Supplemental Information File for

Variations of dissolved greenhouse gases (CO_2, CH_4, N_2O) in the Congo River overwhelmingly driven by fluvial-wetland connectivity

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S1. Spatial analysis

We applied geospatial and statistical methods to compute river width, length, Strahler stream order, surface area, slope, flow velocity, and discharge throughout the Congo River network. All geographic information system (GIS) work was done in ArcMap 10.5 and further geospatial and statistical data analysis was done in R version 3.5.1. The R codes used in this statistical analysis are freely available in the following repository: https://github.com/geoallen/CongoRiverAnalysis We used the following geospatial datasets as input to this analysis:

1) The 30-m Global River Widths from Landsat Dataset (GRWL) Version 1.0 summary statistics polyline shapefile (Allen and Pavelsky, 2018);
2) The 15-arcsecond HydroSHEDS hydrography flowline dataset (Lehner et al., 2008);
3) The HydroSHEDS hydraulically-conditioned digital elevation model (DEM; Lehner et al., 2008);
4) The HydroSHEDS river network connectivity tables from Allen et al. (2018) generated using Reproducible Routing Rituals (https://github.com/c-h-david/rrr). .
5) The Global Land Cover (GLC) 2009 dataset from the European Space Agency (http://due.esrin.esa.int/page_globcover.php);
6) The Global Lakes and Wetland Database (GLWD) Level-1 product (Lehner and Döll, 2004);
7) The HydroBASINS watershed delineation dataset (Lehner and Grill, 2013);
8) The river hydrography dataset published in (Andreadis et al., 2013).

S1.1. Data preprocessing

We clipped all geospatial data layers to the Congo Basin using the HydroBASINS dataset. To delineate the Cuvette Centrale Congolaise (CCC) region, we converted the GLC dataset from raster to polygon vector, and then selected polygon regions in the central Congo basin classified as "Closed to Open Broadleaved Forest Regularly Flooded (Fresh-brackish Water)". We computed all hydrologic parameters (width, length, slope, order, flow velocity, discharge) over the length-scale of a HydroSHEDS river segment, defined as the flowline vector connecting two river network nodes. Using the same procedure as presented in Allen et al. (2018a), we calculated river segment length from the HydroSHEDS flowline dataset and calculated river slope by extracting the elevation of each flowline segment endpoint from the HydroSHEDS DEM and dividing the upstream difference in elevation by the segment length.

S1.2. Spatial join

We fused river width observations from GRWL to HydroSHEDS flowlines using the following spatial join operation: all HydroSHEDS flowlines with a calculated Strahler stream order greater than 4 within 1-km radius of a GRWL centerline was assigned the nearest segment-averaged GRWL river width (Figure S1). Limiting the assignment of GRWL data to segments with orders greater than 4 prevented river widths being assigned to small HydroSHEDS tributaries that do not correspond with the wide rivers in

GRWL. We calculated Strahler stream order (Strahler, 1957) in R using HydroSHEDS connectivity tables (Figure S2). Because HydroSHEDS has been shown to be missing at least one stream order (Benstead and Leigh, 2012), we increased the calculated stream order by one after Raymond et al. (2013), such that 1st order segments became 2nd order, 2nd order segments became 3rd order, etc. Rivers within the CCC region were identified by applying a one-to-one intersection spatial join operation between the GLC-derived CCC region and the HydroSHEDS flowline segments. Similarly, we flagged lakes and reservoirs in the flowline dataset by applying a one-to-one intersection of HydroSHEDS flowlines with the GLWD data product. These flagged lakes and reservoirs were removed from the statistical analysis that is described below.

S2. Statistical analysis

The following text and figures describe the procedure for calculating the width, length, surface area, slope, flow velocity, and discharge of rivers and streams by order within the Congo river basin.

S2.1. River surface area

To estimate the surface area of low-order rivers and streams where the input datasets do not contain observations, we used a width-order and length-order statistical scaling approach similar to that used by Raymond et al. (2013). Long-standing fractal river network theory and observational data show that, within a basin, river length, width, and surface area scale exponentially with stream order (Horton, 1945; Strahler, 1957). As stated above, we removed all lakes and reservoirs from the HydroSHEDS flowline dataset so that we were only considering the surface area of rivers and streams (see red flowlines in Figure S1). Then we statistically modeled the median width of rivers with a stream order of 4 or less by fitting a least-squares exponential regression on the median widths of river orders with GRWL-derived observations (R^2=0.92, p=0.002; Figure S3a).

