Supplement to Author Comment on RC1

This document provides supporting material for the author comment responding to Referee #1. It is intended to document the planned revisions and additional analyses referred to in the author response.

Summary of supporting materials

Item	Purpose in RC1 response	Planned location
Figure A1	Shows the global spatial coverage and regional distribution of the 228 representative basins.	Main manuscript; replaces original Table 2.
Figure A2	Documents the revised robust summary of Fig. 9 parameters using medians and interquartile ranges.	Main manuscript Fig. 9.
Figure A3	Identifies outlying basins and supports the discussion of regional deviations in Fig. 9 parameters.	Supporting Information.
Figure A4	Provides independent validation of H-S order-based discharge scaling using GRADES-hydroDL and MERIT-Basins.	Supporting Information.
Figure A5	Provides independent validation of cumulative runoff-like scaling using local discharge increments from GRADES-hydroDL.	Supporting Information.

A1. Global Distribution of Representative Basins

This material addresses the reviewer's suggestion to replace the original tabular summary of representative basins with a spatial figure. The original table summarized the number of basins by geographic region, but it did not allow readers to evaluate the actual spatial coverage, basin-size variability, or potential regional clustering of the selected basins.

The planned revision will therefore replace the original Table 2 with a global map of the 228 representative basins. The basins will be colored by HydroBASINS geographic region, and an accompanying bar plot will summarize regional counts. This presentation is intended to make the global coverage of the analysis more transparent while retaining the regional information previously provided in the table.

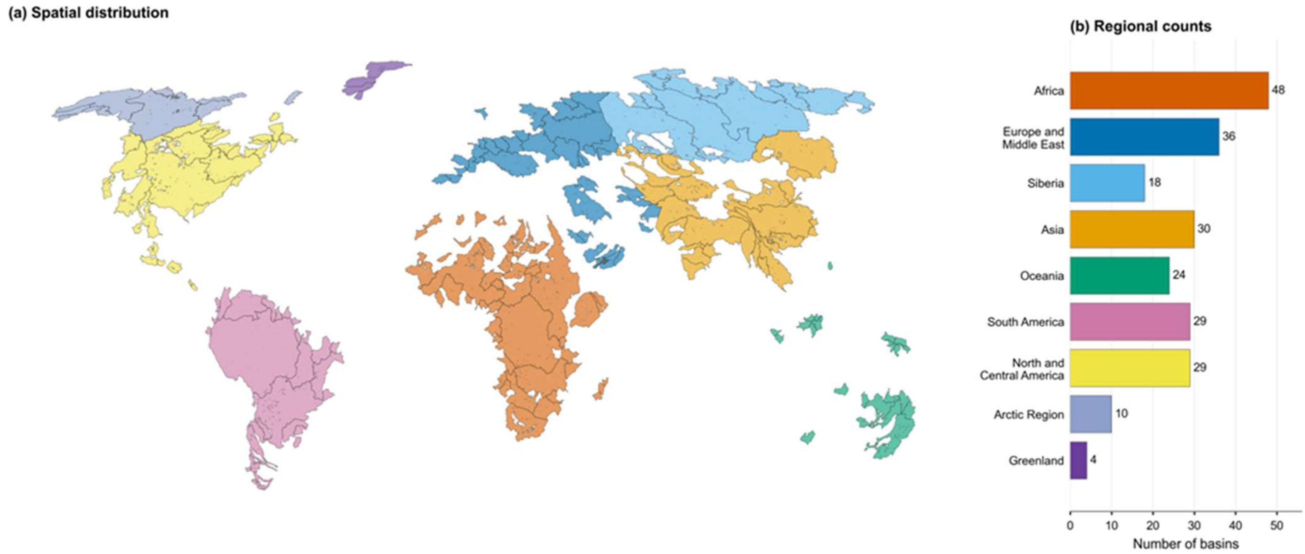

Figure A1. Global distribution of the 228 representative river basins. Basins are shown by HydroBASINS geographic region, with regional basin counts summarized in the accompanying bar plot. This figure will replace the original Table 2 to make the spatial coverage and basin-size variability clearer.

