation in the simulated local depth time series; the configuration in parentheses is the configuration in which it was observed.

At Zone A, configurations C2 (hydrological drying enabled, $\varepsilon_{wd} = 1 \text{ cm}$) and C4 (hydrological drying disabled, $\varepsilon_{wd} = 1 \text{ mm}$) produce depth time series without visible oscillations. Configuration C1 (hydrological drying enabled, $\varepsilon_{wd} = 1 \text{ mm}$) exhibits repeated local fluctuations of approximately 0.05–0.15 m amplitude near the peak, concentrated between $t \approx 1700 \text{ s}$ and $t \approx 2200 \text{ s}$. Configuration C3 (hydrological drying disabled, $\varepsilon_{wd} = 1 \text{ cm}$) shows a step discontinuity on the rising limb and an abrupt depth drop near $t \approx 2600 \text{ s}$, followed by a secondary local peak. This non-smooth behavior occurs during the wet-dry transition and differs from the smoother response obtained under the other configurations. The peak depth at this cell ranges from 0.53 m (C2) to 0.71 m (C3), corresponding to a 0.18 m difference and a 34.0% range across configurations (Table 2).

Across the five selected diagnostic cells, the peak-depth range varied from 2.5% at Zone D to 116.4% at Zone E (Table 2). Zones B and C showed intermediate ranges of 9.0% and 15.1%, respectively, whereas Zone A showed a 34.0% range. These results show that the response at Zone A is one local example and does not characterize the full range of local depth sensitivity observed across the five selected cells. Thus, small differences in outlet peak discharge ($<0.5\%$) can coexist with substantially different local peak-depth responses.

For qualitative context, Figure 8 shows the ACA flood-hazard extent and the location of the Iber model domain in the lower Riera de la Bisbal area [40]. The ACA map shows a larger potentially inundated area than the Iber model domain. The ACA information was used only as qualitative spatial context and not as a quantitative validation of simulated discharge, water depth, timing, or inundation extent. The publicly available ACA information for this reach is limited to an inundation-extent layer and does not include corresponding discharge, water-level, or depth data. In addition, the available ACA layer does not provide the model setup required to establish equivalence of domain, boundary conditions, and event representation. Therefore, no cell-by-cell agreement metrics or direct numerical comparison were attempted.

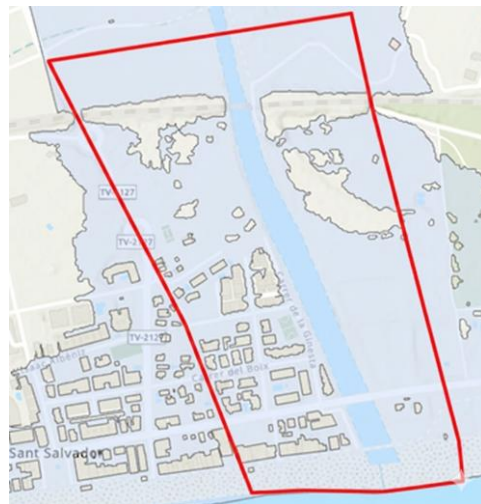


Figure 8. ACA flood-hazard extent for the 500-year return-period scenario in the lower Riera de la Bisbal area according to [40]. The red polygon indicates the Iber model domain.

4. Discussion

The results show that, across the four configurations, the sensitivity of outlet peak discharge and time-to-peak to wet–dry parameterization is low under the high-flow conditions tested: peak discharge ranges from 470 to 473 m^3/s ($\sim 0.5\%$ spread over the imposed 586 m^3/s), and time-to-peak varies by at most 30 s over the 3600 s simulation (Table 1). These findings are consistent with the expectation that, under near-capacity inflow conditions, the dominant control on outlet discharge is the main channel conveyance, which is minimally affected by small changes in the minimum active depth (as evidenced by the 0.5% spread in peak discharge) [11,19]. The outlet hydrographs for C1–C4 are visually nearly identical, as anticipated from previous modeling experience showing that high-flow conditions suppress threshold-driven differences in outflow. The upstream boundary condition was a triangular hydrograph peaking at $t = 1800$ s. Accordingly, the outlet and local depth hydrographs exhibit rising, peak, and recession phases. The outlet peak occurred approximately 140–170 s after the inflow peak (Table 1), reflecting translation and attenuation along the 735 m modeled reach. The wet–dry sensitivity discussed below therefore includes the transient wetting and recession phases of the imposed event.

