Hydrologic versus geomorphic drivers of trends in flood hazard

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Abstract Flooding is a major hazard to lives and infrastructure, but trends in flood hazard are poorly understood. The capacity of river channels to convey flood flows is typically assumed to be stationary, so changes in flood frequency are thought to be driven primarily by trends in streamflow. We have developed new methods for separately quantifying how trends in both streamflow and channel capacity have affected flood frequency at gauging sites across the United States Flood frequency was generally nonstationary, with increasing flood hazard at a statistically significant majority of sites. Changes in flood hazard driven by channel capacity were smaller, but more numerous, than those driven by streamflow. Our results demonstrate that accurately quantifying changes in flood hazard requires accounting separately for trends in both streamflow and channel capacity. They also show that channel capacity trends may have unforeseen consequences for flood management and for estimating flood insurance costs.

1. Introduction

Economic losses due to flooding have increased dramatically over recent decades, and flood hazards (the probability of high river flows and resulting inundation) are expected to grow as climate change accelerates the hydrologic cycle [*Field et al.*, 2012; *Kundzewicz et al.*, 2014]. In the U.S., direct flood losses from 1980 to 2010 averaged US$7.8 billion per year, and the National Flood Insurance Program proposed raising insurance premiums to reflect the "true flood risk" [*Biggert-Waters Flood Insurance Reform Act*, 2012; *King*, 2013]. For planning and insurance purposes, flood hazard based on historical flood records is typically assumed to be statistically stationary. However, there is evidence that changes in climate and land cover are altering river flows [*Kundzewicz et al.*, 2014] and that changes in stream channel cross sections are altering local channel capacity [*Stover and Montgomery*, 2001; *Lane et al.*, 2007]. This raises important questions of how flood hazard may change over time and what drives those changes.

Freshwater flooding occurs wherever river discharge from the upstream basin exceeds the local channel capacity at flood stage, i.e., the volume of flow that can be carried within the channel cross section [*U.S. Water Resources Council*, 1981]. Thus, flood hazard can be amplified either by an increase in the frequency of high flows [*Merz et al.*, 2012] or by a reduction in channel capacity [*Stover and Montgomery*, 2001] (Figure 1). The frequency of high flows can shift in response to basin-wide climatic changes [*Wilby et al.*, 2008; *Field et al.*, 2012; *Kundzewicz et al.*, 2014], anthropogenic modifications of basin water supply (e.g., dams and diversions), and changes in land cover that affect runoff generation [*Blöschl et al.*, 2007]. Channel capacity, on the other hand, can evolve due to bed aggradation/degradation [*Stover and Montgomery*, 2001; *Slater and Singer*, 2013], narrowing/widening of riverbanks, or reductions/increases in average flow velocity associated with changes in bed sediment texture [*Singer*, 2010] and/or in-channel vegetation [*Friedman and Auble*, 2000; *Rutherfurd et al.*, 2006]. Reductions in channel capacity amplify flood hazards even if the flow frequency distribution does not change [*Blench*, 1969; *James*, 1999; *Stover and Montgomery*, 2001; *Pinter et al.*, 2006; *Lane et al.*, 2007].

