Accessible Batch Catchment Delineation: A Semi-Automated Workflow for Non-Hydrologists

Johannes Balkenhol[1], Christoph Schröder[1], Daniel Morant[2], Carlos Rochera[2], Antonio Camacho[2*]

[1]European Topic Centre for Spatial Analysis and Synthesis, University of Malaga, 29010 Malaga, Spain

[2]Cavanilles Institute of Biodiversity and Evolutionary Biology, University of Valencia, Paterna, Valencia E-46980, Spain

[*]Email corresponding author: antonio.camacho@uv.es

KEYWORDS: Drainage Area, Catchment, Upslope Contributing Area, Semi-Automated, Watershed, Delineation

Highlights

- Semi-automated workflow enabling batch catchment delineation for non-hydrologists
- Supplied recommended actions on handling hydrologically difficult cases
- Enables tailor-made, large scale catchment delineation, adapted to a variety of input data (monitoring sites, available DEMs)
- Supports large-scale water quality assessments, e.g. for the EU Water Framework Directive

This manuscript is a non-peer reviewed preprint submitted to EarthArXiv. It was submitted to the Environmental Modelling & Software journal for peer review on 23/12/2025.

Abstract

Catchment delineation is a prerequisite for hydrological and water-quality analyses but remains a practical barrier for non-hydrologists, particularly when large numbers of sites must be processed. We present here a semi-automated, reproducible workflow for batch catchment delineation using openly available GIS tools. The workflow was developed during delineation of 2,870 monitoring sites assessed for the EU Water Framework Directive and evaluated in a 25-site case study in southern Spain. We compare delineations derived from multiple global Digital Elevation Models (DEMs) and assess their congruency with official catchment boundaries using Jaccard similarity. Results show that 1 arcsec DEMs, particularly FABDEM and Copernicus GLO-30, provide the most accurate and consistent delineations, while coarser products show larger variability. We identify recurring failure modes related to infrastructure, artificial drainage, reservoirs and endorheic basins, and propose low-effort quality-control steps. The workflow enables reliable large-scale catchment delineation for research, management and planning with minimal hydrological expertise.

1 Introduction

Catchment delineation is a fundamental step in hydrology, water quality assessment and environmental modelling, as it defines the area from which surface runoff, sediments, nutrients, and pollutants are transported to a monitoring point. Catchment delineation is highly policy relevant, since legislations such as the European Union's Water Framework Directive (WFD) (European Commission, 2000) are organized via river catchments. Databases such as EU-Hydro (CLMS, 2019) or HydroBASINS (Lehner & Grill, 2013) provide prebuild catchment delineations, but they are tailored to whole or sub river catchments. This means that researchers often have to delimit the catchment areas for their study sites themselves if the research question requires a tailor-made delineation.

Even though DEM catchment delineation was already developed in the 1980s (O’Callaghan & Mark, 1984), it still presents a barrier for researchers not specialised in hydrology. Especially in water quality assessment, a multitude of simplified alternatives have been applied to model the effects of land use or land cover on water quality, such as buffer zones around a monitoring site (Huang et al., 2020; Song et al., 2020). While such buffer-based approaches are operationally attractive and easy to implement, they represent a fundamentally different spatial logic than hydrologically defined catchments. Buffer zones assume that areas closest to the waterbody exert the strongest influence, and have therefore been widely used as pragmatic proxies for land-use pressures on water quality, nutrient concentrations, and ecological condition. However, conceptual and empirical evidence indicates that buffers capture proximity-based effects, whereas catchments reflect hydrological connectivity and cumulative upstream influences (Mérot & Durand, 1996). Several studies have shown that catchment-scale land use explains water quality patterns more effectively than buffers, particularly for nutrients, as demonstrated for ponds and lakes across multiple spatial scales (Novikmec et al., 2016; Nielsen et al., 2012). Moreover, land uses located far from the waterbody but hydrologically connected can still exert strong impacts, challenging the assumption that near-shore areas alone drive degradation (Houlahan & Findlay, 2004). The widespread use of buffer approaches can therefore be understood less as a conceptual preference than as a response to persistent practical barriers in catchment delineation. These barriers can be grouped into two main categories. First, the terminology in runoff modelling is not clear-cut. Multiple terms (e.g. watershed, basin, upslope / upland contributing area, drainage area) are used synonymously or have different meanings in different parts of the English-speaking world (Thomas, 2002). This complicates studying literature and might veil discovery of a solution for a specific runoff modelling problem a researcher encounters. Second, the application of available tools might be too unintuitive or not adaptable enough for users to apply. While a lot of tutorials exist on online (video) platforms, they only show catchment extraction workflows for hydrologically simple locations (e.g. unaltered mountain streams with a clear outlet). These workflows are also only intended for single catchments, and do not explain how to scale the delineation process to numerous sites. To our knowledge, only one method for batch catchment delineation, provided by Heberger (2022) exists. This delineator is straight-forward to use and highly performant, but is limited by the limited selection of underlying elevation datasets and method of automatically snapping outlet points to a predefined stream network. Outlet snapping seems convenient, as it eliminates the need for manual placing and therefore reducing the time needed for delineation, but in our experience, this produces inadequate catchment delineations in too many cases. This again increases the volume of necessary post delineation adjustment or manual re-delineation, leading to much higher time effort than manually placing outlet points from the get-go.

To fill these gaps, we present a semi-automated batch delineation workflow developed to meet these needs. The workflow was created and refined while delineating 2,870 catchments for different kinds of wetlands (e.g. glacial lakes, reservoirs, rivers) corresponding to WISE SoE monitoring sites for the improvement of the LUPLES method (Morant et al. 2021) in the context of the Horizon Europe project RESTORE4Cs and has been designed to be accessible to non-hydrologists using openly available GIS tools. To evaluate the sensitivity of delineation outcomes to input DEM choice and conditioning, we also apply the workflow to a 25-site case study across southern Spain and compare delineations derived from FABDEM (Hawker et al., 2022), Copernicus GLO-30 (CDSE, 2022), Copernicus GLO-90 (CDSE, 2022), MERIT (Yamazaki et al., 2019) and HydroSHEDS (Lehner et al. 2008).

Our aims are threefold: (1) to provide a practical, reproducible workflow that enables fast and reproducible batch delineation with minimal specialized expertise; (2) to quantify how DEM choice and preprocessing affect delineation agreement with official catchment boundaries and with each other; and (3) to identify common failure modes and propose concrete, low-effort quality-control steps and recommendations for users working with monitoring datasets. We highlight recurring problems (bridges and embankments, artificial drainage networks and canals, reservoirs and multiple artificial outlets, and endorheic basins) that require localized manual handling. By improving the reliability of catchment delineation, this workflow directly supports land-use based pressure assessments applied in large-scale wetland evaluation frameworks, as exemplified by approaches such as LUPLES (Morant et al., 2021).

