

GEOLOGY

Coseismic river avulsion on surface rupturing faults: Assessing earthquake-induced flood hazard

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Surface-rupturing earthquakes can produce fault displacements that abruptly alter the established course of rivers. Several notable examples of fault rupture–induced river avulsions (FIRAs) have been documented, yet the factors influencing these phenomena have not been examined in detail. Here, we use a recent case study from New Zealand’s 2016 Kaikōura earthquake to model the coseismic avulsion of a major braided river subjected to ~7-m vertical and ~4-m horizontal offset. We demonstrate that the salient characteristics of the avulsion can be reproduced with high accuracy by running a simple two-dimensional hydrodynamic model on synthetic (pre-earthquake) and “real” (post-earthquake) deformed lidar datasets. With adequate hydraulic inputs, deterministic and probabilistic hazard models can be precompiled for fault–river intersections to improve multihazard planning. Flood hazard models that ignore present and potential future fault deformation may underestimate the extent, frequency, and severity of inundation following large earthquakes.

INTRODUCTION

Active tectonics and river morphodynamics are primary drivers of landscape evolution on 10^1 to 10^6 year time scales (1–7). On shorter time scales, deformation and strong ground motion during earthquakes modulate flood hazards and can cause disruptions to both surface and groundwater regimes (8–10). Instantaneous river avulsion can also occur in response to coseismic surface displacement on faults (2). A few notable instances of these fault rupture–induced river avulsions (FIRAs herein) have occurred throughout history (11–14) and are commonly interpreted to have occurred in fault-proximal paleoseismic records (15, 16). For example, the phenomenon happened on a large scale in the 1812 New Madrid earthquake, centered in the eastern United States, when surface deformation associated with the Reelfoot fault temporarily blocked and diverted flow of the Mississippi River and nearby tributaries, contributing to the formation of Reelfoot Lake (17–19). The 1819 $\geq$ moment magnitude (M_w) 7.5 Rann of Kutch earthquake in India produced a ~6-m high scarp called the Allah Bund or “Dam of God”. Retrograde tilting of the Allah Bund hanging wall dammed the Nara River, causing ponding and channel abandonment (20–22). The 1980 rupture of Algeria’s El Asnam thrust fault dammed the flow of the Cheliff and Fodda rivers, flooding ~30 km² of the surrounding area. Paleoseismic investigation suggests that coseismic flooding has occurred many times in the past (23). Despite these accounts, existing literature largely focuses on the long-term response of rivers to fault offset, and the tectonic, hydraulic, and geomorphological factors that interact to drive the rapid initiation of a FIRA event remain largely unknown. The effect of FIRA on flood hazard and risk is thus virtually unconstrained.

River avulsion is traditionally defined as the abrupt rerouting of flow from an established river channel into an enduring new course within the adjacent floodplain (24, 25). The term “avulsion” is also used synonymously to describe flow switching within river systems (i.e., between braid channels) or cutoffs within meandering river

systems (25). A full avulsion occurs when all flow is rerouted, whereas the term “partial avulsion” is applied when only part of the flow is redirected (24, 25). FIRA events are governed by many of the same dynamics driving natural river avulsions. Topography, land cover, and hydrologic conditions at the time of surface rupture are important variables, with increased rainfall, runoff, discharge, and ground saturation increasing the probability of avulsion threshold exceedance (9, 24, 25). The kinematics and orientation of surface fault rupture relative to river channel orientation play key roles in how the river will respond, as these variables interact directly with the morphology and stream power of the river system (2, 6). Vertical deformation on faults (e.g., from dip-slip motion) may produce barriers that impede flow within a river channel (Fig. 1A). Lateral tilting may produce down-tilt avulsion (2, 26), and lateral offset may introduce adjacent topographic barriers into the river system or facilitate stream capture (Fig. 1B) (7, 27). Topography surrounding a faulted river channel (i.e., levees, terraces, or antecedent structures), footwall subsidence, and downstream vertical throw may obstruct rivers and promote the formation of a local backwater upstream of the fault. Resultant increases in water surface elevation upstream of the fault may consequently promote overbank flow, wherein water is directed across the floodplain (5). The nature of any local topographic constriction (or lack thereof), surrounding vegetative cover, and the erosional resistance of the floodplain will contribute to whether fault-impounded river flow is able to effectively mobilize across the floodplain (24, 25). Coseismic ponds or lakes may form in settings that are not conducive to overbank flow (i.e., topographically constricted), and/or reoccupation of the parent channel may occur. Displacements within multi-channeled or meandering river systems may provide additional opportunities for FIRA to occur where a fault intersects with the river channel(s) numerous times (Fig. 1B). Avulsion flow typically seeks pathways with the most advantageous gradient or the least resistance to flow. In most settings, flow will naturally divert toward topographic lows such as local antecedent channels or paleochannels and/or may incise a path through erodible floodplain substrate (2, 9, 25, 28).