Similarly, we modeled the total stream length of 1st-order streams by fitting a least-squares exponential regression on the sum length of river orders that we have length estimates (R^2=0.99, p<0.001; Figure S3b). We computed a sum river and stream surface area (*RSSA*) for each stream order (i) by multiplying river width and length,

$$RSSA_i = \sum(Width_i * Length_i). \qquad \text{(S1)}$$

We used the observed values of width and length where they were available, otherwise we used the modeled values for river segments without observations. We found that 9th-order rivers contain a large proportion of surface area due to their extremely wide and braided morphology in the Congo mainstem (Figure S3c). Summing the surface area of all orders, yielded a total area of 23,670 km^2 or 0.64% of the Congo basin area (compared to 0.61% as estimated by Raymond et al. (2013) and 0.64% from Allen & Pavelsky (2018).

S2.2. Slope, flow velocity and discharge

We used slope-order scaling to estimate the median slope of 1st-order streams in the Congo basin, where HydroSHEDS does not contain information. Consistent with Flint's Law (Flint, 1974), we found that the observed median slope is related to order based on a power-law function (Figure 4a). We apply a least-square power-law regression to extend this relationship to 1st order streams (R^2=0.95, p<0.001; Figure 4a). To calculate flow velocity (u), we used Manning's formula,

$$u = n^{-1}R^{2/3}S^{1/3}, \qquad \text{(S2)}$$

where n is Manning's roughness coefficient, assumed to have a mean value of 0.035, R is the hydraulic radius, and S is river slope. The hydraulic radius is equal to river flow width * depth / (width + 2 × depth) for rectangular cross sections (Manning, 1891). We used estimates of mean annual hydraulic radius in the Congo River basin from the hydrography dataset published in Andreadis et al. (2013). This hydrography dataset was created by developing optimized relationships between gauged-based discharge records and upstream drainage area data from the HydroSHEDS hydrography dataset. Then river width and depth were estimated using downstream hydraulic geometry (Leopold and Maddock, 1953; Moody and Troutman, 2002). Using Equation S2, we calculated flow velocity for orders 2-10. To estimate velocity in 1st-order streams, we applied a least-squares exponential regression between stream order and velocity (R^2=0.88, p<0.001; Figure S4b). Similarly, we developed an exponential regression between stream order and the mean annual discharge estimates from Andreadis et al. (2013), and use this statistical relationship to estimate the median discharge of 1st-order streams in the Congo River basin (R^2>0.99, p<0.001; Figure S4c). Tabulated hydrologic data for the Congo River basin are shown in Table S1.

S3. Spatial estimates inside and outside the CCC region

To estimate river and stream hydrologic parameters inside the Cuvette Centrale Congolaise (CCC) region, we employed the same methods as described above except for two differences: First, we only conducted the statistical analysis on flowlines that were within the CCC area (shown as blue lines in Figure S1). Second, when estimating median river width for stream orders 1-4, we did not include stream order 9 in the least-squares regression because doing so produced unrealistically wide low-order stream widths. This outcome occurred because the 9th-order median river width within the CCC is extremely wide: wider than 5 km, a value more than 8 times the magnitude of 8th-order median river width in the CCC. The 9th-order median width is an outlier because of the relatively small geographic area of the CCC and the unrepresentative wide 9th-order main stem of the Congo River that dominates the river and stream surface area in the CCC region. Estimates for length, slope, flow velocity, and discharge were all based on the exact same methods as those described above. Similarly, for hydrologic parameters outside the CCC region, we used the same methods as described in the sections above except that we removed all rivers and streams within the CCC region in the statistical analysis portion of the analysis. Tabulated statistics for river and stream characteristics are available for inside and outside the CCC region in Table S2 and

Table S3, respectively.

Table S1: Tabulated river and stream statistics for the entire Congo River basin. *Q* is discharge.

Order	Median Width (m)	Sum Length (km)	Sum Area (km^2)	Median Slope	Median Velocity (mps)	Median Q (cms)
1	4.8	658608	3132	0.01963	0.536	0.0196
2	9.1	311398	2835	0.004747	0.751	0.95
3	17.4	140702	2453	0.00222	0.745	4.04
4	33.4	66437	2217	0.001155	0.833	19.58
5	63	34877	2197	0.000715	0.944	84.94
6	94	22228	2089	0.000534	1.212	376.99
7	256	9156	2344	0.000416	1.481	1088.045
8	536	3717	1992	0.000236	1.613	3066.265
9	1421	2649	3765	0.000138	1.559	10474.91
10	1005	643	646	0.000297	3.405	60741.16

Table S2: Tabulated river and stream statistics for the Cuvette Centrale Congolaise within the Congo River basin. *Q* is discharge.

