



Confidence-Aware Framework for Mapping Satellite-Derived River Reaches to Gridded Routing Networks

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Abstract. The Surface Water and Ocean Topography (SWOT) mission delivers reach-scale observations of river water surface elevation, contextualized by the vector-based SWORD database. Assimilating these observations into gridded routing models such as CTRIP is hindered by structural mismatches between object-based river geometries and pixel-based flow networks. We present a global, confidence-aware pipeline that assigns SWORD reaches to CTRIP pixels by combining
10 geometric and hydrological criteria such as intersection, proximity, upstream-area consistency, reach length, and flow-direction alignment into a composite score. Each assignment receives a confidence tier (Tier 1: single; Tier 2: scored; Tier 3: fallback; Tier 4: unassigned), and Tier-2 cases are further refined by a confidence score (high/medium/low). Applied globally at 1/12°, the framework assigns >99% of CTRIP pixels; the vast majority are resolved either unambiguously (Tier 1) or as high-quality scored matches (Tier 2–High), with no fallback assignments and <0.5% unassigned. Independent
15 diagnostics based on basin-hash continuity confirm hydrological integrity. Code and outputs (CSV, NetCDF, shapefiles) are openly available and directly usable for assimilation into CTRIP or can be applied to any other gridded river network, providing a reproducible foundation for bridging SWOT observations with global river routing models.

20 **Keywords:** SWOT, Vector-grid reconciliation, Hydrological modeling, Data assimilation, CTRIP, SWORD, Confidence mapping.



1 Introduction

30 The Surface Water and Ocean Topography (SWOT) mission delivers global, reach-scale observations of water surface elevation (WSE), facilitating the estimation of river discharge (e.g., Biancamaria et al., 2016; Durand et al., 2016). These retrievals are spatially contextualized within the SWOT River Database (SWORD), which structures the global river network as a vector-based representation comprising reaches and nodes, each endowed with geometric, topological, and hydrological attributes (Altenau et al., 2021). These representations are specifically optimized for SWOT data retrieval and capture river morphology at sub-reach scales. In contrast, prevalent large-scale hydrological and river routing models such as CTRIP (Munier & Decharme, 2022), CaMa-Flood (Yamazaki et al., 2011), LISFLOOD (van der Knijff et al., 2010), VIC (Lohmann et al., 1998), and mizuRoute (Mizukami et al., 2016), utilize gridded river networks, where river channels are implicitly represented by flow directions between discrete grid cells (e.g., D8; O’Callaghan and Mark, 1984). Within these frameworks, water routing is typically performed through pixels guided by flow direction schemes derived from digital elevation models (Yamazaki et al., 2017). This fundamental divergence in structural representation between object-based observational datasets like SWORD and pixel-based modeling frameworks poses a significant challenge for the assimilation of SWOT-derived variables into river routing models. These representational discrepancies extend beyond mere spatial resolution differences, encompassing inconsistencies in reach orientation, upstream drainage area attribution, stream order classification, and flow path topology. As demonstrated by recent studies (Wade et al., 2025; Godet et al., 2024), simplistic allocation strategies such as nearest-neighbor pixel assignment or direct upstream area matching can yield hydrologically implausible linkages, particularly within complex fluvial environments like confluences, braided river systems, or endorheic basins. Such misallocations can degrade the performance of data assimilation schemes, misrepresent underlying routing dynamics, and introduce biases in model-observation comparisons. Prior studies have explored diverse methodologies for linking observational features to model pixels, including Euclidean proximity, catchment overlap, and flowline-based matching (e.g., Döll and Lehner, 2002; Fekete et al., 2002; Munier and Decharme, 2022). While effective within regional contexts, these approaches frequently lack robust generalization capabilities for global-scale applications and typically do not incorporate a quantitative assessment of match confidence or hydrological consistency. Moreover, extant solutions infrequently provide modular, open-source implementations conducive to large-scale deployment and enhanced reproducibility. This technical note introduces a novel, confidence-aware, global-scale framework for the unambiguous assignment of SWORD river reaches to CTRIP routing pixels, in order to prepare the assimilation of SWOT observations into the CTRIP-HyDAS (Hydrological Data Assimilation System) framework (Verma et al. 2026). The proposed methodology integrates a suite of geometric and hydrological criteria, encompassing reach-pixel intersection, proximity to the pixel centroid, upstream drainage area consistency, reach length, and angular alignment with the CTRIP flow direction, to derive a composite score that facilitates the selection of the most hydrologically plausible match. Each resulting assignment is classified into a confidence tier (e.g., high-confidence, scored, fallback, or unassigned) determined by predefined threshold criteria. The workflow is designed to operate independently within each Pfafstetter hydrological zone