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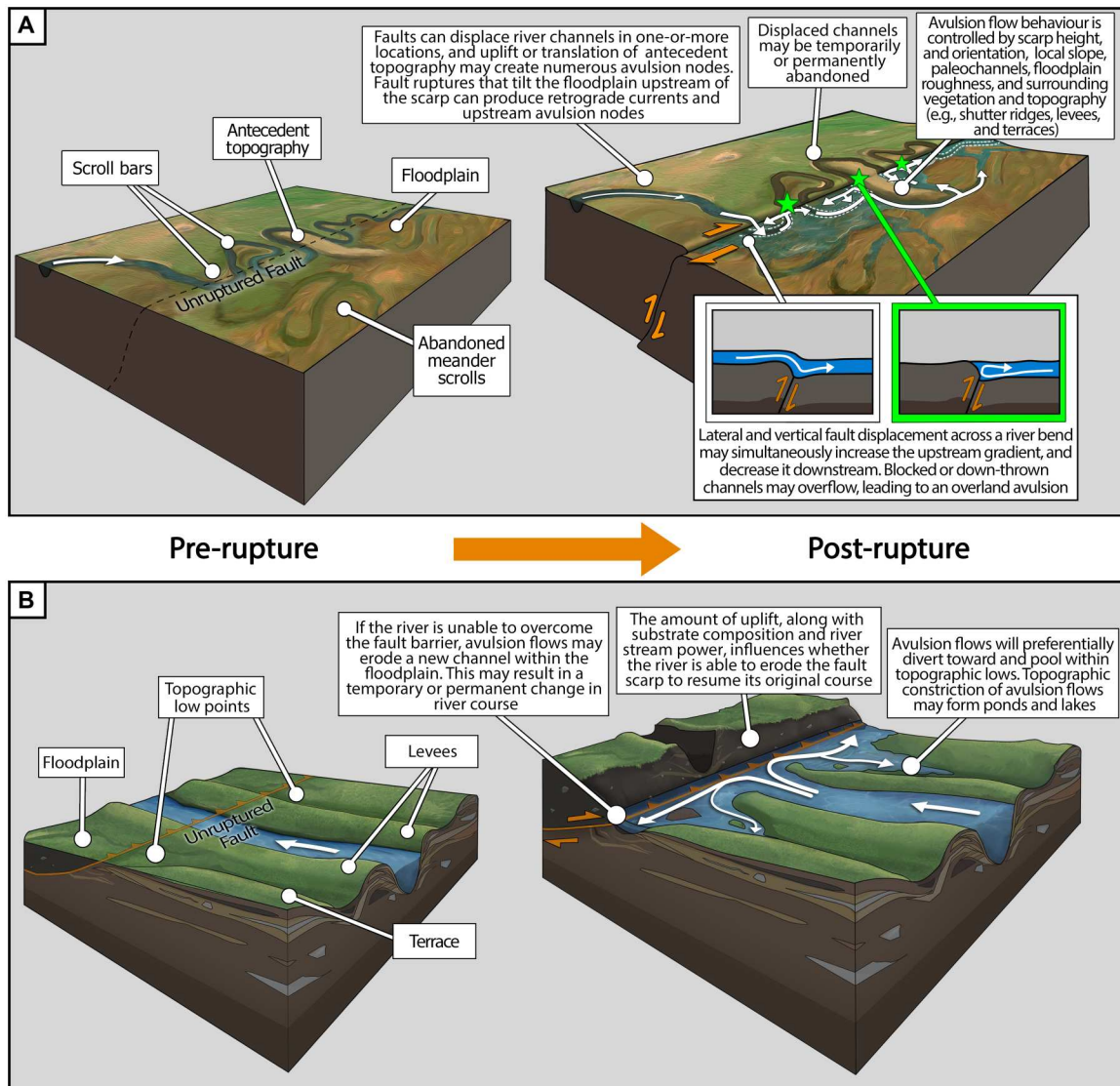