2 Material and Methods

2.1 Workflow

Figure 1 outlines our workflow, which is split into two paths - one for preconditioned DEMs and one for self-conditioning. Settings and actions for all tools employed in the workflow are documented in Appendix T2. On a Windows 10 workstation (eight virtual cores of an AMD EPYC 9354), we achieved processing rates of approximately 500 catchments per day under standard conditions, decreasing to ~300 catchments in hydrologically complex areas requiring additional manual adjustment. Because our research area covers the EU countries as well as WFD contributing countries (Switzerland, Bosnia-Herzegovina), the DEM was partitioned along the major European drainage divides to reduce file size and improve processing performance. Depression breaching for DEM tiles of roughly 10,000 × 10,000 to 20,000 × 20,000 pixels took 20 minutes to 1.5 hours, while generation of drainage direction and flow accumulation rasters required 5–20 minutes. Individual catchment delineations using r.water.outlet took 20–40 seconds, allowing approximately 90–180 catchments to be processed per hour in batch mode.

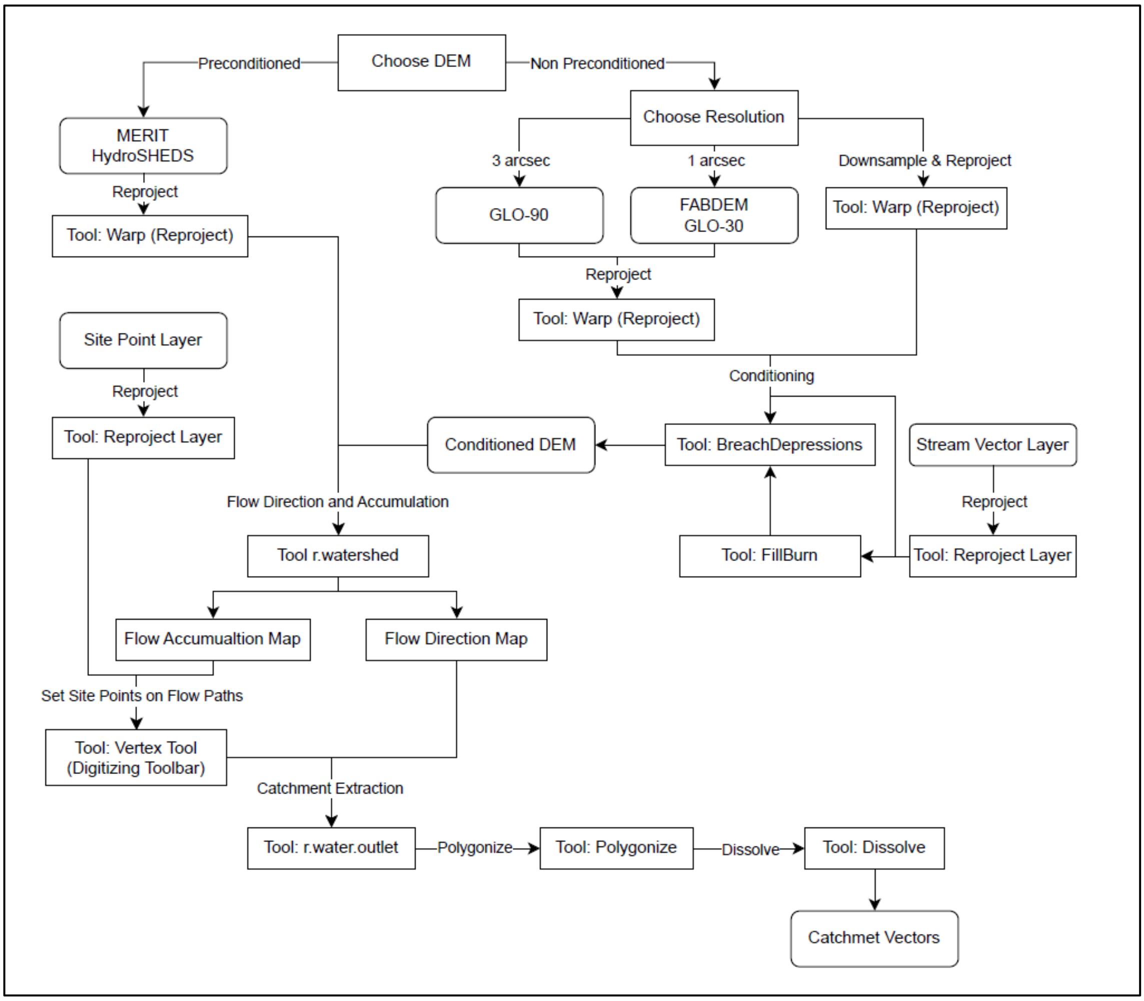

Figure 1: Workflow chart with pathways we recommend for catchment delineation with preconditioned or self conditioned DEMs. Setting / actions for each employed tool are listed in Appendix T2

2.2 Data

DEMs are categorized either as Digital Terrain (DTM) or Digital Surface Models (DSM). DSMs include every visual landscape feature such as buildings or even vehicles, while DTMs represent the bare earth. A DSM may have advantages in urban areas as buildings reroute runoff while DTMs disregard problematically represented landscape features such as bridges and forests. DEMs generally have to be conditioned before application in surface flow modelling to remove inaccurate measurement artifacts. This step can be done by either choosing a preconditioned one such as MERIT and HydroSHEDS (from here on Hydro) or condition it specifically. Choosing a preconditioned DEM saves processing time, and is therefore the most convenient way of conducting surface runoff modelling on larger scales. In some cases, it could be required or beneficial to condition a DEM. This is either the case if preconditioned DEM products are too coarsely resolved for the use case (3 arc sec for both MERIT and HydroSHEDS), or a custom modification is applied, like carving in a specific river network.

Unmodified DEM flow routing accuracy mainly depends on vertical accuracy and horizontal resolution. Both usually go hand in hand with increasing horizontal resolution, vertical accuracy rises as the density of measuring points increases. A highly horizontally resolved DEM based on LIDAR data (e.g. Spains MDT05) will yield the best vertical accuracy, unless systematic errors or biases underlay the dataset.

A comparison of freely available, global DEMs is given by Meadows et al., (2024), who conclude that FABDEM is the most accurate, followed closely by Copernicus GLO-30.

As we aim to compare preconditioned DEMs (Hydro & MERIT) to self-conditioned options, we chose Copernicus GLO-30 (from here on GLO-30), FABDEM and Copernicus GLO-90 (from here on GLO-90) and apply a pit breaching algorithms as a baseline conditioning. We further conditioned GLO-30 by carving in an Open Street Maps derived stream network (from here on GLO-30c) to make it more comparable to Hydro and MERIT, which include this step in their preconditioning as well.