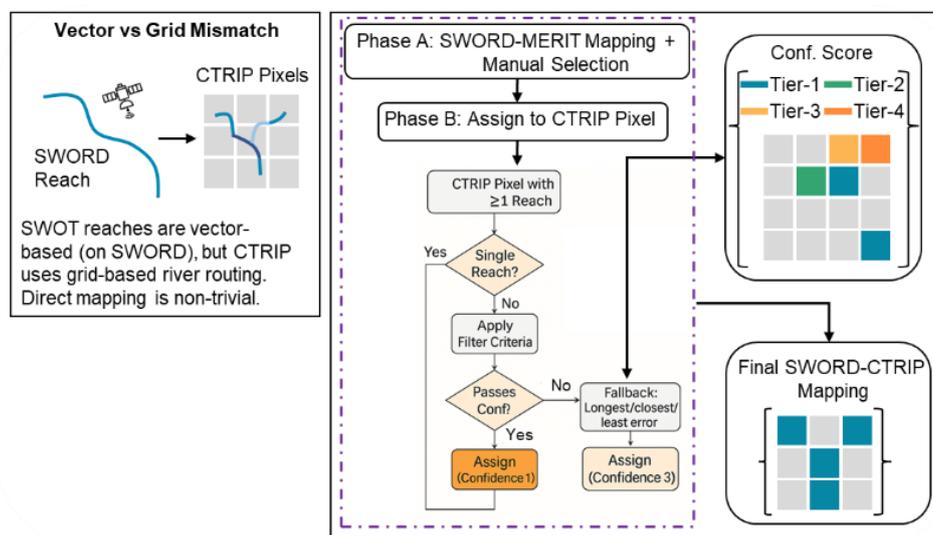


from MERIT Hydro database (Yamazaki et al., 2019), thereby supporting regional reproducibility and generating standardized outputs amenable to both SWOT data assimilation and model benchmarking. The methodology is applied here for the CTRIP river network but may be easily extended to any other grid-based river routing model.

65 The remainder of this technical note is structured as follows: Section 2 outlines the input datasets and the overall framework architecture; Section 3 elaborates on the assignment logic, scoring metrics, and confidence classification schema; Section 4 presents global results and diagnostic analyses; Section 5 discusses the implications for SWOT data assimilation and outlines potential future extensions.

2 Datasets and Pipeline Overview

70 The SWORD–CTRIP mapping pipeline establishes a reconciliation between vector-based river observations and gridded routing models via a modular, zone-wise processing workflow. The system operates at a nominal $1/12^\circ$ global resolution and integrates three primary geospatial datasets: SWORD v17b, representing reach geometry; CTRIP, serving as the gridded routing model framework; and MERIT Hydro, providing foundational drainage topology and spatial masks. A schematic overview of the pipeline architecture is presented in Figure 1.



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80 **Figure 1: Conceptual overview of the SWORD–CTRIP mapping pipeline. (Left)** SWOT reaches are stored as vector objects in the SWORD database, while CTRIP uses a gridded river-routing structure, creating a structural mismatch that complicates direct alignment. **(Center)** The mapping workflow (Phases A–B) identifies candidate reaches for each CTRIP pixel, applies multi-metric filters and scoring, and classifies the final assignment into one of four confidence tiers: Tier 1 (Single), Tier 2 (Scored), Tier 3 (Fallback), or Tier 4 (Unassigned). Within Tier 2, scored assignments are further refined by confidence score (high, medium, low) to capture quality variation across multi-reach cases. **(Right)** The resulting reach-to-pixel assignments, color-coded by tier, are exported in standardized formats (CSV, NetCDF, shapefiles) for direct integration into SWOT assimilation workflows such as CTRIP-HyDAS.