A2. Robust Median and IQR Summary for Fig. 9

This material addresses the reviewer's suggestion that median values may be more informative than means because several indicators show skewed distributions. In the planned revision, Fig. 9 will report medians and interquartile ranges as robust summary statistics, while retaining arithmetic means as complementary information.

The revised analysis shows that runoff-related parameters have very similar mean and median values, indicating that their central tendency is not strongly affected by skewness. In contrast, discharge-related parameters show clearer mean-median separation, which is consistent with their stronger skewness and greater sensitivity to downstream routing, contributing-area aggregation, and regional hydrological heterogeneity.

This revision does not change the main interpretation of the original analysis. Instead, it makes the distributional asymmetry more explicit and provides a more robust basis for comparing the basic-unit parameters across representative basins.

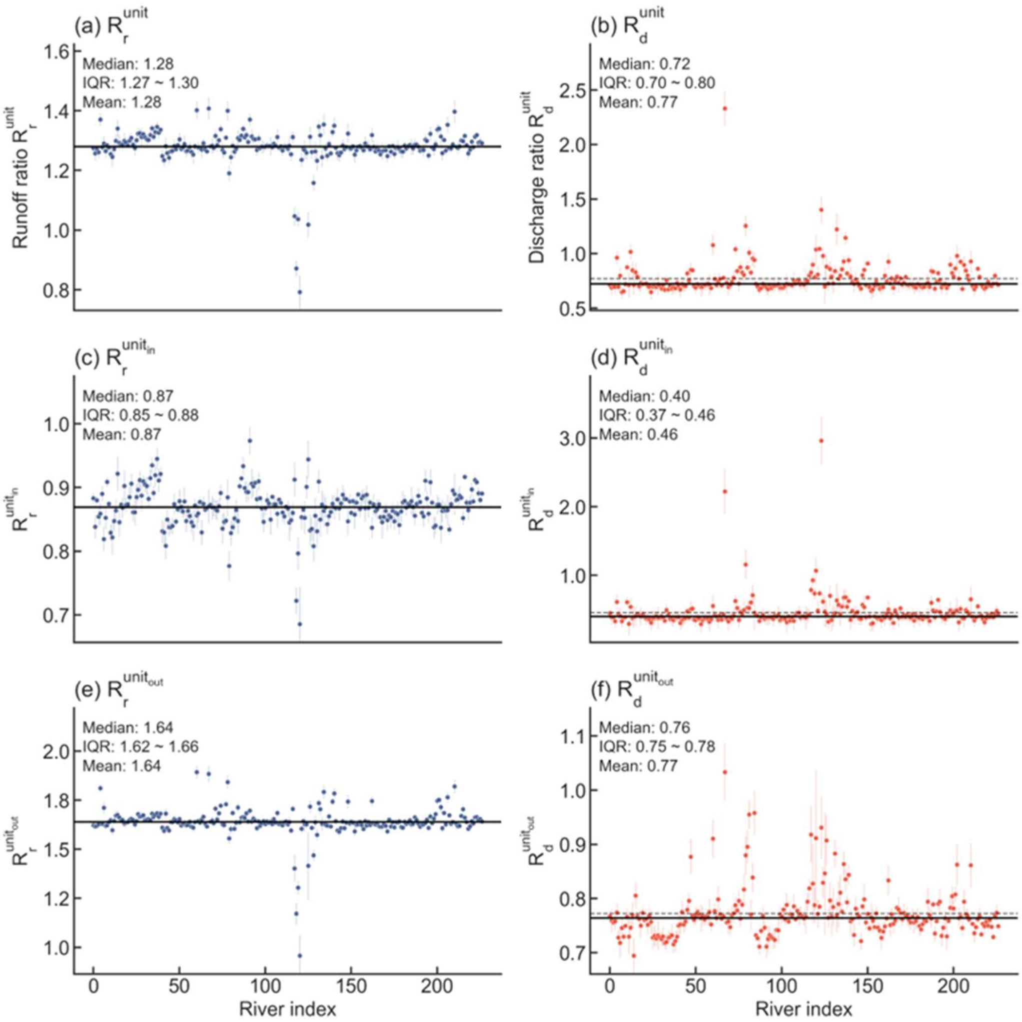

Figure A2. Revised robust summary of basic-unit parameters in Fig. 9. The revised Fig. 9 reports medians and interquartile ranges as robust summary statistics for skewed indicators, while retaining means as complementary information.

A3. Identification and Interpretation of Outlying Basins

Outlying basins will be identified using Tukey's 1.5 x IQR criterion applied separately to the basin-level expected values of each Fig. 9 parameter. A basin is classified as a discharge-related outlier if at least one discharge-related parameter is identified as an outlier; otherwise, if only runoff-related parameters are flagged, it is classified as a runoff-only outlier. This distinction separates deviations associated with discharge ratios from those associated only with runoff ratios.