2.3 Tools

The proposed methodology is executed in the QGIS 3.44.5 environment and is very likely feasible in earlier and future stable versions as well. Additionally, the QGIS plugins GRASS (8.0 version 2.0) and WhiteboxTools (version 1.0.9) are necessary to install. It is also recommended to utilize the QGIS Serval Plugin (version 3.32.0) for specific cases where manual catchment raster editing may be opportune. GRASS provides the solutions for surface runoff modelling algorithms and catchment extraction. WhiteboxTools is employed for hydrological DEM conditioning as it runs multithreaded compared to the singlethreaded options and therefore more performant. Regarding the flow routing algorithms, we suggest using Single Flow Direction (SFD) algorithms as they take less processing power compared to Multiple Flow Direction (MFD) ones.

SFD algorithms channel flow to the lowest elevation neighbouring cell, while MFD algorithms diverge to all or a selection of lower elevation neighbouring cells. Therefore, flow direction maps can be stored in a single band raster for SFD, compared to multi-band for MFD. Because of the diverging or channelling behavioural difference between SFD and MFD, differences in the resulting flow directions are highest in diverging landscape features such as saddles or ridgelines (Prescott, A. et al. 2025). These differences matter less with increasing size of the catchment area and increasing coarseness of the underlying DEM (Erskine, R. et al. 2006; Shelef, E. et al. 2013).

GRASS and WhiteboxTools include tools which depend on input layers to be in a projected coordinate reference system, as their processing algorithms assume uniform and linear cell geometry. We also recommend reprojecting all inputs to the identical projected coordinate system, as it is necessary for carving stream networks and dissimilarity can lead to errors when defining outlet positions.

3 Case Study - Study Area

The 25 sites used for the DEM comparison are located in southern Spain (Figure 2). We selected catchments of varying sizes to examine how catchment scale influences the suitability of differently resolved DEMs. Their sizes range from the approximately 4.8 km² Arroyo del Manzano to the 57,000 km² Guadalquivir catchment. An overview for all study catchments is found in Appendix T1. We cover this broad ranger with the aim to show how delineation accuracy changes with catchment size and DEM resolutions.

We compared our DEM-derived delineations with the official delineation dataset of Spanish catchments and sub-catchments obtained from the Spanish Ministry for Ecological Transition (2025) to assess differences in catchment area and evaluate how well the respective delineations capture local hydrological characteristics. The 25 study sites did not include all the hydrologically challenging cases we want to examine. Therefore, we supplement them with examples from across Europe and provide recommendations for achieving high-accuracy delineations under the specifically difficult hydrological conditions.

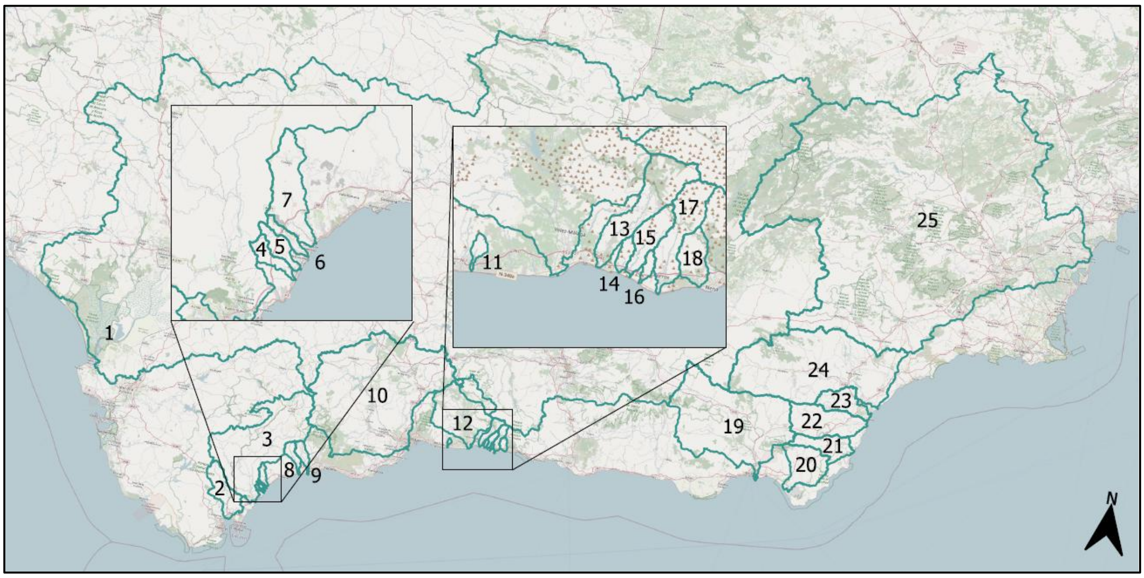

Figure 2: Study Area in southern Spain. Numbers 1–25 reference the study catchment IDs. Site Names and catchment sizes are found in Appendix T1.

4 Results - Case Study Application

We calculated Jaccard Similarity Index (Jaccard, 1908) scores for all combinations of DEM extracted and official catchments as a measure of how well these DEM extracts match the officially delineated catchments. The official delineations are not necessarily perfect presentations of surface runoff, but rather represent the official delineations for river basins management and planning. For example, the official delineation of the Río Segura catchment includes the endorheic catchments of Yecla and Corral-Rubio.

Therefore, we also calculated scores between the DEM delineation as additional accuracy indicators.

Averaged over the 25 catchments, the delineations from the 1 arcsec resolution DEMs FABDEM and GLO-30c perform best in comparison to the official dataset, followed by GLO-30, MERIT and GLO-90 with HydroSHEDS in last place (Figure 3). In DEM-DEM comparisons, FABDEM achieves the highest similarity score with GLO-30 (GLO-30 and GLO-30c excluded). HydroSHEDS performs worst in all its DEM comparisons. All other comparisons reach around 94-95 % congruence.