However, the low sensitivity of outlet peak discharge did not extend uniformly to local water depth. At Zone A, configurations C2 (hydrological drying enabled, $\varepsilon_{wd} = 1$ cm) and C4 (hydrological drying disabled, $\varepsilon_{wd} = 1$ mm) produced depth time series without visible oscillations, whereas C1 (hydrological drying enabled, $\varepsilon_{wd} = 1$ mm) exhibited local fluctuations near the peak and C3 (hydrological drying disabled, $\varepsilon_{wd} = 1$ cm) showed non-smooth behavior during the recession phase. The Zone A peak depth ranged from 0.53 m to 0.71 m across configurations, corresponding to a 0.18 m difference and a 34.0% range.

Across the five selected diagnostic cells, the peak-depth range across configurations varied from 2.5% at Zone D to 116.4% at Zone E, while Zone A showed an intermediate range of 34.0% (Table 2). Hydrographs for Zones B–E are provided in Supplementary Figures S1–S4 and indicate that the observed ranges arose from different response patterns among the selected cells. Zone D showed nearly overlapping hydrographs across C1–C4, with peak depths between 0.79 and 0.81 m and a 2.5% range (Table 2; Supplementary Figure S3). In contrast, the 116.4% range at Zone E was associated with a sustained difference in the C1 hydrograph: its peak depth was 0.67 m, compared with 1.43–1.45 m in C2–C4 (Table 2; Supplementary Figure S4). Zones B and C showed intermediate ranges of 9.0% and 15.1%, respectively, and their maximum observed local fluctuations occurred in C4 at Zone B (0.08 m) and C3 at Zone C (0.21 m). Thus, within the five selected cells, variation in peak-depth sensitivity was associated with whether configuration differences appeared as a sustained displacement of the hydrograph, as at Zone E, or as comparatively smaller differences among the four configurations, as at Zones B–D. The analysis remains limited to five discrete diagnostic cells; a domain-wide assessment of depth differences between configurations was not performed.

The present output data allow a descriptive comparison of the non-smooth responses but do not support attribution to a specific numerical process. At Zone A, C1 showed repeated local fluctuations of approximately 0.05–0.15 m near the peak, whereas C3 showed a step discontinuity on the rising limb and an abrupt depth reduction during recession, followed by a secondary local peak. Across the five diagnostic cells, the maximum observed local fluctuations occurred under C1 at Zone A (0.14 m), C4 at Zone B (0.08 m), and C3 at Zones C and E (0.21 and 0.04 m, respectively), while Zone D showed a maximum fluctuation of 0.01 m (Table 2). Previous studies have reported that sharp transitions between very shallow and dry states can produce numerical oscillations or instability in finite-volume wetting–drying schemes under some conditions. The non-smooth local behavior observed here is consistent with this possibility, but its numerical origin was not independently verified [18,34,46]. Identifying whether these patterns result from wet–dry-state switching, hydrological-drying flux limitation, temporal discretization, or other local numerical effects would require output of cell wet/dry states, interface fluxes, and the hydrological-drying correction through time; these diagnostics were not available for the present simulations.

Regarding inundation extent, and even if differences are in the order of 5%, when hydrological drying is enabled, larger ε_{wd} produces a larger flooded area (69,262 m² for C2 versus 65,687 m² for C1), explained by the threshold serving as a lower bound on active cell volume: when ε_{wd} is larger, cells retain a higher residual volume upon deactivation, as water depth is never forced to zero in Iber to avoid loss of mass [41,46]. This retained volume delays drainage from marginal wet cells by computationally maintaining a water layer within them [14]. When hydrological drying is disabled, however, this relationship reverses: C4 ($\varepsilon_{wd} = 1$ mm) yields 68,429 m², exceeding C3 ($\varepsilon_{wd} = 1$ cm) at 65,688 m². This indicates that the redistribution of volume into topographic lows, caused by the lack of hydrological drying control, has a greater impact than the residual-volume retention effect of ε_{wd} . The influence of the wetting–drying algorithm on inundation extent has been identified in studies of threshold definition in 2D hydrodynamic tools (noting that default

values significantly influence the rising and receding stages) [9,19] and in analyses of surface hydrological connectivity in floodplain systems where system response exhibits abrupt changes relative to ε_{wd} selection [9,21].