2.1 Input Datasets

85 The SWORD (Surface Water and Ocean Topography River Database, version 17b) product defines a global river network as
a series of interconnected reaches and nodes, assembled by combining multiple global hydrography and satellite-related
datasets into a coherent reach–node topology specifically designed for SWOT river observations (Altenau et al., 2021). Each
reach is represented as a polyline and annotated with critical attributes including length, slope, stream order, width, and
metadata pertaining to SWOT observability. For this study, only valid river reaches are retained, identified using SWORD
90 attribute filters: type = 1 selects river reaches (excluding non-river features), lakeflag = 0 excludes lake-associated
geometries, and stream_order \neq -9999 removes ghost or topologically unresolved reaches. This filtering ensures that only
physically meaningful river centerlines are considered in the mapping. CTRIP is a global river routing model that operates
on a structured grid (Decharme et al., 2019; Munier & Decharme, 2022). At the 1/12° resolution, each grid cell (pixel) is
characterized by a centroid location, its upstream drainage area (denoted as dr_area), stream order, and a flow direction
95 vector, typically employing a D8 scheme (e.g., O'Callaghan and Mark, 1984). CTRIP serves as the target domain for the
mapping process; consequently, each routing pixel may intersect with zero, one, or multiple SWORD reaches, contingent
upon network geometry and spatial data density. The primary objective of the pipeline is to identify the single most
hydrologically consistent SWORD reach for each valid CTRIP pixel.
MERIT Hydro (Yamazaki et al., 2019) serves as the foundational topographic and hydrological reference dataset, utilized by
100 CTRIP. We leverage MERIT-derived upstream area (upa), flow direction maps, and zone identifiers (cl_ids) to enforce
topological coherence throughout the reach filtering, assignment, and validation stages.

2.2 Pipeline Architecture

All mapping operations are conducted independently on a per Pfafstetter hydrological zone basis, which intrinsically enables
scalability and facilitates parallel processing. While direct SWOT observations are not incorporated into the assignment logic
105 itself, the generated mapping outputs function as a critical interface layer, bridging the gap between SWOT's reach-based
products and CTRIP's gridded model state. By linking SWORD reaches to CTRIP pixels in a hydrologically coherent and
confidence-tagged logic, the pipeline facilitates the seamless integration of SWOT-derived WSE and discharge estimates
into assimilation frameworks such as CTRIP-HyDAS (Verma et al., 2025).

The overall pipeline is structured into distinct, modular phases, with each phase operating on zone-specific inputs and
110 yielding standardized outputs:

- Phase A – SWORD-MERIT filtering: Initial pre-processing step in which SWORD reaches are filtered to retain only valid
river geometries consistent with the target hydrological domain. This phase removes non-river features, lake-associated
reaches, ghost or unresolved reaches, and SWORD reaches that fall outside the MERIT Hydro basin masks used by
CTRIP, ensuring that only physically meaningful and domain-consistent reaches enter the subsequent assignment stages.



- 115 • Phase B – Reach assignment and scoring: Assignment of SWORD reaches to CTRIP pixels based on intersection criteria and multi-metric scoring, coupled with the application of confidence tiers.
- Phase C – Fallback assignment: Re-evaluation of unmatched CTRIP pixels utilizing broader or relaxed assignment logic.
- Phase Z – Global aggregation: Consolidation of zonal results into unified global outputs in CSV, NetCDF, and visualization formats.
- 120 All input and output data are managed using open, standard formats (e.g., shapefiles, CSV, NetCDF), and the entire pipeline is architected for reproducibility and amenability to extension for use with other grid or vector products or models.

