

Climate controls the length and shape of the world's drainage basins

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Abstract

Climate is thought to affect the structure and evolution of drainage basins, yet it is still widely held that there is universal power law scaling between channel length and drainage area, which is independent of climate. Since climate controls runoff, streamflow, and erosion regimes, we looked for climate dependency within a new, global dataset of drainage basin morphometrics. We show that increasingly arid drainage basins have longer channels and narrower drainage basins, and power law scaling increases monotonically with aridity. We suggest these results arise due to downstream channel extension by extreme events, wherein increasingly large floods erode channels into previously unchanneled terrain, yielding a morphometric signature in drylands that is preserved over long timescales due to a lack of biotic smoothing of topography. This new understanding of drainage basin morphometrics on Earth may be used to inform interpretations of past climates on Earth and other solar system bodies.

1. Introduction

Metrics of topography and topology from drainage networks provide information about the forces involved in their formation (Chen et al., 2019; Dunne, 1990; Horton, 1945; Perron et al., 2012; Rinaldo et al., 1995; Seybold et al., 2017; Slater & Singer, 2013). Channel length (L) is a metric describing the topographic expression of along-channel distance from source to mouth (*Supporting Information*). Length is fundamentally affected by channel head position (the point in

35 the landscape at which fluvial erosion exceeds sediment input (Montgomery & Dietrich, 1988)
36 and the downstream limits on topographic channel extension. Channel head position is assumed
37 to be approximately fixed for a given stationary climate regime, for example, where larger
38 upstream drainage areas are required to incise a channel head in more arid climates due limits
39 on the production of water (Montgomery & Dietrich, 1988). The downstream extent of channels
40 is controlled by the presence of downstream water bodies. For example, perennial river channels
41 in humid regions typically debouch into a higher order stream, lake, sea, or ocean, while
42 endorheic (internally draining) basins, common to drylands, are only limited in their downstream
43 extent by the supply of water from upstream required to erode the channel farther downstream.
44 Drainage basin area (A), or area upstream of the most downstream point on a channel, reflects
45 the topological spreading of the channel network, bifurcation frequency, and tributary junction
46 angles (Horton, 1945; Montgomery & Dietrich, 1988; Seybold et al., 2017; Yi et al., 2018), and the
47 along-channel length to area ratio (L/A) expresses how much the dominant channel fills its
48 drainage area. L/A can be thought of as a hydrologic aspect ratio, and it is an approximate
49 measure of basin shape. Higher values of L/A correspond to relatively short channels in wider
50 basins and lower values represent relatively long channels in narrow basins.

51
52 The relationship between L and A is generalized regionally and across the globe by Hack's Law (L
53 $= cA^h$), where c is a dimensionless coefficient and h is a dimensionless exponent. This empirical
54 formulation is based on regional field surveys (Hack, 1957), which was later shown to emerge
55 statistically based on fractal characteristics in natural networks (Rigon et al., 1996). The Hack's
56 Law exponent h has been shown to be approximately 0.6 from datasets, theoretical analysis, and
57 lab experiments (Rigon et al., 1996). Hack's Law is a widely agreed upon universal, increasing
58 relationship between channel length and drainage area for the world's basins (Hack, 1957), which
59 is commonly used to characterize the emergent properties of networks on Earth and other
60 planetary bodies (Rigon et al., 1996), to quantify hydrologic response times (Rinaldo et al., 1998),
61 and to parameterize geomorphic landscape evolution models in order to assess the effects of
62 tectonics and other environmental phenomena on network development (Tucker & Whipple,
63 2002).

64
65 Each of these diagnostic drainage basin morphometrics (L , A , L/A , h) should vary across the globe,
66 depending on the regionally relevant set of controls (climate, lithology, tectonics, land use).
67 Generalizations of drainage basin evolution have largely focused on time as the key variable,
68 arguing that networks become more elaborate over longer timescales following tectonic uplift or
69 base level change, and that they may develop in random fashion (Leopold et al., 1964; Rinaldo et

70 al., 1998). Implicit in these generalizations is an assumption that climatic forcing is more
71 equivocal in terms of its systematic imprint within morphometrics. However, climate controls the
72 regional water cycle and its translation into streamflow generation, channel erosion regimes, and
73 vegetative resistance, so its expression over the relevant spatial and temporal scales must have a
74 primary influence on drainage network development (Chen et al., 2019; Collins & Bras, 2008;
75 Tucker, 2004). Since climate is nonuniformly expressed across the globe, we might expect to see
76 broad differences in drainage basin metrics in distinct climatic zones, irrespective of spatial
77 variations in lithology, tectonics, and land use.

78
79 Recent research has indicated that regional climate controls some aspects of drainage network
80 topography and topology (Bonnet, 2009; Chen et al., 2019; Rinaldo et al., 1995; Seybold et al.,
81 2017; Slater & Singer, 2013; Solyom & Tucker, 2004; Tucker & Bras, 2000; Yi et al., 2018). Some of
82 these studies suggest that arid climate zones have a higher number of narrower drainage basins
83 for a given area than humid climate zones and that the drainage area upstream of a channel head
84 is larger for arid regions. However, it is challenging to generalize the understanding of climatic
85 controls on drainage basins from previous research beyond the local site/region of study,
86 dataset, model setup, or laboratory flume conditions.

87 88 **2. Methods**

89 To investigate the influence of climate on drainage basin morphometrics over a wide range of
90 climates, we developed a new, open-access Global Drainage Basin Morphometrics database
91 (GDBM) between 60°N and 56°S (Fig.S1a;Dataset S1). The creation of a new database was
92 required to explore morphometrics in basins that exist entirely within a single climate regime, to
93 investigate channel topography instead of river hydrography, and in order to characterize how
94 morphometrics vary across a spectrum of humid and arid climate zones, the latter of which are
95 less studied (*Supporting Information*).

96
97 This near-global, spatially explicit drainage basin dataset was extracted from NASA's 30-m Shuttle
98 Radar Topography Mission Digital Elevation Model (SRTM-DEM), using software designed for
99 extracting morphometrics with speed and reproducibility, and without prior assumptions about
100 channel locations or extent (*Supporting Information*). The GDBM database enables: 1) analysis of
101 key basin morphometrics (L , A , L/A) from all basins above a consistent threshold area (*Supporting*
102 *Information*); 2) characterization of Hack's h , the scaling between channel length and drainage
103 area, for a range of A over which Hack's h is not expected to vary (Willemin, 2000); and 3)
104 quantification of the number of drainage basins or subbasins within particular regions or climate

105 categories. Subbasins refer to subdivisions of a basin that contains more than one extracted
106 channel that exceeds the drainage area threshold (*Supporting Information*).

107
108 We interrogated GDBM to generalize about the role of climate in drainage basin evolution using
109 the Köppen-Geiger climate classification (Fig.S1b) and categories of the quantitative Aridity Index
110 (Precipitation/Potential Evapotranspiration, Fig.S1c). Köppen-Geiger incorporates various rules
111 regarding temperature and precipitation thresholds emphasizing vegetation response to climate.
112 Aridity Index, a scale that (nonintuitively) declines with aridity, more straightforwardly
113 characterizes the hydrologic expression of climate as a simplified water balance. We use these
114 classifications to test whether aridity in the hydrologic cycle is detectable in key basin
115 morphometrics. By climate-classifying the basins, and also by limiting our analysis to small basins
116 (*Supporting Information*), we can more straightforwardly constrain and explore the climatic
117 controls on drainage basins development. We treat the two classifications independently in our
118 analysis and pose the null hypothesis that there are no differences in morphometrics between
119 climate categories in each. To simplify the analysis, we did not control for other natural or
120 anthropogenic variables, which likely produce higher variability in the resulting data. Therefore,
121 we posit that any signals that arise from these environmental data based on climatic
122 classifications can be assumed to be strong enough to overprint the scattering effects of other
123 variables.

125 3. Results

126 In total, we documented 355,123 individual drainage basins within GDBM, including mainstem
127 channels and subbasin channels that exceed the threshold area (*Supporting Information*). Of this
128 total number of drainage basins, our analysis of climate dependency in morphometrics includes
129 only those entirely contained within one Köppen-Geiger climate subzone (72% of extracted
130 channels), and it excludes those spanning two or more Köppen-Geiger subzones (28%) (Fig.S2;
131 Table S1). Global medians of L , A , and L/A for channels contained within a single Köppen-Geiger
132 climatic subzone are 32 km, 220 km², and 0.14 km/km², respectively (Fig.1, Figs.S4;S5).

133
134 But are climatic signatures systematically expressed within drainage basin metrics globally? L is
135 similar among the four main Köppen-Geiger categories except the Arid category, which contains
136 relatively long channels with high values of L/A (Fig.1a,c). Looking at the role of aridity in more
137 detail, we found that surprisingly, within the Aridity Index classification, L and L/A increase
138 systematically with increasing aridity (Fig.1b,d). Furthermore, if we group the GDBM basins into
139 dryland (Semi-arid, Arid, Hyperarid) versus non-dryland (Dry Subhumid, Humid) categories, we

140 find that dryland channels are disproportionately longer with higher values of L/A . This result
141 holds despite no systematic differences in drainage basin areas between classes, apart from
142 notably larger basins in the Hyperarid Aridity Index category (Fig.1e-f; Fig.S4d-f).

143
144 These findings suggest a systematic control of climate on drainage basin development in
145 drylands, in which higher aridity produces progressively longer channels and narrower drainage
146 basins. The results are consistent with prior observations suggesting that arid regions produce
147 narrower drainage basins (Bonnet, 2009) with more acute junction angles (Seybold et al., 2017),
148 yet it contrasts with previous research indicating that arid regions have shorter channels for a
149 given drainage area (Yi et al., 2018). It also contradicts prior work suggesting that Hack's h is not
150 sensitive to climate (Sassolas-Serrayet et al., 2018).

151
152 To investigate this further, we looked for climate dependency within Hack's Law. It is generally
153 assumed that Hack's Law provides a universal scaling relationship between L and A for channels
154 across the globe, and that Hack's h only varies with basin area (Rigon et al., 1996; Willemin, 2000)
155 above a threshold of $\sim 20,000 \text{ km}^2$ (well above the scale of basins studies here, *Supporting*
156 *Information*), and not with basin shape (Sassolas-Serrayet et al., 2018). We plotted the L versus A
157 data from GDBM classified by Aridity Index on a log-log scale and computed h based on least
158 squares regression for each Aridity Index category (Fig.2).

159
160 Surprisingly, we found that the global average value of h (0.758) for all basins is $\sim 25\%$ higher than
161 what has been reported (Hack, 1957; Rigon et al., 1996), suggesting that channels are longer for a
162 given basin area than previously thought. Upon further investigation, we found that this
163 difference can be explained by the method of computing channel length. Specifically, our method
164 accounts for sinuosity along the channel, which we feel most accurately represents channel
165 length and consequently, fluvial processes, while previous work has apparently relied on simple
166 Euclidean distance along the channel axis or utilized coarser data (*Supporting Information*; Fig.S3).

167
168 Regarding climate dependence, we found an unprecedented result that h systematically
169 increases with aridity (from 0.746 to 0.796 between Humid and Hyperarid basins, respectively,
170 Fig.2). This result is corroborated by the fact that the Arid zone within the Köppen-Geiger
171 classification also has the highest value of h (Fig.S6).

172
173 A recent paper obtained the opposite result, namely that Hack's h is systematically lower for arid
174 basins than humid ones within the continental USA (Yi et al., 2018). However, that study used a

175 hydrography dataset developed by a drainage enforcement technique that involves burning
176 previously mapped stream networks (blue lines) into a digital elevation model. Our results are
177 not directly comparable to that study because drainage enforcement would always yield shorter
178 river lengths for dryland regions, as arid channels flow discontinuously and less frequently and
179 therefore their full extent does not show up on stream network maps (*Supporting Information*).
180 In contrast, our unsupervised approach to channel extraction identifies the full extent of channels
181 within humid and arid areas alike (subject the limits of the 30-m SRTM dataset), revealing a
182 strong climate dependency in Hack's h (Fig.2; Fig.S6).

183
184 Another recent study showed that Hack's h is insensitive to climate (mean annual rainfall, rather
185 than aridity) and shape (Sassolas-Serrayet et al., 2018), but that study focused on one of the most
186 tectonically active areas of the world (Himalayas), where tectonic forcing would tend to overprint
187 any climatic controls on drainage basin development (Tucker, 2004). That study argued that the
188 Hack's Law dimensionless coefficient, c , is a more sensitive parameter that reflects basin shape.
189 Correspondingly, in corroboration of the Hack's h results, we also found from GDBM that Hack's c
190 monotonically increases with aridity (*Supporting Information*), further supporting the conclusion
191 that basin shape becomes more elongate (Sassolas-Serrayet et al., 2018) in drier climatic regions.
192

193 4. Discussion

194 We view the L , L/A , and Hack's h results (Fig.1) as global confirmation of the tendency for longer,
195 narrow drainage basins to develop in arid climates typified by precipitation/runoff regimes that
196 are highly variable in space and time (Bonnet, 2009; Seybold et al., 2017; Solyom & Tucker, 2004;
197 Tucker & Bras, 2000), but by what potential mechanisms? It has been suggested that arid regions
198 have relatively high areas of unchannelized basin due to limited runoff generation at small
199 drainage areas (Montgomery & Dietrich, 1988), so we expected to find correspondingly short arid
200 channel lengths. In fact, the GDBM pattern is the opposite, namely higher L and L/A in
201 progressively more arid environments (Fig.1b,d;Figs.S4;S5). These results are strong evidence of a
202 climatic control on drainage basin evolution favoring network extension (channel elongation)
203 (Wolman & Gerson, 1978) and splitting of drainages into narrow basins in arid regions (Bonnet,
204 2009).