Fig. 1. FIRA scenario block diagrams. (A) Visualization of a complex FIRA scenario, where an oblique strike-slip fault truncates multiple bends of a meandering river system. White arrows indicate flow direction, green stars demarcate the main avulsion nodes, and dotted white lines outline the edges of the submerged river channel. An initial avulsion node is created within the western meander bend, where a FSB obstructs flow from entering the parent channel located on the down-stream side of the bend. Water pools against the fault scarp until the existing channel (dotted lines) overtops, resulting in an avulsion. If the fault truncates multiple bends, then multiple avulsion nodes may be created at each displaced bend (green stars). An avulsion analogous to this example is the 2010 Greendale fault rupture in Canterbury, New Zealand, where a single bend of the Hororata River and an active paleochannel of the neighboring Selwyn River were laterally and vertically offset, causing avulsion along the Greendale fault scarp (9, 12). (B) Visualization of how a dip-slip FSB may influence river flow behavior. White arrows indicate flow direction and orange arrows demarcate relative displacements on the fault.

In this study, we detail a recent FIRA case study in New Zealand and model the parameters that influenced the avulsion of a major braided river along a surface-rupturing fault during the 2016 M_w 7.8 Kaikōura earthquake (14). We demonstrate that the avulsion can be accurately reproduced using a two dimensional (2D) hydrodynamic model and a post-earthquake lidar digital elevation model (DEM). Furthermore, we show that potential FIRA events can be forecast with pre-earthquake paleoseismic, topographic, and hydrologic constraints. We highlight that surface-rupturing faults change flood hazards and risk and call for similar forecasts to be used to inform planning for possible future events.

Recent FIRA case studies in South Island, New Zealand

Two well-documented FIRA events occurred in 2010 and 2016 during surface rupturing earthquakes in New Zealand's South Island. In 2010, the Greendale fault surface rupture produced up to ~5 m of dextral displacement during the M_w 7.1 Darfield earthquake (29). Dextral-normal slip within a releasing bend segment of the fault produced ~1.5 m of vertical offset through a meander bend of the Hororata River, increasing the upstream gradient while simultaneously decreasing the gradient downstream of the fault. (12). Precipitation in the preceding days had saturated soils, and local rivers were in high flow conditions at the time of the

earthquake (9). Fault-generated gradient differences within the Hororata meander bend produced an avulsion directed along the hanging wall of the fault, flooding ~28 ha of farmland. Avulsion flow went on to exploit low-lying Selwyn River paleochannels situated along the fault, escaping to the footwall and resulting in an additional ~23 ha of flooding (9, 12).

A larger FIRA event occurred during the 2016 M_w 7.8 Kaikōura earthquake, during which >20 faults or fault segments ruptured throughout the north-eastern part of the South Island (30–32). The ~19-km-long Papatea fault ruptured at approximately 00:02 a.m. [New Zealand Standard Time (NZST)] near the center of the ~180-km-long surface rupture (Fig. 2A) (14). Oblique left-lateral reverse displacement produced some of the largest offsets recorded in the Kaikōura event (31, 33), with the Papatea fault scarp displacing the Waiau Toa/Clarence River in four locations in an area referred to as Priam's flat (Fig. 2B). Vertical separation measured ~6.5 m near the northernmost fault scarp barrier (FSB herein); however, these values increased to the south, reaching ~9.0 m near the Wharekiri Fan (14, 34). The avulsion occurred when river flow encountered the northernmost FSB just south of Glen Alton Bridge, causing flow to partially avulse along the fault scarp (Fig. 2C). Diverted flow traversed farmland for ~1.7 km on the footwall side of the fault before re-entering the main braid plain via a small subsidiary braid channel. Avulsion flow continued south to pool against a secondary FSB near Corner Hill. Trapped floodwater deepened to form Lake Murray, which inundated ~34 ha of land and persisted for ~7 to 10 months. Maxar satellite imagery on Google Earth confirms avulsion flow overtopped the Corner Hill FSB and re-entered the main Waiau Toa/Clarence River channel on the day of the fault rupture, with avulsion flow then progressing past a coseismic knickpoint at the toe of the Wharekiri Fan (14, 35).