3 Assignment Methodology

The assignment logic delineates the process for identifying the SWORD reach most consistent with each CTRIP routing pixel. This process is a critical prerequisite for accurately mapping SWOT-derived observations to hydrological model states. The methodology is structured around three primary steps: candidate identification via spatial intersection, multi-metric scoring for ambiguous cases, and confidence tier classification. Each CTRIP pixel is represented by a fixed-area grid cell. The initial step identifies all SWORD reaches whose polyline geometries intersect this cell using spatial overlay operations. This leads to three distinct scenarios:

- 130 (i) Single Intersecting Reach: If exactly one SWORD reach intersects the CTRIP pixel, it is assigned directly. This represents the most unambiguous case and is classified as Tier 1.
- (ii) Multiple Intersecting Reaches: If two or more reaches intersect the pixel, a multi-metric scoring system is invoked to rank the candidates and select the most plausible match. This scenario typically results in a Tier 2 or Tier 3 assignment, depending on whether the selected candidate passes quality filters.
- 135 (iii) No Intersecting Reach: If no reach intersects the pixel, it is initially designated as unassigned (Tier 4). These pixels may subsequently be assigned a reach via optional fallback logic.

For cases with multiple candidates reaches, each is evaluated using four metrics designed to quantify geometric and hydrological consistency. These metrics are summarized in Table 1.

140 **Table 1. Metrics used for scoring and ranking multiple SWORD reach candidates within a single CTRIP pixel.**

Metric	Description	Rationale for Minimization
D	Great-circle distance (km) between the pixel centroid and the reach centroid.	Prioritizes reaches centrally located within the pixel.
L^{-1}	The inverse reach length (km^{-1}).	Prioritizes longer, more representative reaches.



A	Fractional absolute difference between the reach's MERIT-derived upstream area and the pixel's CTRIP drainage area.	Enforces hydrological consistency between datasets.
Θ	Absolute difference (degrees) between the reach's primary orientation and the pixel's D8 flow direction.	Ensures alignment of flow paths.

The upstream-area consistency metric A is computed by comparing MERIT Hydro upstream area and CTRIP pixel drainage area at the candidate reach location. Specifically, UPA_{MERIT} is obtained by sampling the MERIT upstream area field (upa) in a local window centered on the SWORD reach coordinate, while dr_area_{CTRIP} is obtained by sampling the CTRIP drainage-area field (dr_area converted from m^2 to km^2) at the same location. The mismatch is defined as $A = |UPA_{MERIT} - dr_area_{CTRIP}| / dr_area_{CTRIP}$, and A is set to NaN when $dr_area_{CTRIP} \leq 0$ to avoid numerical instability in near-zero headwater pixels. River identifiers ($MERIT_river_id$) are used to restrict candidate CTRIP pixels during the assignment step, but are not used in the computation of A .

For pixels intersected by multiple SWORD reaches, candidate reaches are ranked using a composite score that combines geometric and hydrological consistency metrics. Let D denote the great-circle distance between the CTRIP pixel centroid and the reach centroid, L^{-1} the inverse of the reach length, A the upstream-area mismatch metric, and Θ the absolute angular difference between the reach orientation and the CTRIP flow direction. For each pixel, these metrics are computed for all candidate reaches and min–max normalized across the candidate set; normalized quantities are denoted by the superscript $(\cdot)^*$. The composite score for candidate reaches i is then defined as:

$$S_i = \omega_d D_i^* + \omega_l L_i^{-1*} + \omega_a A_i^* + \omega_\theta \Theta_i^*$$

where, ω_d , ω_l , ω_a , and ω_θ are non-negative weights summing to one. The candidate with the lowest score is selected. Inverse reach length is included to favor longer reaches, which are typically more representative of channel morphology and better aligned with SWOT observability. Rather than prescribing a single global set of weights, the relative contributions of distance, reach length, and angular alignment are determined empirically for each Pfafstetter zone. For each zone, we perform a grid search over all admissible weight combinations (step 0.1, weights summing to one) and select the combination that maximizes the number of high-confidence scored assignments. This adaptive strategy accounts for regional variability in river network geometry while preserving a consistent scoring framework across the globe. The optimal weights selected for each zone are reported in Table S1 (Supplement). The resulting optimal weights exhibit marked regional variability (Table S1), with distance frequently emerging as the dominant discriminant. In many zones, the optimal solution assigns zero weight to reach length and/or angular alignment. This behavior reflects the hierarchical structure of the mapping pipeline: hydrological consistency and river identity are enforced prior to scoring; such that geometric ambiguity is often limited to closely spaced candidate reaches. In these cases, distance alone is sufficient to uniquely identify the most plausible assignment, and additional geometric metrics do not improve discrimination.