205
206 Given the obvious limitation of water in arid regions, what might explain longer channels and
207 higher values of L/A ? Dryland hydrology is characterized by brief spells of often intense rainfall
208 expressed over a limited area of a basin, partial area runoff during intense rainstorms, and the
209 development of channel flow only when the period of runoff generation is long enough (Carson &

210 Kirkby, 1972; Michaelides et al., 2018b; Singer & Michaelides, 2017). Dryland channel flow
211 regimes are characterized by long periods of no flow, discontinuous flow along the channel, and
212 infrequent extreme flood events that topographically reshape channels due to inherently low
213 erosion thresholds (Singer & Michaelides, 2014; Wolman & Gerson, 1978). Channel bed erosion
214 can occur easily in drylands, in part due to a lack of vertical sorting and channel bed armoring
215 associated with high sediment supply during brief flood events that is incompletely sorted along
216 the channel (Laronne et al., 1994; Singer & Michaelides, 2014). Arid basins also tend to be
217 internally draining (endorheic), so they typically do not have a base level that is fixed by a
218 perennial water body (larger river, lake, or sea), as is often the case in humid environments. Thus,
219 arid channels have room to grow downstream, with a measurable topographic imprint, when the
220 conditions are suitable.

221
222 These factors enable channel elongation by downstream extension of the arid fluvial network
223 during rare, extreme flood events (Leopold & Miller, 1962; Rinaldo et al., 1995; Wolman &
224 Gerson, 1978). Upstream extension of the network in drylands is unlikely due to limits on the
225 generation of runoff capable of eroding a channel head (Montgomery & Dietrich, 1988). The
226 topographic imprint of downstream channel extension arising from infrequent extreme events
227 may be subsequently preserved over long timescales (Solyom & Tucker, 2004; Tucker & Bras,
228 2000), due to the limited effects of vegetation and bioturbation in arid regions (Rinaldo et al.,
229 1995; Wolman & Gerson, 1978). Furthermore, arid basins tend to have limited sediment delivery
230 from upstream that might otherwise infill the channel and obscure the signature of episodic
231 erosion because flood events derived from dryland rainstorms are too short-lived and spatially
232 restricted to efficiently export sediment from upstream to downstream (Michaelides et al.,
233 2018a; Singer & Michaelides, 2014; Singer & Michaelides, 2017). Thus, we observe longer
234 channels, higher L/A , and higher Hack's h in progressively arid regions (Figs.1;2).

235
236 The general differences between humid and arid regions in terms of drainage basin morphology
237 are summarized schematically (Fig.3a-b) and correspondingly for extracted basins in GDBM
238 (Fig.3c-d), while Fig.3e shows how the key morphometrics studied here vary with aridity. In
239 summary, our analysis revealed clear climatic signatures within drainage basin morphometrics
240 across the globe without controlling for additional interacting independent variables such as
241 tectonics or land use. These climate signatures can be seen in both Köppen-Geiger and Aridity
242 Index classifications.

244 We showed that L , L/A , and Hack's h increase with aridity, while A is mostly insensitive to climate
245 (Figs.1b,d-f;2;3e;Figs.S4;S5). This suggests that aridity in basins preserves major erosion episodes
246 and their downstream extension of drainage networks, producing long, narrow basins that are
247 closely spaced (Bonnet, 2009; Perron et al., 2009), and that preservation of the imprint of these
248 extreme events is higher with increasing aridity (*sensu* (Rinaldo et al., 1995)). Finally, we found
249 that the number of classified drainage basins in GDBM ($< 3000 \text{ km}^2$, Fig.S4) increases from
250 Hyperarid to Semi-arid aridity classes, then drops again in the Dry Subhumid class, before
251 reaching its maximum in the Humid class ($n=114,201$;Fig.3e;Table S1). This latter result may
252 indicate a bimodality in drainage basin organization due to feedbacks between climate and
253 vegetation. It suggests that many narrow subbasins are created in Semi-arid environments via
254 network splitting (Bonnet, 2009), yielding higher sediment loads where there is enough water to
255 erode the landscape by overland flow (Horton, 1945), but where there is not enough vegetation
256 to resist this erosion (Collins & Bras, 2008). Once the vegetation becomes more dense in Dry
257 Subhumid basins, the water travels along subsurface flow paths (Dunne, 1990), leading to
258 topological spreading that increases drainage density (Collins & Bras, 2010) and generates
259 numerous subbasins in Humid basins (Fig.3).

260
261 The morphometric patterns observed here lend strong support to the hypothesis that climate
262 plays a first-order role in drainage basin development, broadly supporting evidence from
263 previous research (Bonnet, 2009; Chen et al., 2019; Seybold et al., 2017; Solyom & Tucker, 2004).
264 While there are numerous published examples of how drainage basin evolution is influenced by
265 independent variables such as human impacts, tectonics, and lithology, we show that climate
266 leaves indelible signatures within morphometrics. These signatures are clearly detectable,
267 irrespective of multiple confounding factors and regardless of the climate classification scheme
268 used. They may provide insights into how drainage basins will evolve to climate change on Earth
269 and into the climate history of other solar system bodies.

275 **References**

- 276 Bonnet, S. (2009). Shrinking and splitting of drainage basins in orogenic landscapes from the
277 migration of the main drainage divide. *Nature Geosci*, 2(11), 766-771. 10.1038/ngeo666.
278 <http://dx.doi.org/10.1038/ngeo666>
- 279 Carson, M. A., & Kirkby, M. J. (1972). *Hillslope Form and Process*: Cambridge University Press.
- 280 Chen, S.-A., Michaelides, K., Grieve, S. W. D., & Singer, M. B. (2019). Aridity is expressed in river
281 topography globally. *Nature*, 573, 573–577. <https://doi.org/10.1038/s41586-019-1558-8>
- 282 Collins, D. B. G., & Bras, R. L. (2008). Climatic control of sediment yield in dry lands following
283 climate and land cover change. *Water Resources Research*, 44(10), 8. Article. <Go to
284 ISI>://000259993200002
- 285 Collins, D. B. G., & Bras, R. L. (2010). Climatic and ecological controls of equilibrium drainage
286 density, relief, and channel concavity in dry lands. *Water Resources Research*, 46(4),
287 W04508. <http://dx.doi.org/10.1029/2009WR008615>
- 288 Dunne, T. (1990). Hydrology, mechanics, and geomorphic implications of erosion by subsurface
289 flows. In C. G. Higgins & D. R. Coates (Eds.), *Groundwater geomorphology: The role of*
290 *subsurface water in earth-surface processes and landforms* (pp. 1-28). Boulder, CO: Geol.
291 Soc. Amer. Special Paper 252.
- 292 Hack, J. T. (1957). *Studies of longitudinal stream profiles in Virginia and Maryland* (294-B).
293 Retrieved from Menlo Park, CA:
- 294 Horton, R. E. (1945). Erosional development of streams and their drainage basins; hydrophysical
295 approach to quantitative geomorphology. *Geol. Soc. Amer. Bull.*, 56, 275-370.
- 296 Laronne, J. B., Reid, I., Yitshak, Y., & Frostick, L. E. (1994). The non-layering of gravel streambeds
297 under ephemeral flood regimes. *Journal of Hydrology*, 159(1-4), 353-363.
298 [http://www.sciencedirect.com/science/article/B6V6C-487DTBV-](http://www.sciencedirect.com/science/article/B6V6C-487DTBV-16/2/208964486e0bc7aaa3836d7dad610ccb)
299 [16/2/208964486e0bc7aaa3836d7dad610ccb](http://www.sciencedirect.com/science/article/B6V6C-487DTBV-16/2/208964486e0bc7aaa3836d7dad610ccb)
- 300 Leopold, L., Wolman, M. G., & Miller, J. P. (1964). *Fluvial Processes in Geomorphology*. San
301 Francisco, CA: W.H. Freeman & Co.
- 302 Leopold, L. B., & Miller, J. (1962). *Ephemeral streams: hydraulic factors and their relation to the*
303 *drainage net*. Retrieved from Washington, D.C.:
- 304 Michaelides, K., Hollings, R., Singer, M. B., Nichols, M. H., & Nearing, M. A. (2018a). Spatial and
305 temporal analysis of hillslope–channel coupling and implications for the longitudinal
306 profile in a dryland basin. *Earth Surface Processes and Landforms*.
307 <http://dx.doi.org/10.1002/esp.4340>
- 308 Michaelides, K., Hollings, R., Singer, M. B., Nichols, M. H., & Nearing, M. A. (2018b). Spatial and
309 temporal analysis of hillslope–channel coupling and implications for the longitudinal
310 profile in a dryland basin. 43(8), 1608-1621.
311 <https://onlinelibrary.wiley.com/doi/abs/10.1002/esp.4340>
- 312 Montgomery, D. R., & Dietrich, W. E. (1988). Where do channels begin. *Nature*, 336(6196), 232-
313 234. <Go to ISI>://WOS:A1988Q954200042
- 314 Perron, J. T., Kirchner, J. W., & Dietrich, W. E. (2009). Formation of evenly spaced ridges and
315 valleys. *Nature*, 460(7254), 502-505. <Go to ISI>://WOS:000268257000036
- 316 Perron, J. T., Richardson, P. W., Ferrier, K. L., & Lapotre, M. (2012). The root of branching river
317 networks. *Nature*, 492(7427), 100-103. 10.1038/nature11672.
318 <http://dx.doi.org/10.1038/nature11672>
- 319 Rigon, R., Rodriguez-Iturbe, I., Maritan, A., Giacometti, A., Tarboton, D. G., & Rinaldo, A. (1996).
320 On Hack's Law. 32(11), 3367-3374.
321 <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/96WR02397>