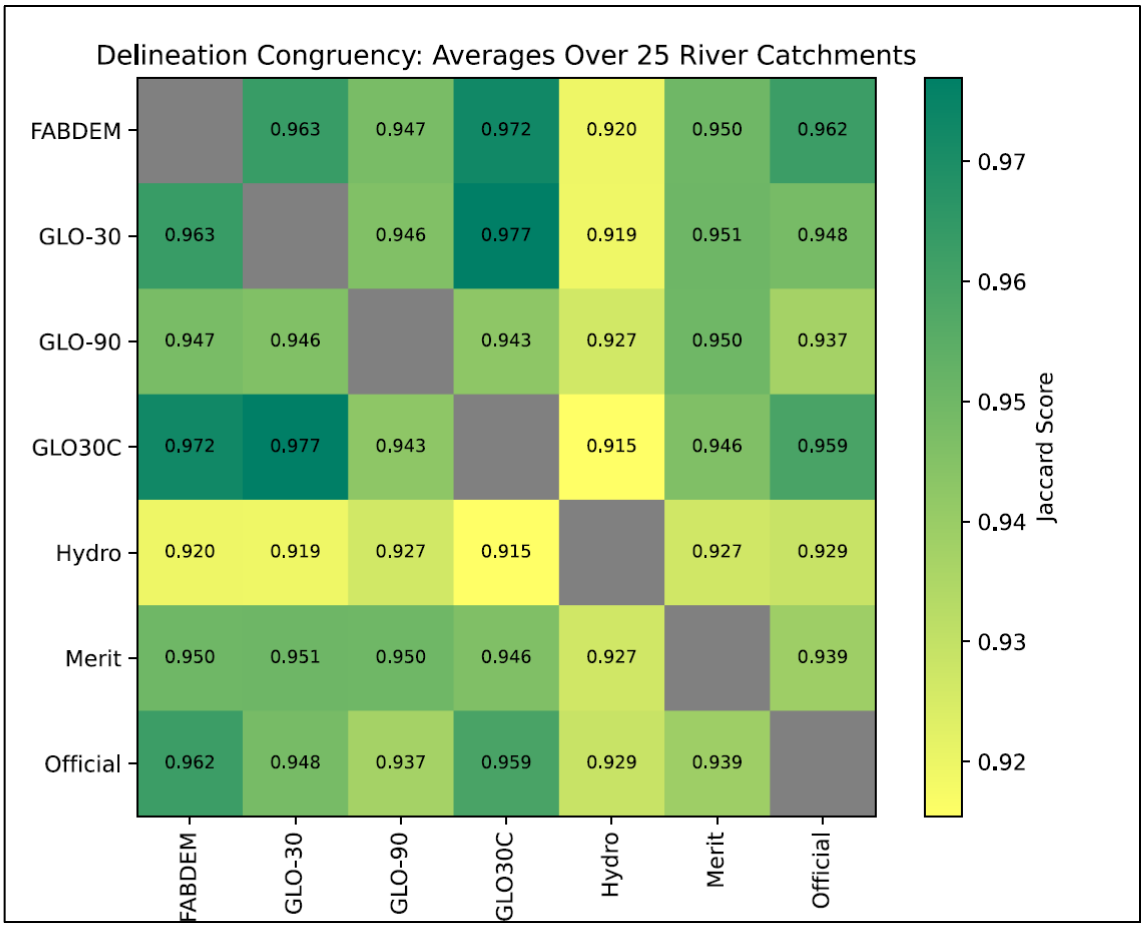

Figure 3: Heat map of average Jaccard scores over the 25 study sites. FABDEM reaches the highest values in comparison with GLO-30 and the official dataset. HydroSHEDS produces the least equal delineations in comparison to all other DEMs and the official dataset.

Variability wise, FABDEM exhibits the smallest interquartile range when compared to the official dataset, indicating the most consistent delineation performance across sites

(Figure 4). Hydro expresses the highest variability when compared to other DEM delineations. All comparisons contain at least one outlier below 80 % similarity, which underlines the importance of quality checking delineation results.

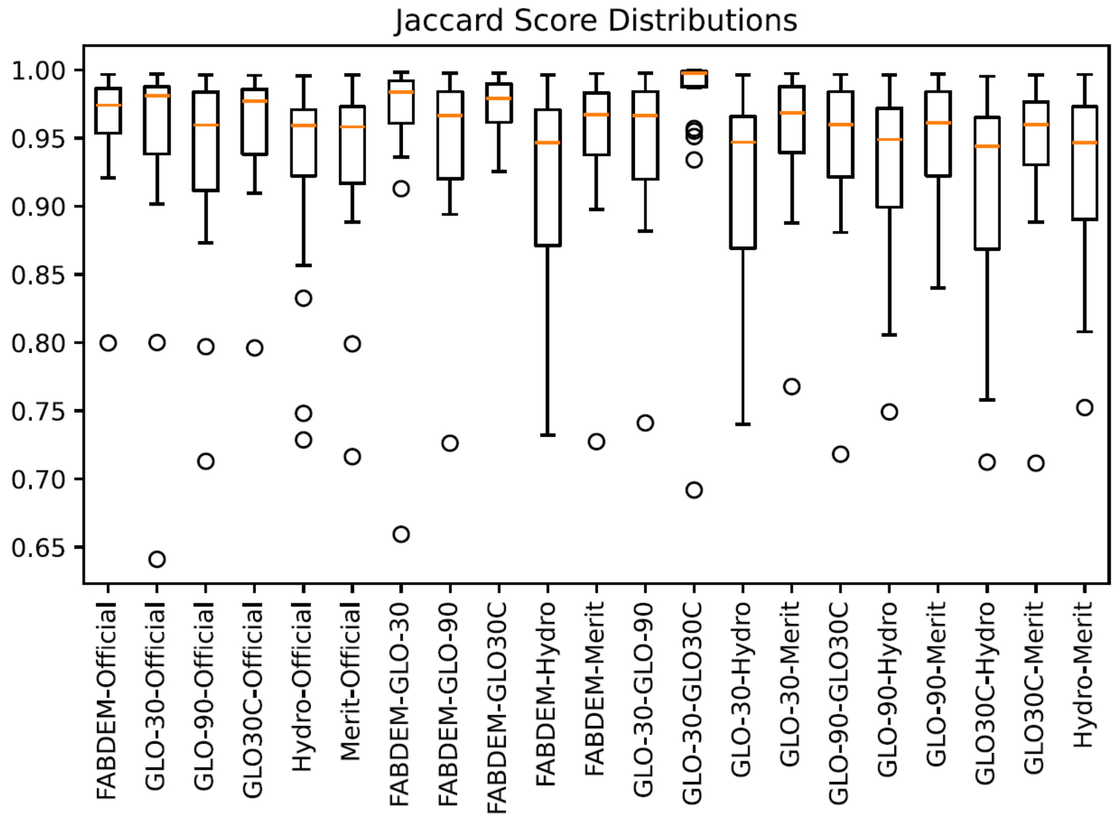

Figure 4: Jaccard score distributions for each dataset pairing. The whiskers reach the highest or lowest value within a 1.5 interquartile range. Outliers are represented by circles. Outliers most are most commonly linked to the presence of endorheic catchments.

5 Discussion

5.1 Infrastructure-related artefacts as sources of delineation error

Across the study area, the most frequent and consequential flow routing errors originate from major transportation infrastructure, particularly the A-7 highways and associated bridge and embankment structures (Figure 5). These features appear as impermeable barriers in DEMs, causing surface runoff to be routed around instead of following the true channel path beneath. This behaviour is observed in all tested DEM products, including those that are preconditioned for hydrological applications.

These artefacts have particularly strong impacts in small and medium-sized catchments, where a single misrouted flow path near the outlet can substantially alter the delineated drainage area. We therefore recommend visual inspection of flow accumulation paths near major infrastructure, especially close to outlet points.