Creating a FIRA hydrodynamic model

Excellent pre- and post-event data covering the Papatea fault rupture and associated avulsion provided an opportunity to analyze FIRA variables in more detail. Landscape change was captured through multitemporal lidar and allowed us to measure high-resolution near-field displacements (33, 34). River discharge of $187 \text{ m}^3 \text{ s}^{-1}$ was recorded by an Environment Canterbury gauge attached to Glen Alton Bridge (Fig. 2), providing detailed flow data up until 1 hour before fault rupture. Detailed fault mapping and paleoseismology constrain the range of displacements and kinematics on the Papatea fault (14, 32, 34). We developed a 2D fixed-bed hydrodynamic model capable of simulating flow and fault displacements in the immediate aftermath of the event (i.e., before earthquake-modulated sediment transport). The goal was to reproduce the Waiau Toa/Clarence River FIRA using post-event lidar with the natural Papatea fault scarp (referred to as the benchmark model) to confirm that the real-world observed avulsion flow paths and flood extents could be accurately simulated. A pre-event (2012) DEM was then modified with a synthetic fault scarp using Papatea fault displacement vectors (referred to as the calibration model) to determine whether the same post-event hydrology could have been predicted before the earthquake. A range of synthetic scarp displacement and river flow regimes were then modeled using pre-event lidar to produce 25 additional model runs (hereafter referred to as the scenario models), which could have been used to assess FIRA hazard before the earthquake. Model accuracy was assessed by comparing modeled inundation

extent to satellite and aerial imagery from the day of the event (Materials and Methods).

Some simplifying assumptions were made with regard to tectonic and hydraulic inputs. DEMs modified with a synthetic scarp do not incorporate far-field or off-fault deformation (e.g., from an elastic dislocation model), and displacement is not varied along the fault scarp. While not critical in our case study due to the temporal and spatial scales being considered, real faults are often more complex than we model, and the Papatea fault is a good example of how fault geometry and displacements may vary considerably along their length. We also do not incorporate infiltration or sediment dynamics in our models. These are key components when modeling natural river systems, particularly those affected by coseismic landsliding; however, the time frame of interest for this study is restricted to examining the minutes to hours following an initial fault rupture. Thus, these factors are unlikely to play key roles in flow diversion within such a narrow time window.

There are a few limitations to this approach and how it may be applied elsewhere. First, prior knowledge of fault geometry, kinematics, and location is required to simulate rupture scenarios. The floodplain DEM and imagery immediately preceding and following fault surface rupture may not be representative of actual conditions. For instance, the Papatea fault ruptured around midnight, whereas the aerial imagery that we used to classify a raster of "wet" cells was obtained many hours later in daylight—infiltration of avulsion flow into the underlying alluvial floodplain almost certainly occurred in the intervening hours. In addition, the post-event (2016) lidar DEM was obtained over a month following fault rupture, when avulsion flow had already scoured a small channel along the fault scarp, and pre-event lidar is from ~4 years before the event. When combined, these factors influence our estimates of accuracy. Models run with more up-to-date DEMs will be more accurate than those modeled using legacy data. Lidar-derived DEMs also do not typically contain bathymetry, and river surfaces in our models were represented as flat surfaces at elevations analogous to river level at the time the lidar was collected. We consider it unlikely that bathymetry will alter the spatial behavior of a modeled FIRA in this particular setting. Floodplain elevation near the upstream avulsion node is substantially elevated above the water surface level of the Waiau Toa/Clarence River, making floodplain topography (for which we have good constraint) of more concern than channel bathymetry. In addition, the parent channel is topographically constricted to the west and north-east by steep, elevated banks and mountainous topography, meaning overbank flow is most likely to be routed to the lower-lying alluvial plains found to south-east of the avulsion node. Nevertheless, bathymetry may have some influence on the timing, depths, and thresholds of avulsions, and multiband lidar that can simultaneously resolve shallow bathymetry and land surface elevations would be an improvement in future models.

RESULTS

Comparison between benchmark and synthetic scarp scenario models

After model initialization, the post-event benchmark model generated a rapid partial avulsion of the Waiau Toa/Clarence River (Fig. 3A). Flow partially diverts along the fault scarp and over farmland while simultaneously entering the parent channel. Diverted

