

1           **Quantifying geomorphically effective floods using**  
2           **satellite observations of river mobility**

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9           **Key Points:**

- 10           • We develop a method to quantify river planform change during flood events, us-  
11           ing Google Earth Engine
- 12           • We do so for a dataset of 160 floods that exceeded the 80th percentile stage, at  
13           41 flow gauging sites on laterally active rivers
- 14           • Erosion during these high-flow events was most correlated with the event dura-  
15           tion and summed hydrograph

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## Abstract

Geomorphologists have long debated the relative importance of disturbance magnitude, duration and frequency in shaping landscapes. For river-channel adjustment during floods, some argue that cumulative flood ‘power’, rather than magnitude or duration, matters most. However, studies of flood-induced river-channel change often draw upon small datasets. Here, we combine Sentinel-2 imagery with flow data from laterally-active rivers to address this question using a larger dataset. We apply automated algorithms in Google Earth Engine to map rivers and detect their lateral shifting; we generate a large dataset to quantify channel change during 160 floods across New Zealand, Russia, and South America. Widening during these floods is best explained by their duration and cumulative hydrograph. We use a random forest regression model to predict flood-induced channel widening, with potential applications for hazard management. Ultimately, better global data on sediment supply and caliber would help us to understand flood-driven change to river planforms.

## Plain Language Summary

Some rivers change their shape over time. In this paper, we explore how high-flow events drive these river channels to reshape themselves. We use Google Earth Engine to automatically map the shapes of rivers in satellite images. We apply this method to pairs of satellite images before and after high-flow events, to understand how the river shape is changed by the event. We compare the amount of channel-widening measured to aspects of the high-flow event, including its peak, duration and total flow. We do so for 160 high-flow events, and find that the duration and total flow are most important for explaining how much a channel widens during the event. Finally, we build a statistical model to predict the average amount of channel widening for a given high-flow event. This method has potential applications for hazard management in rivers that are known to change their shape.

## 1 Introduction

The relative importance of disturbance magnitude, duration and frequency for shaping landscapes is a crucial question in geomorphology. Many studies have considered the effects of high-magnitude versus high-frequency events: for cumulative sediment transport (Wolman & Miller, 1960; Webb & Walling, 1982), for generating and reworking landforms (Wolman & Gerson, 1978; Kale, 2002, 2003; Surian et al., 2015), and for the resulting sedimentology (Magilligan et al., 1998; Marren, 2005). Others have considered the duration and total energy expenditure of individual disturbances and how this relates to their ability to transport sediment and reshape river channels (Costa & O’Connor, 1995; Magilligan et al., 2015). In rivers, understanding which disturbances perform the most geomorphic work — both instantaneously, and cumulatively over time — has important implications for sediment budgeting, flood conveyance, depositional records, and natural hazard management.

In rivers, the major disturbances are flood events, which have the power to reshape the channels that convey them. Such reshaping ranges from bar deposition and bank erosion (Bryndal et al., 2017) or aggradation (Morche et al., 2007; Hooke, 2016) through to widening (Fuller, 2008; Yousefi et al., 2018), reoccupation of abandoned channels (Arnaud-Fassetta et al., 2005) and large-scale reworking of floodplains (Miller, 1990). The latter can have severe impacts for society, including erosion of agricultural or residential land (Yousefi et al., 2018) or the destruction of transport and river management infrastructure (Arnaud-Fassetta et al., 2005). Conversely, aggradation during floods can raise riverbeds by several meters (Morche et al., 2007; Tunnicliffe et al., 2018), reducing a channel’s conveyance capacity and the freeboard below bridges (Johnson et al., 2001). Quantitative

65 methods are needed to understand, model, and predict how river channels can be reshaped  
66 by individual flood events.

67 The geomorphic effectiveness of a flood is thought to be a function of its duration  
68 and magnitude. Here, we define geomorphic effectiveness as the extent to which a flood  
69 alters the channel form by eroding or depositing sediment. We use the term 'flood' to  
70 mean any temporary rise in the water level (in our analysis, one that exceeds the 80th  
71 percentile of the water surface elevation measurements). Previous studies have suggested  
72 that the cumulative stream power (defined by Bagnold (1966) as the product of water  
73 density, acceleration due to gravity, discharge and slope) beneath a flood hydrograph must  
74 be high for the event to be geomorphically effective; the implication is that high-magnitude  
75 but brief floods, and low-magnitude but long floods, are not likely to be effective (Costa  
76 & O'Connor, 1995). However, others have suggested that additional factors (not just the  
77 cumulative power) make a flood geomorphically effective. For instance, Middleton et al.  
78 (2019) demonstrated that flood magnitude does influence geomorphic effectiveness: in  
79 the proglacial braided river they studied, planform change during floods increased with  
80 their peak discharges. Others propose that a flood's geomorphic effectiveness is not deter-  
81 mined by the hydrograph alone, but also by the sediment supply (Church, 2014; Hooke,  
82 2016; Bennett et al., 2017; Pfeiffer et al., 2019) or the time since the previous flood, which  
83 can influence both sediment availability and the looseness of the riverbed (Gintz et al.,  
84 1996; Hooke, 2015). These studies have advanced our understanding of geomorphic ef-  
85 fectiveness, but almost all were small-sample case studies of 1-10 flood events or river  
86 reaches, often in similar regional or climatic contexts. Larger samples of flood events from  
87 a more geomorphically and geographically diverse set of rivers are required to produce  
88 a robust empirical assessment of what makes a geomorphically effective flood.