In flood risk analysis and channel design engineering, channel capacity has generally been assumed to be constant over management time scales [*U.S. Water Resources Council*, 1981; *Horritt and Bates*, 2002; *Wilby et al.*, 2008], and trends in flood frequency have been assumed to be driven primarily by changes in streamflow [*Douglas et al.*, 2000; *McCabe and Wolock*, 2002; *Lins and Slack*, 2005; *Villarini et al.*, 2009; *Villarini and Smith*, 2010]. Previous studies have used an approach termed "specific gauge analysis" to infer the effects of channel capacity trends on flood hazard by observing the trend in stage (water level) associated with a
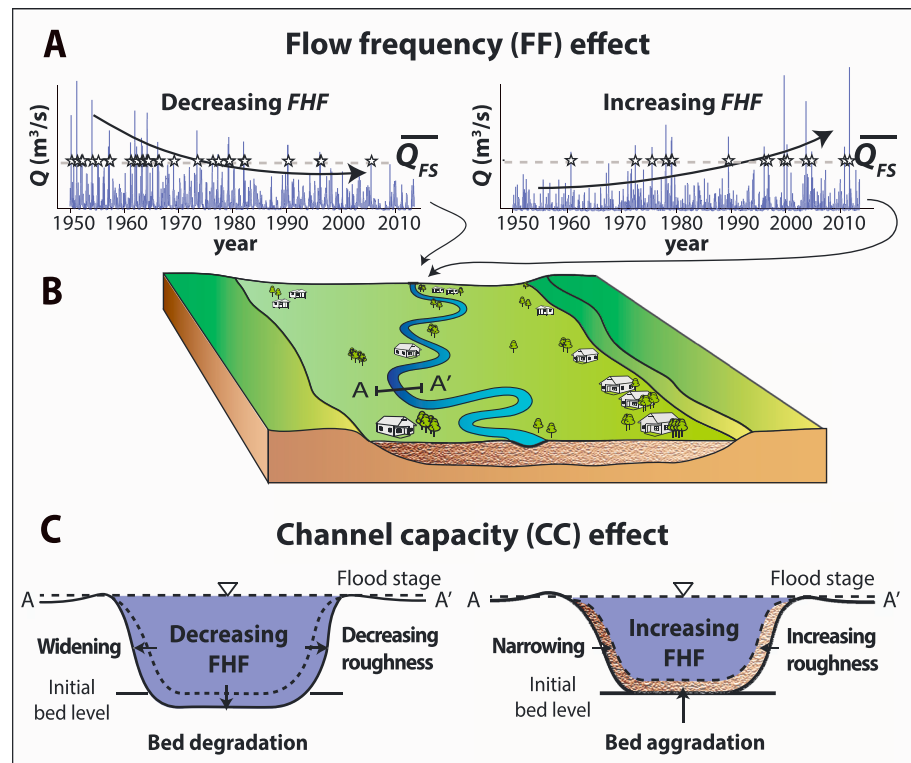
Figure 1. Schematic of flow frequency and channel capacity effects on flood hazard frequency (FHF). (a) Time series showing decreasing and increasing flow frequency effects on flood hazard frequency (days with Q equaling or exceeding $\overline{Q_{FS}}$ indicated by a star). (b) Flood hazard frequency at channel-floodplain cross section A–A' may change due to the flow frequency effect (Figure 1a) and/or to the channel capacity effect (Figure 1c). (c) Changes in channel capacity alter flood hazard frequency at cross section A–A' through shifts in cross-sectional area and/or roughness.

reference discharge over time [e.g., *Pinter et al.*, 2006]. Although specific gauge analysis provides an indication of how channel capacity is shifting, it does not allow river managers to quantify the effects of geomorphic change on flood hazard. Thus, it has not been possible to separate trends in channel capacity from trends in the frequency of high flows and to compare their effects on flood hazard frequency over decadal and continental scales. Here we present novel methods for measuring long-term trends in channel capacity of gauged rivers and for quantifying how these trends affect flood frequency. We apply these methods to 401 U.S. rivers in order to quantify the relative contributions of channel capacity and flow frequency to historical flood hazard and to assess how they interact.

2. Methods

Our procedures are fully described and illustrated in the supporting information, so here we provide only an outline. Our source data are daily discharge (Q) records for United States Geological Survey (USGS) gauging stations and manual USGS field measurements of channel width, cross-sectional flow area, and average flow velocity for a range of flows from these same sites. We assume that each river's flood stage—the absolute altitude at which rising flows create a hazard to lives, property, or commerce—is constant. Since estimates of that critical stage may improve over time, we used the most recent National Weather Service flood stage estimates for each site. Using a constant flood stage allows us to quantify temporal changes in the discharge that is required to reach it (i.e., the channel capacity).

Estimating trends in channel capacity depends on the quality of the stage-discharge data. Therefore, the cross-sectional channel measurements were filtered for location and accuracy as described in the supporting information. We identified and removed all sites with artificial controls at the gauging station (e.g., concrete weirs) that would prevent the channel from adjusting its shape naturally, all field measurements made in a different (or potentially different) location, and all field measurements made in icy conditions, as these

might affect measurements of channel geometry. We retained only sites with complete time series; thus, each site had, on average, 99.7% streamflow record completeness and 40 channel cross-section measurements between 1950 and 2013.