- 322 Rinaldo, A., Dietrich, W. E., Rigon, R., Vogel, G. K., & Rodriguez-Iturbe, I. (1995).
323 Geomorphological signatures of varying climate. *Nature*, 374(6523), 632-635.
324 10.1038/374632a0. <http://dx.doi.org/10.1038/374632a0>
- 325 Rinaldo, A., Rodriguez-Iturbe, I., & Rigon, R. (1998). Channel networks. *Annual Review of Earth*
326 *and Planetary Sciences*, 26(1), 289-327.
327 <https://www.annualreviews.org/doi/abs/10.1146/annurev.earth.26.1.289>
- 328 Sassolas-Serrayet, T., Cattin, R., & Ferry, M. (2018). The shape of watersheds. *Nature*
329 *Communications*, 9(1), 3791. <https://doi.org/10.1038/s41467-018-06210-4>
- 330 Seybold, H., Rothman, D. H., & Kirchner, J. W. (2017). Climate's watermark in the geometry of
331 stream networks. *Geophysical Research Letters*, 44(5), 2272-2280.
332 <http://dx.doi.org/10.1002/2016GL072089>
- 333 Singer, M. B., & Michaelides, K. (2014). How is topographic simplicity maintained in ephemeral
334 dryland channels? *Geology*, 42(12), 1091-1094.
335 <http://geology.gsapubs.org/content/42/12/1091.abstract>
- 336 Singer, M. B., & Michaelides, K. (2017). Deciphering the expression of climate change within the
337 Lower Colorado River basin by stochastic simulation of convective rainfall. *Environmental*
338 *Research Letters*, 12.
- 339 Slater, L. J., & Singer, M. B. (2013). Imprint of climate and climate change in alluvial riverbeds:
340 Continental United States, 1950-2011. *Geology*, 41(5), 595-598.
341 <http://geology.gsapubs.org/content/41/5/595.abstract>
- 342 Solyom, P. B., & Tucker, G. E. (2004). Effect of limited storm duration on landscape evolution,
343 drainage basin geometry, and hydrograph shapes. *Journal of Geophysical Research-Earth*
344 *Surface*, 109(F3). <Go to ISI>://000236711300001
- 345 Tucker, G. E. (2004). Drainage basin sensitivity to tectonic and climatic forcing: Implications of a
346 stochastic model for the role of entrainment and erosion thresholds. *Earth Surface*
347 *Processes and Landforms*, 29(2), 185-205. <Go to ISI>://000189226700005
- 348 Tucker, G. E., & Bras, R. L. (2000). A stochastic approach to modeling the role of rainfall
349 variability in drainage basin evolution. *Water Resources Research*, 36(7), 1953-1964. <Go
350 to ISI>://000087928800028
- 351 Tucker, G. E., & Whipple, K. X. (2002). Topographic outcomes predicted by stream erosion
352 models: Sensitivity analysis and intermodel comparison. *J. Geophys. Res.*, 107(B9), 2179.
353 <http://dx.doi.org/10.1029/2001JB000162>
- 354 Willemin, J. H. (2000). Hack's Law: Sinuosity, convexity, elongation. *Water Resources Research*,
355 36(11), 3365-3374.
356 <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2000WR900229>
- 357 Wolman, M. G., & Gerson, R. (1978). Relative time scales of time and effectiveness of climate in
358 watershed geomorphology. *Earth Surface Processes & Landforms*, 3, 189-208.
- 359 Yi, R. S., Arredondo, Á., Stansifer, E., Seybold, H., & Rothman, D. H. (2018). Shapes of river
360 networks. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering*
361 *Sciences*, 474(2215), 20180081.
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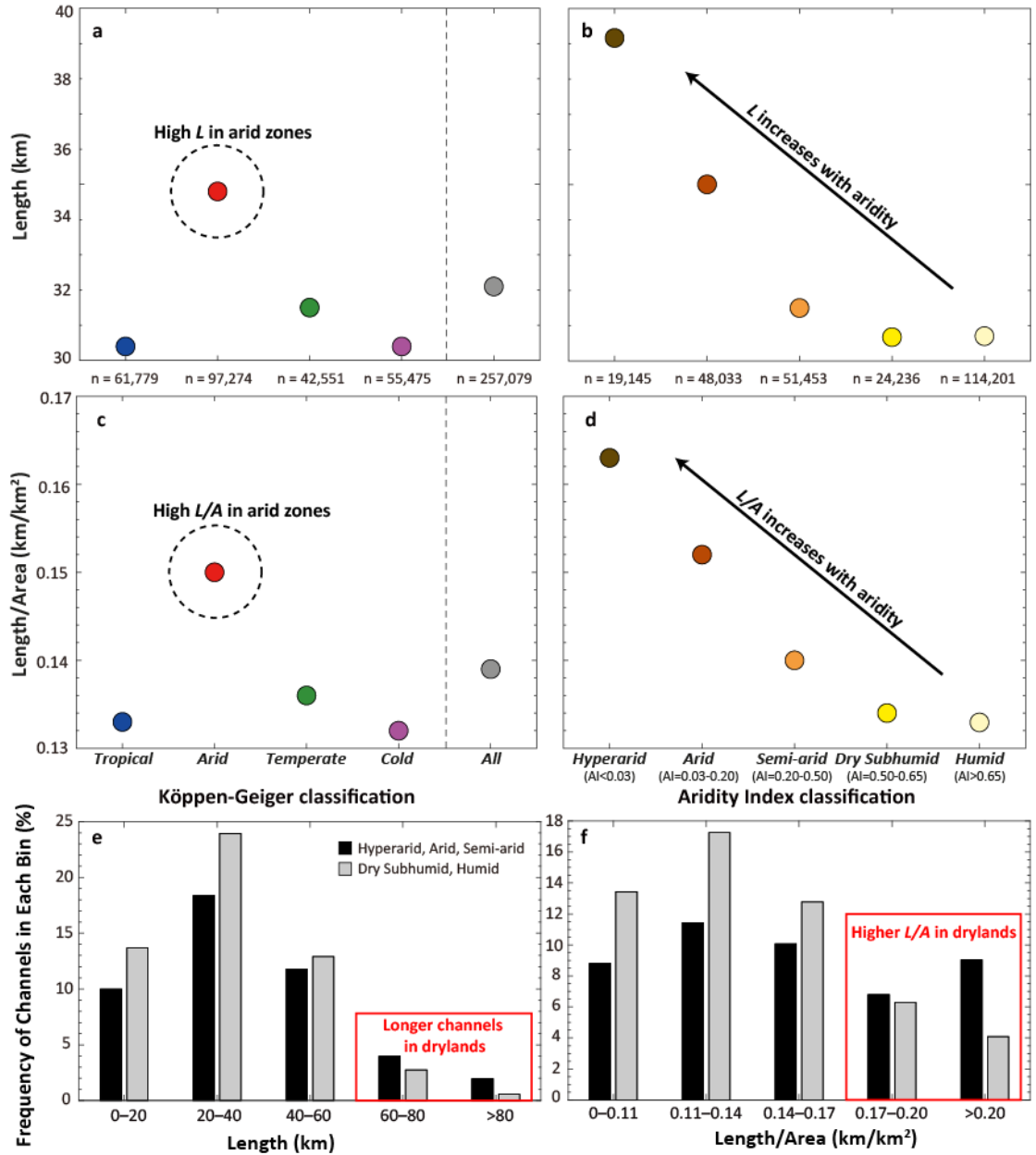


Fig. 1 | Morphometrics from GDBM for Köppen-Geiger and Aridity Index climate classifications. Median values of distributions by main Köppen-Geiger zone and Aridity Index classes for channel length, L (a,b) and L/A (c,d), corresponding to the distributions in Figs.S4;S5. Number of basins in each climate category is contained below a and b. Panels e and f shows the frequency (%) of basins by bins of L (e) and L/A (f), grouped by drylands (Hyperarid, Arid, Semi-arid) versus non-drylands (Dry Subhumid, Humid) from the Aridity Index classification.

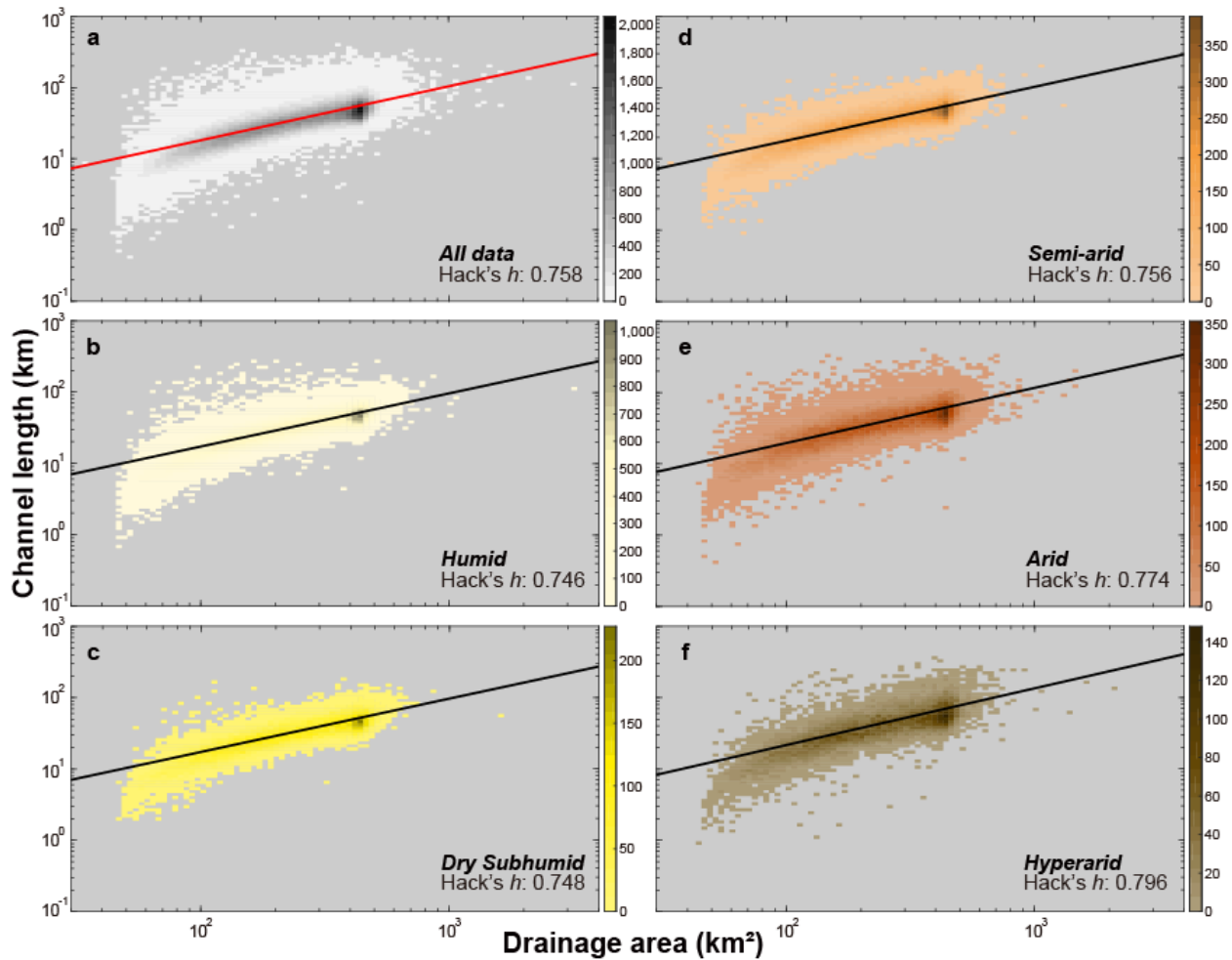
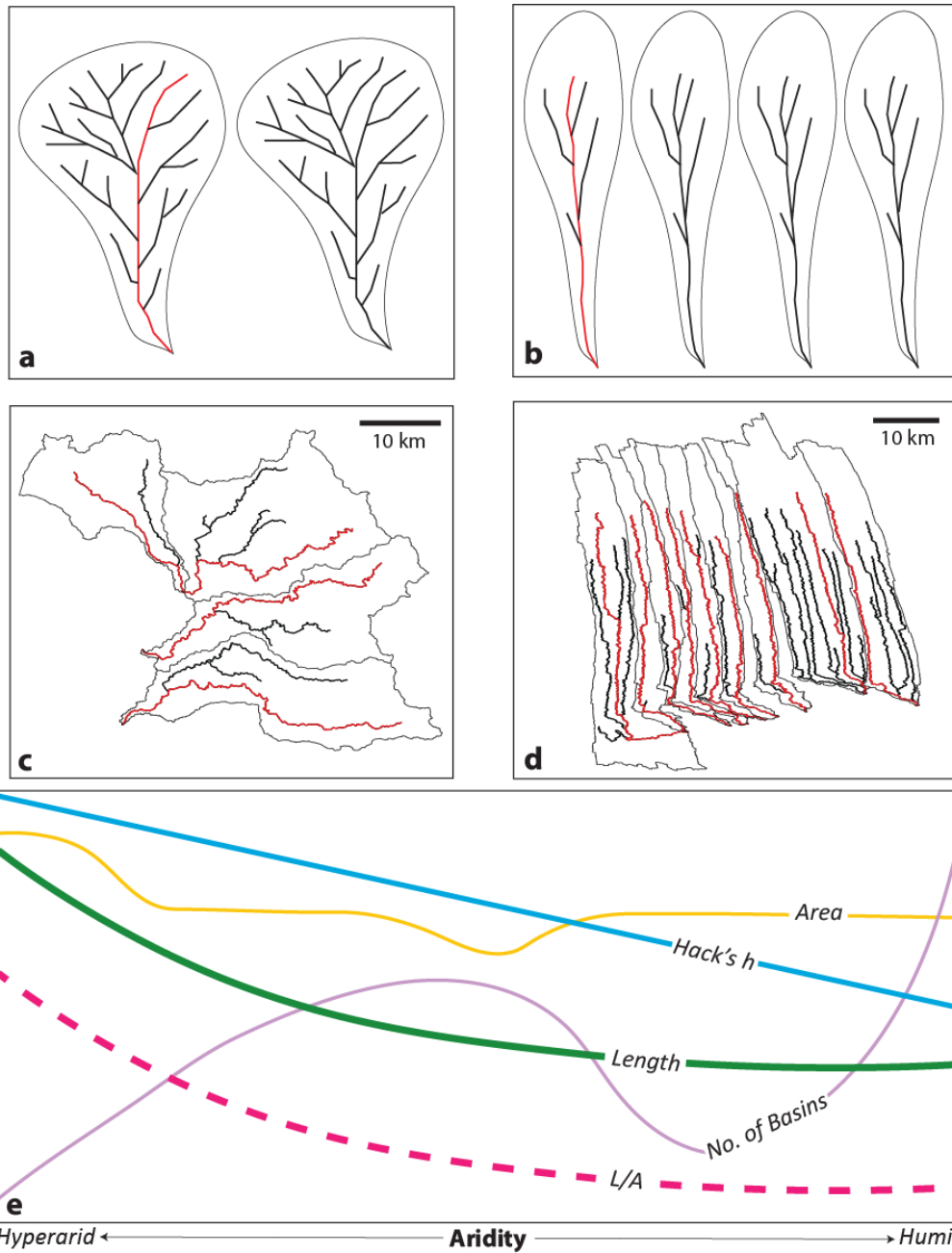


Fig. 2 | Climate-classified Hack's Law. Data by Aridity Index category for relationships between channel length (L) and drainage area (A). Density of points in areas of the scatterplot are shown in the scale bars to the right of each panel. All data are shown in panel **a**. The Hack exponents (h) for each panel (**b-f**) indicate a climatic dependency on the steepness of this relationship, where increasing aridity yields a higher value of h .