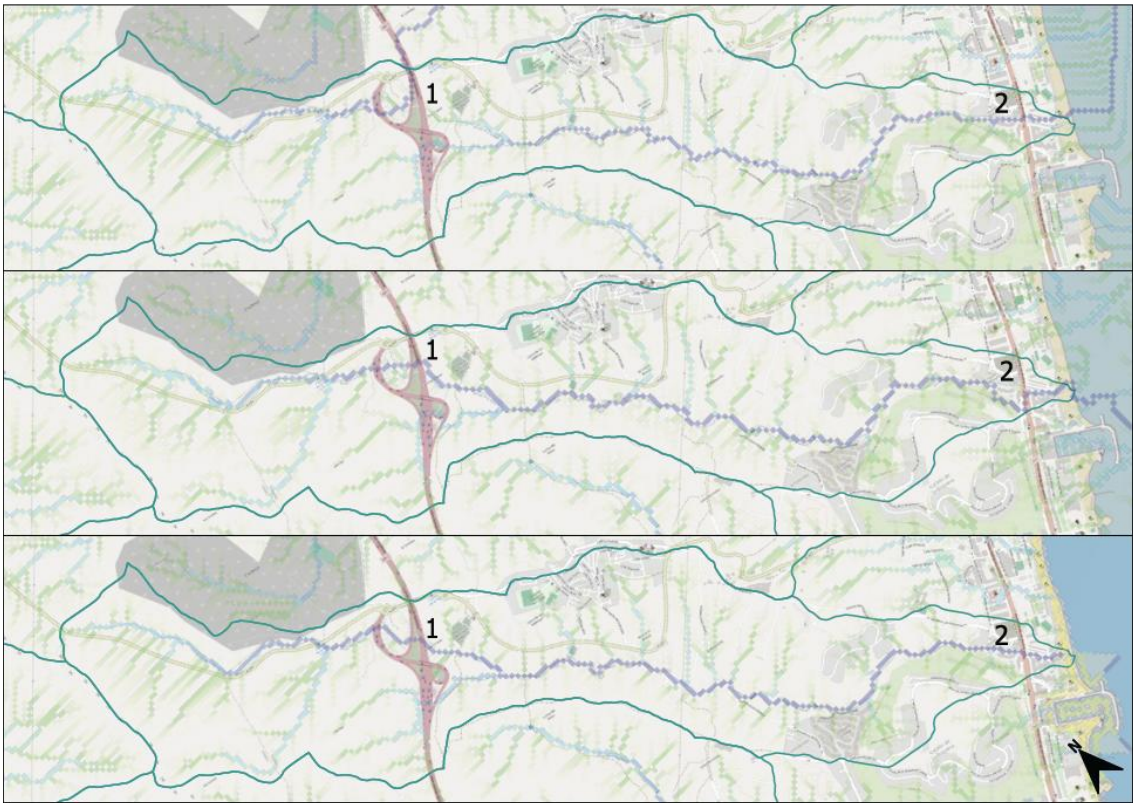

Figure 5: The flow accumulation in the Arroyo de la Peñuela catchment from GLO-30 (top), FABDEM (middle) and GLO-30c (bottom). At point 1 GLO-30 diverges the flow into the neighbouring watershed, drastically reducing delineation accuracy, while FABDEM routes correctly. At point 2 FABDEM diverges the flow over an embankment but reroutes to the correct path afterwards. GLO-30c routes accurately at both points.

5.2 Additional recurring modes of failure

Beyond transportation infrastructure, several other hydrologically challenging situations repeatedly produced delineation errors during both the case study and the larger batch delineation of 2,870 WISE-linked sites. These issues are not specific to individual DEM products but arise from fundamental limitations of surface runoff modelling based on elevation alone. The following examples are visualized in Figure 6.

Water bodies with multiple engineered outlets, such as large reservoirs (e.g. the Lago di Campotosto near L'Aquila in Italy), frequently lead to subdivision into multiple catchments by flow-routing algorithms. In such cases, delineating each sub-catchment separately and merging them post hoc with the QGIS raster calculator provides a simple and robust solution. Reservoirs located on topographic highs (e.g. the Lago di Sant'Anna near Crotone in Italy) pose a more fundamental problem, as surface runoff modelling cannot capture pumped inflows unless the inlet is located in a known surface water body. Endorheic catchments pose another problem to surface runoff routing. DEM conditioning methods, e.g. breaching depressions or filling sinks, connect them to nearby catchments, lifting their endorheic status. E.g. for our Rio de Vélez study site all DEMs, except HydroSHEDS, counted the endorheic Arroyo Madre de la Alcaicería as part of the Río de Vélez catchment, resulting in an around 20% larger catchment area than the official delineation. HydroSHEDS is the only product, that handles larger endorheic catchments well. This is due to the manual "seeding" of over 16,000 visually identified endorheic catchments during the creation of HydroSHEDS (Lehner, 2022). The seeding procedure involves placing a "no data" value cell at the lowest point in the DEM, which flow routing algorithms interpret as an outlet point, keeping the catchment enclosed.