We classified all sites based on their relative degree of anthropogenic flow modifications (*Least*, *Intermediate*, and *Most* modified) to assess human effects on flood hazard trends and to determine whether flood hazard trends at sites with little anthropogenic modification can be related to observed trends in regional climate. To evaluate the level of flow modification for each gauging station, we scrutinized each site's mean daily streamflow time series and USGS Annual Water Data Reports, as well as maps and aerial images covering each river basin in Google Earth, as described in the supporting information.

Our methods are based on the idea that at any river cross section, the flood hazard frequency (i.e., the number of days per year that river discharge equals or exceeds the local channel capacity and causes overbank flooding) can be altered by changes in either channel capacity or flow frequency (Figure 1). These two components of flood hazard can be separated and quantified by holding one component constant while observing shifts in the other as explained below.

First, we measured the "flow frequency effect" (Figure 1a) as the trend in flood hazard frequency that would arise from shifts in the flow frequency distribution if channel capacity were held constant. We estimated the average discharge at flood stage ($\overline{Q_{FS}}$) for each site and calculated the trend in how frequently this fixed discharge was equaled or exceeded each year (in d/yr) using a mean unbiased exponential least squares curve, which allowed us to avoid predicting negative values (see supporting information for details).

Second, we measured the "channel capacity effect" (Figure 1c) as the trend in flood hazard frequency that would arise from the observed shifts in channel capacity if the flow frequency distribution were held constant. From manual USGS field measurements, we calculated the residuals around the average stage-discharge rating curve for each site. Each residual was added to $\overline{Q_{FS}}$ to obtain an estimate of the volume of the flow that could be carried within the channel at flood stage (i.e., the channel capacity) at the time of each measurement. We then evaluated the frequency of each estimated value of channel capacity (at different points in time) within the historic flow frequency distribution. The trend in these frequency values was computed similarly to the flow-frequency effect but using iteratively reweighted least squares to mitigate the influence of any outliers (which arise from inaccuracies in the stage-discharge rating curve or measurement location; for details, see supporting information). Both the channel capacity and flow frequency effects were assessed at the same flood hazard threshold, namely, flood stage, so the total change in flood hazard frequency is the sum of the channel capacity and flow frequency effects at each site.

3. Results and Discussion

More than half of our sites (57%, 227/401) showed statistically significant ($p < 0.05$) channel capacity or flow frequency effects on flood hazard frequency, suggesting that flood hazard is generally nonstationary. This finding undermines most efforts to characterize flood hazard over decadal time scales by fitting theoretical probability distribution functions to historical flood records.

Flow frequency effects on flood hazard were typically larger than channel capacity effects (Figure 2). However, statistically significant channel capacity effects were nearly 3 times more common than statistically significant flow frequency effects (190 versus 71 sites; Figures 1 and 2), suggesting that trends in channel capacity are more widespread and/or easier to detect over decadal time scales. Also, because our analysis relies on USGS gauging stations, which are generally sited in relatively stable channel cross sections [*Carter and Davidian*, 1968], channel capacity effects on flood hazard may even be larger and more widespread than those that we document here. Thus, although flow frequency effects typically dominate discussions about trends in flood hazard, our results suggest that channel capacity trends are important contributors that may alter flood risks independently from streamflow trends and even in the absence of climate change.