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 401 **Fig. 3 |** Climatic controls on drainage basins. Schematic of drainage basin size and length within a
 402 spatial area of humid (a) and arid (b) basins. Red trace on each plot indicates the longest (highest
 403 order) channel (mainstem). Example drainage basins of similar basin area extracted from SRTM-
 404 DEM for humid (c) and arid (d) climates in the Philippines and Australia (the area in each box
 405 corresponds to 2900 and 4000 km², respectively). Panel e summarizes how channel length,
 406 drainage area, L/A , Hack's h , and number of basins vary with aridity.
 407
 408

409 **Supporting Information for ‘Climate controls the length and shape of the**
410 **world’s drainage basins’ by Singer et al.**

411
412 ***Rationale for a New Global Database.*** Our aim in this study was to investigate drainage basin
413 morphometrics stratified by climatic forcing across the globe without making any assumptions
414 about hydrography from previously created maps. We sought to investigate morphometrics and
415 their climatic dependence in an unbiased way, and at a scale appropriate for identifying climatic
416 controls on drainage basin developments. Although global hydrography datasets exist, e.g.,
417 (Lehner et al., 2008; Ouellet Dallaire et al., 2019), none contained the relevant information to
418 accomplish these goals. In particular, we required accurate topographic metrics (Grieve et al.,
419 2016) within individual small drainage basins and their subbasins that lie entirely within a single
420 climatic zone, so we could isolate the effects of climate on drainage basin development.
421 Additionally, we needed morphometrics from all channels within drainage basins that have
422 topographic expression, irrespective of whether they contain water and would be mapped as
423 blue lines on topographic maps. Widely used global river hydrography datasets (e.g., HydroSHEDS
424 (Lehner et al., 2008)) and corresponding classifications based upon them (e.g., GLoRiC (Ouellet
425 Dallaire et al., 2019)) were developed using ~90 m (3 arc second) SRTM data, so they are not
426 appropriate for analysis of small basins. Furthermore, they are focused on perennial rivers,
427 relying on drainage enforcement (or stream burning) techniques to confirm channel locations, so
428 they cannot be used to explore how drainage basin morphometrics vary across a wide range of
429 climates including arid regions where blue lines are typically not mapped for ephemeral channels
430 because they are not readily visible and are therefore not stored in hydrography GIS layers. This
431 may lead to analysis biases toward humid regions and errors of interpretation for arid region. We
432 have shown in previous work (Chen et al., 2019), that interesting lessons can be learned from
433 fully investigating drainage basin topographic morphometrics across climatic gradients from
434 Humid to Hyperarid.

435
436 To fill this gap, we developed a new global database of drainage basin morphometrics (GDBM),
437 which relies on the same underlying DEM (SRTM) used as the basis for most other global river
438 databases. However, three major differences between GDBM and existing databases are: 1) our
439 database is built upon the higher resolution SRTM DEM (1 arc second or 30-m at the equator); 2)
440 our channel extraction methods include all channels above a drainage area threshold, whether
441 dry or wet; and 3) we limit our analysis to drainage basins in which the longest channel does not
442 cross Köppen-Geiger climate zone boundaries (see below for details).

443
444 **Creation of *Global Drainage Basin Morphometrics (GDBM)*.** In order to create the GDBM
445 database (Fig.S1a), the 30-m global Shuttle Radar Topography Mission (SRTM) DEM was broken
446 into contiguous climate zone tiles based on Köppen-Geiger climate subzone data (Fig.S1b; (Peel
447 et al., 2007)). This allowed each individual climate zone segment to be processed in parallel. In
448 some cases, the Köppen-Geiger climate subzones were still too large to be efficiently processed
449 and were further subdivided. The result of this processing was a collection of 1,805 DEM tiles
450 (Fig.S2a), each corresponding to a single contiguous Köppen-Geiger climate subzone.

451
452 Fluvial networks were extracted for each of these DEM tiles using LSDTopoTools (Clubb et al.,
453 2017). The DEM tile was first hydrologically corrected, using an algorithm which removes local
454 topographic depressions (sinks) from the data, allowing each pixel in the tile to flow to the local
455 base level (Wang & Liu, 2006). The initiation point of each channel was identified using an area-
456 threshold technique (Tarboton David et al., 1991), which identifies each cell in the DEM which
457 exceeds the threshold drainage area and has no upslope cells of higher drainage area (Fig.S2). We
458 did not correct for any local effects (e.g., vegetation cover) because we did not want to introduce
459 any user artifacts into the dataset that would limit the power of the internally consistent 30-m
460 SRTM DEM. We worked under the assumption that the roughness of vegetation along channels
461 responds directly to the underlying topography, so we can detect channel morphometrics, even
462 under vegetation cover. Most importantly, we sought to have a product that required the
463 minimum amount of processing prior to channel extraction.

464
465 The accuracy of any channel extraction methodology is governed in part by the resolution of the
466 topographic data being used. It has been demonstrated that attempting to identify channel
467 initiation points using non-threshold based methods in 30-m resolution data is challenging,
468 particularly in the headwaters of catchments, where signals of fluvial incision are less
469 pronounced and more transient (Montgomery & Dietrich, 1988). These challenges are even more
470 pronounced in the case of a global analysis, where an area threshold appropriate for one
471 landscape will be unsuitable for another. As channel extraction confidence is proportional to
472 channel size (Grieve et al., 2016), a deliberately conservative drainage area threshold of 22.5 km²
473 was employed for this study, irrespective of latitude. This value balances the need for
474 computational efficiency with the requirement to extract the properties of the longest subbasin
475 channel in which we can have confidence. Note that we did not extract any channels from the
476 Polar zone of the Köppen-Geiger classification in order to avoid permanent snow/glacier
477 coverage that would obscure channel topography.

478
479 From the extracted channel initiation points, steepest descent traces were run downslope until
480 every initiation point connected with the lowest point in each tile. The steepest descent
481 algorithm used is the D8 method, which directs flow based on the gradient between the DEM cell
482 of interest and its 8 neighboring cells (Fig.S2). This procedure is optimized as described by the
483 FastScape algorithm (Braun & Willett, 2013), to allow it to be run on such a large dataset. These
484 channels were further processed to ensure that only channels entirely contained within a tile
485 (Köppen-Geiger climate subzone) were sampled, ensuring the preservation of any climate signal
486 in the results. We also counted the total number of basins which crossed between tiles, which
487 when added to the total count of all basins falling within a single tile, gives a count of the total
488 number of drainage basins globally (Table S1).

489
490 The channel extraction method used to develop the GDBM database is designed to detect
491 channel topography, rather than flowing rivers. At a resolution of 30 m, local roughness
492 (topographic) differences between pixels leads to flow convergence in the flow accumulation
493 algorithm. The accumulated flows produce channel networks from which we subsequently
494 extract the longest channel satisfying the criteria specified above. This means that there is a
495 reasonable likelihood of detecting and extracting a channel in an arid landscape (corresponding
496 to the topographic gradient, Fig.S2f), in regions with significant topographic variation in the SRTM
497 data. This aspect distinguishes GDBM from many other hydrography databases, which often
498 remove arid channels because they are not mapped as blue lines.

499
500 The mainstem channel in each basin or subbasin exceeding the drainage area threshold,
501 identified as the channel with the maximum flow length per basin, was then sampled on a per
502 pixel basis to record the channel flow distance. The latitude/longitude of the most downstream
503 point on each channel profile is stored in the database (Fig.S1a). The extracted data were then
504 used to compute channel length (L). Drainage basin area (A) for each channel was also stored
505 from the channel network extraction process, and it was used to compute L/A . Aridity Index
506 values were assigned to each channel in GDBM based on the median value from every pixel along
507 the channel profile. From these data, we compiled counts of all sampled channels by Köppen-
508 Geiger climate zone (both subzones and major zone categories, Fig.S1b), and by Aridity Index
509 climate categories (Fig.S1c), to create a user-friendly database that can be queried for specific
510 data subsets. Metrics of channel relief (total drop in elevation along the channel from upstream
511 to downstream) and channel gradient (mean slope along the topographic channel profile) are
512 also included in the GDBM database, although they are not discussed here.

513
514 Aridity Index values were sampled at the centroid of every channel pixel, yielding an average
515 sampling frequency of 36 meters along the length of each channel. From these sampled values,
516 the mean and median Aridity Index values were computed, along with the standard deviation
517 and the maximum and minimum values of Aridity Index. The number of samples recorded for a
518 channel is also reported, to allow users of GDBM to only select basins for further study that have
519 an adequate number of measurements. Individual channels with a small number of Aridity Index
520 measurements along their length (< 10) occur in GDBM due to the discrepancy between the
521 resolution of the SRTM dataset (~30 m) and the Aridity Index dataset (~900 m). However, they
522 are rare, accounting for 23 channels, or 0.01% of GDBM.
523

524 Our analysis was performed on the latest SRTM dataset (Shuttle Radar Topography Mission
525 (SRTM) - NSF OpenTopography Facility-doi:10.5069/g9445jdf, 2013), which has an approximate
526 spatial resolution of 30 meters, which allows smaller channels to be identified, and more detail to
527 be resolved within extracted channels, increasing the utility of these data beyond the goals of
528 this paper. The structure of GDBM as a relational database of drainage basin topographic metrics
529 also facilitates much more rapid analysis of global scale basin geometry and climate signatures
530 than previous datasets, which have a focus predominantly on the location of channels and
531 provision of these data in GIS formats. In all, GDBM includes ~9 million km of channel length,
532 equivalent to ~225 times the Earth's circumference, within 115 million km² of global land area
533 (Table S1).
534

535 We checked whether our channel length results (e.g., Fig.1) might be affected by sinuosity and
536 further, whether our extraction method captures channel sinuosity for the 30-m SRTM data. We
537 tested that GDBM is adequately capturing the true lateral geometry of channels by measuring
538 reach-scale sinuosity across the entire dataset. Each channel in the dataset was broken into
539 approximately 10-km long reaches and sinuosity was calculated as the ratio of the along-channel
540 distance divided by the Euclidean distance between the start and end of that reach. If this
541 sinuosity ratio is greater than 1, the flow length of a reach is longer than the Euclidean distance,
542 indicating a meandering channel planform. In cases where the sinuosity ratio is equal to 1, the
543 channel may be meandering at much longer wavelengths than 10 km, but most of our studied
544 rivers are <100 km in length. Our tests demonstrate that our channel extraction method on 30-m
545 SRTM data well represents channel sinuosity at a high enough fidelity to capture along-channel
546 length (Fig.S3). In lower resolution data (e.g., 90-m SRTM), channel meanders will not be
547 captured, resulting in artificially straight (and shorter) sections of channel. Fig.S3 shows a range

548 of sinuosity values from these 10-km reaches, clearly indicating that our channel extraction
549 procedure captures channel planform meandering, so there should be no obvious bias in channel
550 length introduced for regions with meandering channels versus those with straight channels.

551
552 **GDBM Database.** Our new drainage basin morphometrics database, GDBM is meant to be
553 broadly useful to a wide range of researchers (geomorphologists, hydrologists, hydrologic
554 modelers, land surface modelers, ecologists, biogeochemists, etc.). We provide the entire
555 database on a long-term data storage access site. In addition to the elements described in the
556 paper, the database also includes the latitude/longitude for the most downstream point on each
557 channel, the country and continent in which the most downstream point resides, the relief and
558 slope of each extracted channel, and statistics on downstream variations in Aridity Index along
559 the channel.

560
561 **Analysis of GDBM.** We analyzed the metrics contained within GDBM in several ways. First, we
562 organized data by Köppen-Geiger main climate zones and subzones (Fig.1a,c;Figs.S4;S5), as well
563 as by major Aridity Index climate categories (Fig.1b,d). For each of these categories, we
564 computed the total number of basins contained within each, the total length of channel (L) for
565 basins entirely contained within a single climate zone, drainage basin area (A), and L/A (Table S1).

566
567 We used the GDBM data to generate violin plots in Matlab
568 (<https://github.com/bastibe/Violinplot-Matlab>). These plots are enhancements of standard
569 boxplots because they use kernel density estimation to generate box widths that represent the
570 density of values at each magnitude. This is how we generated the plots in Figs.S3-S5. To
571 generate Fig.2 and Figs.S6 and S7, we used the *binscatter* function within Matlab. We computed
572 Hack's Law exponents based on a fixed value of the coefficient based on the fit for all data
573 (0.554). In other words, we fixed the y-intercept and evaluating the slope on the relationship
574 between L and A . To further explore how the coefficient in Hack's Law might vary with climate,
575 we separately fixed h based on the fit for all data (0.758) and allowed c to vary. This analysis (not
576 included in Fig 2) showed that c also increases monotonically with aridity as follows: 0.516
577 (Humid), 0.522 (Dry Subhumid), 0.546 (Semi-arid), 0.610 (Arid), 0.690 (Hyperarid). We include
578 this here since it has been suggested that c in Hack's Law specifically represents basin shape,
579 such that higher values indicate more elongate basins (Sassolas-Serrayet et al., 2018). This result
580 is consistent with our interpretation of downstream channel extension and preservation in
581 increasingly arid environments.

583 To evaluate our computed metrics and compare them, we checked whether the compiled GDBM
584 metrics for each climate zone (category) are statistically distinct from one another, using the two-
585 sample Kolmogorov-Smirnov test in a pairwise manner (using Matlab's function *kstest2*).
586 Statistics and p-values for these comparisons are contained within Table S2 (Köppen-Geiger
587 climate zones and Aridity Index climate categories). In Matlab there is a minimum p-value of
588 1.00E-323, thus the preponderance of such values in these tables. It must be noted that tests of
589 statistical difference between distributions are often affected by large sample sizes, such that all
590 K-S tests performed here yielded significant differences between Köppen-Geiger and Aridity
591 Index climate classes. However, large differences between climate zones and categories are
592 easily identified by very low p-values. For example, channel length comparisons between Arid
593 and other climate zones for the Köppen-Geiger zones yielded p-values at the minimum value
594 (1.00E-323). This p-value can be easily contrasted with, for example, the p-value of 3.54E-21 for
595 the comparison of channel length between Temperate and Tropical zones (Table S2). In other
596 words, the distributions of length values within Temperate and Tropical zones are much more
597 similar to one another than those for Arid and any other zone, in spite of the statistical difference
598 between Temperate and Tropical zones. We also used the Kruskal-Wallis (K-W) test (a non-
599 parametric version of ANOVA) to compare distribution medians between climate categories in
600 both classification schemes (Table S3). Again, due to large sample size, many of these tests
601 yielded significant differences, so we thresholded the dataset at 1.00E-5 to identify highly
602 significant differences between distribution medians. To better identify the most significant
603 differences between distributions for all climate categories, we highlighted in Tables S2 and S3
604 with grey shading p-values less than 1.00E-50 for K-S and 1.00E-5 for K-W.

