

Article

Effects of DEM Resolution on the Characterization of a Small Agroforestry Basin for Hydrological Modelling: The Case of Idanha—Portugal

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Abstract

Digital elevation models (DEMs) are key fundamental inputs in hydrological modelling, yet the influence of spatial resolution on basin delineation and process representation remains insufficiently understood, particularly in small catchments. This study investigates the influence of DEM resolution on topographic characterization and hydrological response in a small agroforestry basin in central Portugal. Three DEMs with resolutions of 5 m, 10 m, and 30 m were generated from contour data and satellite sources and processed using the TOPAZ-based TopAGNPS delineation framework. The sensitivity of basin structure to delineation parameters—critical source area (CSA) and minimum source channel length (MSCL)—was assessed, and the resulting configurations were used as inputs to the AnnAGNPS model. Results show that DEM resolution strongly influences the representation of hydrological cells and stream reaches. Increasing resolution from 30 m to 5 m leads to a nearly doubling of average cell slope and increases reach slope by more than four times, with corresponding changes in drainage network density and connectivity. Log-linear relationships were identified between slope and contributing area, as well as between slope and reach length, consistent with established geomorphic scaling laws. Hydrological simulations further indicate that resolution-dependent delineation significantly influences runoff, erosion, and peak discharge estimates, with finer resolutions increasing sensitivity to parametrization. Among land-cover scenarios, desertified conditions generate substantially higher runoff and peak flows compared to naturalized and forested conditions. Overall, the findings demonstrate that DEM resolution, together with preprocessing and delineation choices, exerts a critical control on hydrological model outputs. These effects are particularly pronounced in low-relief, human-influenced catchments, where coarse-resolution DEMs may lead to systematic underestimation of hydrological responses. The study highlights the need for resolution-aware modelling strategies and careful parametrization to improve the reliability and transferability of hydrological simulations.

Keywords: DEM; topographic modelling; hydrological simulation; TOPAZ; AnnAGNPS



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1. Introduction

Agroforestry systems are essential for sustaining human livelihoods, and their effective management is critical for long-term environmental and socio-economic sustainability. These systems are shaped by the interaction of natural processes and anthropogenic activities, such as tillage, irrigation, and agrochemical application, which influence productivity, ecosystem functioning, and resilience at both local and downstream areas. During storm events, surface runoff and erosion can severely impact catchments, reducing land productivity and limiting access to mountainous and hillside areas (e.g., Ref. [1]). Moreover, soil erosion and the transport of dissolved and sediment-bound chemicals affect agricultural productivity, food security, and public health [2,3]. Climate change further intensifies these challenges by increasing the frequency and intensity of extreme events, including floods and wildfires, thereby amplifying risks to both human safety and ecosystem stability [4,5].

Despite the inherent complexity of agroforestry systems, hydrological modelling has been widely applied for decades. In large basins, accurate representation of the stream network is typically the primary requirement for reliable simulations (Ref. [6]). In contrast, in small and medium-sized catchments, hydrological processes are more strongly controlled by detailed topographic attributes, particularly slope, terrain configuration, and channel morphology [7,8].

These attributes are derived from digital elevation data [9], obtained through land surveys, aerial photogrammetry, and remote sensing techniques [10]. LiDAR systems can achieve horizontal resolutions of a few centimetres [11]; however, most satellite-derived products provide digital surface models (DSMs) or digital terrain models (DTMs) that may still be influenced by vegetation and built structures. Consequently, the accurate extraction of bare-earth elevation (DEM) remains challenging [12,13], even when using unmanned aerial vehicles (UAVs) [14]. As a result, the digitization of paper topographic maps—despite being labor-intensive—continues to serve as a relevant source of elevation data.

Topographic maps, often produced through military surveys and updated by geo-hydrological agencies, are generally unaffected by vegetation and built structures. Although they may be outdated and influenced by ongoing geomorphic processes (e.g., slow-moving landslides and erosion), they remain valuable for generating high-resolution, high-accuracy DEMs [15]. Digitized elevation data can be represented as discrete points or contour lines, which are then interpolated into continuous surfaces and converted into regular grids (rasters) or alternative formats such as triangulated irregular networks (TINs) or polygonal coverages (e.g., Thiessen polygons). Vector-based approaches often better preserve contour-derived information [16,17]. However, contour interpolation is highly sensitive to the chosen method [18], and most hydrological models rely on raster DEMs [19] due to their computational efficiency and widespread availability, despite their typically coarser resolution (>10 m) [20].

Topographic resolution has been shown to significantly influence the delineation of stream networks and hillslope structures [21]. For example, Rusli et al. [15] demonstrated that elevation errors derived from raster DEMs increase with decreasing terrain relief, with particularly high uncertainties in flat areas. The influence of grid size on hydrological model outputs has been investigated extensively [22], with evidence indicating that model uncertainty—particularly in discharge estimates—tends to increase with basin size [23].

Hydrological simulation models are widely used to assess the effects of (synthetic) digital elevation models (DEMs). Several studies have examined the influence of spatial resolution on one of the most commonly applied models, AGNPS, often treating it as a black-box system. For example, Singh et al. [24] evaluated model responses for cell sizes ranging from 30 to 150 m, Wu et al. [25] analysed annual responses across resolutions from 30 m to 1920 m, and Bhuyan et al. [26] examined the effects of cell sizes between 4 and

260 ha. Despite these contributions, studies explicitly focused on small catchments (i.e., sub-kilometer or <200 ha) remain limited [27], even though they are critically important for agricultural management and local-scale hazard assessment.

More broadly, the relationship between DEM resolution and the representation of key hydrological processes (e.g., runoff generation and sediment transport) remains insufficiently constrained, particularly in small catchments.

Within hydrological modelling frameworks, DEMs are primarily used for basin delineation. A range of metrics has been proposed to evaluate the effects of delineation uncertainty and variability [28]. At coarser resolutions, the relationship between cell size, contributing area, and tributary initiation has been extensively investigated through the concept of drainage area thresholds (e.g., Refs. [29–31]).