At our sites with the *Least* and *Intermediate* levels of anthropogenic flow modification, streamflow trends increased flood hazards almost twice as often as they decreased them (Figure 2a; 193 versus 98 sites, $p < 0.001$ by sign test). These less impacted sites are more likely to reveal climatic effects on flood hazards, whereas climatically driven trends at the "*Most*" altered sites are more likely to be obscured by anthropogenic flow
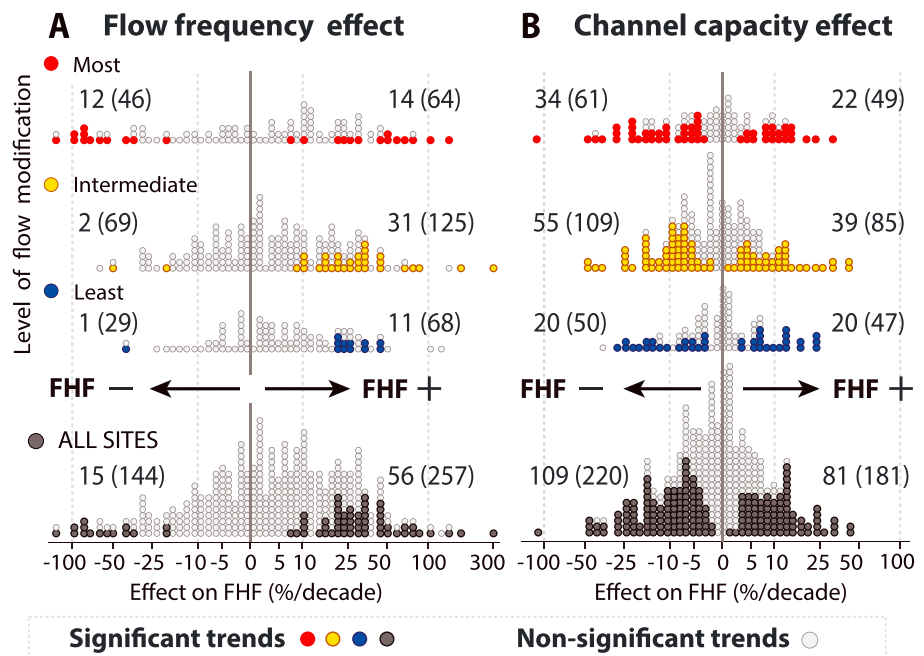
Figure 2. Histograms of (a) flow frequency effects and (b) channel capacity effects on flood hazard frequency (%/decade). Each circle represents one gauging site, and statistically significant sites are represented with color-filled circles. Sites are grouped based on their degree of streamflow modification. The numbers of significant sites (and total sites in parentheses) with positive/negative trends are indicated above each distribution. Inverse hyperbolic sine transformations were used to display the distributions, because they were strongly leptokurtic. Positive FHF trends indicate more frequent flooding.

modifications. Most previous flood hazard studies have found no systematic increase in flood frequency across the U.S. during the twentieth century [*Douglas et al.*, 2000; *McCabe and Wolock*, 2002; *Lins and Slack*, 2005]. However, some recent work has suggested that streamflows have increased in the northeastern and midwestern U.S. [*Villarini et al.*, 2009; *Villarini and Smith*, 2010] and have decreased in the southeastern and southwestern parts [*Hirsch and Ryberg*, 2012]. Among our sites, increasing flow frequency trends were concentrated within the Mississippi River Basin and the northeast, whereas decreasing flow frequency trends were found in more circumscribed areas of the northwestern and southeastern U.S. (Figure 3a). This geographic pattern is consistent with documented trends in heavy and extreme precipitation events [*DeGaetano*, 2009; *Villarini et al.*, 2013; *Janssen et al.*, 2014] and 10 year trends in regional groundwater levels inferred from Gravity Recovery and Climate Experiment (GRACE) satellite observations [*Famiglietti and Rodell*, 2013], suggesting that climatic trends translate into measurable changes in flood hazard frequency.

In contrast to the flow frequency results, we found approximately equal numbers of sites with increasing and decreasing channel capacity, with no significant differences among flow modification categories (Figure 2b). This suggests that channel capacity trends do not respond in a simple way to anthropogenic streamflow modification and instead may result from local interactions between discharge and the net channel sediment mass balance and/or boundary roughness. Channel capacity effects tended to reduce flood hazard frequency in the Mississippi River Basin (through increasing channel capacity) and tended to increase flood hazard in the northwest (Figure 3b), suggesting that there may be regional imbalances between volumes of streamflow and sediment supplied to channels. The two components of channel capacity, i.e., changes in channel cross-sectional area and average flow velocity, contributed almost equally to channel capacity trends. On average, a 1% decrease in channel velocity or in flow area generated a 2% increase in flood hazard frequency. These findings suggest that shifts in sediment flux, grain size, and/or vegetation may have a substantial role in controlling flood hazard frequency, particularly in basins undergoing land use changes or in tectonically active regions.