605
606 **Hack's Law.** Our analysis of Hack's Law was based on using a single data pair of L and A for each
607 basin or subbasin that exceeded our area threshold. This sits in contrast to the original work by
608 Hack and others that followed, which plotted multiple data pairs with increasing distance
609 downstream along the stream channel. In our analysis of GDBM, we found ~ 2 orders of
610 magnitude of scatter in the Hack power law relationship (Fig.2), which indicates Hack's Law may
611 be more limited than previously thought. One reason for the strong difference in scatter between
612 our analysis and that of Hack may be a function of statistical independence. Specifically, each of
613 our data points was generated from an individual channel, thus satisfying the assumption of
614 independent and identically distributed random variables (IID), while Hack's original plot includes
615 data from multiple locations on each stream. Therefore, Hack's data are not IID, due to serial
616 correlation (each length-area point is inherently related to the other points on the same
617 channel). This may explain the lower amount of scatter in Hack's original plot (Hack, 1957).

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We also found a large difference between the global average Hack's h from GDBM (0.758) compared to what has been previously reported (~ 0.6) (Hack, 1957). We believe this difference is merely a consequence of two different methods for quantifying channel length. Our method uses along-channel length, while many prior efforts simply used channel axis as a Euclidean distance. This is supported by previous work showing that strong differences in Hack's h can be obtained by using different methods of computing channel length (Willemin, 2000). For example, Table 1 in (Willemin, 2000) showed that h for the same river in Oregon varied from 0.7 for along-channel length (our method) to 0.52 when using Euclidean distance. This illustrates that accounting for along-channel distance, incorporating sinuosity (Fig.S3a) in length calculations may reasonably lead to overall higher values of Hack's exponent. To test this further, we selected a random sample of $\sim 10,000$ channels from GDBM, and we plotted Euclidean distance from the start to the end point of each channel against basin area. We plotted these data and calculated h for comparison with h computed via the along-channel method. We found that the Euclidean distance method resulted in an h value of 0.58, which is more in line with previous literature, while the along-channel distance method produced an h value of 0.78 (Fig.S3b-c). We believe our method is a more accurate characterization of channel length, and owing to the large sample size in GDBM, our global average of Hack's h is thus a more robust estimate than presented in previous work.

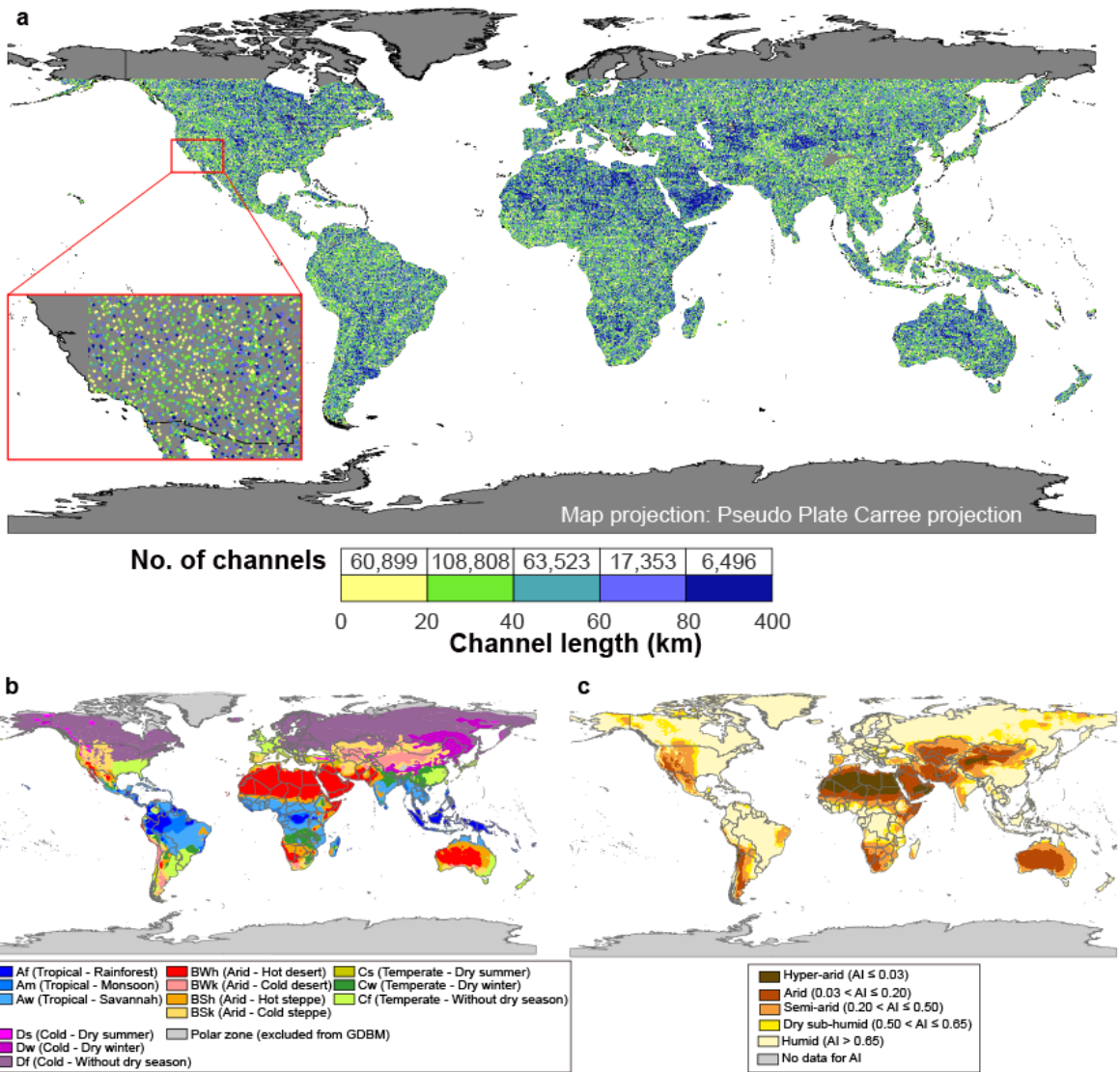
In addition to the climate dependence on Aridity Index discussed in the paper, we also show that Hack's h varies for Köppen-Geiger zones. In particular, we found that h is highest for the Arid Köppen-Geiger zone and lowest for the Cold zone (Fig.S6). Previous work has suggested there may be an area dependence within Hack's law, so we classified the GDBM data by area bins and recomputed Hack's h for each bin. The results show that Hack's Law is not scale dependent for the relatively small basin areas contained within GDBM (Fig.S7). The scale dependence in h that has been documented elsewhere (Rigon et al., 1996) only occurs at drainage areas $> 20,000 \text{ km}^2$. Basins of this scale were generally excluded from GDBM, since they more likely cross Köppen-Geiger climate subzones.

Timescales of Basin Evolution. In our paper, we do not explicitly address the timescale over which climate creates an imprint within drainage basins. We instead show that we can detect relationships between topographic metrics from basins and climate classifications. Clearly, the time required to evolve the landscape is dependent on the expression of its climate regime, which differs for different regions. Arid regions have less frequent rainfall and flooding, so it

653 might take longer for the climate signal to be expressed in these regions, compared to humid
654 regions, which have a more regular climate expression. Here we work under the assumption that
655 the current climate regime (that which is reflected in either Köppen-Geiger or Aridity Index
656 climate classifications) has prevailed for long enough in each drainage basin such that the
657 morphometrics reflect the drainage basin evolution under this climate. Clearly, there may be
658 cases in which climate change has dramatically altered the processes and patterns of drainage
659 basin development, but we see these as the exception, rather than the rule. We assume, for
660 example, that arid regions have been arid for long enough to record the climate signature of
661 aridity within their drainage basins, even if they preserve signatures of ancient flood events
662 (Rinaldo et al., 1995). Furthermore, when looking at drainage basin morphometrics from any
663 channel (even on Mars or other solar system bodies), we can only speculate about the forces that
664 shaped the channel network, but we can be confident that larger flood events will be better
665 preserved in topography than smaller ones (Singer & Michaelides, 2014; Wolman & Gerson,
666 1978).

667
668 ***GDBM v. GLoPro.*** We previously published a study showing how river longitudinal profiles
669 segregate by aridity, in which we showed that straight profiles are more common in dry climate
670 regions (Chen et al., 2019). That paper showed that aridity is also a dominant control on
671 longitudinal profile concavity through its expression in stream hydrology. The previous study
672 generated a dataset of Global Longitudinal Profiles (GLoPro), which includes the topographic
673 profiles along each channel (elevation versus distance), the latitude/longitude of the most
674 downstream point on each channel, the classification of each channel based on Köppen-Geiger
675 and Aridity Index classification systems, and the normalized concavity index (NCI). The GDBM
676 dataset presented here is largely based on the same channel locations (same reported
677 downstream point on each channel), but the dataset is otherwise distinct. The GDBM dataset has
678 fewer basins/channels overall than GLoPro, since here we adopted a uniform threshold drainage
679 area threshold that does not vary by latitude. The GDBM dataset includes the following
680 information for each channel: length, drainage basin area, L/A , total channel relief, and average
681 channel gradient. We view GDBM and GLoPro as complementary datasets. However, the results
682 presented here should be considered independent of those in the previous work. Namely, the
683 arid channels that exhibited straight profiles within GLoPro should not be considered the same as
684 those which are longer with larger basin areas with GDBM. In both databases, there is
685 considerable overlap between climate classifications that arises due to a range of factors that we
686 did not control for. Furthermore, we view these sets of climate signatures as independent of
687 each other, based on the controlling processes and the timescales over which they occur.

688 Specifically, relatively straight long profiles in drylands evolve based on the time integral of all
689 flows in the channel that are capable of eroding the channel bed and shaping the profile, in
690 which a similar flow integral of flow-based erosion occurs everywhere along the channel (Chen et
691 al., 2019). In contrast, aridity expresses within channel length, L/A , and Hack's h due to the
692 topographic preservation of brief episodic flood events that extend the channel downstream.
693 Thus, the results presented here likely occur based on the frequency of extreme high-flow
694 events, rather than the integral of all events above a threshold. Thus, it is not surprising that long
695 channels with large drainage basins do not necessarily have straight longitudinal profiles.
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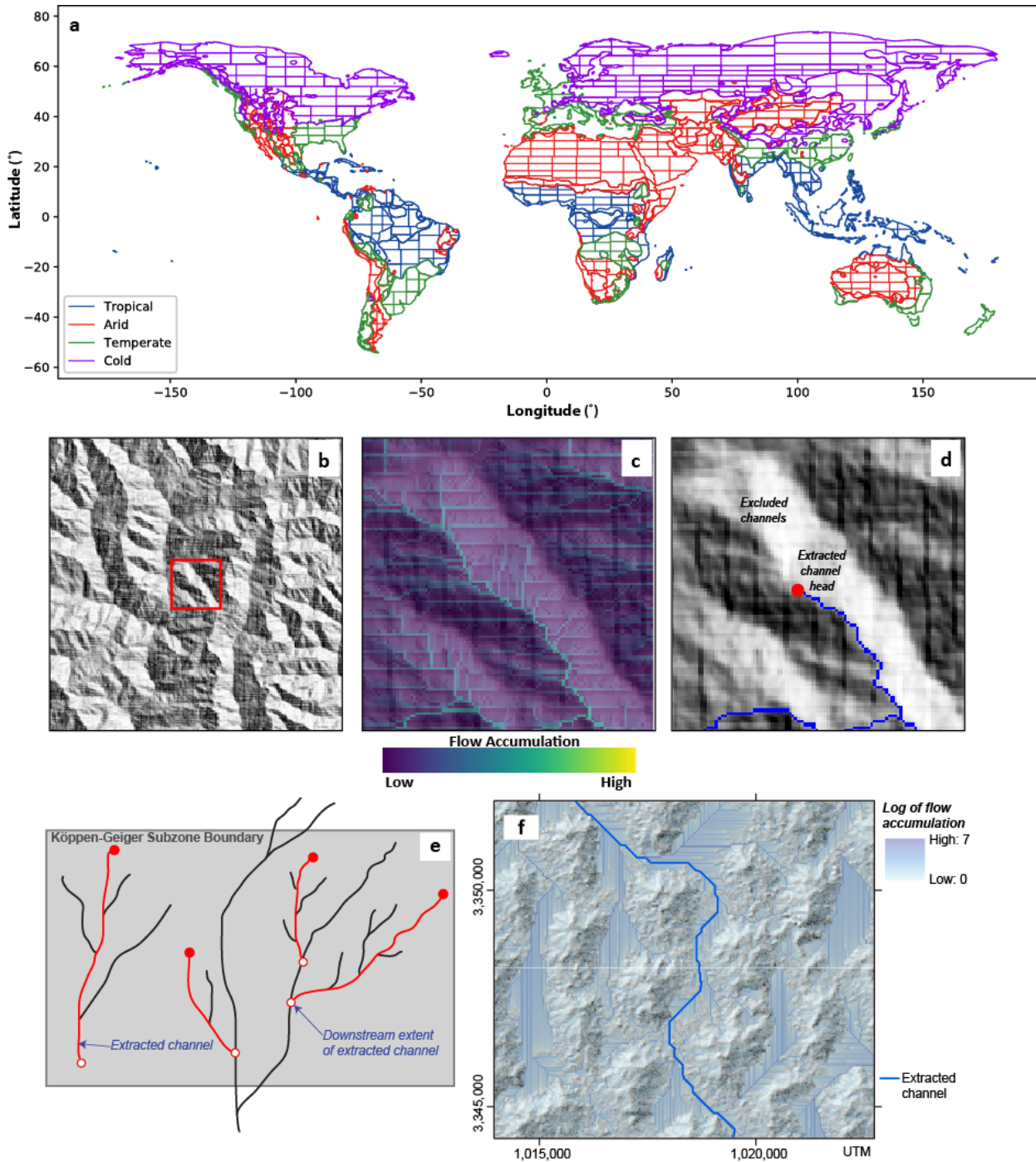
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Fig.S1 | Maps of analyzed channels in climate context. **a**, Map showing most downstream point on each channel included in GDBM, color coded by bins of channel length. **b**, Global map of Köppen-Geiger climate classification from (Peel et al., 2007). **c**, Global map of Aridity Index (data source of the background map: Natural Earth (<https://www.natureearthdata.com/>)). Note: the data are only available between 60°N and 56°S, corresponding to the limits of the SRTM 30-m dataset.