Order	Median Width (m)	Sum Length (km)	Sum Area (km^2)	Median Slope	Median Velocity (mps)	Median Q (cms)
1	5.5	63233	350	0.004208	0.362	0.0042
2	10.8	31070	335	0.001399	0.461	1.22
3	21.1	15359	324	0.000768	0.5	5.235
4	41.1	7069	291	0.000527	0.627	26.72
5	77	3614	278	0.000406	0.845	160.84
6	189	2541	480	0.000302	1.059	648.45
7	237	688	163	0.000233	1.18	1329.67
8	663	552	366	0.000272	1.606	3096.65
9	5794	200	1158	9.50E-05	1.647	33726.82

Table S3: Tabulated river and stream statistics for the Congo River basin, excluding the Cuvette Centrale Congolaise. *Q* is discharge.

Order	Median Width (m)	Sum Length (km)	Sum Area (km^2)	Median Slope	Median Velocity (mps)	Median Q (cms)
1	3.9	574398	2235	0.022787	0.568	0.0228
2	7.6	280328	2143	0.005158	0.787	0.92
3	15	125343	1883	0.00244	0.786	3.9
4	29.5	59368	1752	0.00127	0.868	18.71
5	54	31263	1688	0.000774	0.962	78.15
6	90	19687	1772	0.000571	1.24	334.055
7	256	8468	2168	0.00044	1.52	1076.23
8	536	3164	1696	0.000234	1.613	2956.56
9	1421	2450	3481	0.000144	1.553	10466.86
10	1005	643	646	0.000297	3.405	60741.16