The outlying basins are not confined to a single region, but their spatial distribution is uneven. Discharge-related outliers occur most frequently in Africa and Europe-Middle East, with additional clusters in Greenland, South America, and Asia. This pattern suggests that the deviations are unlikely to reflect a single regional artefact. Instead, they likely arise from the interaction among river-network topology, regional hydrological setting, and model-derived discharge attributes.

Several mechanisms may contribute to these deviations. Discharge ratios are sensitive to downstream routing and contributing-area aggregation because discharge integrates upstream water fluxes along the channel network. Deviations may therefore be amplified in basins with complex branching structures, strong contrasts between tributary and trunk-stream contributions, or large differences in upstream contributing area. In arid and semi-arid regions, intermittent flow, transmission losses, and spatially heterogeneous runoff generation can further weaken the proportionality between local runoff depth and downstream discharge. In high-latitude and Greenland basins, snow, glacier, permafrost, and seasonal storage processes may also introduce hydrological behaviours that are not fully represented by long-term annual mean discharge estimates.

Runoff-only outliers are fewer and generally less spatially clustered. This supports the interpretation that runoff ratios are more tightly constrained at the basic-unit scale, whereas discharge ratios are more sensitive to downstream accumulation, basin-scale heterogeneity, and uncertainties in the WaterGAP-derived discharge estimates. The presence of these outliers therefore does not overturn the main statistical pattern, but indicates where the hydrological-topological relationships are most sensitive to regional conditions and data-product limitations.