89 Google Earth Engine (GEE) has recently emerged as a key tool facilitating large-  
90 sample analyses of landscape characteristics — through both its computational platform  
91 and archive of quality controlled satellite data. The 'large-sample' approach, which ad-  
92 dresses environmental questions using data from tens to thousands of sites, is popular  
93 in hydrology (Addor et al., 2017; Klingler et al., 2021) and has begun to be applied in  
94 geomorphology (Slater et al., 2015; Slater, 2016; Pfeiffer et al., 2019; Sylvester et al., 2019;  
95 Valenza et al., 2020; Ahrendt et al., 2022; Brooke et al., 2022; Clubb et al., 2022; Ed-  
96 monds et al., 2022). A large-sample approach to studying planimetric river adjustments  
97 can be readily deployed in GEE, drawing on automated methods to map river planform  
98 (Allen & Pavelsky, 2015; Pekel et al., 2016; Zou et al., 2018; Isikdogan et al., 2019; Pick-  
99 ens et al., 2020; Boothroyd et al., 2021) and to track planform deformation (Wickert et  
100 al., 2013; Rowland et al., 2016; Schwenk et al., 2017; Jarriel et al., 2021; Chadwick et  
101 al., 2022; Langhorst & Pavelsky, 2022). By automating river planform tracking in GEE,  
102 the geomorphic effectiveness of a large sample of flood events can be assessed.

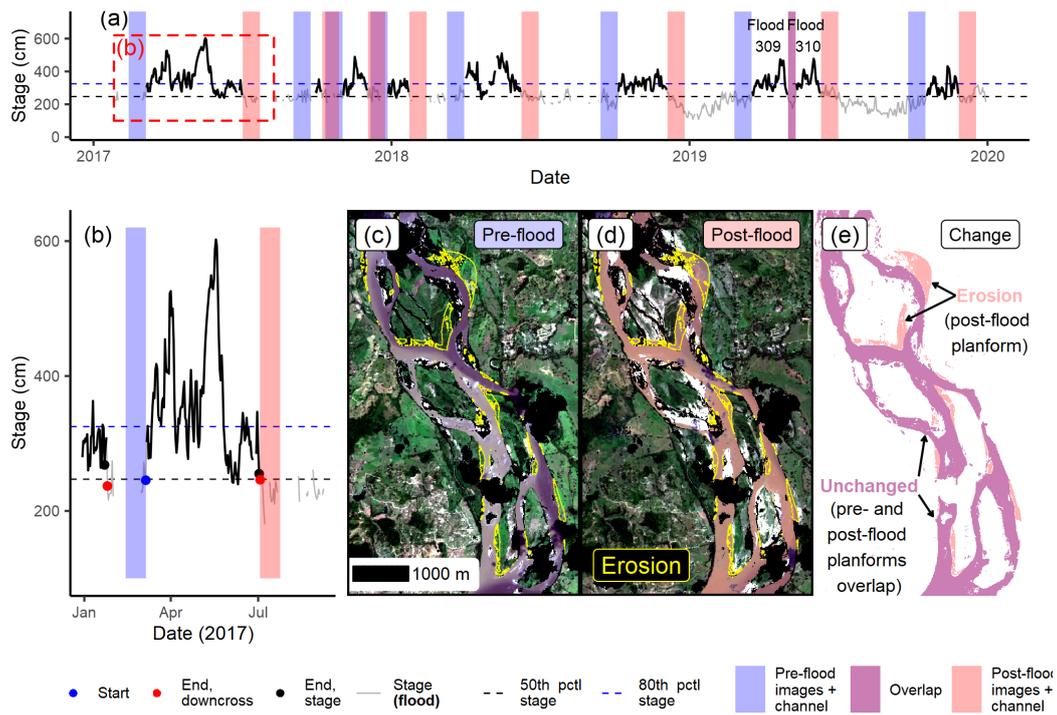
103 In this paper, we investigate the streamflow drivers of geomorphically effective floods  
104 using Sentinel-2 satellite imagery in GEE. We pursue two research questions:

- 105 1. Which hydrograph metrics best explain a flood's 2D geomorphic effectiveness?
- 106 2. How well can a flood's 2D geomorphic effectiveness be predicted from hydrologic  
107 and environmental variables?

108 We measure geomorphic effectiveness as the reach-averaged channel widening during a  
109 flood. We compute this planimetric erosion in GEE for flood events in Brazil, Colom-  
110 bia, New Zealand and Russia. We use 160 flood events at 41 flow gauging sites on lat-  
111 erally active rivers to evaluate our research questions (see Figure S1, Supplementary Ma-  
112 terial (SM), for gauge locations). We ascertain the influence of hydrograph shape on ge-  
113 omorphic effectiveness in our dataset. Finally, we develop an empirical model to predict  
114 flood-induced erosion. When coupled with streamflow forecasts, the model may be use-  
115 ful for hazard management in sites that are known to be laterally active.