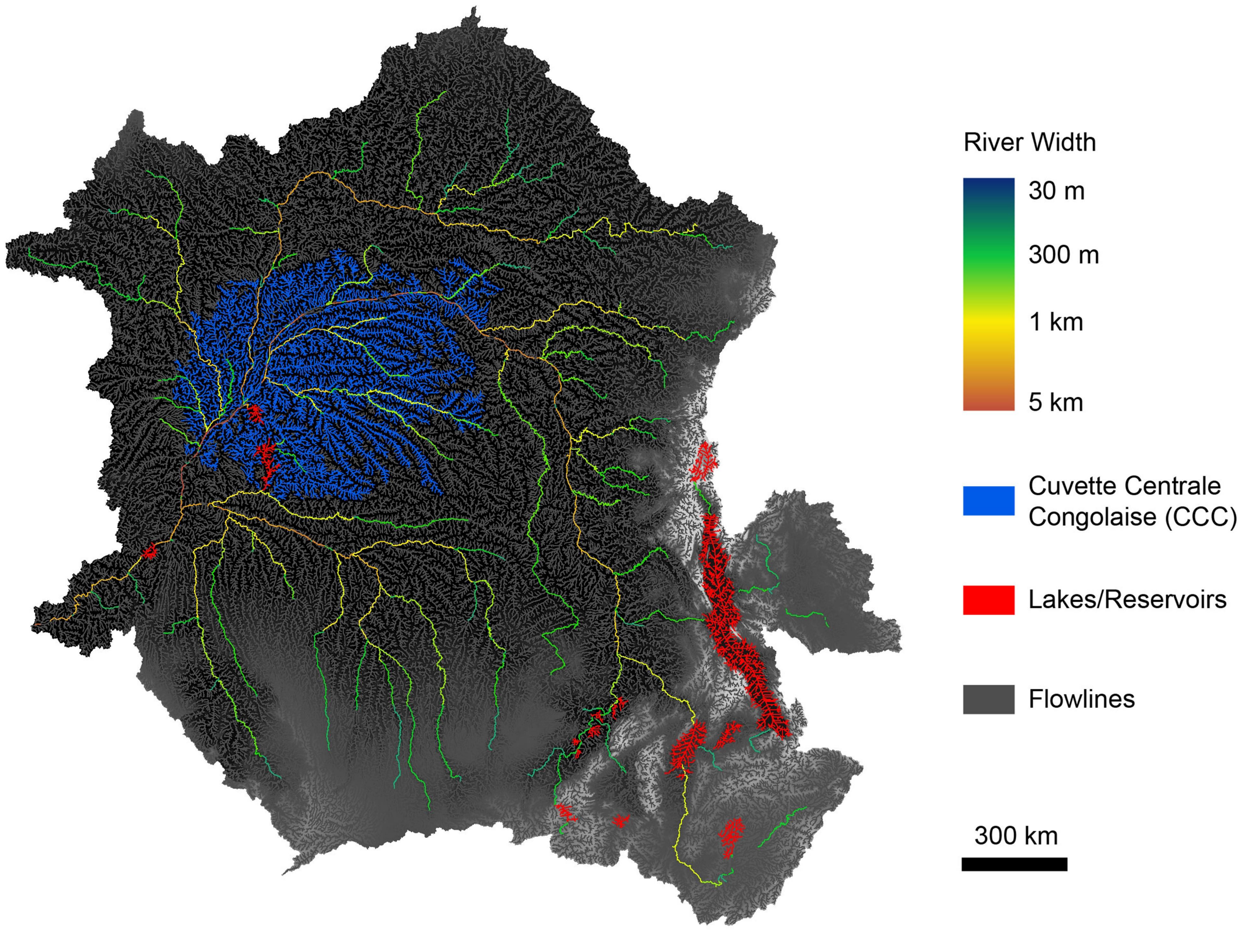

Figure S1: HydroSHEDS flowlines with river widths from GRWL, CCC region from the GLC dataset, and Lakes/Reservoirs from the GLWD. Land surface elevation is shown in the background.