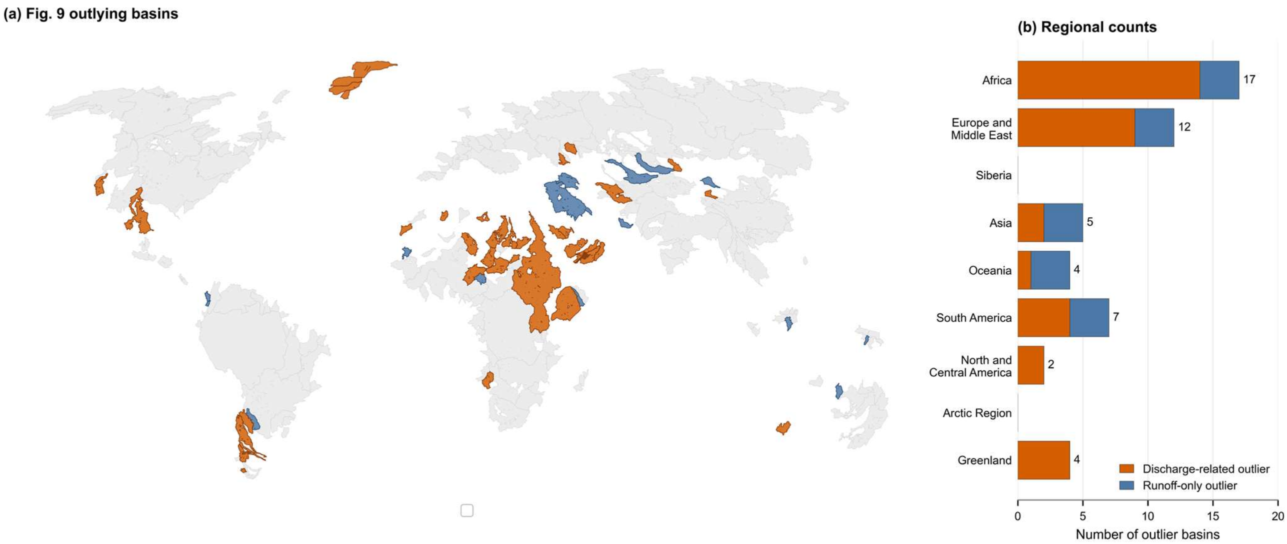

Figure A3. Spatial distribution of outlying basins identified from the Fig. 9 basic-unit parameters. Outliers were identified using the 1.5 × IQR criterion applied separately to each parameter. Orange basins indicate discharge-related outliers, defined as basins with at least one discharge-related parameter identified as an outlier. Blue basins indicate runoff-only outliers. Grey basins indicate non-outlying representative basins. The right panel summarizes the number of outlying basins in each HydroBASINS geographic region.

A4. Independent Validation Using GRADES-hydroDL and MERIT-Basins

This material addresses the reviewer's request for additional validation against independent hydrological products or hydrographic datasets. We performed a supplementary independent validation using GRADES-hydroDL V2.0 discharge and MERIT-Basins river topology. The analysis used MERIT-Basins Pfafstetter level-1 region 4, which mainly covers Asia, and daily GRADES-hydroDL discharge data for 2015-2024. GRADES reach discharge was linked to MERIT-Basins river reaches using COMID, which is shared by the discharge coordinate rivid and the MERIT-Basins river and catchment files.

For discharge, we calculated the 2015-2024 mean Qout for each reach and summarized mean discharge by H-S order. The adjacent-order discharge ratio averaged 4.22 for orders 3-7, close to the characteristic discharge ratio reported in the HydroATLAS-based analysis. The yearly estimates were also stable, with the mean ratio for orders 3-7 remaining close to 4.2 across 2015-2024.

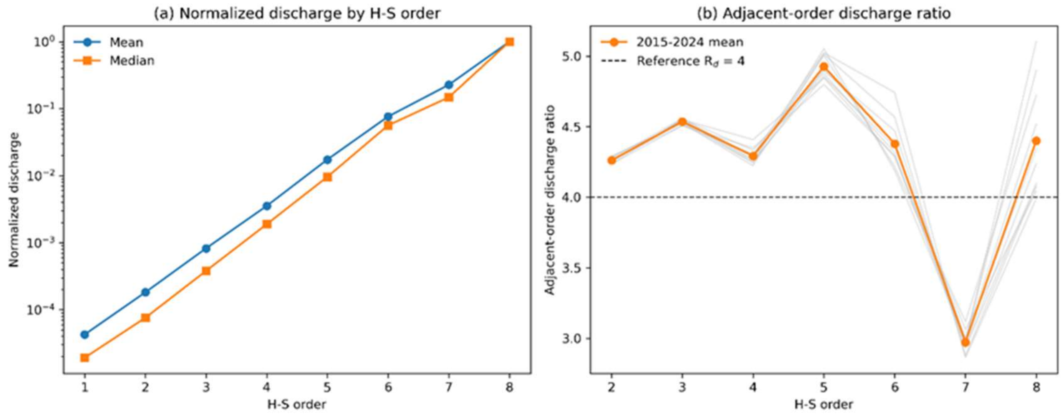

Figure A4. Independent discharge-ratio validation using GRADES-hydroDL and MERIT-Basins. (a) Normalized mean and median discharge by H-S order, calculated from 2015-2024 mean GRADES-hydroDL Qout for MERIT-Basins Pfafstetter level-1 region 4. (b) Adjacent-order discharge ratios. The orange line shows the multi-year mean ratio, grey lines show annual ratios, and the dashed line indicates the reference discharge ratio of 4.