At finer resolutions, however, the spatial distribution of physical attributes within the primary computational units—cells and reaches—becomes increasingly important for prediction of runoff, sediment yield, and nutrient transport in agroforestry catchments [32,33]. These attributes include soil properties, land use (LU), and land cover (LC) [34,35], although slope typically remains the dominant controlling factor.

The relationship between DEM resolution and slope, at both cell and channel scales, has been investigated, including for high-resolution datasets. However, limited attention has been devoted to systematically quantifying how resolution affects the statistical distribution of slopes of cells and reaches as a function of the key parameters governing the delineation algorithm. In TOPAZ, these are defined by the critical source area (CSA) and minimum source channel length (MSCL).

The present study aims to investigate the effects of DEM resolution derived from different sources, together with key parameters controlling basin delineation and slope distribution and evaluates their implications for hydrological response in a small agroforestry catchment. The analysis focuses on spatial resolutions ranging from 5 m to 30 m. Basin delineation is performed using the TopAGNPS raster tool, while AnnAGNPS is used to generate simulation outputs that provide quantitative metrics for comparing model responses across resolutions.

2. Materials and Methods

2.1. Study Area

The study area is the Idanha creek basin, located in mainland Portugal within the Beira Baixa region (7.170° W–7.149° W, 39.841° N–39.868° N), as shown in Figure 1. The basin covers approximately 1.90 km² and has a perimeter of 6.51 km. It is oriented NNE–SSW and ranges in elevation from 210 to 248 m a.s.l. The drainage density of permanent channels is 12.2 m ha^{−1}. The terrain is predominantly flat to gently rolling, with slopes typically ranging from 0% to 4%. The Idanha creek is a third-order tributary of the Tagus river, which rises in central Spain and flows westward into the Atlantic Ocean at Lisbon.

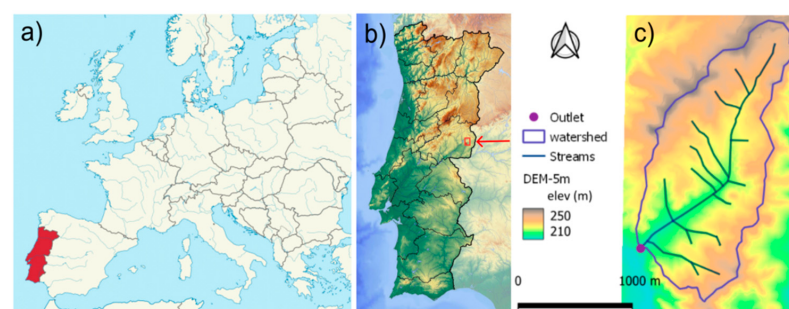


Figure 1. Location of Idanha basin (a) in Portugal (b), together with its elevation map and hydro-network (c).

The basin is predominantly characterized by Cambisols and Luvisols, with Fluvisols restricted to the lower-lying areas adjacent to the stream (Figure 2). The area is sparsely populated, comprising only a limited number of farmsteads. It forms part of the Idanha Irrigation Project, which covers approximately 8000 ha and is distinguished by its relatively uniform agricultural land use.

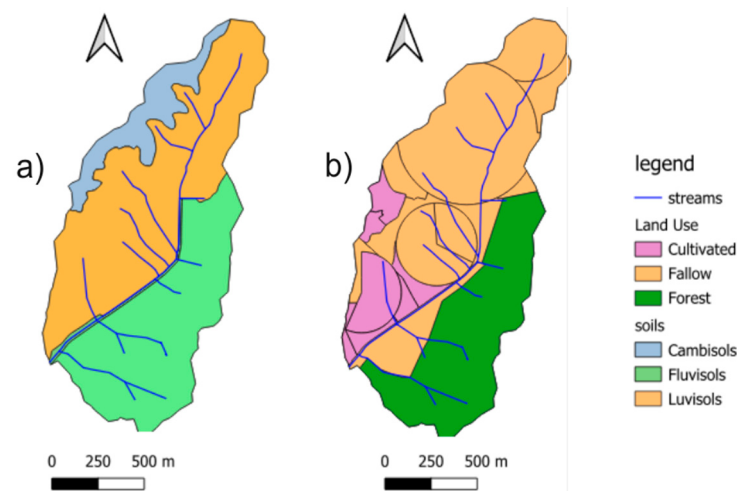


Figure 2. Soil types (a) and land use (b) of Idanha basin (circles identify surfaces with an irrigation plant).

Cropping systems include winter cereals (primarily wheat), as well as irrigated crops such as maize, pasture, tomato, and tobacco. Following Portugal's accession to the European Union, agricultural practices underwent substantial change under the Common Agricultural Policy, leading to shifts in cropping intensity with consequent impacts on water use, hydrological response, and soil erosion rates [36].

At present, land use within the basin and the surrounding irrigation district is dominated by irrigated pasture and more recently, perennial crops, particularly almond orchards. Natural areas consist of Mediterranean shrubland communities dominated by *Cistus ladani-fer* L., *Erica arborea* L., *Lavandula stoechas* L., and *Phillyrea angustifolia* L., with scattered trees including *Arbutus unedo* L., *Quercus suber* L., and *Quercus ilex* L. subsp. *rotundifolia* (Lam.).

2.2. Methodology

The methodological framework comprises two main components: (i) data preprocessing and basin delineation, and (ii) hydrological simulation and output analysis. The first component (left-hand side of Figure 3) focuses on the preparation of input datasets and the generation of basin configurations. Basin delineation is controlled by two key parameters—critical source area (CSA) and minimum source channel length (MSCL)—as described below. Their combination yields multiple raster-based representations of the basin.

In the second component, hydrological simulations are performed for each delineation scenario. Model outputs, including runoff, streamflow (outflow), and soil erosion, are used as quantitative indicators to assess the influence of basin discretization on model response. The delineation results are further integrated with the soil maps of the study area to ensure the spatial consistency of model inputs.

Additionally, three hypothetical land cover scenarios and two extreme-event forcing conditions are incorporated into the analysis (right-hand side of Figure 3). This approach enables a systematic evaluation of model sensitivity to variations in both surface characteristics and hydroclimatic drivers.