116 **2 Methods**

117 Our method can be summarized as follows. First, we identified sites with historical  
 118 daily stage (water level) measurements and a laterally active channel. For those rivers,  
 119 we identified peaks in the stage records. Second, for each flood peak we extracted the  
 120 pre- and post-flood channel planform from Sentinel-2 data in GEE, and conducted a change  
 121 detection between the two planforms to quantify erosion during the flood hydrograph. Ultimately,  
 122 we compared the lateral erosion detected to parameters of the flood hydrograph. Figure 1  
 123 illustrates these steps with an example of one flood in Colombia. Our code is available  
 124 at <https://github.com/a-leenman/2dFloodsPublic>; GEE processing was per-  
 125 formed via the ‘rgee’ r package (Aybar, 2022).



**Figure 1.** Methods used to define floods and detect planform change. (a) The pre-flood (blue) and post-flood (red) search windows for a sequence of floods (bold lines), showing how the windows can overlap (purple). (b) Example flood from Colombian gauge 23097040, with the flood start date (blue circle), two options for flood end date (black and red circles; the ‘downcross’ (red circle) method was most appropriate) and the pre- and post-flood search windows. (c) Pre-flood channel morphology, mosaicked from all cloud-free pixels in the six satellite images covering part of the AOI within the pre-flood search window. Erosion during the following flood is outlined in yellow. Black patches have no data due to cloud. (d) Corresponding post-flood mosaic (10 source images within the time and space filter). (e) The pre- and post-flood channel planforms are overlaid, highlighting the erosion (red) detected.

126 **2.1 Site selection and area of interest**

127 Hydrologic records are crucial to our analysis, providing flood occurrence and hydro-  
 128 graph shape data. We obtained publicly available stage records and gauging locations

129 for Brazil, Colombia, New Zealand and Russia. These countries were chosen for their lat-  
 130 erally active rivers and availability of recent daily stage records.

131 Other authors used discharge or stream power records to pursue this problem. How-  
 132 ever, we chose to use stage data so that differences in stage could provide a proxy for  
 133 depth fluctuations when estimating the time series of shear stress. Ultimately, we aimed  
 134 to approximate the sediment transport capacity of each hydrograph.

135 We filtered the stage records to include only those gauges that:

- 136 1. Were located on a river with a mean annual discharge above  $100 \text{ cm}^3 \text{ s}^{-1}$  (data from  
 137 Grill et al. (2019)), to ensure these rivers were large enough to be visible in our  
 138 10 m satellite imagery.
- 139 2. Were located on a laterally active river whose dynamics could be measured from  
 140 satellite data. Laterally active rivers were identified by filtering the ‘water per-  
 141 manence’ layer from Pekel et al. (2016). After computing planform change dur-  
 142 ing floods, a site was removed if the eroded area never exceeded 1% of the water  
 143 surface area or if the flood-induced widening never exceeded 3 m. These thresh-  
 144 olds enabled the largest possible dataset while excluding channels that were not  
 145 laterally active.
- 146 3. Were not adjacent to large lakes or dams.
- 147 4. Overlapped with the Sentinel-2 record (June 2015 - present) by at least one year.

148 This filtering isolated a sample of 41 gauges. River widths ranged from 60 to 1000  
 149 m; their gradients ranged from 0.00001 to 0.002. Their mean long-term discharge ranged  
 150 from 100 to  $7000 \text{ cm}^3 \text{ s}^{-1}$ , and upstream catchment area ranged from 3800 to 430000  $\text{km}^2$ .  
 151 Values of the Richards-Baker index (Baker et al., 2004) ranged from 0.005 (very seasonal)  
 152 to 0.33 (moderately flashy). Gauge altitudes ranged from 3 to 500 m. Forest cover at  
 153 the gauges ranged from 0 to 100%, and mean annual rainfall from 440 to 4100 mm. The  
 154 range of rivers (including braided, wandering and meandering forms) encompassed by  
 155 these values highlights the geographic and geomorphic diversity of the rivers we incor-  
 156 porate.

157 For each gauge, we defined an ‘Area of Interest’ (AOI) in which we extract the river  
 158 planform and monitor its deformation. The ‘HydroSHEDS Free Flowing Rivers’ vector  
 159 network (Lehner et al., 2008; Grill et al., 2019) was used to select all river segments within  
 160 40 km of each gauge. We kept only the segments on the same branch as the gauge, and  
 161 also removed segments that were past a jump in average discharge of  $>20\%$ , implying  
 162 that a ‘major’ tributary had been passed; we computed such jumps using the average  
 163 discharge data for each segment in Grill et al. (2019). If two gauges were nearby on the  
 164 same river, we divided the intervening segments between them. This left a remaining ‘linked  
 165 reach’ (comprising one or more HydroSHEDS segments) assigned to each gauge. We ex-  
 166 tracted water masks along each reach from Allen and Pavelsky (2018a, 2018b), as a first  
 167 approximation of the channel area. However, these masks do not always encompass the  
 168 entire channel in our study reaches (which are extremely laterally mobile: some shift by  
 169 more than 30 m in a single flood) and so we buffered these masks by 500 m to create the  
 170 AOI. Finally, lakes in the HydroLAKES (Messenger et al., 2016) dataset were subtracted  
 171 from the AOI, to avoid spurious change detection from varying lake levels. We thus as-  
 172 signed to each gauge a unique AOI within which we extracted the river planform before  
 173 and after each flood.