170 Thresholds are applied at two distinct stages of the assignment framework and serve different purposes. First, during weight
optimization, provisional score thresholds ($S \geq 0.8$, $0.5 \leq S < 0.8$, and $S < 0.5$) are used internally to classify candidate
assignments as high, medium, or low-quality for the sole purpose of selecting the optimal weight combination within each
Pfafstetter zone. These thresholds are not used directly in the final mapping product. Second, after final reach selection,
composite scores are rescaled to the [0,1] interval to define a confidence metric that is used for reporting, visualization, and
175 tier assignment. This separation ensures that thresholding used for internal optimization does not bias the final confidence
classification.”

Each final assignment is classified into one of four confidence tiers (Table 2), which describe the logic by which a pixel is
matched to a SWORD reach:

Table 2. Confidence tier classification scheme for SWORD-to-CTRIP assignments.

Tier	Label	Assignment Logic
1	High-Confidence (Single)	Exactly one reach intersects the pixel; directly assigned.
2	Scored	Multiple reaches intersect; best candidate selected by scoring. Internally subdivided into high-, medium-, and low-score classes based on the composite score.
3	Fallback	Pixel intersects reaches, but none pass thresholds; longest or most observable reach assigned.
4	Unassigned	No intersecting reach, or assignment failed even under fallback.

180 The quality filters applied to select Tier 2 assignments include thresholds for maximum allowable distance to the pixel center
(D_{max}), maximum upstream area error (A_{max}), maximum angular difference (Θ_{max} , e.g., ≤ 45 -degree), and an optional
minimum reach length (L_{min}). Fallback logic (Tier 3) is invoked when multiple reaches intersect a pixel, but none of the
candidates pass the stringent quality filters. In such cases, the pipeline assigns a reach based on a relaxed criterion (e.g., the
185 longest intersecting reach or the one with the highest SWOT observability score) to ensure spatial coverage in structurally
complex or ambiguous regions. This approach prevents data gaps while explicitly flagging the assignment as being of lower
confidence. The tier label is persisted alongside the selected reach ID in all outputs, enabling users to filter or weight
observations by confidence in downstream workflows.

The pipeline generates a suite of standardized outputs designed for direct use in downstream applications. These include: (i)
190 CSV files detailing per-pixel assignments, all scoring metrics, and final confidence tier labels; (ii) NetCDF grids containing
the assigned reach identifiers and confidence tiers for efficient spatial analysis; and (iii) a series of diagnostic plots
summarizing metric distributions and overall mapping performance. These outputs are structured to support transparent
filtering, visualization, and seamless integration into assimilation workflows like CTRIP-HyDAS.



4 Results and Evaluation

195 This section delineates the global outcomes of the SWORD-CTRIP mapping pipeline, with a focus on the spatial
 distribution, inherent quality, and characteristic patterns of the pixel-level assignments. The primary objective is to assess the
 efficacy with which the pipeline reconciles vector-based SWOT river reaches with gridded CTRIP routing pixels across
 diverse hydrological regimes. The confidence levels assigned to each reach-pixel mapping serve as an intrinsic diagnostic
 metric for reliability. Figure 2 summarizes the global outcomes of the SWORD-CTRIP assignment pipeline. All statistics
 200 reported here (Figure 2c; Table 3) are computed over CTRIP routing pixels for which a SWORD reach was successfully
 assigned in the merged global product; pixels without any assigned reach are excluded from this summary. Panel (a) shows
 the spatial distribution of confidence categories, distinguishing between single-reach assignments (Tier 1) and scored
 matches (Tier 2, further subdivided into high, medium, and low score quality). Single assignments dominate across much of
 the globe, reflecting structural agreement between the SWORD vector network and CTRIP’s gridded routing pixels. Tier 2
 205 assignments are concentrated into hydrologically complex areas such as the Amazon, Southeast Asia, and the Ganges–
 Brahmaputra delta, where multiple reaches intersect a pixel and the scoring framework is required to select the best
 candidate. This typically occurs where rivers are braided or within deltas. Panel (b) shows the distribution of composite
 scores by category. High-score Tier 2 cases cluster toward low score values, confirming that the scoring system reliably
 identifies plausible matches. Medium and low-score cases extend to higher values, reflecting more ambiguous geometry or
 210 hydrology. Panel (c) shows the pixel count by category (see also Table 3). Within the assigned-pixel subset, 65.1% of
 CTRIP routing pixels correspond to unambiguous Tier 1 assignments. When including Tier 2–High cases resolved by the
 scoring framework, 94.1% of assigned pixels are mapped with high confidence (Table 3).