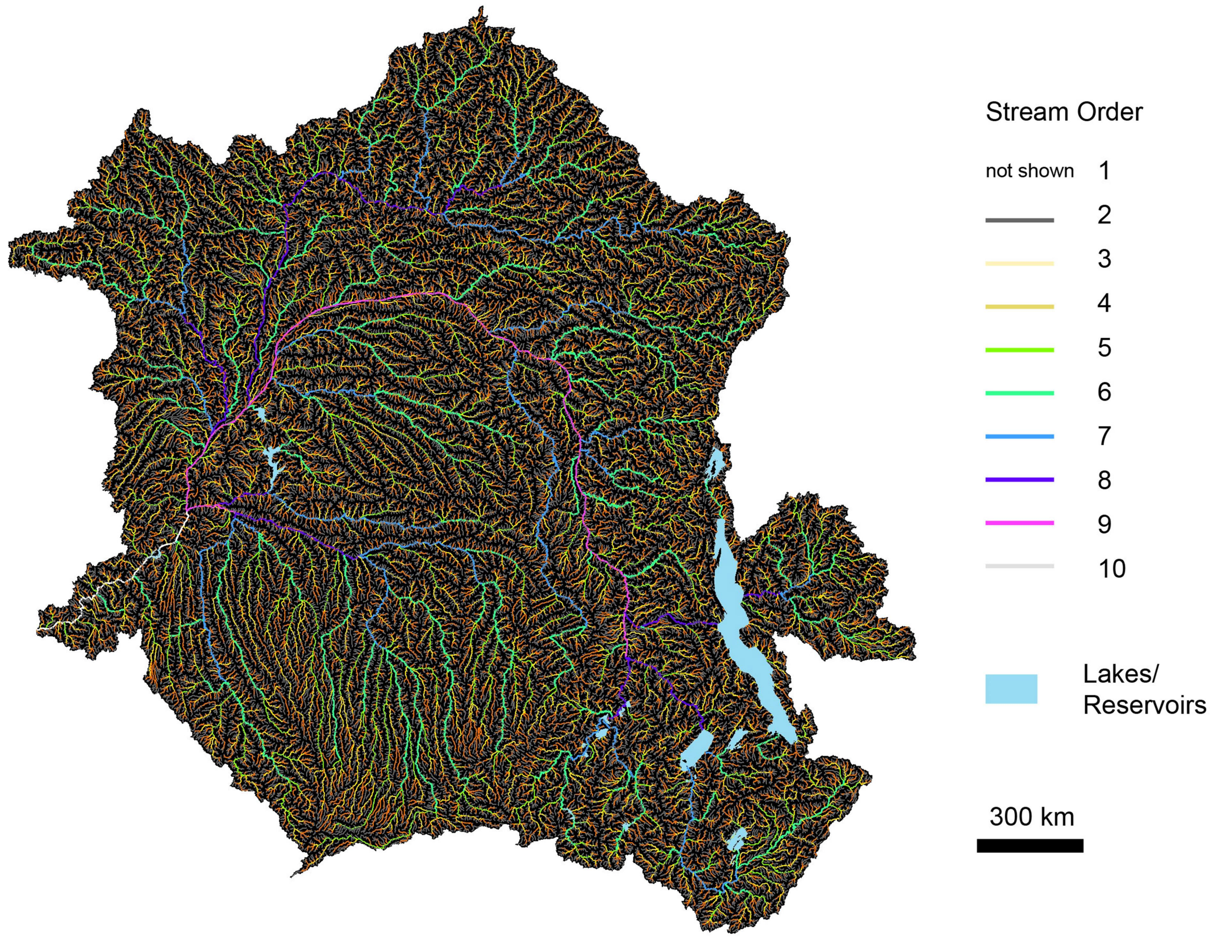

Figure S2: Congo River network colored by Horton-Strahler stream order.

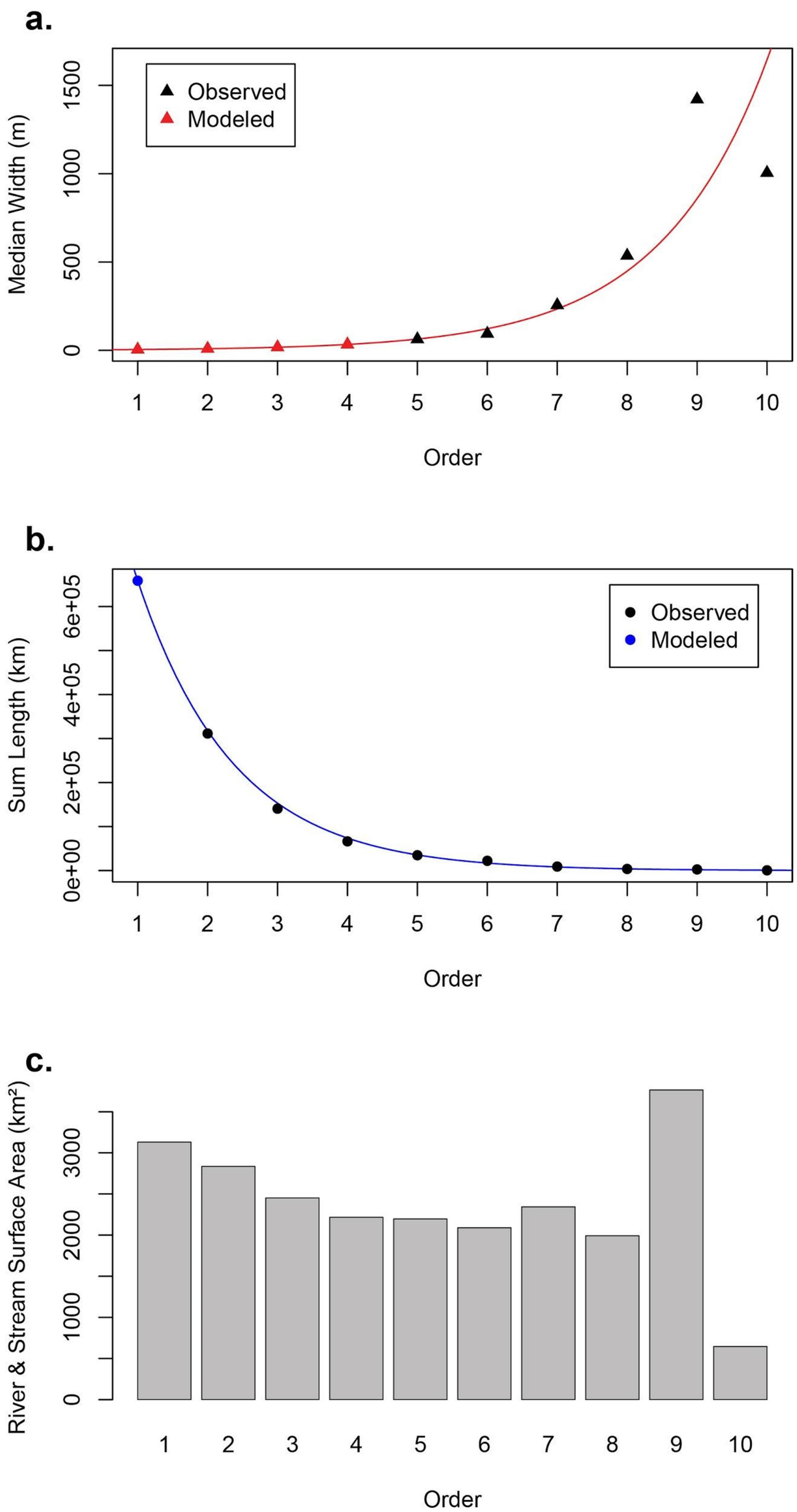

Figure S3: Statistical approach used to estimate: (a) river and stream width; (b) river and stream length; and (c) river and stream surface area by stream order. The large surface area exhibited by 9th-order rivers corresponds to the very wide and braided section of the Congo mainstem.