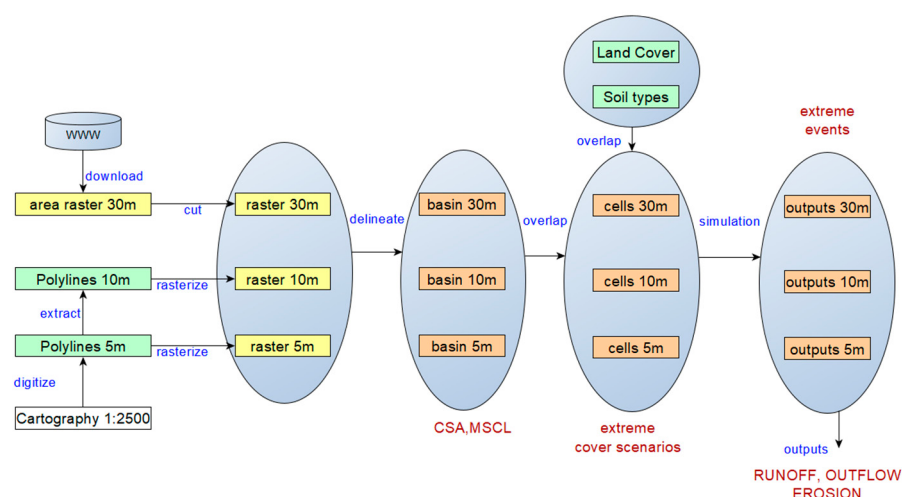


Figure 3. Workflow illustrating the progression of the study from data acquisition to hydrological modeling outputs. Spatial datasets were collected and standardized (30 m, 10 m, and 5 m), including raster and vector layers. Rasterization and delineation generated basin-scale inputs, which were integrated within the CA–MSCL framework by overlaying land cover and soil data to create scenario-based maps. These inputs were used to simulate hydrological responses, producing runoff, outflow, and erosion outputs at corresponding resolutions, highlighting the effect of spatial refinement on model results.

2.2.1. Data Collection

Topographic information for the study area was derived from paper topographic maps at a scale of 1:2500 [37]. In addition, a 1 arc-second DEM from the Shuttle Radar Topography Mission (SRTM) [11] was incorporated into the analysis. Comparable elevation datasets are also available from [38,39], with spatial resolutions similar to those commonly used in widely accessible mapping platforms.

The stream network was initially delineated from orthophotography provided by the National Centre of Geographic Information, based on aerial imagery acquired in 1995. This dataset was subsequently refined through a GPS-based field survey conducted in 2009 using a TRIMBLE GeoExplorer3 device with differential correction. Field observations confirmed the absence of significant topographic changes between the two acquisition periods. Therefore, it was assumed that the terrain has remained stable, and the dataset was considered representative of current conditions.

2.2.2. Data Preprocessing

All geospatial data were processed using the open-source platform QGIS, adopting the projected coordinate reference system EPSG:20790 (Lisbon/Portuguese National Grid). The spatial extent of the study area is defined by the following coordinates: N = 322'644 m, S = 319'571 m, W = 282'378 m, and E = 284'234 m.

Three raster DEMs, with spatial resolutions of 5 m, 10 m, and 30 m, were generated for the study area. The 5 m and 10 m DEMs were derived from digitized contour lines extracted from paper topographic maps, with contour intervals of 1 m and 5 m, respectively (Figure 4a,b). The resulting vector datasets were interpolated and smoothed using the GRASS library [40], specifically the *v.surf.rst* function, with parameters set to tension = 50 and smooth = 1.5. The 1 arc-second (~30 m) DEM (file code ALPSMLC30_N039W008, given in WGS84) was obtained from [41] (Figure 4c). All datasets were subsequently reprojected to the EPSG:20790 coordinate system to ensure spatial consistency across analyses.

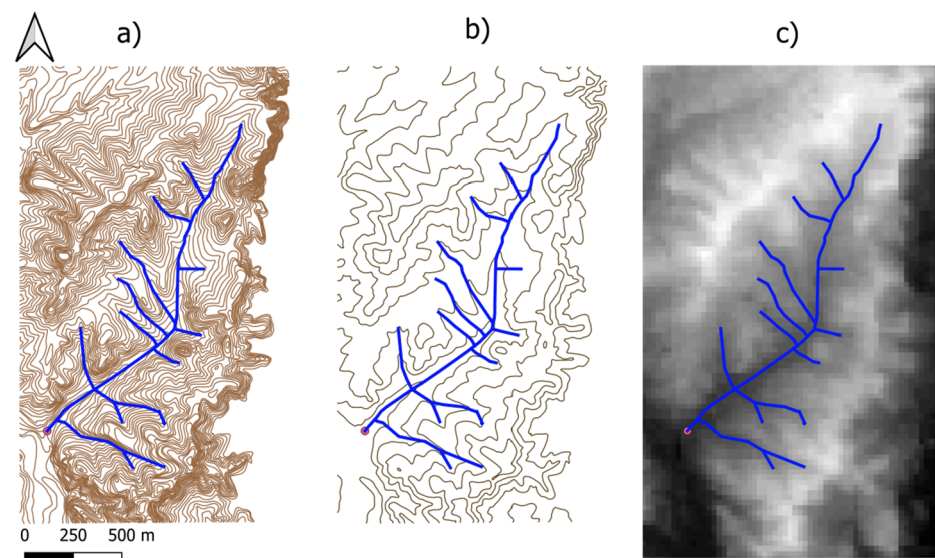


Figure 4. Topographic information used in the analysis obtained from (a) 1 m and (b) 5 m contour lines, and (c) 30 m raster DEM. The blue lines represent the observed hydro-network, and pink dot represents the outlet of the basin.

The three derived DEMs, with spatial resolutions of 5 m, 10 m, and 30 m, comprise grids of 371×615 , 186×307 , and 62×102 cells, respectively.