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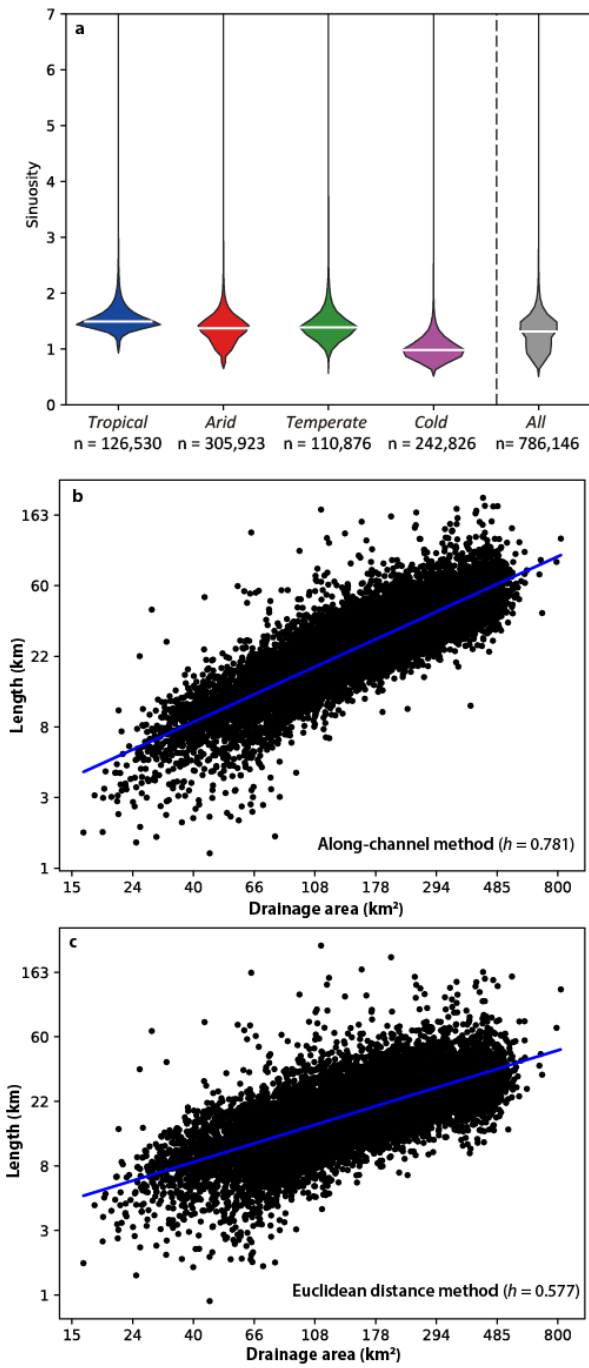
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Fig.S2 | Schematic outlining channel extraction methodology. **a**, Map showing tiles used to extract channels across the globe. **b**, Shaded relief of a 70.5 km² area of Northern California. Red box shows location of **c** and **d**. **c**, Logarithmically scaled flow accumulation map, showing concentration of flow in valley bottoms, higher values correspond to a higher likelihood of a channel being present. **d**, Channel head (red circle) and channel (blue) flowing downslope from channel head, following the line of steepest descent. The area covered in **c** and **d** is 7.8 km². The area threshold for a channel in GDBM is ~22.5 km², so channels with smaller upstream areas were excluded from GDBM. **e**, Schematic of the selection of extraction channels for inclusion in GDBM. The method requires that the extracted channel is the longest in its basin or subbasin, but which does not cross Köppen-Geiger subzone boundaries. Channel length is measured as distance from

719 channel head (solid red circle) to most downstream point (white circle with red boundary). Multiple
720 channels (subbasins) may be included, as long as they satisfy the drainage area threshold and do not cross
721 Köppen-Geiger subzone boundaries. **f**, Dominant channel extraction in the drylands of the Grand Erg
722 Oriental (Sahara Desert) based on the flow accumulation algorithm in LSDTopoTools. The image shows
723 that although there are many parallel drainages derived from D8 flow accumulation, these channels
724 ultimately converge, so that only a single dominant channel is included in the database according to the
725 criteria listed above. Note: the extracted channel does not appear as a blue line on topographic maps, so it
726 would not be included in hydrography databases or hydrography/DEM products that use drainage
727 enforcement.
728



729 **Fig.S3** | Sinuosity and its impact on Hack's h. **a**, Reach-scale sinuosity for the four main climate zones
 730 (Köppen-Geiger), and the full dataset. Values below labels indicate the number of 10-km reaches sampled
 731 for a given category. White bar on each violin plot denotes the median value. **b**, Hack's Law relationship for
 732 along-channel distance method (accounting for sinuosity). **c**, Hack's Law relationship for Euclidean distance
 733 method.
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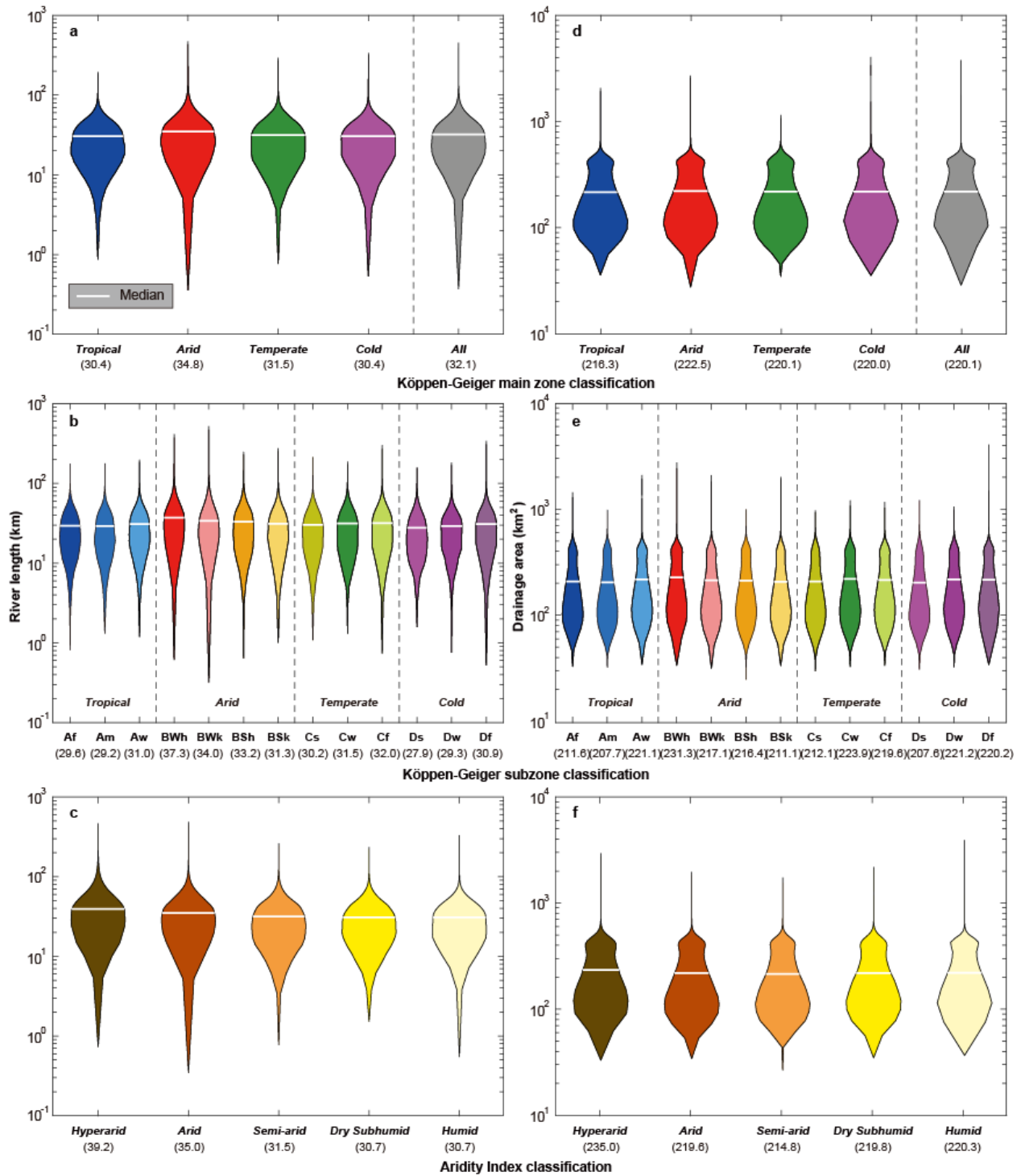


Fig.S4 | Drainage basin metrics from GDBM classified by climate. We show detailed sub-categories of Köppen-Geiger and all available data for length (a-c) and drainage basin area (d-f) for Köppen-Geiger main climate zones (a,d), Köppen-Geiger climate subzones (b,e), and Aridity Index classes (c,f). Plots are based on channels contained entirely within a single Köppen-Geiger subzone. Colors correspond to Köppen-Geiger subzones and Aridity Index classes (Fig.S1b,c). Median values for each sub-category are listed below each plot.

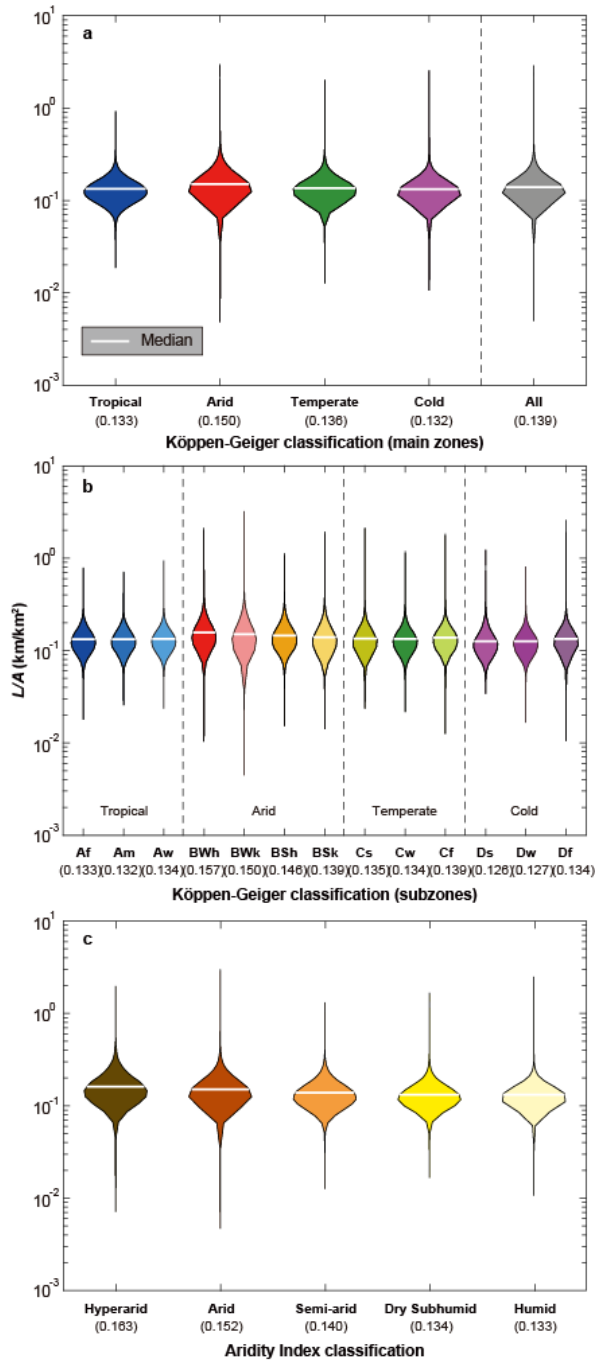


Fig.S5 | L/A from GDBM classified by climate. We show detailed sub-categories of Köppen-Geiger and all available data for L/A for Köppen-Geiger main climate zones (a), Köppen-Geiger climate subzones (b), and Aridity Index classes (c). Colors correspond to Köppen-Geiger subzones and Aridity Index classes (Fig.S1b,c). Median values for each sub-category are listed below each plot.