## 174 2.2 Flood delineation and search window definition

175 We delineated floods temporally based on the daily stage record for each gauge.  
 176 Although higher frequency records were available for some countries, we resampled them  
 177 by taking the daily mean stage. While this process smoothed some maxima and min-

178 ima, it gave all records the same frequency. We defined a flood as any period exceeding  
 179 the 80th percentile of the stage record during the Sentinel-2 record (June 2015 onwards;  
 180 Figure 1a, b). Floods were extracted from the daily stage records using the hydroEvents  
 181 R package (Wasko & Guo, 2022). To ensure we captured the rising and falling limbs, we  
 182 defined the flood start date as the first measurement before the peak which was also be-  
 183 low the 50th percentile of stage (Figure 1a, blue points). We defined the flood end date  
 184 in two ways: either as

- 185 1. the first measurement following the peak which also fell below the 50th percentile  
 186 of stage (Figure 1a, red points), or
- 187 2. the first measurement following the peak which was within 30 cm of the stage at  
 188 the start of the flood (Figure 1a, black points). Occasionally, missing data meant  
 189 that the first method created flood end dates that were unreasonably far after the  
 190 end of the flood, necessitating the second method.

191 For each flood, we chose the flood end date with the stage measurement that was clos-  
 192 est to the stage on the start date. Following the discussion in Slater et al. (2021), floods  
 193 separated by less than seven days were counted as one event, and floods lasting more than  
 194 5 months were discounted as these were mostly anomalies from missing data. While this  
 195 approach of using the 50th percentile to give the start and end dates assigns a longer length  
 196 to floods than some standard approaches, it allows us to capture the geomorphic effects  
 197 of the rising and falling limbs, and recognizes that geomorphic change and sediment en-  
 198 trainment likely start before the 80th percentile stage is exceeded.

199 Directly before and after each flood, we defined pre- and post-flood time windows  
 200 of up to three weeks (Figure 1a, b). We truncated a time window if floods were less than  
 201 three weeks apart; for example, flood 309 (Figure 1a) finished nine days before the fol-  
 202 lowing event, and so its post-flood window was truncated. If sequential events were less  
 203 than six weeks apart, their pre- and post-flood windows were allowed to overlap; the post-  
 204 flood window for one flood could even overlap entirely with the pre-flood window of the  
 205 following event, as with floods 309 and 310 (Figure 1a; this would mean that the post-  
 206 flood channel mask of flood 309 was reused as the pre-flood mask of flood 310). We used  
 207 these pre- and post-flood time windows to search the Sentinel-2 archive (Level 1C, har-  
 208 monized).

### 209 **2.3 Planform extraction and change detection**

210 Within each pre- and post-flood time window, we extracted the river planform from  
 211 Sentinel-2 (S2) imagery. First, we mosaicked all cloud-free S2 pixels within the time win-  
 212 dows and AOI, taking the minimum reflectance in each band if multiple copies of one pixel  
 213 were available. Figure 1c and d are examples of these mosaics. We proceeded with an  
 214 event if at least 50% of its AOI was cloud-free; only pixels that were cloud-free in both  
 215 mosaics were used. For sites in New Zealand and Russia, we also mapped snow using the  
 216 normalized difference snow index, following Hofmeister et al. (2022). For snow-free scenes  
 217 that met our cloud threshold, we mapped channel planform from a combination of spec-  
 218 tral indices, following Zou et al. (2018) and Boothroyd et al. (2021); these were the nor-  
 219 malized difference vegetation index (Rousel et al., 1973), modified normalized difference  
 220 water index (Xu, 2006), and enhanced vegetation index (Huete et al., 2002). Following  
 221 Boothroyd et al. (2021), we counted both water and exposed sediment (i.e. non-vegetated  
 222 bars) as part of the channel, given that a lack of vegetation indicates bars are frequently  
 223 inundated. While this mapping method is simple, it is generalizable to rivers with dif-  
 224 ferent lighting conditions and suspended sediment concentrations.

225 We conducted change detection between the pre- and post-flood planforms to es-  
 226 timate each flood's geomorphic impact. To isolate areas that were permanently (as op-  
 227 posed to transiently) changed during a flood, we tracked the state (wet or dry) of each

228 pixel at monthly intervals for the following 24 months, loosely following the pixel-by-pixel  
229 trend analysis of Nagel et al. (2022). We only considered a pixel to be eroded if it switched  
230 from dry-to-wet in the flood and then continued to be wet for the subsequent two years.  
231 If cloud cover meant there were <18 months of these after-flood observations for an event,  
232 we discounted it; we chose this threshold by checking the change detection for bias due  
233 to stage fluctuations. This pixel-tracking method allowed us to eliminate spurious change  
234 detection resulting from transient stage fluctuations.