The DEMs derived from photogrammetric contour data (5 m and 10 m resolution) exhibit a horizontal accuracy of approximately 0.5 m and a vertical accuracy of approximately 0.15 m. In contrast, the SRTM-based DEM (30 m resolution) has a lower spatial accuracy, with horizontal and vertical accuracy of approximately 10 m and 5 m, respectively.

2.2.3. Basin Delineation Methodology

Hydrological delineation is used to derive a synthetic stream network, typically enhancing the observed network through the inclusion of higher-order channel elements [42]. A variety of delineation algorithms is available in commonly used GIS platforms [43–45], many of which are based on the TOPAZ model [46]. In this study, basin delineation was performed using TopAGNPS [47], an implementation of TOPAZ integrated within the AGNPS modelling framework [48].

The delineation procedure comprises three main steps:

- Flow direction assignment: Each raster cell is assigned a flow direction based on the steepest downslope gradient, using the D8 algorithm, which routes flow toward one of the eight neighboring cells.
- Flow connectivity analysis: Cells are connected according to their assigned flow directions, thereby generating a continuous drainage network.
- Stream definition and ordering: A Strahler stream order classification scheme is assigned, whereby stream order (s) increases with flow convergence. Cells with stream order below a user-defined threshold (e.g., $s < 6$, determined from preliminary analysis) are excluded, as they typically represent hill-slope flow rather than permanent channels.

Following these steps, a user-defined outlet is specified to delineate the basin and its associated drainage network, extending upstream to all contributing cells, including headwater cells (Strahler order = 0). The resulting raster representation is subsequently aggregated into hydrological response units (cells) and stream reaches for use in hydrological simulations (Figure 5).

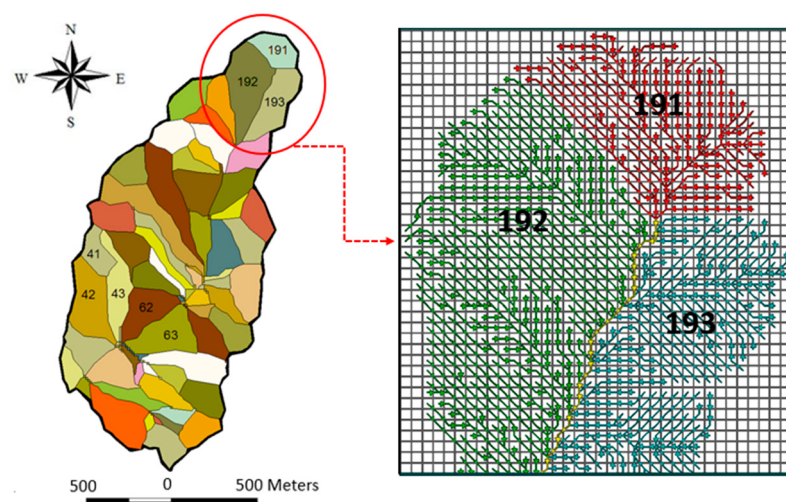


Figure 5. The Idanha basin is represented through a raster-based interpretation of its hydrological network. On the right side, the raster cells are displayed alongside the stream reaches (yellow lines). Within the 1st order channel, the sub-catchment is composed of three types of hydrological cells: cell 191, draining the catchment ahead, and cells 192 and 193, draining the right and left sides of the main channel, respectively.

2.2.4. Sensitivity Analysis of Delineation Parameters

TOPAZ delineates drainage networks based on two key parameters: the critical source area (CSA), which defines the contributing area threshold for channel initiation, and the minimum source channel length (MSCL), which specifies the minimum length of first-order channels. The influence of the CSA has been widely investigated in previous studies [49,50] for catchments ranging from 0.5 to 8 km², and it remains a central parameter in model calibration [51].

To assess the effects of DEM resolution on basin structure, a sensitivity analysis was conducted for both CSA and MSCL. In accordance with recommendations of TOPAZ developers [52], CSA values were set to be greater than or equal to 10 grid cells and MSCL values were defined at least twice the DEM spatial resolution. The range of parameter values considered in the sensitivity analysis is reported in Table 1.

Table 1. Values of CSA and MSCL adopted in TopAGNPS for the sensitivity analysis.

Resolution (m)	CSA (ha)	MSCL (m)
5	0.05, 0.1, 0.2	(5, 10, 20; 5, 10, 20; 10, 20, 50)
10	0.1, 0.2, 0.5	(10, 20, 50; 10, 20, 50; 20, 50, 100)
30	1, 2, 5	(50, 100, 200; 50, 100, 200; 100, 200, 500)

2.2.5. Hydrological Modelling

The AnnAGNPS model was developed to simulate hydro-chemical responses to agricultural and forestry management practices [53]. It estimates the water balance by integrating key components, including precipitation, irrigation (and associated management parameters), evapotranspiration, infiltration, surface runoff, and baseflow [54].

Surface runoff is a fundamental process in hydrological modelling. In AnnAGNPS, it is estimated using the Soil Conservation Service Curve Number (SCS-CN) method [55], which expresses direct runoff (Q) as $Q = (P - I_a)^2 / (P - I_a - S)$, a function of rainfall (P), initial abstraction (I_a), and potential maximum retention (S). The retention parameter S is derived from the Curve Number (CN) according to: $S = 25,400 \cdot CN - 254$, where CN values are obtained from standard tables based on hydrological soil groups [55]. The initial

abstraction I_a , representing interception, depression storage, evaporation, and infiltration prior to runoff generation, is typically related to S through a proportionality coefficient λ : $I_a = \lambda \cdot S$, where λ is the initial abstraction coefficient. According to [56], λ may range from 0.095 to 0.38, but it is commonly assumed to be 0.2, including in AnnAGNPS. Under this assumption, the runoff equation simplifies to: $Q = (P - 0.2 S)^2 / (P - 0.8 S)$. Further details on the implementation of the SCS-CN method within AnnAGNPS are provided in [54] (Section 6.1).

Soil erosion, expressed as soil loss (A), is estimated using the Revised Universal Soil Loss Equation (RUSLE) [56]: $A = R \cdot K \cdot LS \cdot CP$.