As for the depth distribution shown in Figure 5, the configuration without hydrological drying (C4) contains a larger deep-band proportion than C1 under the same $\varepsilon_{wd} = 1$ mm setting: the deep band ($h > 1.27$ m) accounted for 41.5% of the flooded area in C1 (27,238 m²) and 47.7% in C4 (32,664 m²). The hydrological drying algorithm limits outflow from near-dry elements by a factor of V_{out}/V , to prevent negative depths while maintaining mass conservation [45]. With hydrological drying enabled, the simulated depth distribution contains a larger proportion of shallow-band area than when hydrological drying is disabled; when hydrological drying is disabled, the simulated distribution contains a larger proportion of deep-band area. These contrasting distributions are consistent with the different drainage treatments described in Section 2.3 and with previous analyses showing that flood and dry threshold definitions can influence simulated inundation dynamics in 2D hydrodynamic tools [19]. However, the present simulations did not quantify local storage changes and flow redistribution. These results are consistent with the relevance of grid design and wet–dry treatment for spatially distributed 2D hydrodynamic outputs, as addressed in hydrodynamic scaling and Iber benchmarking studies [11,49]. Notably, C1 and C3 produced the same end-of-event flooded area (65,687 m²), despite differing in both ε_{wd} and hydrological-drying configuration. This equality does not isolate the effect of either factor on inundation extent, but shows that similar aggregate inundation extent can coexist with different configuration-dependent local responses.

The contrast between limited variation in outlet peak discharge and larger differences in local depth responses can be considered alongside related 2D hydrodynamic studies, although direct quantitative comparison is constrained by differences in model formulation, mesh design, forcing, and output variables. Costabile and Costanzo [11] examined hydrodynamic scaling properties and implications for non-uniform grid generation in catchment-scale 2D-SWE simulations. David and Schmalz [14] conducted a systematic analysis of the interaction between rain-on-grid simulations and spatial resolution in 2D hydrodynamic modeling, reporting differences associated with mesh and terrain-model resolution. These studies show that discretization choices require explicit consideration in 2D hydrodynamic applications, but they do not examine the same wet–dry configurations used here. Barbero et al. [9] applied a 2D hydrodynamic approach to lag-time estimation in small watersheds. In the present study, the 140–170 s delay between the imposed inflow peak and outlet peak describes the simulated response under the adopted boundary condition and is not a validation metric. Salvan et al. [19] examined flood and dry threshold definitions in two-dimensional hydrodynamic flood-modeling tools. The present results complement these studies by evaluating, within Iber, how ε_{wd} and hydrological drying affect outlet peak discharge, inundation extent, and local water-depth response under the tested conditions.

In relation to the practical implications for flood-risk mapping, such as the RENAT3R project [37], the 5.4% difference in flooded area and the 34% difference in local peak depth have direct operational consequences. Flood-risk zoning in the urban area adjacent to the lower Riera de la Bisbal, where the RENAT3R project addresses the renaturalization of the stream and its integration into urban blue–green infrastructure, relies on accurately delineating inundation extent and estimating local flow depths [35]. A 5.4% underestimation of the flooded area corresponds to approximately 3575 m², a nontrivial area at urban parcel scale. The ~0.18 m difference in local peak depth between C3 and C4 (shown in Figure 7) is sufficient to move cells across standard flood-hazard depth thresholds (e.g., [50]), with consequences for hazard classification and design criteria. These results are consistent with

findings from 2D hydrodynamic sensitivity analyses showing that ε_{wd} selection directly affects inundation dynamics in intermittent environments where connectivity is highly sensitive during rising and receding phases, and extends them to the specific context of reach-scale urban flood modeling [11,19,21].