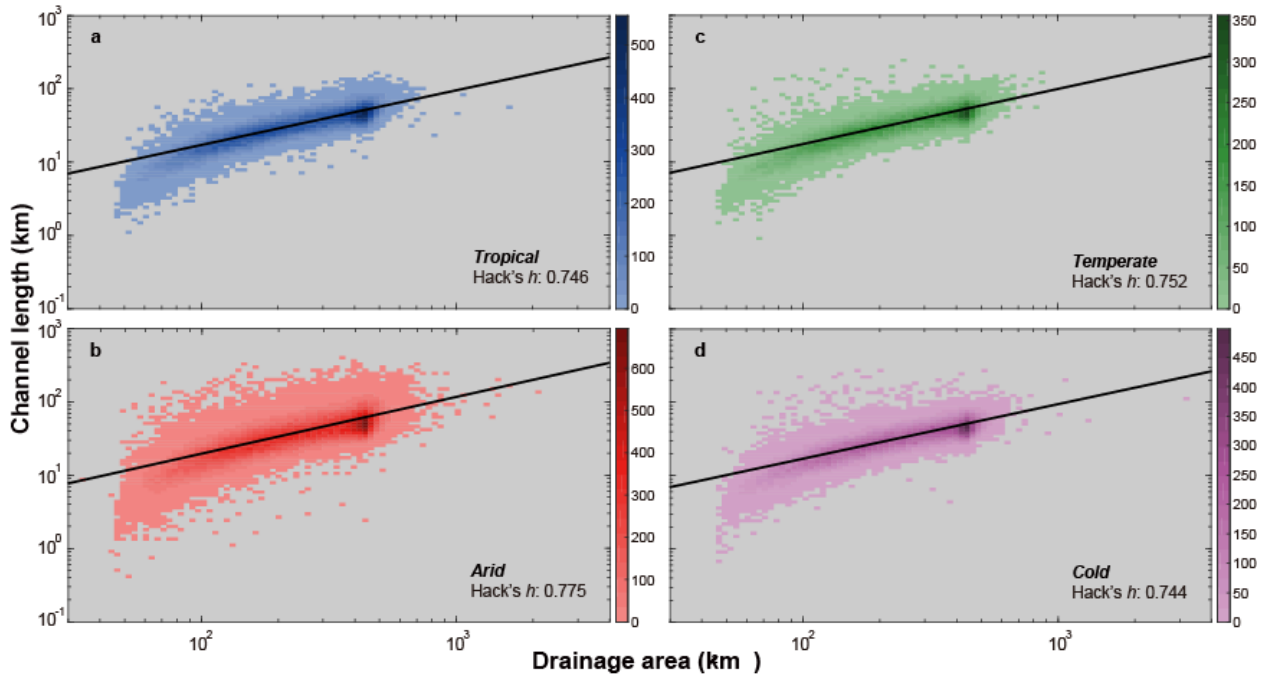
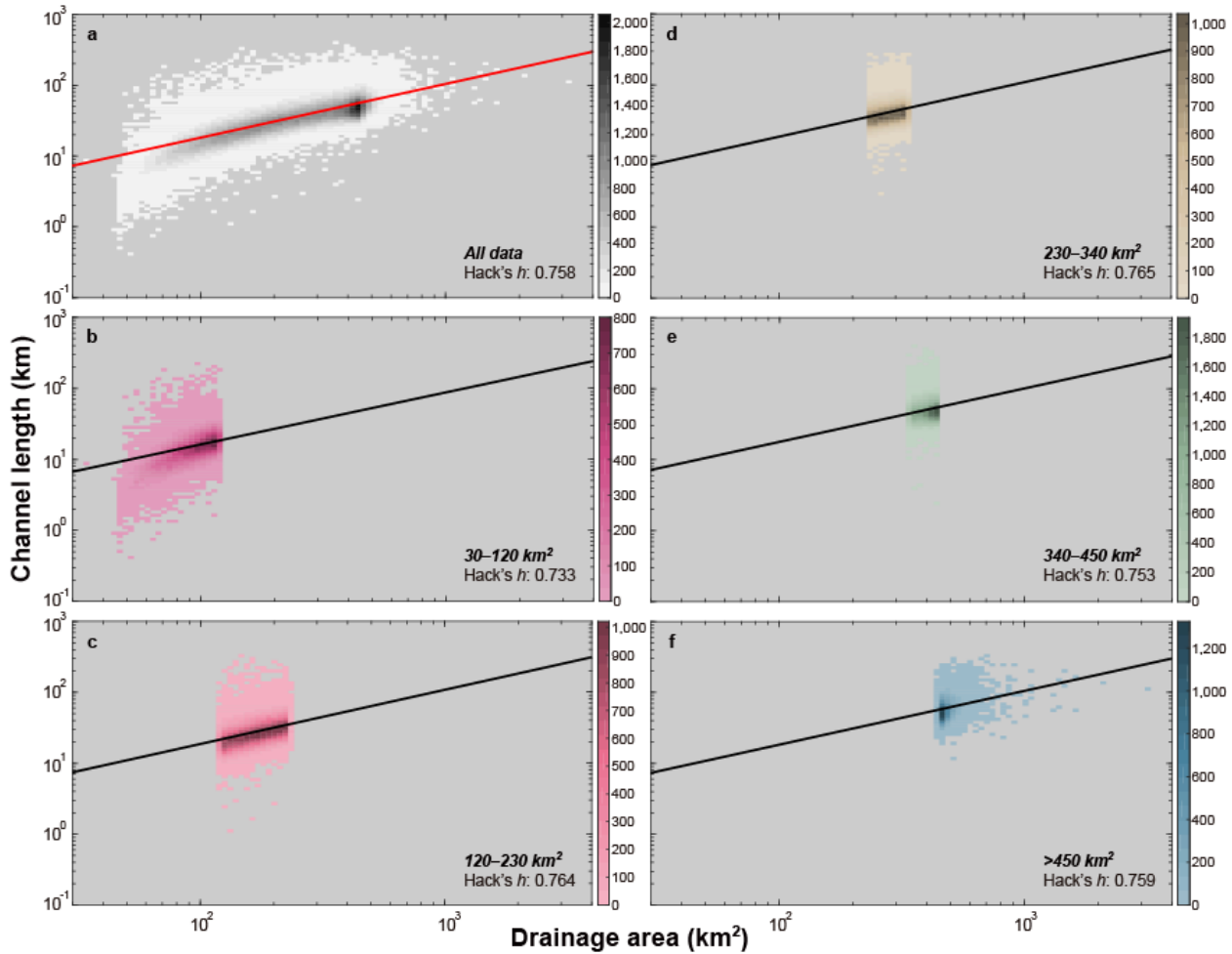


Fig.S6 | Climate-classified Hack's Law. Data by Köppen-Geiger category for relationships between channel length (L) and drainage area (A). Density of points in areas of the scatterplot are shown in the scale bars to the right of each panel. The Hack exponents for each panel (**a-d**) indicate a climatic dependency on the steepness of this relationship, where arid basins exhibit the highest value of h .



757
 758 **Fig.S7** | Hack's Law power fits for different bins of drainage basin area. Density of points in areas
 759 of the scatterplot are shown in the scale bars to the right of each panel. Panel **a** contains all the
 760 data and panels **b-f** contain data for different area bins. There is no significant variation in Hack's
 761 h by area for the range of basin sizes contained within GDBM.

764 **Table S1 |** Summary data on number of drainage basins, area, total length by Köppen-Geiger

765 climate zones (a) and Aridity Index categories (b). Colors correspond to maps in Fig.S1b,c.

a) RELEVANT K-G DATA																		
Climate sub-zone	AF	Am	Aw	BWh	BWk	BSh	BSk	Cs	Cw	Cf	Ds	Df						
No. of channels	14,114	10,581	37,084	46,999	13,040	18,408	18,827	5,785	15,794	20,972	2,318	40,988						
Climate main zone			Tropical			Arid				Temperate		Cold						
No. of channels			61,779			97,274				42,551		55,475						
Multiple zones	AF	Am	Aw	BWh	BWk	BSh	BSk	Cs	Cw	Cf	Ds	Df						
No. of channels	6059	5666	12072	11515	4913	6948	9276	3818	4521	14069	1597	14443						
Climate sub-zone	AF	Am	Aw	BWh	BWk	BSh	BSk	Cs	Cw	Cf	Ds	Df						
Clipped Area (km ²)	6,144,065	5,009,227	17,145,309	20,010,965	6,936,283	7,952,759	10,079,873	3,024,883	6,834,180	10,098,897	923,080	16,391,045						
Climate main zone			Tropical			Arid				Temperate		Cold						
Clipped Area (km ²)			28,298,600			44,979,880				19,957,960		21,752,465						
Climate sub-zone	AF	Am	Aw	BWh	BWk	BSh	BSk	Cs	Cw	Cf	Ds	Df						
Total Length (km)	446,998	327,969	1,221,818	1,953,189	502,366	661,593	639,604	186,930	531,130	716,606	69,829	374,218						
Climate main zone			Tropical			Arid				Temperate		Cold						
Total Length (km)			1,996,785			3,756,753				1,434,666		1,796,305						
b) RELEVANT AI DATA																		
AI Climate Category	Hyperarid			Arid			Semi-arid			Dry Subhumid			Humid			All		
No. of channels	19,145			48,033			51,453			24,236			114,201			257,068		
Clipped Area (km ²)	5,741,619			14,735,228			18,202,791			11,850,357			64,458,911			114,988,905		
Total Length (km)	851,989			1,852,702			1,754,338			800,389			3,724,981			8,984,399		

Table S2 | Kolmogorov-Smirnov statistics for comparisons between Köppen-Geiger climate zones (a) and Aridity Index climate categories (b) for channel length, drainage area, and L/A. Grey shading indicates highly significant differences between distributions (p-values less than 1.00E-50).

a) K-G KOLMOGOROV-SMIRNOV STATISTICS		L		A		L/A	
K-G climate main zone comparison		p-value	K-S Statistic	p-value	K-S Statistic	p-value	K-S Statistic
Tropical	Arid	1.00E-323	1.09E-01	3.69E-07	1.43E-02	1.00E-323	1.72E-01
Tropical	Temperate	3.54E-21	3.08E-02	1.24E-02	1.00E-02	7.67E-24	3.27E-02
Tropical	Cold	7.22E-02	7.50E-03	2.17E-02	8.80E-03	3.73E-13	2.24E-02
Arid	Temperate	8.83E-163	7.94E-02	8.74E-02	7.30E-03	1.00E-323	1.44E-01
Arid	Cold	1.00E-323	1.14E-01	9.19E-02	6.60E-03	1.00E-323	1.73E-01
Temperate	Cold	4.89E-27	3.56E-02	5.59E-01	5.10E-03	1.03E-39	4.33E-02

b) AI KOLMOGOROV-SMIRNOV STATISTICS		L		A		L/A	
Aridity Index category comparison		p-value	K-S Statistic	p-value	K-S Statistic	p-value	K-S Statistic
Hyperarid	Arid	1.16E-89	8.65E-02	6.86E-16	3.60E-02	5.83E-79	8.12E-02
Hyperarid	Semi-arid	1.00E-323	1.64E-01	5.28E-27	4.68E-02	1.00E-323	1.88E-01
Hyperarid	Dry Subhumid	1.93E-318	1.85E-01	1.04E-11	3.48E-02	1.00E-323	2.52E-01
Hyperarid	Humid	1.00E-323	1.92E-01	2.91E-17	3.44E-02	1.00E-323	2.68E-01
Arid	Semi-arid	1.33E-132	7.82E-02	1.20E-03	1.22E-02	2.25E-254	1.08E-01
Arid	Dry Subhumid	6.55E-142	1.01E-01	3.34E-01	7.40E-03	1.00E-323	1.74E-01
Arid	Humid	1.00E-323	1.06E-01	9.68E-02	6.70E-03	1.00E-323	1.89E-01
Semi-arid	Dry Subhumid	3.67E-09	2.47E-02	5.15E-04	1.58E-02	5.86E-64	6.66E-02
Semi-arid	Humid	7.45E-27	2.93E-02	5.35E-07	1.46E-02	9.23E-208	8.20E-02
Dry Subhumid	Humid	1.17E-02	1.13E-02	7.32E-01	4.90E-03	3.49E-06	1.82E-02

Table S3 | Kruskal-Wallis statistics for comparisons between Köppen-Geiger climate zones (**a**) and Aridity Index climate categories (**b**) for channel length, drainage area, and *L/A*. Grey shading indicates highly significant differences between distributions medians (p -values less than $1.00E-5$).