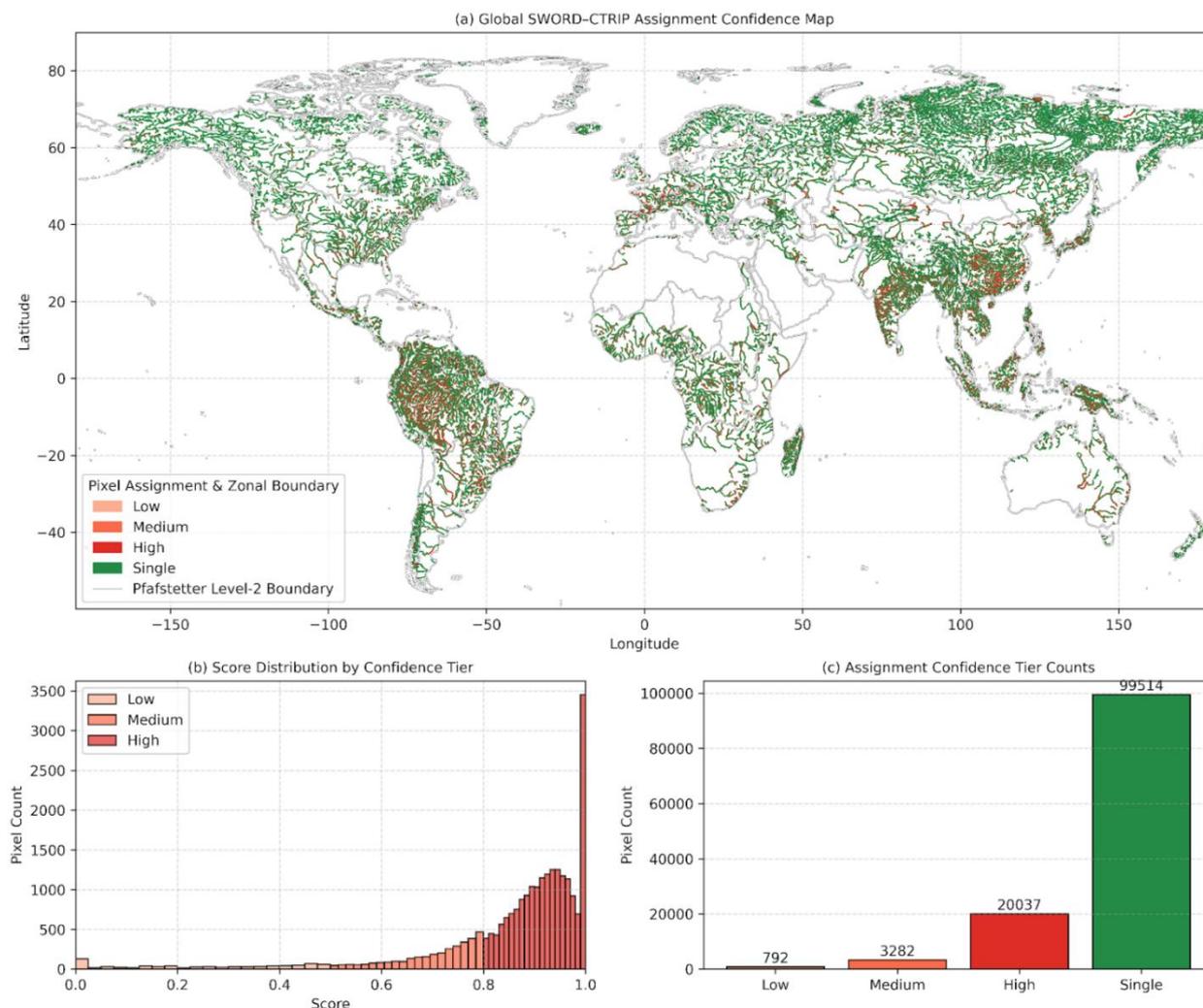
Table 3. Global distribution of assigned CTRIP routing pixels by SWORD-CTRIP assignment tier and score.