235 We measured a flood's geomorphic effectiveness as the area that was permanently  
236 eroded (i.e. changed from 'dry' to 'wet') during the event. We normalized this eroded  
237 area by the reach length to give the reach-averaged channel widening. Because we counted  
238 non-vegetated bars as part of the channel, it was difficult to measure deposition follow-  
239 ing the flood; newly deposited sediment was typically registered as 'channel' by our map-  
240 ping algorithm. This is why we consider post-flood erosion to be the most appropriate  
241 metric of geomorphic change in our data.

242 Our procedures for gauge selection, cloud- and snow-filtering isolated a dataset of  
243 160 events for which we measured geomorphic effectiveness. Because there were less than  
244 11 floods in some countries, we pooled all floods for our subsequent analyses.

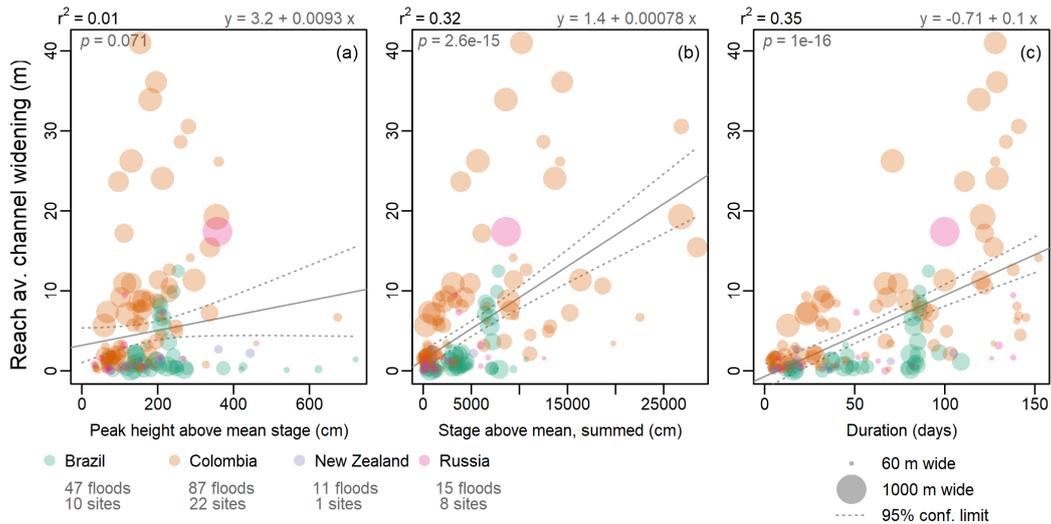
## 245 2.4 Regression and prediction

246 Our first research question considers the influence of hydrograph shape on geomor-  
247 phic effectiveness. There are numerous metrics to characterize hydrographs, including  
248 measures of height, duration, integrated power, volume or transport capacity, and asym-  
249 metry (Brunner et al., 2021; Slater et al., 2021). Because these rivers feature a range of  
250 hydrographs (for instance, flashy versus seasonal), we use three simple metrics that al-  
251 low comparison with previous studies. The first is the flood peak height, relative to the  
252 mean daily stage. The second is the cumulative value of all daily stage measurements  
253 during the flood, measured relative to mean daily stage. This cumulative water level met-  
254 ric is akin to the 'volume' of a hydrograph when using discharge records (e.g. Brunner  
255 et al. (2021), Figure 3). Because we use stage records, the metric accounts for the com-  
256 bined influence of changes in flow depth during the flood (exerting stress on the river banks/bed)  
257 and of flood duration; we refer to it as the 'summed hydrograph'. The third metric is  
258 the flood duration.

259 As well as exploring how hydrograph metrics correlated with erosion, we built a  
260 random forest regression model to rank the predictors' importance (by estimating how  
261 much they decreased the model's mean square error, MSE). In addition to these hydro-  
262 graph metrics, we incorporated the pre-flood channel width, as channel size can positively  
263 influence channel mobility (Constantine et al., 2014; Nanson & Hickin, 1986; Langhorst  
264 & Pavelsky, 2022). Although sediment supply also increases channel mobility (e.g. Constantine  
265 et al. (2014); Ahmed et al. (2019); Donovan et al. (2021)), we do not have sediment sup-  
266 ply time-series for our gauging sites. Instead, we used stream gradients and stage records  
267 to estimate the sediment transport capacity for each flood (see Section S1, SM for de-  
268 tails), and added these estimates to the random forest model. We built the model us-  
269 ing the randomForest r package (Liaw & Wiener, 2002) with 500 trees and two variables  
270 randomly sampled at each split. We used the model to predict each flood's reach-averaged  
271 erosion using leave-one-out cross-validation (LOOCV).