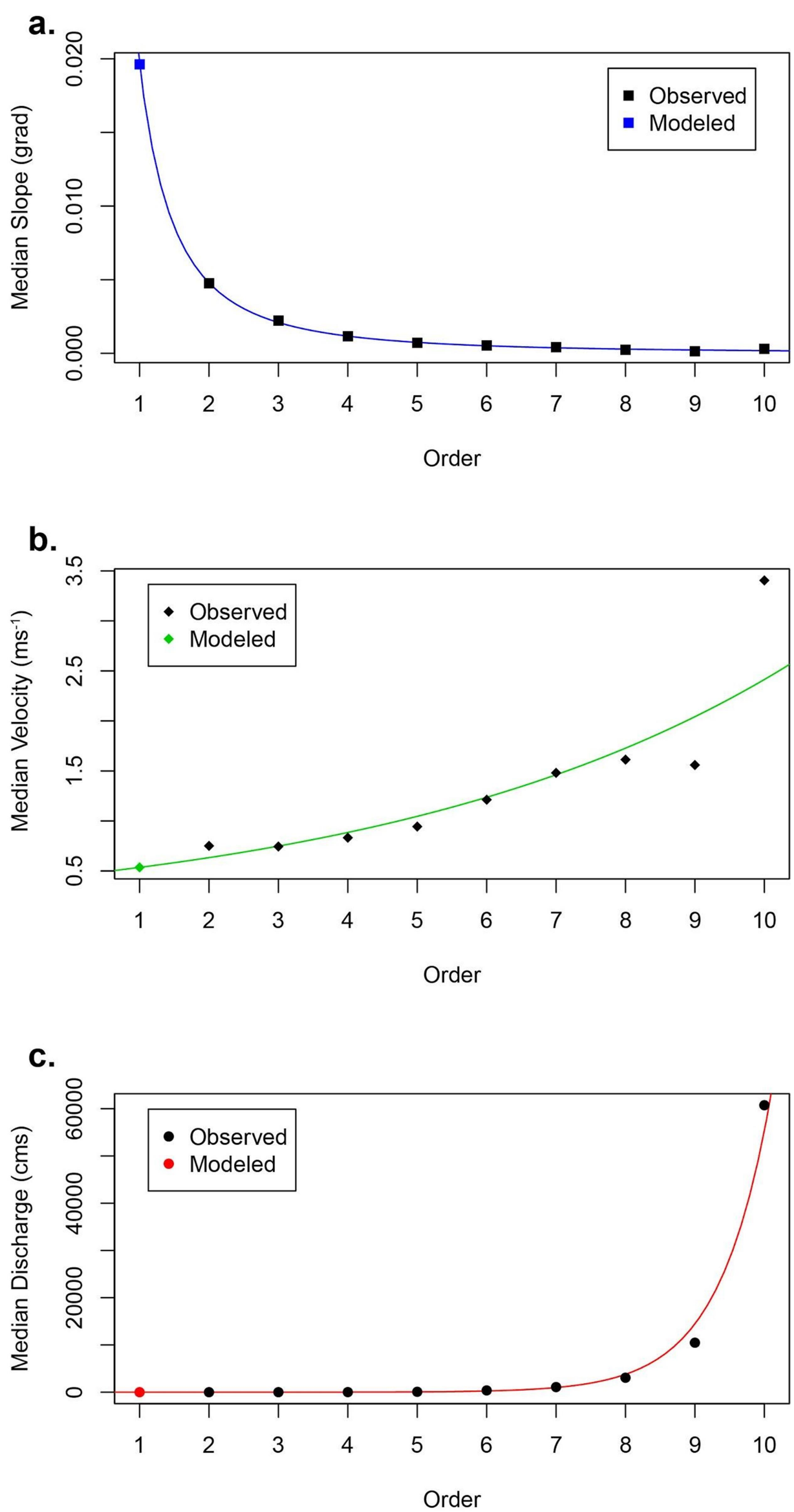

Figure S4: Statistical approach used to calculate 1st-order median stream (a) slope, (b) velocity, and (c) discharge.

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