The comparison with the ACA flood-hazard map (Figure 8) should be interpreted only as qualitative spatial context, not as validation of simulated discharge, water depth, timing, or inundation extent. The ACA map delineates a larger potentially inundated area than the footprint simulated for the present 735 m reach. However, the public ACA layer [40] provides an inundation extent without corresponding discharge, water-level, or depth data for numerical evaluation. In addition, the two products are not directly comparable because the available ACA information does not provide the model setup required to establish equivalence of domain, boundary conditions, and event representation. Consequently, quantitative agreement statistics and cell-by-cell evaluation were not performed.

This study has several limitations. The upstream boundary condition is a single symmetric triangular inflow hydrograph; wet–dry front dynamics under alternative transient shapes (e.g., asymmetric or multi-peaked events) were not evaluated and may differ from those reported here. The diagnostic-cell analysis, while extended in this study to five locations (zones A–E), remains limited to discrete points rather than a fully distributed, domain-wide characterization of local depth stability. Moreover, the evaluation focuses on a single reach at a single flow magnitude; broader hydro-geomorphic conditions and grid resolutions were not explored. Future studies should extend these findings by testing threshold sensitivity under transient inflows, varying terrain complexities, and alternative 2D solvers. Additionally, no observations of flow depth or inundation extent were available for the simulated event; the results therefore represent a numerical sensitivity assessment of the relative influence of the wet–dry configuration on model response and do not allow determination of which configuration best reproduces actual flood conditions.

The analysis used one symmetric triangular inflow hydrograph (586 m³/s peak at $t = 1800$ s and a 3600 s duration). It therefore does not assess wet–dry-front sensitivity under asymmetric or multi-peaked hydrographs. The reported results should be interpreted as specific to the tested boundary-condition shape. Local water-depth comparisons were conducted at five diagnostic cells (Zones A–E; Figure 6 and Table 2), with hydrographs for Zone A shown in Figure 7 and those for Zones B–E provided in Supplementary Figures S1–S4. Although this expanded comparison documents variation among the selected locations, it does not establish whether the observed differences are systematic across the full domain; a spatially distributed analysis, such as zonal statistics or difference maps between configurations, would be required to assess domain-wide representativeness. The experimental design varied only the ε_{wd} and the hydrological drying option, while mesh resolution, terrain-treatment method, and time step were held fixed; possible interactions between ε_{wd} and these other numerical parameters were therefore not evaluated. The comparison against the ACA reference (Figure 8) inundation layer is qualitative and spatial, and does not amount to a quantitative validation against measured discharge or water-level time series. Future work should also extend the threshold range explored here (e.g., $\varepsilon_{wd} = 10^{-4}$ m and 10^{-5} m) to better characterize convergence behavior, and assess wet–dry sensitivity in rainfall–runoff (rain-on-grid) applications, where threshold effects have been shown to be particularly relevant [10,51]. No mesh-refinement or time-step/CFL sensitivity analysis was performed. Consequently, the results quantify the sensitivity to ε_{wd} and hydrological drying for the mesh resolution and CFL setting used in this study; they do not demonstrate that the reported local depths, inundation extent, or outlet indicators are independent of spatial or temporal discretization. Future work should include a systematic convergence analysis across mesh resolutions and time-step controls.

5. Conclusions

This study assessed the effects of wet–dry tolerance configurations on 2D hydrologic–hydrodynamic modeling using the Iber modeling tool, applied to the lower reach of the Riera de la Bisbal (El Vendrell, Catalonia) under a 500-year return-period inflow condition. Four configurations combining two wet–dry tolerance values ($\varepsilon_{wd} = 1$ mm and $\varepsilon_{wd} = 1$ cm) with two hydrological drying settings produced quantifiable, systematic differences in inundation extent, depth distribution, and local hydrograph behavior, while remaining nearly indistinguishable at the outlet scale.