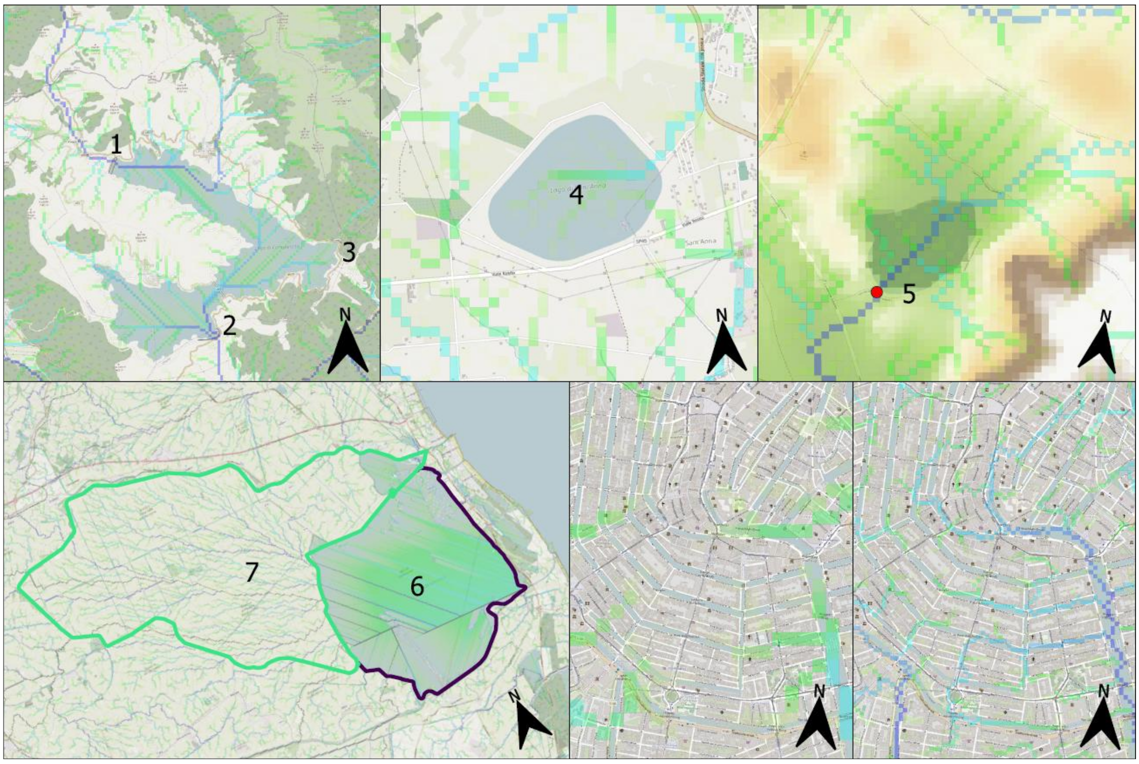

Figure 6: top left: Lago di Campotosto - the reservoir is framed by three dams (1-3); top middle: Lago di Sant'Anna. The reservoir (4) is located solely on a hilltop; top right: Laguna Salada near Campillas in Spain. The endorheic catchment is falsely breached by algorithms. We suggest locating the outlet point (5) where the saddle of the ridgeline is breached; bottom left: the area of the Valli di Comacchio. Still existing, tidal influenced waterbody (6) and actively drained area (7) surrounded by a canal and river network (green line); bottom right: Comparison of the Amsterdam centre between MERIT and GLO-30 - the higher resolution GLO-30 represents the canals more accurately, but flow directions are still questionable.

Artificial drainage networks represent another critical failure mode. E.g. in the Valli di Comacchio in Italy, a majority of the historic wetlands are drained by an extensive network of canals and pumping stations. This leads to unsolvable flow routing issues, as water can only travel down slope in DEM derived surface runoff modelling. The still intact wetlands of the Valli di Comacchio present another common problem. As lagoons, they are directly connected to the Mediterranean Sea and are therefore subject to tidal influence, which cannot be adequately modelled with surface runoff modelling alone. Canals pose a last often occurring problem. They don't follow a clear gradient, therefore deriving the natural flow direction is questionable in most cases. If they occur as dense networks, like in the centre of Amsterdam in the Netherlands, flow routing becomes highly uncertain. If catchment delineation is attempted anyway, we suggest utilizing a high resolution DEM or to delineate via a buffer around the study site in drastic cases.

5.3 Influence of DEM resolution on delineation outcomes

Choosing an adequate DEM resolution depends on multiple factors. As we showed, higher resolutions usually produce more accurate catchment delineations than lower resolved ones and should therefore be preferred. On the other hand, the trade-offs of choosing a higher resolved DEM manifest in lower processing speeds and a need for higher RAM and drive capacity.

As catchment size increases, the importance of DEM resolution on catchment delineation progressively decreases. Two mechanisms primarily explain this pattern. First, small-scale landscape features (e.g., individual buildings, berms) become subsumed within larger geomorphic units (e.g., city blocks, valleys), which can be adequately represented in DEMs with coarser spatial resolution. Second, the precision of the delineated drainage divide is dependent on DEM resolution. Higher-resolution DEMs more accurately approximate the complex geometry of drainage divides, except in the idealized case of a perfectly rectangular catchment. This effect is analogous to the "coastline paradox" (Mandelbrot, 1967), wherein the measured length of a boundary increases as the unit of measurement decreases. The length of a drainage divide theoretically approaches infinity with increasingly fine measurement scales, yet remains bound between one- and two-dimensionality (Mandelbrot, 1967). Consequently, these 1.x-dimensionally scaling boundary effects become progressively less influential relative to the two-dimensional scaling of catchment area (assuming a two-dimensional planimetric representation) as catchment size increases.

This effect can also be shown with our study sites (Figure 7). With increasing catchment scale, the delineation results from the 1 and 3 arcsec DEMs become increasingly similar.

Because DEMS with higher resolution handle hydrologically difficult cases (which produce the largest outliers) better, we do not want to give a recommendation at which scales to choose which DEM resolution. Nevertheless, FABDEM proved to be the most reliable 1 arcsec and MERIT the most reliable 3 arcsec DEM, which we therefore recommend.

We also have to mention again, that our hydrological conditioning of GLO-30, GLO-90 and FABDEM for the case study only includes breaching depressions, while MERIT and HydroSHEDS have rivers carved in. The carving in step of rivers takes additional time (dependent on the size and density of the stream network), but can be expected to improve the delineation accuracy significantly.

We emphasized the usefulness of catchment delineation in combination with WISE/WFD datasets, but we experienced misplacement in the official georeferenced point data of WISE 6 monitoring sites, e.g. for monitoring site IDs FR05106400, FRGLK0-300T, BAHE-SALAKOVAC and IT18-R18071LA001. For most misplaced sites, we could find the assumingly correct location by interpreting the site description, but in the case of FRRFR0420 the site description was too cryptic.

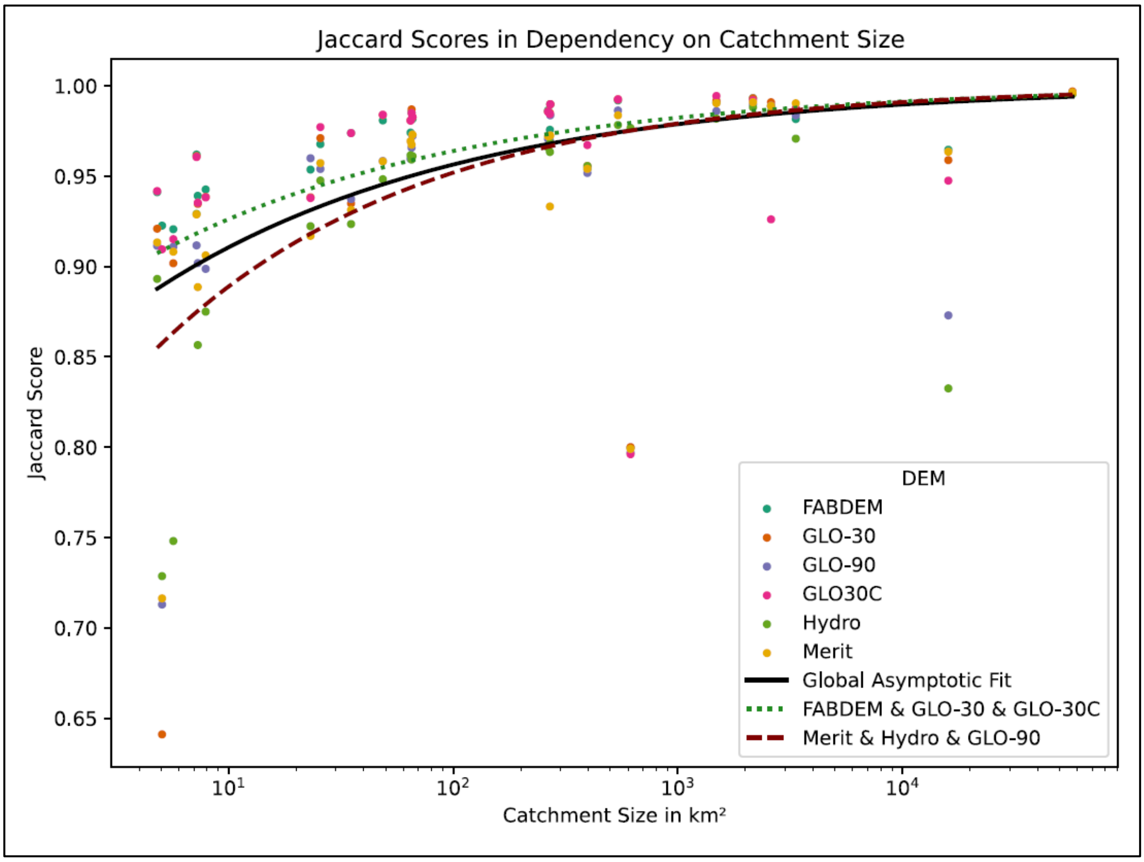

Figure 7: Jaccard scores for the DEM catchment delineations (compared to the official delineations) in dependency on catchment size. It can be assumed, that with theoretical inclusion of infinitely small catchments, the asymptotes would originate at the origin of coordinates.