## 272 3 Results

273 In the laterally active rivers we study, floods and their geomorphic impacts vary  
274 by orders of magnitude. Peak heights vary from 30 to 700 cm above mean daily stage.  
275 The summed hydrographs vary from 40 to 30000 cm above mean daily stage, and flood  
276 durations from 1 to 152 days. The geomorphic effects of these floods are diverse, with

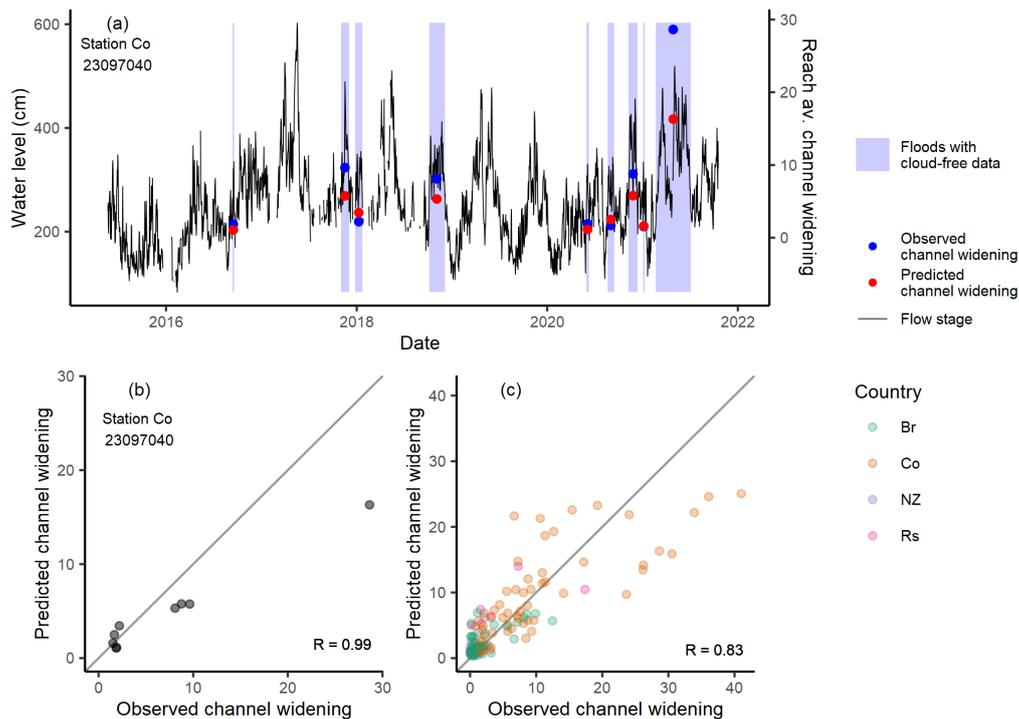


**Figure 2.** Flood metrics and their relationship to reach-averaged channel widening (i.e. plan-view erosion normalized by reach length) during each flood. (a) Flood peak height above the mean daily stage. (b) Cumulative stage exceeding mean daily stage (‘summed hydrograph’). (c) Flood duration. Each point represents one event; colors indicate the four countries; point size is proportional to pre-flood channel width. The solid gray line shows a linear regression and dotted lines show 95% confidence limits; the regression equation is at the top-right.  $r^2$  and  $p$ -values are at the top left.  $r^2$  values for individual countries are in Table S1, SM.

277 reach-averaged widening as low as 0.005 m and as high as 41 m. The least geomorphi-  
 278 cally active country is New Zealand, with an average flood-induced widening of 0.9 m,  
 279 while the most active is Colombia, with an average widening of 7 m across all floods.

280 Our first research question considers the erosional response of river channels to flood  
 281 hydrographs. Figure 2 demonstrates how reach-averaged erosion varies with three hy-  
 282 drograph metrics in the 160 floods we study. Each point represents one event, with the  
 283 reach-averaged erosion compared to the flood’s peak height (a), summed hydrograph (b),  
 284 and flood duration (c). Figure 2 therefore shows how hydrograph metrics influence ge-  
 285 omorphic effectiveness for 160 floods at 41 sites across Brazil, Colombia, New Zealand  
 286 and Russia between 2015 and 2021.

287 Our results indicate that reach-averaged channel widening is only weakly related  
 288 to flood height in our dataset (Figure 2a). A linear regression of reach-averaged erosion  
 289 during each flood against the peak height had an  $r^2$  of just 0.01. Erosion scaled more  
 290 strongly with the summed hydrograph (Figure 2b), with an  $r^2$  of 0.32, and most strongly  
 291 with flood duration (Figure 2c), with an  $r^2$  of 0.35. See Table S1 (SM) for country-specific  
 292 relationships. These coefficients of determination are surprisingly high, considering that  
 293 they represent observations from real systems and are thus confounded by other natu-  
 294 ral variables in each location. Some of the relationships in Figure 2 appear non-linear  
 295 (especially panel (c)), but we lack sufficient data to fit non-linear models and so we use  
 296 linear regression to make a first-order comparison. These metrics are correlated among  
 297 themselves (see Figure S2, SM); longer floods often had higher peaks, so that the  $r^2$  val-  
 298 ues shown here indicate *relative* importance and we cannot say that the increase in ero-  
 299 sion with flood duration was independent of the concurrent increase in height for many  
 300 floods. Nevertheless, panels a-c indicate that, at least for our sample of laterally active



**Figure 3.** Predictions from our random forest regression model. (a) The stage record for Colombian gauge 23097040; flood events with sufficient cloud-free satellite data are highlighted. The observed and predicted reach-averaged erosion (channel widening) during each flood are overlain and scale with the secondary y-axis. (b) A comparison of observed and predicted channel-widening at this gauge; each point is one flood. (c) A comparison of observed and predicted channel-widening for all floods in our dataset. Grey lines in (b) and (c) show a 1:1 relation.