The RUSLE formulation is based on several key factors: rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), and the cover-management and conservation practice factor (CP). In this study, the CP factor was set to 1, reflecting the absence of specific conservation practices. The model adopts a unit-area approach, whereby the K factor is defined assuming uniform slope and slope length conditions.

TopAGNPS produces a set of raster outputs (18 in total), including the LS factor for each hydrological cell. These cells are subsequently attributed with soil properties and land use/land cover (LULC) information based on dominance criteria. In addition, the model generates input template files describing the physical and hydraulic characteristics of cells and stream reaches, which are completed prior to executing AnnAGNPS simulations.

Land cover data are further used to parametrize key hydraulic properties, in particular Manning's roughness coefficient (n ; Table 2).

Table 2. Manning coefficients for the land covers simulated in Idanha basin from values suggested by Engman [57].

n	Surface Description
0.02	Bare, compacted soil (hardpan, crusted)
0.05	Rangeland (natural, sparse cork trees)
0.13	Forest

Reach geometry was parametrized using three variables: top width, valley width, and flow depth. A minimum top width of 1 m was assigned to the upstream reaches, increasing to a maximum of 3 m at the basin outlet. For intermediate reaches, valley width was estimated as a function of reach length and the maximum width of contributing upstream reaches, which was adopted as the corresponding top width. Flow depth was approximated as one-half of the valley width. Channel bed material was assumed to be sand ($Sand_Scour_Code = Y$).

To evaluate the effects of short-duration rainfall, storm events were generated using a Neyman–Scott rectangular pulse model. AnnAGNPS was configured to simulate 24-h events with a temporal resolution of 6 min. Two high-intensity rainfall scenarios were considered (30 mm h^{-1} and 60 mm h^{-1}), each evaluated under three contrasting Curve Number (CN) conditions:

- NAT: naturalized conditions (rangeland; $CN = 50$);
- DES: degraded conditions typical of post-disturbance environments (e.g., post-fire), characterized by bare soil ($CN = 70$);
- TRO: “tropicalized” conditions, representing increased vegetation cover due to land abandonment and climate-driven shifts (forest; $CN = 30$).

AnnAGNPS (version 5.5) was implemented using a simplified configuration, limited to essential inputs, including weather data, simulation settings, basin characterization, and land management. Advanced modules and optional components were intentionally

excluded. Specifically, the model setup did not incorporate user-defined hydraulic geometry coefficients, gully processes (classical or ephemeral), wetlands, impoundments, landslides, or detailed erosion sub-models. Agricultural management practices such as irrigation, fertilisation, pesticide application, and feedlots were also omitted. Likewise, additional conservation measures and infrastructure elements—including riparian buffers, contour farming, strip cropping, tile drainage, field ponds, aquaculture, and point-source pollution—were not considered. No calibration parameters or adjustments available in version 5.5 were applied.

The exclusion of these components was motivated by two main considerations. First, field observations indicate that processes such as waterlogging and badland formation are not relevant within the study area. Second, a parsimonious model configuration was adopted to minimize the introduction of uncertainty associated with uncalibrated parameters, which could otherwise affect model outputs in a non-systematic and difficult-to-interpret manner.

3. Results

3.1. Basin Delineation

The effects of DEM resolution and delineation parameters (CSA and MSCL) are evident across all selected metrics. In particular, the number of hydrological cells varies substantially as a function of both resolution and parameter combinations.

At the coarsest resolution (30 m; Figure 6a), the number of cells ranges from 13 to 149. This increases to between 83 and 1930 cells at the intermediate resolution (10 m; Figure 6b), and further to between 277 and 4809 cells at the finest resolution (5 m; Figure 6c).

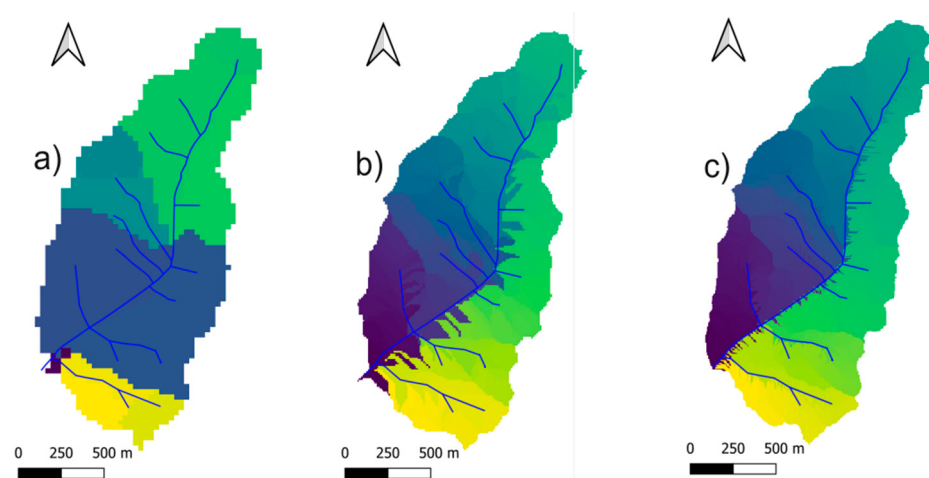


Figure 6. The study area was delineated into sub-basins using DEM resolutions of 30 m, 10 m, and 5 m. Corresponding parameter values were set to CSA = 5 ha and MSCL = 500 m (a), CSA = 0.2 ha and MSCL = 50 m (b), and CSA = 0.05 ha and MSCL = 5 m (c). The observed hydro-network is represented by the blue line.

Figure 5 illustrates the corresponding variability in basin delineation through three representative configurations.

Delineation parameters exert a significant influence on the estimation of cell slope (Figure 7). At the highest resolution (5 m), the average slope is approximately 6%, whereas at the intermediate resolution (10 m) it decreases to about 4%, corresponding to a reduction of more than 2 percentage points.