Tier	Subclass	Description	Pixel Count	Percentage (%)
1	Single	Single intersecting reach; directly assigned	99,524	65.1
2	High Score	Multi-reach case; best candidate passes thresholds	44,380	29
2	Medium Score	Multi-reach case; candidate passes partially	7,238	4.7
2	Low Score	Multi-reach case; candidate fails most thresholds	1,854	1.2
3	Fallback	No candidate passes scoring; longest/observable assigned	0	0.0



Total — — 152,996 100.0

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Figure 2. Global assignment confidence and quality between SWORD reaches and CTRIP pixels. (a) Spatial distribution of assignment categories: green = Tier 1 (Single), red = Tier 2–High, orange = Tier 2–Medium, brown = Tier 2–Low. (b) Composite-score distribution for scored cases (Tier 2 only). (c) Pixel counts per category, showing dominance of Single and High-Score assignments. No fallback (Tier 3) occurred. Panel (c) reports counts for pixels with an assigned SWORD reach in the merged global product; pixels without assignment are excluded from the count summary.

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To evaluate whether the reach-to-pixel assignment preserves large-scale hydrological topology, Figure 3 presents a basin-hash coherence diagnostic. Each CTRIP pixel inherits the basin hash of its assigned SWORD reach, where basin hashes encode upstream connectivity derived from MERIT Hydro. If assignments were hydrologically inconsistent, basin hashes would appear spatially fragmented or interleaved across neighboring river systems. Instead, major basins such as the Amazon, Congo, and Nile form spatially contiguous, internally consistent regions, indicating that the mapping preserves



upstream–downstream structure at pixel scale. The alignment of basin-hash regions with Pfafstetter Level-2 boundaries further confirms that zone-wise processing does not introduce artificial cross-basin connections. This diagnostic provides an independent, topology-based validation of the assignment framework, complementary to confidence tiers and score-based metrics.