We evaluated the interaction between channel capacity and flow frequency effects across our sites by comparing the direction of channel capacity and flow frequency effects on flood hazard frequency at each site. If channels adjust to increases in streamflow by widening, deepening, or reducing their roughness
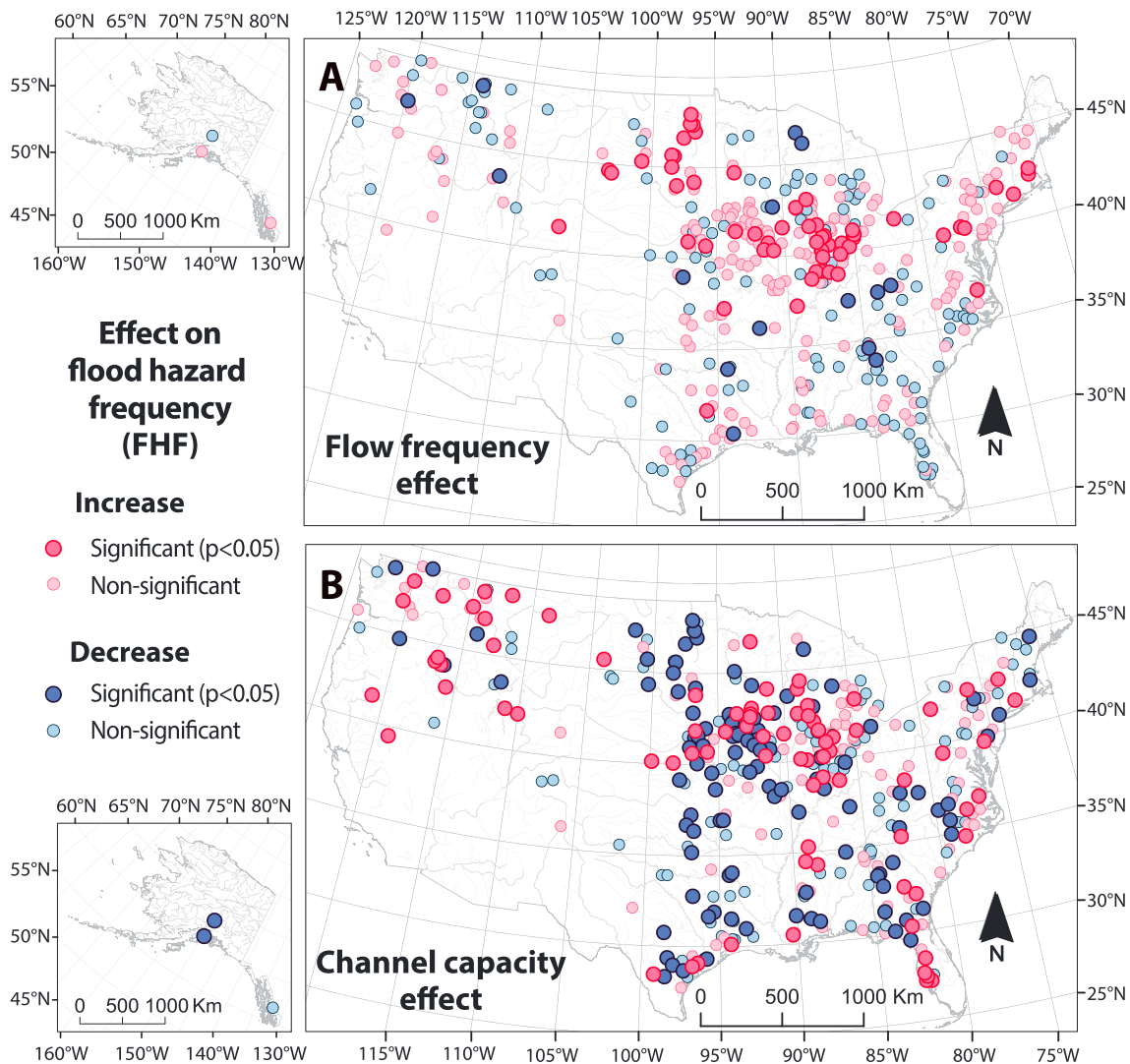
Figure 3. Spatial distributions of (a) flow frequency and (b) channel capacity effects on flood hazard frequency. Red symbols represent net increases in flood hazard frequency, and blue symbols represent net decreases in flood hazard frequency. Deeper colors indicate sites with statistically significant trends.