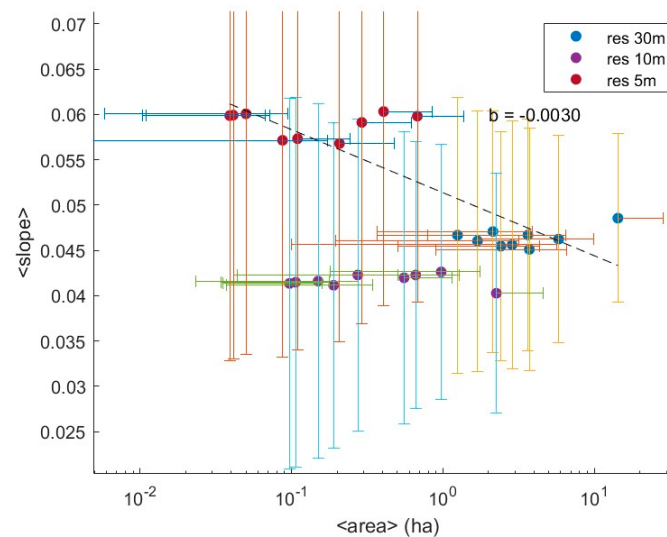


Figure 7. Relationship between average slope and the average area of hydrological cells, with standard deviations reported for both values, based on cells.

The relationship between average slope and contributing area, as affected by DEM resolution, was described using a log-linear model of the form: $slope = a + b \log(area)$ with $b \approx -0.003$, indicating an approximate decrease of 1 percentage point in slope for each order-of-magnitude increase in contributing area. Data associated with the 10 m resolution were classified as outliers and were therefore excluded from the regression analysis.

Reach length is strongly influenced by DEM resolution (Figure 8), although the relationship exhibits an approximately linear trend. Variations in delineation parameters resulted in changes in reach slope ranging from 1 to 4.5 percentage points (absolute values). This behaviour suggests that, while reach geometry scales predictably with resolution, slope estimates remain sensitive to parametrization, reflecting the combined influence of network structure and topographic smoothing.

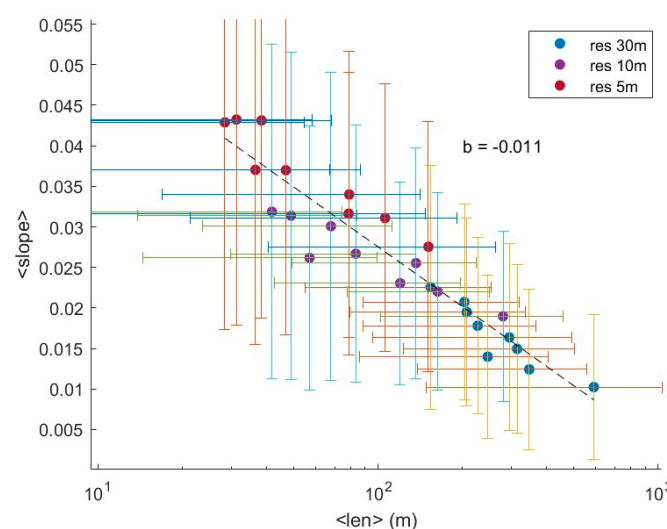


Figure 8. Relationship between average slope and length of reaches.

The relationship between average slope and reach length across different DEM resolutions can be described by a log-linear function of the form: $slope = a + b \log(length)$. The fitted coefficient $b \approx -0.011$, indicating a decrease of about 1.5 percentage points in slope for each order-of-magnitude increase in reach length. This pattern is consistent with established geomorphic scaling relationships linking channel slope to contributing area

and channel length and reflects the tendency of fluvial systems to adjust toward lower gradients at increasing spatial scales.

The delineation procedure produced drainage networks that are broadly consistent with the observed network. However, coarser resolutions led to an under-representation of channel branching. At 10 m resolution (Figure 9b), finer structural elements begin to emerge, whereas the 5 m resolution (Figure 9c) captures additional small-scale features. These higher-resolution representations provide improved support for field-based investigations, including the identification of previously unmapped reaches and the refinement of the permanent drainage network (Figure 9).

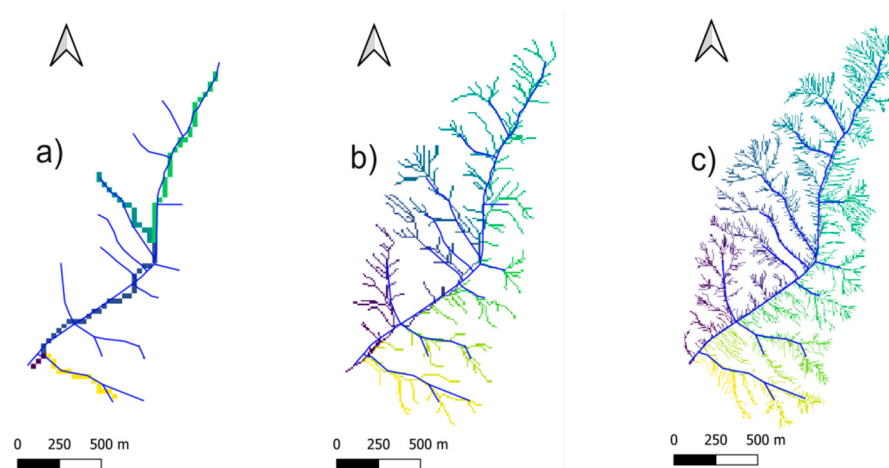


Figure 9. The observed natural channel network observed (blue line) overlaid with the hydro-network generated by TopAGNPS at resolutions of 30 m (a), 10 m (b), and 5 m (c). The corresponding CSA and MSCL parameter values are 5 ha and 500 m (left, (a)), 0.2 ha and 50 m (centre, (b)), and 0.05 ha and 5 m (right, (c)).

3.2. Hydrological Simulations

The influence of rainfall magnitude on basin response, under the delineation configurations defined above, is summarized in Figure 10. The figure presents runoff (Figure 10a), peak discharge (Figure 10b), and soil erosion (Figure 10c) for the three land-cover scenarios considered: naturalized (NAT), desertified (DES), and tropicalized (TRO).