301 rivers, flood duration was the most important variable for explaining flood-driven erosion of the vegetated channel boundary.  
302

303 We built a random forest regression model to rank the importance of the hydro-  
304 graph metrics, channel width, and estimated sediment transport for explaining flood ero-  
305 sion. The random forest model ranked these variables in the following order: estimated  
306 transport, channel width, flood duration, summed hydrograph and peak height; the rank-  
307 ings reflect how much each variable reduced the model’s MSE. This ranking is similar  
308 to the  $r^2$  values in Figure 2 and Figures S3-S4 (SM). Because the summed hydrograph  
309 and flood duration were correlated ( $R = 0.79$ ), we ran two additional model versions,  
310 omitting either summed hydrograph or flood duration. Although these omissions altered  
311 the variables’ MSE reductions, neither altered the remaining variable rankings, imply-  
312 ing that the rankings are not affected by this co-linearity in the predictors.

313 We predicted erosion for all floods in our dataset using the random forest model  
314 with LOOCV. We were able to predict erosion with at least 60% accuracy ( $R = 0.83$ ;  
315 Figure 3c) using the pooled dataset. The model performed best for sites in Colombia with  
316 numerous floods, such as site 23097040 (Figure 3a,b). For Colombian sites with data for  
317  $> 7$  floods,  $R$  values were 0.78–0.99. The model tended to under-predict the highest val-  
318 ues of reach-averaged erosion.

## 4 Discussion

Although there is no firm consensus, previous literature has laid the case for a hydrograph's cumulative power as the best explainer of a flood's geomorphic effectiveness. For instance, based on 10 events in Arkansas, California, Colorado, Idaho, Oregon and Washington, Costa and O'Connor (1995) suggested that a flood's geomorphic effectiveness reflected the cumulative unit stream power exceeding the threshold for alluvial erosion. Rose et al. (2020) likewise found that the most geomorphically effective floods in a sample of seven had a high energy expenditure, high peak and long duration. Kale and Hire (2007) observed that sediment transport (a proxy for geomorphic effectiveness) during monsoons rose exponentially with their cumulative stream power. Magilligan et al. (2015) attributed the limited widening during an extreme flood to its low cumulative power, resulting from a high peak but short duration. Our data partly support this hypothesis; the summed hydrograph was positively correlated with erosion during the floods we studied. However, in our dataset flood duration was a slightly better predictor of erosion of the vegetated channel boundary. This result was consistent when we raised the flood definition threshold to the 90th percentile of stage, and the summed hydrograph and flood duration had equal effects when we lowered the threshold to the 70th percentile (Figures S5 and S6, SM).

One reason for the weaker influence of the summed hydrograph in our data may be that these previous studies used the unit stream power hydrograph, whereas we used the stage hydrograph. We used stage so that changes could be used as a proxy for depth fluctuations when estimating shear stress and each hydrograph's sediment transport capacity. Although the unit transport capacity was a weaker predictor than the summed hydrograph or duration, transport became a stronger predictor when multiplied by channel width (see section S1 and Figure S3 (SM) for more detail).

The importance of flood duration in our dataset implies that, once these floods exceed the entrainment threshold, further stage increases have a smaller effect than the duration above the threshold. That is, shear stress exposure duration has a greater effect than the peak stress. This result suggests that the threshold for entrainment was low in the rivers we studied, so that full mobility of all sediment sizes was attained frequently. The regional breakdown of Figure 2 (Table S1, SM) supports this notion, as the influence of duration is strongest for Colombia where some studies have reported sand beds (e.g. Smith (1986); Martínez Silva and Nanny (2020)).

Other studies have used flood peak height, rather than cumulative power, to explain geomorphic effectiveness. For instance, Middleton et al. (2019) mapped planimetric change during floods in a proglacial river and showed that, once an annually-reset threshold discharge had been exceeded, planimetric change increased with peak discharge. Miller (1990) found that, in alluvial rivers wider than 200 m, peak unit stream power during floods was correlated with geomorphic effectiveness. In alluvial fan experiments featuring different hydrographs of the same volume, surface reworking increased with the peak discharge (Leenman et al., 2022). Nevertheless, in our dataset flood height was only weakly related to geomorphic change. It is possible that a threshold above which peak height becomes important can only be extracted by analyzing numerous floods at one location. Such an analysis is difficult in the remote sensing of real rivers, either due to seasonal floods or to persistent cloud cover, both of which limit the number of events that can be assessed.