[*Lane*, 1955; *Griffiths*, 1983], channel capacity effects should tend to offset flow frequency effects on flood hazard frequency rather than reinforce them. Overall, channel capacity effects at least partially offset flow frequency trends at a small majority of sites (55%; Figure 4). This result suggests that in some cases, channel capacity effects may be important in attenuating the impacts of climate on flood frequency.

Finally, we computed the total change in flood hazard frequency as the sum of channel capacity and flow frequency effects, irrespective of significance levels, and found a statistically significant majority of sites with increasing flood hazard frequency (59% of sites, 235 versus 166, $p < 0.001$; Figure 4). Whether they contributed to increasing or decreasing flood hazard frequency, flow frequency effects again were larger than channel capacity effects at 69% of all sites, while channel capacity effects were larger than flow frequency effects at the other 31%. Therefore, although the total increase in flood hazard (from the sum of channel capacity and flow frequency effects) is primarily driven by flow frequency trends, channel capacity may also be a dominant influence on flood hazard trends in many locations.

Our findings demonstrate that nonstationarity in flood frequency is common and emerges as a result of interacting hydrologic and geomorphic effects. Trends in channel capacity are widespread, and they affect flood hazard on a scale that is broadly comparable to flow frequency trends, challenging existing paradigms of flood frequency analysis and channel design [*U.S. Water Resources Council*, 1981; *Biggert-Waters Flood*
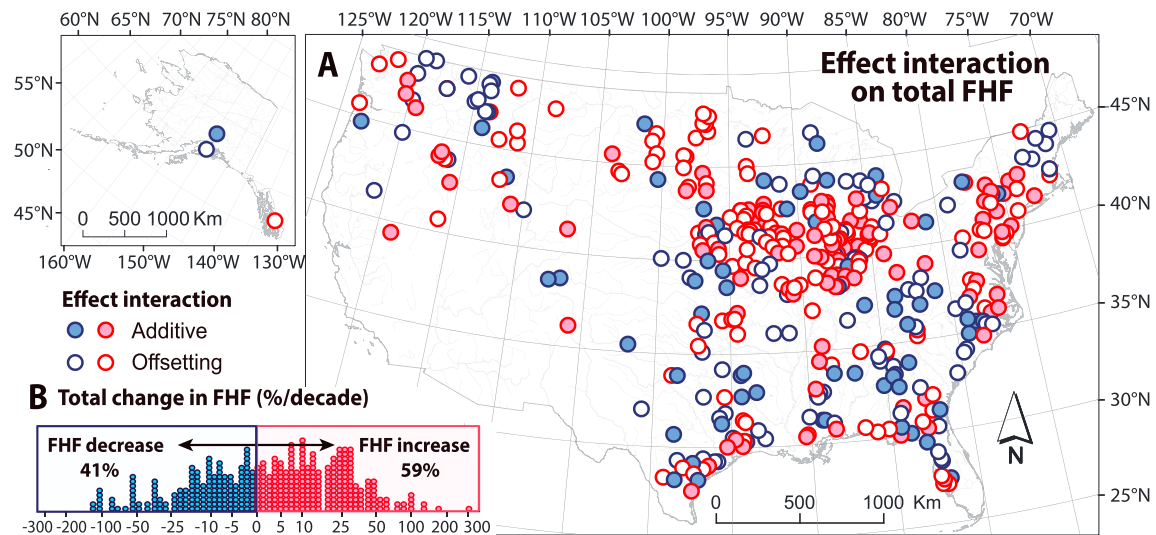
Figure 4. Interaction between flow frequency and channel capacity effects on flood hazard frequency. (a) The sites where flow frequency and channel capacity effects reinforce one another and offset one another are indicated by the filled and open circles, respectively. Red symbols represent net increases in flood hazard frequency, and blue symbols represent net decreases in flood hazard frequency. (b) Histogram of total change in flood hazard frequency using the same data transformation as in Figure 2.

Insurance Reform Act, 2012]. Thus, trends in flow frequency and channel capacity may have important, unanticipated effects on flood hazard frequency. In particular, in some cases, they may act synergistically to exacerbate the frequency, extent, and duration of flooding. These findings suggest that accurately predicting flood hazards, for either flood insurance or river management, requires quantifying future trends in both flow frequency and channel capacity.

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