Colored bars represent the range of simulation outputs (minimum–maximum) across delineations at the three spatial resolutions. Results are reported for rainfall intensities of 30 mm h^{-1} (left panels) and 60 mm h^{-1} (right panels).

As expected, the desertified scenario (DES) produces substantially higher runoff and peak discharge compared to both the naturalized (NAT) and tropicalized (TRO) scenarios, which yield broadly similar responses. In contrast, model outputs in terms of soil erosion are less sensitive to land-cover conditions. The markedly higher peak discharge at the basin outlet under DES highlights the role of vegetation loss in enhancing runoff generation, with direct implications for flood risk.

A comparison of the simulation ranges within each group indicates that runoff and erosion become increasingly sensitive to delineation parameters at finer resolutions, whereas peak discharge exhibits the opposite tendency.

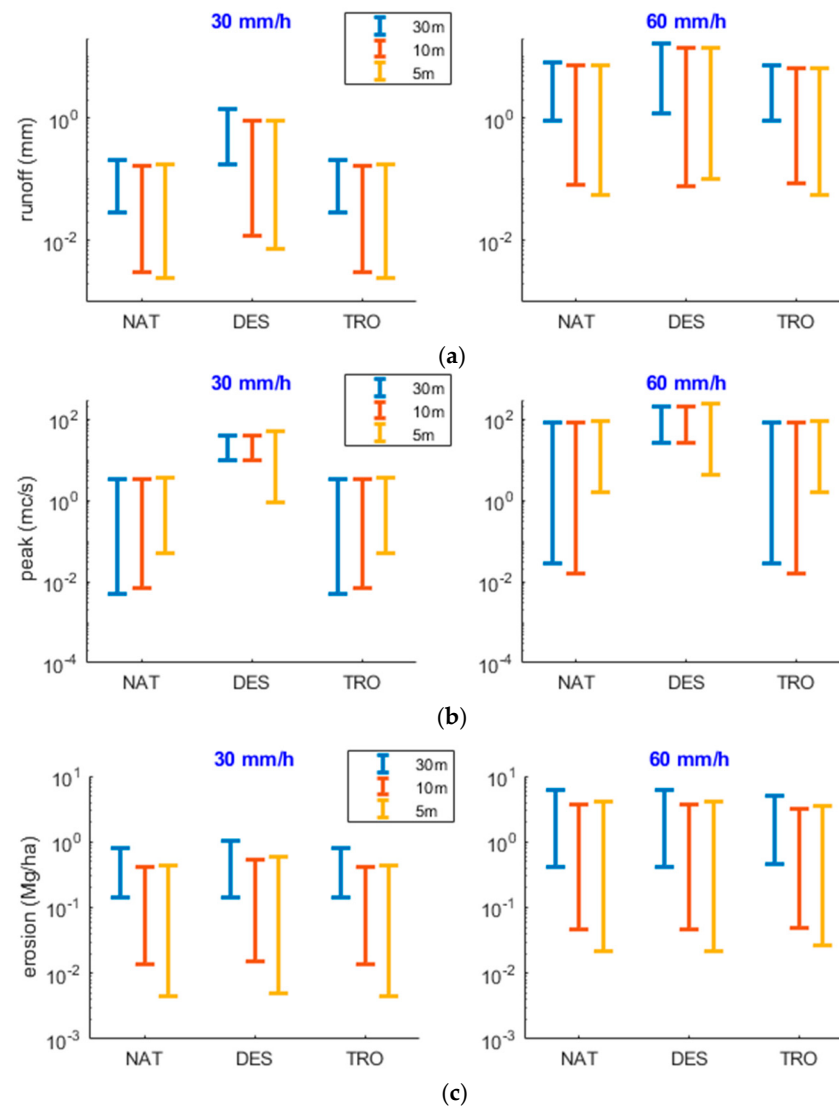


Figure 10. Simulation results for the three different scenarios: naturalized (NAT), desertified landscape (DES), and tropicalized landscape (TRO). Error bars represent the variability generated by different CSA and MSCL values for run-off (a), peak flow (b) and erosion (c).

Table 3 reports the numerical values corresponding to the results shown in Figure 10. Under the 30 mm h⁻¹ rainfall scenario, the NAT and TRO conditions exhibit limited hydrological response, with erosion (Figure 10c) ranging between 0.2 and 0.5 t ha⁻¹, runoff (Figure 10a) between 0.06 and 0.1 mm (Figure 10a), and peak discharge between 0.003 and 0.007 m³ s⁻¹ (Figure 10b). In contrast, the DES scenario yields substantially higher responses: minimum erosion values nearly double, while both runoff and peak discharge increase by more than an order of magnitude relative to the other scenarios. In addition, maximum erosion values at 30 m resolution (~0.6 t ha⁻¹) are approximately 1.5–2 times higher than those obtained at 10 m and 5 m resolutions.

Under the 60 mm h⁻¹ rainfall scenario, all metrics increase markedly. Maximum erosion rises from approximately 0.5 t ha⁻¹ to 3 t ha⁻¹, runoff from less than 1 mm to about 9 mm, and peak discharge from below 0.05 m³ s⁻¹ to over 2 m³ s⁻¹. While minimum values remain relatively consistent across scenarios (Figure 10), maximum peak discharge values at 5 m resolution exceed those obtained at coarser resolutions.