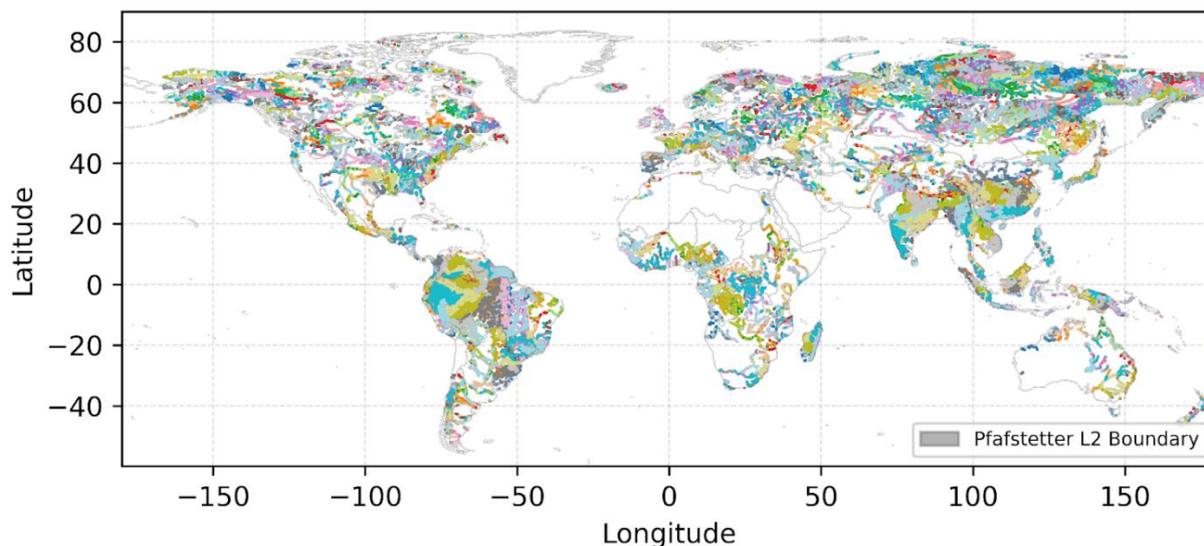


Figure 3. Basin-hash coherence diagnostic for the SWORD–CTRIP mapping. Global map of CTRIP routing pixels colored by the basin hash inherited from the assigned SWORD reach, where basin hashes are derived from MERIT Hydro upstream connectivity. Pixels belonging to the same hydrological basin should form spatially contiguous regions if reach–pixel assignments preserve upstream–downstream structure. Gray lines indicate Pfafstetter Level-2 hydrological zone boundaries. The absence of fragmentation or interleaving of basin hashes across major river systems (e.g., Amazon, Congo, Nile) demonstrates that the assignment procedure maintains basin-scale topological consistency and does not introduce spurious cross-basin linkages.

5 Conclusion

This study introduced a confidence-aware framework to reconcile vector-based SWOT observations, via the SWORD database, with the gridded routing structure of CTRIP. By combining geometric and hydrological criteria into a composite scoring system and classifying each assignment into distinct confidence tiers, the method achieves near-complete coverage of the global CTRIP river-routing domain. The large majority of routing pixels were successfully assigned a SWORD reach, with most cases resolved either unambiguously (Tier 1) or through high-quality scored matches (Tier 2–High). The framework is designed for transparency and practical use in data assimilation. Confidence tiers define the assignment pathway (single, scored, fallback, or unassigned), while confidence scores within Tier 2 provide finer discrimination of assignment quality. This dual structure enables assimilation systems such as CTRIP-HyDAS to weight or filter observations in a principled way, balancing coverage with reliability. Validation using basin-hash diagnostics confirmed the hydrological integrity of assignments, showing that the mapping preserves basin connectivity and river network structure across



Pfaffstetter hydrological zones. Looking ahead, the framework is readily extensible: adaptive weighting schemes, integration
250 with alternative routing models, and incorporation of additional hydrological metrics could further refine assignment
confidence. Beyond SWOT, the approach provides a generalizable solution for linking vector-based river networks and
point-based hydrological observations with gridded hydrological models, establishing a reproducible foundation for bridging
observational and modeling domains in global hydrology.

255 **Code and data availability.**

The complete SWORD-CTRIIP mapping pipeline, encompassing all processing scripts (Phases A–Z), scoring utilities, and
diagnostic plotting tools, is openly accessible via Zenodo archive (<https://doi.org/10.5281/zenodo.18402332>) (Verma and
Munier, 2026). This repository contains example input data, structured output files, and a comprehensive quick-start guide
specifically designed for reproducing the primary assignments and diagnostics presented in this study. The SWORD v17b
260 reach shapefiles and NetCDF products are accessible through the SWOT data portal (<https://www.swordexplorer.com/>), with
a persistent DOI provided as <https://doi.org/10.5281/zenodo.15299138>. The MERIT Hydro dataset is publicly available, as
described by Yamazaki et al. (2019), and can be accessed at https://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_Hydro/. The
CTRIIP model grid and associated river routing data are fully described in Munier and Decharme (2022) and accessible at
<https://doi.org/10.5281/zenodo.6482906>. The derived assignment products, including final reach–pixel matches, confidence
265 tiers, and diagnostic datasets, are provided via Zenodo archive (<https://doi.org/10.5281/zenodo.18402332>) (Verma and
Munier, 2026) to ensure long-term accessibility and reproducibility.

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