6 Conclusion

The methodology presented here provides a practical, semi-automated workflow for batch catchment delineation which we developed during the delineation of 2870 catchments linked to WISE monitoring sites. We applied the workflow to 25 additional study sites to evaluate DEM performance and delineation quality.

Across our case study, 1-arcsec products (in particular FABDEM and GLO-30) yielded the highest agreement with official delineations and the smallest variability in Jaccard Similarity; coarser products (MERIT, HydroSHEDS and GLO-90) were less consistent and produced larger outliers.

We identify several recurring, practically relevant failure features (roadway bridges and embankments, artificial drainage networks and canals, endorheic basins, reservoirs with engineered outlets) that require supervised manual handling and review. Even with the best DEMs, automated workflows should therefore be complemented by a quality control step, mainly focused around the outlet vicinity and known hydrological anomalies.

Overall, we consider that this workflow can facilitate the integration of hydrological context into large-scale catchment-based assessment frameworks. Therefore, we see a clear policy relevance as it can provide the necessary base data for the large-scale assessment of pollution and degradation of Europe's water bodies in the context of the Water Framework Directive, as well as for nature conservancy EU commitments such as those under the Habitats Directive and the Nature Restauration Regulation.

Funding

This research has received funding from the project RESTORE4Cs - Modelling RESTORation of wEtlands for Carbon pathways, Climate Change mitigation and adaptation, ecosystem services, and biodiversity, Co-benefits (DOI: 10.3030/101056782), co-funded by the European Union under the Horizon Europe research and innovation programme (Grant Agreement ID: 101056782). The views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the granting authority.Work by the University of Valencia was also co-supported by projects CLIMAWET-CONS (PID2019-104742RB-I00), funded by the Agencia Estatal de Investigación of the Spanish Government, and by the project ECCAEL (PROMETEO CIPROM-2023-031), funded by the Generalitat Valenciana, both granted to Antonio Camacho.

References

CDSE, 2022. Copernicus DEM. https://doi.org/10.5270/ESA-c5d3d65.

CLMS, 2019. EU-Hydro River Network Database 2006-2012 (vector), Europe - version 1.3, Nov. 2020. https://sdi.eea.europa.eu/catalogue/copernicus/api/records/393359a7-7ebd-4a52-80ac-1a18d5f3db9c?language=all.

Erskine, R., Green, T., Ramirez, J., MacDonald, L., 2006. Comparison of grid-based algorithms for computing upslope contributing area. Water Resources Research, 42(9), Article 2005WR004648. https://doi.org/10.1029/2005WR004648.

European Commission. Directive 2000/60/EC of the European Parliament and the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy. Official Journal of the European Communities, L327/1.

Hawker, L., Uhe, P., Paulo, L., Sosa, J., Savage, J., Sampson, C., Neal, J., 2022. A 30 m global map of elevation with forests and buildings removed. Environmental Research Letters, 17(2), 24016. https://doi.org/10.1088/1748-9326/ac4d4f.

Heberger, M., 2022. mheberger/delineator: 1.0. Zenodo. https://zenodo.org/records/7314287 https://doi.org/10.5281/zenodo.7314287.

Houlahan, J., & Findlay, C., 2004. Estimating the ‘critical’distance at which adjacent land-use degrades wetland water and sediment quality. Landscape Ecology, 19(6), 677-690. https://doi.org/10.1023/B:LAND.0000042912.87067.35. https://doi.org/10.1002/jgrf.20127.

Jaccard, P., 1908. Nouvelles recherches sur la distribution florale. Bull. Soc. Vaud. Sci. Nat., 44, 223–270. https://cir.nii.ac.jp/crid/1573668925301098880.

Lehner, B., 2022. HydroSHEDS Technical Documentation. World Wildlife Fund. https://data.hydrosheds.org/file/technical-documentation/HydroSHEDS_TechDoc_v1_4.pdf.

Lehner, B., Grill, G., 2013. Global river hydrography and network routing: Baseline data and new approaches to study the world's large river systems. Hydrological Processes, 27(15), 2171–2186. https://doi.org/10.1002/hyp.9740.

Lehner, B., Verdin, K., Jarvis, A., 2008. New Global Hydrography Derived From Spaceborne Elevation Data. Eos, Transactions American Geophysical Union, 89(10), 93–94. https://doi.org/10.1029/2008eo100001.

Luxembourg. 2000. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32000L0060.

Mandelbrot, B., 1967. How long is the coast of Britain? Statistical self-similarity and fractional dimension. Science (New York, N.Y.), 156(3775), 636–638. https://doi.org/10.1126/science.156.3775.636.

Meadows, M., Jones, S., Reinke, K., 2024. Vertical accuracy assessment of freely available global DEMs (FABDEM, Copernicus DEM, NASADEM, AW3D30 and SRTM) in flood-prone environments. International Journal of Digital Earth, 17(1), Article 2308734, 2308734. https://doi.org/10.1080/17538947.2024.2308734.

Merot, P., Durand, P., 1996. Modelling the interaction between buffer zones and the catchment. Buffer Zones, 208. http://www.hec-ltd.co.uk/HEC-Limited/projects/ewExternalFiles/BufferZones(unlocked).pdf#page=216.

Morant, D., Perennou, C., Camacho, A., 2021. Assessment of the Pressure Level over Lentic Waterbodies through the Estimation of Land Uses in the Catchment and Hydro-Morphological Alterations: The LUPLES Method. Appl. Sci. 11(4), 1633. https://doi.org/10.3390/app11041633.

Nielsen, A., Trolle, D., Søndergaard, M., Lauridsen, T. L., Bjerring, R., Olesen, J. E., Jeppesen, E., 2012. Watershed land use effects on lake water quality in Denmark. Ecological applications, 22(4), 1187-1200. https://doi.org/10.1890/11-1831.1.

Novikmec, M., Hamerlík, L., Kočický, D., Hrivnák, R., Kochjarová, J., Oťaheľová, H., Paľove-Balang, P., Svitok, M., 2016. Ponds and their catchments: size relationships and influence of land use across multiple spatial scales. Hydrobiologia, 774(1), 155-166. https://doi.org/10.1007/s10750-015-2514-8.