At the outlet, peak discharge varied by approximately 0.5% across configurations, indicating low sensitivity of peak discharge to the tested wet–dry configurations under the high-flow conditions considered. This low sensitivity did not extend uniformly to local water depth. At Zone A, configurations C2 (hydrological drying, $\varepsilon_{wd} = 1$ cm) and C4 (no hydrological drying, $\varepsilon_{wd} = 1$ mm) yielded depth time series without visible oscillations, while C1 (hydrological drying, $\varepsilon_{wd} = 1$ mm) produced oscillations of ~ 0.05 – 0.15 m amplitude near the peak and C3 (no hydrological drying, $\varepsilon_{wd} = 1$ cm) showed non-smooth behavior during the recession phase. The Zone A peak depth ranged from 0.53 m to 0.71 m across configurations, corresponding to a 0.18 m difference and a 34.0% range. Across the five selected diagnostic cells, the peak-depth range across configurations varied from 2.5% at Zone D to 116.4% at Zone E. Thus, similarity in outlet peak discharge does not imply equivalent local depth responses across the selected locations. These results are limited to the tested reach, mesh resolution, CFL setting, inflow hydrograph, and five diagnostic locations; domain-wide depth-difference analysis and independent observational validation were not performed.

Regarding inundation extent, the results show that, when hydrological drying is enabled, a larger ε_{wd} produces a larger flooded area, whereas without hydrological drying, the configuration with a smaller ε_{wd} yields the larger flooded area. This behavior is consistent with the role of ε_{wd} as a lower bound on active cell volume when water depth is never forced to zero, and with the fact that disabling hydrological drying allows water to redistribute more freely into topographic lows. In addition, the deep band ($h > 1.27$ m) accounts for a larger share of the flooded area when hydrological drying is disabled, indicating that drying control and the wet–dry tolerance interact to shape the partitioning of volume between the shallow and deep parts of the floodplain. These patterns align with previous work showing that wet–dry tolerance choices and algorithm design directly affect the modeled inundation dynamics and connectivity in shallow, intermittent flow regimes.

From a practical perspective, the findings imply that the choice of wet–dry configuration cannot be treated as a purely numerical detail in applications such as flood-risk mapping and renaturalization planning for urban intermittent streams. For the lower Riera de la Bisbal, differences in flooded area and local peak depth across configurations are large enough to affect flood-prone zoning and hazard-level classification at specific locations, even though the outlet hydrographs are almost indistinguishable. As a result, wet–dry tolerance and hydrological drying settings should be explicitly reported and subjected to targeted sensitivity analysis in 2D hydrologic–hydrodynamic studies that aim to support water-resources planning and design in data-scarce or intermittent systems.

The evaluation presents several limitations. The analysis was limited to one symmetric triangular inflow hydrograph; wet–dry-front sensitivity under alternative hydrograph shapes was not evaluated. Future work should extend this analysis to transient inflow conditions, multiple diagnostic locations, and additional combinations of terrain complexity, grid resolution, and numerical solvers in order to better characterize how wet–dry parameterization affects both stability and hydrological realism at larger scales. Because no observational discharge or inundation data were available for calibration or validation, the

conclusions reported here concern the numerical behavior of Iber under different wet–dry configurations, and their applicability to real flood-risk assessment is limited by the absence of field verification. The conclusions are limited to the tested mesh resolution and CFL setting because mesh- and time-step-independence were not evaluated; future work should include a formal numerical convergence analysis.

From an operational standpoint, these findings translate into four practical recommendations for modelers and water-resources managers. The ε_{wd} value and the hydrological drying configuration used in any 2D hydrologic–hydrodynamic study intended for flood-risk assessment should be explicitly reported and justified rather than left at default settings. Default thresholds should not be adopted without at least a minimal sensitivity check, particularly in headwater reaches and intermittent-flow segments, where the present results show the largest local sensitivity. Prioritize more restrictive (smaller) thresholds when the objective is delineating local inundation extent, while more permissive thresholds may be acceptable when numerical stability is prioritized over local resolution. Fourth, consider the temporal persistence of local depth differences, not only their peak magnitude, when judging the practical relevance of wet–dry parameterization for infrastructure and risk-management decisions.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/limnolrev26040060/s1>: Figure S1: Local water-depth hydrographs at Zone B (1.546240° E, 41.185498° N) for the four wet–dry configurations; Figure S2: Local water-depth hydrographs at Zone C (1.545339° E, 41.185103° N) for the four wet–dry configurations; Figure S3: Local water-depth hydrographs at Zone D (1.545923° E, 41.184000° N) for the four wet–dry configurations; Figure S4: Local water-depth hydrographs at Zone E (1.547794° E, 41.184083° N) for the four wet–dry configurations.

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