For runoff, GRADES-hydroDL does not provide the same local runoff attribute as HydroATLAS. We therefore computed a runoff-like contribution from local discharge increments, defined as local_Q = Qout(current reach) - sum(Qout of immediate upstream reaches). The cumulative runoff-like volume for each H-S order was calculated by summing non-negative local_Q contributions and converting them to annual volume. This provides a proxy for the cumulative runoff structure, but it should not be interpreted as a direct reproduction of the HydroATLAS runoff attribute. The negative local_Q fraction in the 2015-2024 mean calculation was 0.293 %, indicating that the local differencing estimate was stable for most reaches.

The cumulative runoff-like volume decreased monotonically with increasing H-S order. The adjacent-order cumulative runoff-like ratio averaged 0.476 for orders 3-7, close to the runoff ratio of approximately 0.5 reported in the main analysis. The order-2 ratio was lower than the intermediate-order ratios, consistent with the low-order deviation observed in the HydroATLAS-based analysis. This repeated pattern suggests that the order-2 deviation is not unique to HydroATLAS preprocessing, although it should still be interpreted cautiously as a low-order boundary effect related to headwater extraction thresholds and the transition from hillslope-dominated to channelized flow organization.

This validation is intended as an external robustness check of the H-S order-based scaling patterns. It does not replace a full validation using gauged observations, synthetic benchmark networks, or alternative global hydrographic products, nor does it reproduce the full pyramid-based basic-unit analysis. These broader validation tasks remain important directions for future work.

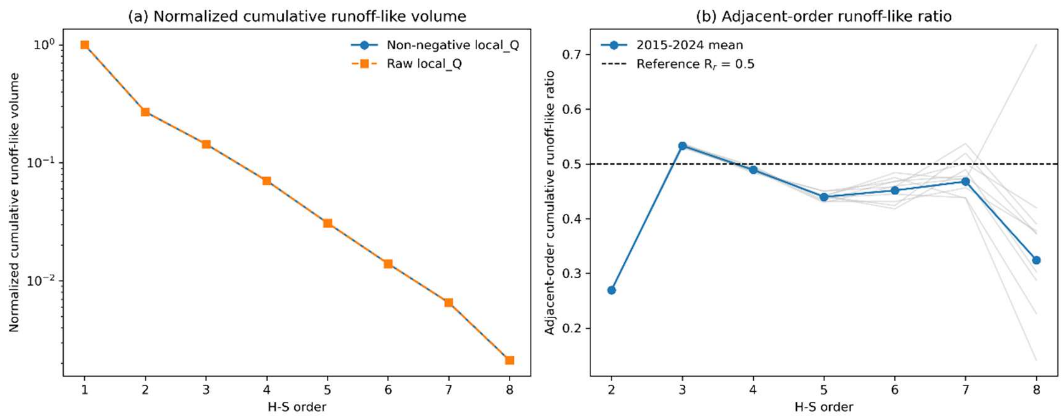

Figure A5. Independent cumulative runoff-like ratio validation using GRADES-hydroDL and MERIT-Basins. (a) Normalized cumulative runoff-like volume by H-S order, calculated from local discharge increments. (b) Adjacent-order cumulative runoff-like ratios. The blue line shows the 2015-2024 mean, grey lines show annual ratios, and the dashed line indicates the reference runoff ratio of 0.5.

Summary

Together, these supporting materials document the planned response to the reviewer's main concerns. The basin map improves transparency of the global sampling design; the revised median/IQR presentation and outlier map address skewness and regional deviations in basic-unit parameters; and the GRADES-hydroDL/MERIT-Basins validation provides an independent check of the main H-S order-based discharge and runoff-like scaling patterns.