O'Callaghan, J., & Mark, D., 1984. The extraction of drainage networks from digital elevation data. Computer Vision, Graphics, and Image Processing, 28(3), 323–344. https://doi.org/10.1016/S0734-189X(84)80011-0.

Prescott, A., Pelletier, J., Chataut, S., Ananthanarayan, S., 2025. An evaluation of flow-routing algorithms for calculating contributing area on regular grids. Earth Surface Dynamics, 13(2), 239–256. https://doi.org/10.5194/esurf-13-239-2025.

Shelef, E., Hilley, G., 2013. Impact of flow routing on catchment area calculations, slope estimates, and numerical simulations of landscape development. Journal of Geophysical Research: Earth Surface, 118(4), 2105–2123.

Spanish Ministry for Ecological Transition, 2025. Cuencas y subcuencas hidrográficas. https://www.miteco.gob.es/es/cartografia-y-sig/ide/descargas/agua/cuencas-y-subcuencas.html (accessed 17 December 2025).

Thomas, D. (Ed.)., 2002. The dictionary of physical geography (3. ed., repr). Blackwell.

Yamazaki, D., Ikeshima, D., Sosa, J., Bates, P., Allen, G., Pavelsky, T., 2019. MERIT Hydro: A High-Resolution Global Hydrography Map Based on Latest Topography Dataset. Water Resources Research, 55(6), 5053–5073. https://doi.org/10.1029/2019WR024873.

Appendix T1: Site overview

ID	Name	Size (km²)	FAB DEM	GLO -30	GLO -30C	GLO -90	Hydr.	Merit
1	Río Guadalquivir	57085.2	0.997	0.997	0.996	0.996	0.995	0.996
2	Río Guadarranque	270.3	0.990	0.990	0.990	0.984	0.968	0.973
3	Río Guadiaro	1484.1	0.991	0.992	0.994	0.986	0.982	0.990
4	Arroyo del Alcorrin	7.3	0.939	0.935	0.935	0.902	0.857	0.889
5	Arroyo del Indiano	7.9	0.943	0.939	0.938	0.899	0.875	0.906
6	Arroyo de la Penueña	5.1	0.923	0.641	0.910	0.713	0.729	0.716
7	Río de Manilva	35.1	0.974	0.935	0.974	0.937	0.924	0.931
8	Río Guadalmansa	65.2	0.985	0.987	0.985	0.966	0.959	0.967
9	Río Guadalmina	65.8	0.982	0.983	0.983	0.972	0.961	0.973
10	Río Guadalhorce	3349.3	0.982	0.988	0.987	0.984	0.971	0.990
11	Arroyo de Santillán	5.7	0.921	0.902	0.915	0.911	0.748	0.908
12	Río de Vélez	615.4	0.800	0.800	0.796	0.797	0.977	0.799
13	Río de Algarrobo	64.5	0.974	0.981	0.981	0.960	0.962	0.969
14	Río de los Lagos	7.2	0.962	0.961	0.961	0.912	0.929	0.929
15	Río Güi	25.6	0.968	0.971	0.977	0.954	0.948	0.957
16	Arroyo del Manzano	4.8	0.941	0.921	0.942	0.912	0.893	0.913
17	Río de Torrox	48.6	0.981	0.984	0.984	0.958	0.948	0.958
18	Río Seco	23.1	0.954	0.938	0.938	0.960	0.922	0.917
19	Río Andarax	2158.9	0.993	0.993	0.992	0.990	0.988	0.991
20	Rambla Morales	395.3	0.954	0.956	0.967	0.952	0.956	0.954
21	Rambla de Saltador	264.2	0.986	0.986	0.986	0.971	0.966	0.972
22	Río de Aguas	541.0	0.992	0.993	0.993	0.986	0.978	0.984
23	Río Antas	269.3	0.976	0.985	0.984	0.970	0.963	0.933
24	Río Almanzora	2598.0	0.989	0.991	0.926	0.989	0.986	0.989
25	Río Segura	15991.2	0.965	0.959	0.948	0.873	0.833	0.964

Table notes: columns 4-9 show the Jaccard scores for each DEM/official delineation comparison.

Appendix T2: Recommended settings and actions for each tool utilzed in our workflow

Tool	Settings / Actions
Warp (Reproject)	Input layer: choose DEM Target CRS: choose fitting projected CRS (Downsampling: set “output file resolution in target georeferenced units” to desired resolution)
Reroject Layer	Input layer: choose stream or site point vectors Target CRS: choose fitting projected CRS
FillBurn	Input DEM File: select projected DEM Input Vectors Streams File: select projected vector stream file
BreachDepressions	Input DEM file: select projected or stream carved DEM Tick: “Fill single-cell pits?”
r.watershed	Elevation: select the condition DEM Tick: “Enable Single Flow Direction (D8) flow” Skip all outputs (by clicking on “…”) besides: - “Number of cells that drain through each cell” - “Drainage direction”
Vertex Tool	Is found in the Digitizing Toolbar For moving site points: - The flow accumulation map style of grass is convenient for visual interpretation - Set the flow accumulation map transparency to 30 % - Underlay satellite imagery or OSM - Move site points to fitting raster pixels in flow accumulation paths At this point, you will likely encounter sites with problematic flow paths near the outlet: note them for later manipulation
r.water.outlet	Run as a batch process: Coordinates of outlet point: Autofill → Add Values by Expression (without exclamation marks): “aggregate('*YourSitePointLayerName*','array_agg',$geometry)” - Aggregates coordinates from your site points - Make sure to remove the now invalid first row Drainage direction raster: - Select the Drainage Direction Raster for the first field → Autifill → Fill Down Basin: Autofill → Add Values by Expression (without exclamation marks): “array_foreach(aggregate('*YourSitePointLayerName*','array_agg',*IDColumnName*), concat('*C:/Save/Location/Example/*',to_string(@element),'.tif'))" - This will generate a TIF at a file location of your choice - Files are named after a column in the attribute table of your site point layer in which you specify the site names (*IDColumnName)*
Polygonize (raster to vector	Run as a batch process: Input layer: Autofill → Select files: select catchment rasters - Make sure to remove the now invalid first row Vectorized: click on “…” → enter “Polygonized” as file name → press Enter → Autofill mode: “Fill with parameter values”; Parameter to use: “Input layer” - This will create the file name e.g. “Polygonized*InputLayerName*” at chosen file location for every catchment raster
Dissolve	This is necessary as sometimes single pixels are only connected by a corner to the main area of the catchment rasters: Run as a batch process: Input layer: Autofill → Select files: select catchment vectors - Make sure to remove the now invalid first row Dissolved: click on “…” → enter “Dissolved” as file name → press Enter → Autofill mode: “Fill with parameter values”; Parameter to use: “Input layer” - This will create the file name e.g. “Dissolved*InputLayerName*” at chosen file location for every catchment vector