a) K-G KRUSKAL-WALLIS STATISTICS		L		A		L/A	
K-G climate main zone comparison		p-value	K-W Statistic	p-value	K-W Statistic	p-value	K-W Statistic
Tropical	Arid	3.77E-09	-1.84E+04	1.72E-05	-1.79E+03	3.77E-09	-2.72E+04
Tropical	Temperate	3.77E-09	-4.79E+03	1.19E-02	-1.43E+03	3.77E-09	-5.10E+03
Tropical	Cold	1.00E+00	2.73E+01	5.13E-02	-1.11E+03	9.04E-07	2.28E+03
Arid	Temperate	3.77E-09	1.36E+04	8.43E-01	3.55E+02	3.77E-09	2.21E+04
Arid	Cold	3.77E-09	1.84E+04	3.18E-01	6.75E+02	3.77E-09	2.94E+04
Temperate	Cold	3.77E-09	4.82E+03	9.09E-01	3.20E+02	3.77E-09	7.38E+03

b) AI KRUSKAL-WALLIS STATISTICS		L		A		L/A	
Aridity Index category comparison		p-value	K-W Statistic	p-value	K-W Statistic	p-value	K-W Statistic
Hyperarid	Arid	9.92E-09	1.42E+04	9.92E-09	6.11E+03	9.92E-09	1.52E+04
Hyperarid	Semi-arid	9.92E-09	2.75E+04	9.92E-09	7.90E+03	9.92E-09	3.28E+04
Hyperarid	Dry Subhumid	9.92E-09	3.07E+04	9.93E-09	5.17E+03	9.92E-09	4.32E+04
Hyperarid	Humid	9.92E-09	3.18E+04	9.92E-09	5.30E+03	9.92E-09	4.50E+04
Arid	Semi-arid	9.92E-09	1.33E+04	1.39E-03	1.79E+03	9.92E-09	1.76E+04
Arid	Dry Subhumid	9.92E-09	1.65E+04	4.86E-01	-9.46E+02	9.92E-09	2.80E+04
Arid	Humid	9.92E-09	1.76E+04	2.54E-01	-8.17E+02	9.92E-09	2.98E+04
Semi-arid	Dry Subhumid	2.19E-07	3.24E+03	2.26E-05	-2.73E+03	9.92E-09	1.04E+04
Semi-arid	Humid	9.92E-09	4.30E+03	1.03E-08	-2.60E+03	9.92E-09	1.22E+04
Dry Subhumid	Humid	2.55E-01	1.06E+03	9.99E-01	1.28E+02	8.04E-03	1.74E+03

785 **Supplementary Dataset**

786 **Dataset S1 (separate file)**

787 The data can be downloaded in chunks by Köppen-Geiger climate subzones upon request. These
788 files contain the entire database of Global Drainage Basin Morphometrics (GDBM) organized as
789 listed above. This download link should not be shared and is only valid for the review process.

790 Once the paper is accepted, we will post these data on a long-term data storage server.

791
792
793 **References**

- 794 Bonnet, S. (2009). Shrinking and splitting of drainage basins in orogenic landscapes from the
795 migration of the main drainage divide. *Nature Geosci*, 2(11), 766-771. 10.1038/ngeo666.
796 <http://dx.doi.org/10.1038/ngeo666>
- 797 Braun, J., & Willett, S. D. (2013). A very efficient O(n), implicit and parallel method to solve the
798 stream power equation governing fluvial incision and landscape evolution.
799 *Geomorphology*, 180-181, 170-179.
800 <http://www.sciencedirect.com/science/article/pii/S0169555X12004618>
- 801 Carson, M. A., & Kirkby, M. J. (1972). *Hillslope Form and Process*: Cambridge University Press.
- 802 Chen, S.-A., Michaelides, K., Grieve, S. W. D., & Singer, M. B. (2019). Aridity is expressed in
803 river topography globally. *Nature*, 573, 573–577. [https://doi.org/10.1038/s41586-019-](https://doi.org/10.1038/s41586-019-1558-8)
804 [1558-8](https://doi.org/10.1038/s41586-019-1558-8)
- 805 Clubb, F. J., Mudd, S. M., Milodowski, D. T., Grieve, S. W. D., & Hurst, M. D. (2017).
806 LSDChannelExtraction V1.0, <https://doi.org/10.5281/zenodo.824198>.
- 807 Collins, D. B. G., & Bras, R. L. (2008). Climatic control of sediment yield in dry lands following
808 climate and land cover change. *Water Resources Research*, 44(10), 8. Article. <Go to
809 [ISI>://000259993200002](https://doi.org/10.1029/2009WR008615)
- 810 Collins, D. B. G., & Bras, R. L. (2010). Climatic and ecological controls of equilibrium drainage
811 density, relief, and channel concavity in dry lands. *Water Resources Research*, 46(4),
812 W04508. <http://dx.doi.org/10.1029/2009WR008615>
- 813 Dunne, T. (1990). Hydrology, mechanics, and geomorphic implications of erosion by subsurface
814 flows. In C. G. Higgins & D. R. Coates (Eds.), *Groundwater geomorphology: The role of*
815 *subsurface water in earth-surface processes and landforms* (pp. 1-28). Boulder, CO: Geol.
816 Soc. Amer. Special Paper 252.
- 817 Grieve, S. W. D., Mudd, S. M., Milodowski, D. T., Clubb, F. J., & Furbish, D. J. (2016). How
818 does grid-resolution modulate the topographic expression of geomorphic processes? *Earth*
819 *Surf. Dynam.*, 4(3), 627-653. <https://www.earth-surf-dynam.net/4/627/2016/>
- 820 Hack, J. T. (1957). *Studies of longitudinal stream profiles in Virginia and Maryland* (294-B).
821 Retrieved from Menlo Park, CA:
- 822 Horton, R. E. (1945). Erosional development of streams and their drainage basins; hydrophysical
823 approach to quantitative geomorphology. *Geol. Soc. Amer. Bull.*, 56, 275-370.
- 824 Laronne, J. B., Reid, I., Yitshak, Y., & Frostick, L. E. (1994). The non-layering of gravel
825 streambeds under ephemeral flood regimes. *Journal of Hydrology*, 159(1-4), 353-363.
826 [http://www.sciencedirect.com/science/article/B6V6C-487DTBV-](http://www.sciencedirect.com/science/article/B6V6C-487DTBV-16/2/208964486e0bc7aaa3836d7dad610ccb)
827 [16/2/208964486e0bc7aaa3836d7dad610ccb](http://www.sciencedirect.com/science/article/B6V6C-487DTBV-16/2/208964486e0bc7aaa3836d7dad610ccb)
- 828 Lehner, B., Verdin, K., & Jarvis, A. (2008). New Global Hydrography Derived From Spaceborne
829 Elevation Data. *Eos, Transactions American Geophysical Union*, 89(10), 93-94.
830 <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008EO100001>

- 831 Leopold, L., Wolman, M. G., & Miller, J. P. (1964). *Fluvial Processes in Geomorphology*. San
832 Francisco, CA: W.H. Freeman & Co.
- 833 Leopold, L. B., & Miller, J. (1962). *Ephemeral streams: hydraulic factors and their relation to*
834 *the drainage net*. Retrieved from Washington, D.C.:
- 835 Michaelides, K., Hollings, R., Singer, M. B., Nichols, M. H., & Nearing, M. A. (2018a). Spatial
836 and temporal analysis of hillslope–channel coupling and implications for the longitudinal
837 profile in a dryland basin. *43*(8), 1608-1621.
838 <https://onlinelibrary.wiley.com/doi/abs/10.1002/esp.4340>
- 839 Michaelides, K., Hollings, R., Singer, M. B., Nichols, M. H., & Nearing, M. A. (2018b). Spatial
840 and temporal analysis of hillslope–channel coupling and implications for the longitudinal
841 profile in a dryland basin. *Earth Surface Processes and Landforms*.
842 <http://dx.doi.org/10.1002/esp.4340>
- 843 Montgomery, D. R., & Dietrich, W. E. (1988). Where do channels begin. *Nature*, *336*(6196), 232-
844 234. <Go to ISI>://WOS:A1988Q954200042
- 845 Ouellet Dallaire, C., Lehner, B., Sayre, R., & Thieme, M. (2019). A multidisciplinary framework
846 to derive global river reach classifications at high spatial resolution. *Environmental*
847 *Research Letters*, *14*(2), 024003. <http://dx.doi.org/10.1088/1748-9326/aad8e9>
- 848 Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the Köppen-
849 Geiger climate classification. *Hydrol. Earth Syst. Sci.*, *11*(5), 1633-1644.
850 <https://www.hydrol-earth-syst-sci.net/11/1633/2007/>
- 851 Perron, J. T., Kirchner, J. W., & Dietrich, W. E. (2009). Formation of evenly spaced ridges and
852 valleys. *Nature*, *460*(7254), 502-505. <Go to ISI>://WOS:000268257000036
- 853 Perron, J. T., Richardson, P. W., Ferrier, K. L., & Lapotre, M. (2012). The root of branching river
854 networks. *Nature*, *492*(7427), 100-103. 10.1038/nature11672.
855 <http://dx.doi.org/10.1038/nature11672>
- 856 Rigon, R., Rodriguez-Iturbe, I., Maritan, A., Giacometti, A., Tarboton, D. G., & Rinaldo, A.
857 (1996). On Hack's Law. *32*(11), 3367-3374.
858 <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/96WR02397>
- 859 Rinaldo, A., Dietrich, W. E., Rigon, R., Vogel, G. K., & Rodriguez-Iturbe, I. (1995).
860 Geomorphological signatures of varying climate. *Nature*, *374*(6523), 632-635.
861 10.1038/374632a0. <http://dx.doi.org/10.1038/374632a0>
- 862 Rinaldo, A., Rodriguez-Iturbe, I., & Rigon, R. (1998). Channel networks. *Annual Review of Earth*
863 *and Planetary Sciences*, *26*(1), 289-327.
864 <https://www.annualreviews.org/doi/abs/10.1146/annurev.earth.26.1.289>
- 865 Sassolas-Serrayet, T., Cattin, R., & Ferry, M. (2018). The shape of watersheds. *Nature*
866 *Communications*, *9*(1), 3791. <https://doi.org/10.1038/s41467-018-06210-4>
- 867 Seybold, H., Rothman, D. H., & Kirchner, J. W. (2017). Climate's watermark in the geometry of
868 stream networks. *Geophysical Research Letters*, *44*(5), 2272-2280.
869 <http://dx.doi.org/10.1002/2016GL072089>
- 870 Shuttle Radar Topography Mission (SRTM) - NSF OpenTopography Facility-
871 doi:10.5069/g9445jdf. (2013).
- 872 Singer, M. B., & Michaelides, K. (2014). How is topographic simplicity maintained in ephemeral
873 dryland channels? *Geology*, *42*(12), 1091-1094.
874 <http://geology.gsapubs.org/content/42/12/1091.abstract>
- 875 Singer, M. B., & Michaelides, K. (2017). Deciphering the expression of climate change within the
876 Lower Colorado River basin by stochastic simulation of convective rainfall.
877 *Environmental Research Letters*, *12*.
- 878 Slater, L. J., & Singer, M. B. (2013). Imprint of climate and climate change in alluvial riverbeds:
879 Continental United States, 1950-2011. *Geology*, *41*(5), 595-598.
880 <http://geology.gsapubs.org/content/41/5/595.abstract>

- 881 Solyom, P. B., & Tucker, G. E. (2004). Effect of limited storm duration on landscape evolution,
882 drainage basin geometry, and hydrograph shapes. *Journal of Geophysical Research-Earth*
883 *Surface*, 109(F3). <Go to ISI>://000236711300001
884 Tarboton David, G., Bras Rafael, L., & Rodriguez-Iturbe, I. (1991). On the extraction of channel
885 networks from digital elevation data. *Hydrological Processes*, 5(1), 81-100.
886 <https://doi.org/10.1002/hyp.3360050107>
887 Tucker, G. E. (2004). Drainage basin sensitivity to tectonic and climatic forcing: Implications of a
888 stochastic model for the role of entrainment and erosion thresholds. *Earth Surface*
889 *Processes and Landforms*, 29(2), 185-205. <Go to ISI>://000189226700005
890 Tucker, G. E., & Bras, R. L. (2000). A stochastic approach to modeling the role of rainfall
891 variability in drainage basin evolution. *Water Resources Research*, 36(7), 1953-1964. <Go
892 to ISI>://000087928800028
893 Tucker, G. E., & Whipple, K. X. (2002). Topographic outcomes predicted by stream erosion
894 models: Sensitivity analysis and intermodel comparison. *J. Geophys. Res.*, 107(B9), 2179.
895 <http://dx.doi.org/10.1029/2001JB000162>
896 Wang, L., & Liu, H. (2006). An efficient method for identifying and filling surface depressions in
897 digital elevation models for hydrologic analysis and modelling. *International Journal of*
898 *Geographical Information Science*, 20(2), 193-213.
899 <https://doi.org/10.1080/13658810500433453>
900 Willemin, J. H. (2000). Hack's Law: Sinuosity, convexity, elongation. *Water Resources Research*,
901 36(11), 3365-3374.
902 <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2000WR900229>
903 Wolman, M. G., & Gerson, R. (1978). Relative time scales of time and effectiveness of climate in
904 watershed geomorphology. *Earth Surface Processes & Landforms*, 3, 189-208.
905 Yi, R. S., Arredondo, Á., Stansifer, E., Seybold, H., & Rothman, D. H. (2018). Shapes of river
906 networks. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering*
907 *Sciences*, 474(2215), 20180081.
908
909