Our results, and particularly the importance of flood duration, highlight some complexities of investigating flood impacts with a large-sample remote-sensing analysis. First, while we measured the flood-induced erosion of the vegetated channel boundaries, others simply categorized flood-driven change (e.g. (Costa & O'Connor, 1995)) or quantified sedimentological impacts (Magilligan et al., 2015). The importance of duration here is relevant to vegetated channel boundaries, but results may differ if measuring a differ-

371 ent aspect of channel morphology — for instance, Magilligan et al. (2015) highlight how  
372 a flood event can have large sedimentological effects but a smaller impact on channel shape.  
373 Second, our large-sample analysis highlights the difficulty of finding a single parameter  
374 explaining flood effectiveness in all rivers. Flood duration was the most important driver  
375 of erosion in some rivers in our dataset, but not all; Table S1 shows that peak height was  
376 more important in Russia. Third, the relationship between a flood hydrograph and the  
377 erosion caused can be compounded by other variables, including the presence and char-  
378 acter of vegetation, the caliber and structure of bed and bank sediment, the sediment  
379 supplied from upstream, and the time elapsed since the previous flood. In this paper,  
380 we make a first attempt at a large-sample analysis of geomorphically effective floods, and  
381 our work highlights the need for global datasets on these additional variables in order  
382 to fully address this problem.

383 Others have suggested that the causal relationship between a flood and its geomor-  
384 phic effectiveness is moderated by sediment supply. For instance, in comparing two events  
385 on the Peace River (Canada), Church (2014, Chapter 10) found that their geomorphic  
386 effects were best explained by differences in the sediment influx. Pfeiffer et al. (2019) found  
387 that bed-level changes in Washington State were not related to high-flow events, but to  
388 sediment supply from glaciers upstream. Dean and Schmidt (2013) observed that geo-  
389 morphic change during a flood in the Rio Grande was highest downstream of sediment-  
390 rich tributaries. For longer-term channel mobility, sediment supply positively influences  
391 channel migration (Constantine et al., 2014), and some rivers in our dataset (e.g. the  
392 Magdalena) have very high sediment loads (Restrepo et al., 2006; Higgins et al., 2016;  
393 Dethier et al., 2022). This question is an interesting and important one, and further work  
394 to measure sediment transport alongside flow during floods is crucial for understanding  
395 how sediment availability modulates a hydrograph’s geomorphic effectiveness.

396 Our methods have some limitations which provide avenues for further research. The  
397 first is the suitability of using planform measurements to quantify three-dimensional chan-  
398 nel adjustment. For landslides, erosional area scales with volume (Guzzetti et al., 2009;  
399 Larsen et al., 2010), but in rivers a 2D for 3D substitution would not be appropriate where  
400 channels are laterally confined. We have side-stepped this problem by using only later-  
401 ally mobile rivers, which are therefore the rivers where a 2D for 3D substitution is most  
402 appropriate. Middleton et al. (2019) demonstrated experimentally that sediment trans-  
403 port scaled linearly with planimetric change, providing further justification for 2D change  
404 detection. However, further work on the suitability of measuring geomorphic change in  
405 planview would be valuable.

406 Further potential limitations include that of data resolution; the Sentinel-2 imagery  
407 we use has a 10 m resolution. Because erosion may occupy a smaller footprint than de-  
408 position of the same volume (Lindsay & Ashmore, 2002), finer-scale imagery may bet-  
409 ter capture erosion and would facilitate equal monitoring of both processes. An inves-  
410 tigation of improvements with higher-resolution imagery would be worthwhile. In ad-  
411 dition, our method computes change in the vegetated channel boundaries, so that non-  
412 vegetated bars moving through these rivers are not counted. Work comparing different  
413 algorithms to quantify river dynamics would be a useful contribution. Finally, similar-  
414 ity between the spectral signatures of snow and water in the mNDWI (Huang et al., 2018)  
415 meant we had to discard snowy scenes. We thus compromised slightly on our goal of a  
416 geomorphically diverse set of rivers. As the S2 record approaches a decade, the main lim-  
417 itation on this work is the availability of flow records, which constrains the range of sites  
418 that can be used. Methods to measure or model flow in ungauged basins could extend  
419 this work to an even more geographically diverse range of rivers.

420 **5 Conclusions**

421 We used Google Earth Engine and the Sentinel-2 satellite archive to map planform  
422 geomorphic change in laterally-mobile rivers during 160 flood events. By tracking each  
423 pixel for two years, we were able to separate permanent planform change from transient  
424 water extent fluctuations arising from stage variability. We measured each flood's geo-  
425 morphic effectiveness as the reach-averaged erosion during the flood, and compared this  
426 to the flood hydrograph.

427 In the 41 laterally active rivers studied, we found that the flood peak height was  
428 only weakly correlated with erosion. The summed hydrograph was a better predictor,  
429 but erosion was most closely correlated with flood duration in our dataset of events ex-  
430 ceeding the 80th percentile of stage.

431 We built a random forest regression model to predict geomorphic change for each  
432 flood, using hydrograph metrics, estimated sediment transport and channel size. The model  
433 had a prediction accuracy above 60%, which is promising for the predictability of river-  
434 bank erosion in mobile reaches.

435 Our work highlights the need for high-frequency flow monitoring in the world's lat-  
436 erally active rivers, to better understand how a flood's hydrograph controls its erosional  
437 impact. Moreover, better data on land cover, bank strength, and sediment caliber at stream  
438 gauging sites would elucidate how these characteristics modulate flood-driven erosion.  
439 Finally, monitoring sediment transport alongside river flows would help us to understand  
440 how sediment availability influences a flood's geomorphic effectiveness.

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