Table 3. Summary of minimum and maximum simulated values of runoff, erosion, and peak flow for the various combinations of DEM resolution, delineation parameters, land cover scenarios, and the two rainfall events.

	sce	RES (m)	30 mm/h		60 mm/h	
			min	max	min	max
Erosion (m ³)	DES	30	0.304	0.585	2.388	3.231
		10	0.280	0.280	1.763	1.855
		5	0.291	0.299	2.031	2.074
	NAT	30	0.177	0.467	2.388	3.231
		10	0.210	0.210	1.763	1.855
		5	0.217	0.226	2.031	2.074
	TRO	30	0.177	0.467	1.877	2.785
		10	0.210	0.210	1.492	1.589
		5	0.217	0.226	1.793	1.793
Runoff (mm)	DES	30	0.451	0.795	6.478	8.911
		10	0.453	0.453	7.135	7.135
		5	0.442	0.450	7.129	7.252
	NAT	30	0.060	0.117	2.667	4.463
		10	0.081	0.084	3.477	3.620
		5	0.082	0.087	3.592	3.704
	TRO	30	0.060	0.117	2.286	4.101
		10	0.081	0.084	3.115	3.268
		5	0.082	0.087	3.241	3.355
Peak Flow (m ³ /s)	DES	30	0.027	0.049	0.829	1.520
		10	0.025	0.025	0.848	1.415
		5	0.025	0.025	0.841	2.208
	NAT	30	0.003	0.007	0.198	0.341
		10	0.005	0.005	0.231	0.345
		5	0.005	0.005	0.216	0.437
	TRO	30	0.003	0.007	0.208	0.363
		10	0.005	0.005	0.229	0.392
		5	0.005	0.005	0.505	0.505

4. Discussion

While the rasterization procedure produced a high-quality DEM at 5 m resolution, the lower density of contour lines associated with the 10 m dataset resulted in anomalously low slope values, reflecting an inadequate reconstruction of the terrain surface. This artifact was not observed in the distribution of channel slopes.

Excluding the 10 m dataset, the delineation results are consistent with those reported by [24], who observed a 53.7% reduction in flow path length and a 20.9% decrease in average slope (relative to the reference condition) as cell size increased from 30 m to 180 m. The magnitude of slope reduction observed in this study is also consistent with previous findings [58,59], which report relative decreases of approximately 10–20% between 5 m and 10 m resolutions, and 25–50% between 5 m and 30 m resolutions.

The importance of slope representation is further supported by Muthusamy et al. [60], who demonstrated that channel slope exerts a strong control on hydraulic processes, significantly affecting channel conveyance and the reliability of flow simulations.

Given the application framework of AnnAGNPS, model outputs (runoff, erosion, and peak discharge) are interpreted here as comparative indicators rather than absolute estimates. In this context, the results are consistent with those of [25], who reported a substantial decrease in the reliability of runoff estimates with increasing cell size (30–1920 m). Similarly, Bhuyan et al. [26] highlighted the sensitivity of peak discharge estimates to cell size. Nazari-Sharabian et al. [61], using the SWAT model, reported that runoff estimates derived from a 12.5 m DEM were only marginally higher (0.74% and 2.73%) than those obtained from 30 m and 90 m DEMs, respectively. In contrast, Rocha et al. [62], also using SWAT on a catchment of comparable size, found no statistically significant differences in seasonal outflow.

Finally, the analysis highlights the sensitivity of hydrological response to hypothetical land-cover changes associated with long-term processes (e.g., climate change) or disturbance events (e.g., wildfires). While the effect on soil erosion is relatively limited under the simulated extreme events, substantial increases are observed in both runoff and peak discharge.

5. Conclusions

Hydrological modelling plays a key role in understanding the processes driving hazards such as floods and landslides, whose frequency and intensity are increasing under changing climatic conditions. In this context, the digital elevation model represents a fundamental input, as higher-resolution datasets generally improve the representation of terrain and associated hydrological processes. However, model performance is not controlled by resolution alone: the data source, preprocessing procedures, and basin delineation methods all exert a significant influence on simulation outputs.

This study evaluates the effect of DEM resolution on the topographic characterization of a small catchment using the raster-based TOPAZ algorithm, with particular emphasis on the influence of automated delineation on the area, length, and slope of hydrological cells and stream reaches.

Results demonstrate that DEM resolution has a pronounced effect on both the mean and variability of slopes, even in a low-relief basin such as the one considered. Increasing resolution from 30 m to 5 m results in an approximate doubling of average cell slope, while reach slopes increase by more than a factor of four.

The hydrological implications of resolution-dependent delineation were assessed using the AnnAGNPS model. Physically based hydrological models require a large number of input parameters, which often limits their practical applicability and predictive robustness. In this study, AnnAGNPS was primarily used as a metric-generating tool, with outputs interpreted as comparative indicators within scenario-based analyses of land use and land cover change under extreme rainfall events (30 and 60 mm h^{−1}). Simulation results indicate that the naturalized (NAT) and tropicalized (TRO) scenarios produce comparable responses, whereas the desertified (DES) scenario leads to substantial increases in erosion, runoff, and peak discharge.

These findings confirm that DEM resolution exerts a significant influence on hydrological simulations—a relationship well established for large basins, but still insufficiently explored in small catchments. The analysis highlights two key methodological issues:

- Preprocessing sensitivity: DEM resolution and preprocessing choices can substantially affect derived topographic attributes, potentially introducing biases in both primary observations and secondary model outputs;

- Validation constraints: the validation of digitized terrain models remains challenging, as accurate delineation of reference stream networks and identification of channel initiation points require detailed local knowledge, often available only through field surveys.

Beyond the specific case of the Idanha basin, these results have broader implications for hydrological modelling in small to medium-sized catchments, particularly in agroforested and Mediterranean environments. The strong sensitivity of basin delineation and model outputs to DEM resolution suggests that similar effects are likely in other low-relief landscapes characterized by heterogeneous land use and significant anthropogenic influence. In such contexts, where subtle variations in slope and drainage connectivity can substantially alter runoff generation and sediment transport, the use of coarse-resolution DEMs may lead to systematic underestimation of hydrological responses. This has important implications for flood risk assessment, soil conservation planning, and the evaluation of land-use change scenarios under climate variability.

Furthermore, the results demonstrate that the influence of DEM resolution extends beyond geomorphological representation, directly affecting the reliability of process-based models used for environmental management and decision support. Although the increasing availability of high-resolution elevation data from LiDAR and UAV platforms offers significant opportunities to improve model performance, resolution alone is not sufficient. Careful consideration of data sources, preprocessing workflows, and model parametrization remains essential. The findings of this study therefore contribute to the development of more robust and transferable hydrological modelling practices across diverse environmental settings.

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