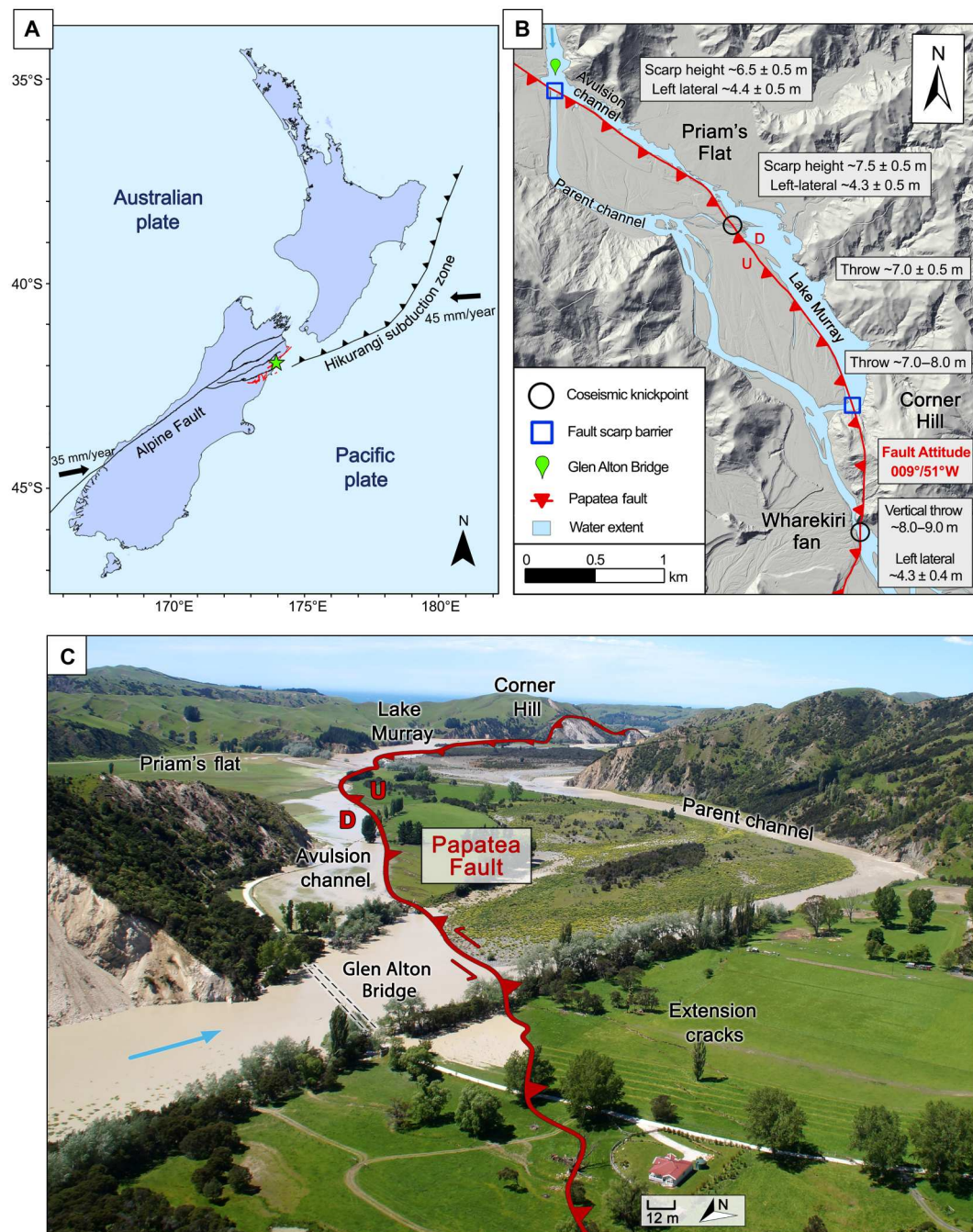


Fig. 2. Tectonic Setting of the Papatea fault rupture. (A) New Zealand tectonic setting. Red lines represent fault ruptures in the 2016 Kaikōura earthquake, with a green star marking the Papatea fault location (B) The Waiau Toa/Clarence River valley setting following the 2016 Papatea fault rupture. Aerial imagery taken 1 day following the fault rupture was used to constrain the general avulsion extent. The main geomorphic markers (i.e., Glen Alton Bridge and notable topographic or floodplain features) and fault displacement vectors are labeled, as per observations and data collected in the field (14). (C) Aerial imagery taken 1 day following the Papatea fault rupture showing the extent of the FIRA event. Image taken and provided by Environment Canterbury.

flow directed along the downthrown side of the fault formed Lake Murray (Figs. 2 and 3) before lastly passing the location of the southernmost FSB to re-enter the parent river channel west of Corner Hill. The benchmark model achieved $\sim 94\%$ accuracy, and adjusting for floodplain bias (Materials and Methods), it achieved $\sim 78\%$ accuracy (Fig. 3B).

The calibration model (i.e., based on the pre-event DEM and synthetic fault scarp) generated a similar flood extent to the benchmark model (Fig. 3C). Water initially pools against the northernmost FSB, generating a temporary backwater. A partial avulsion initiates, and diverted flow is directed along the fault scarp until impeded for a second time by the Corner Hill FSB. Lake Murray

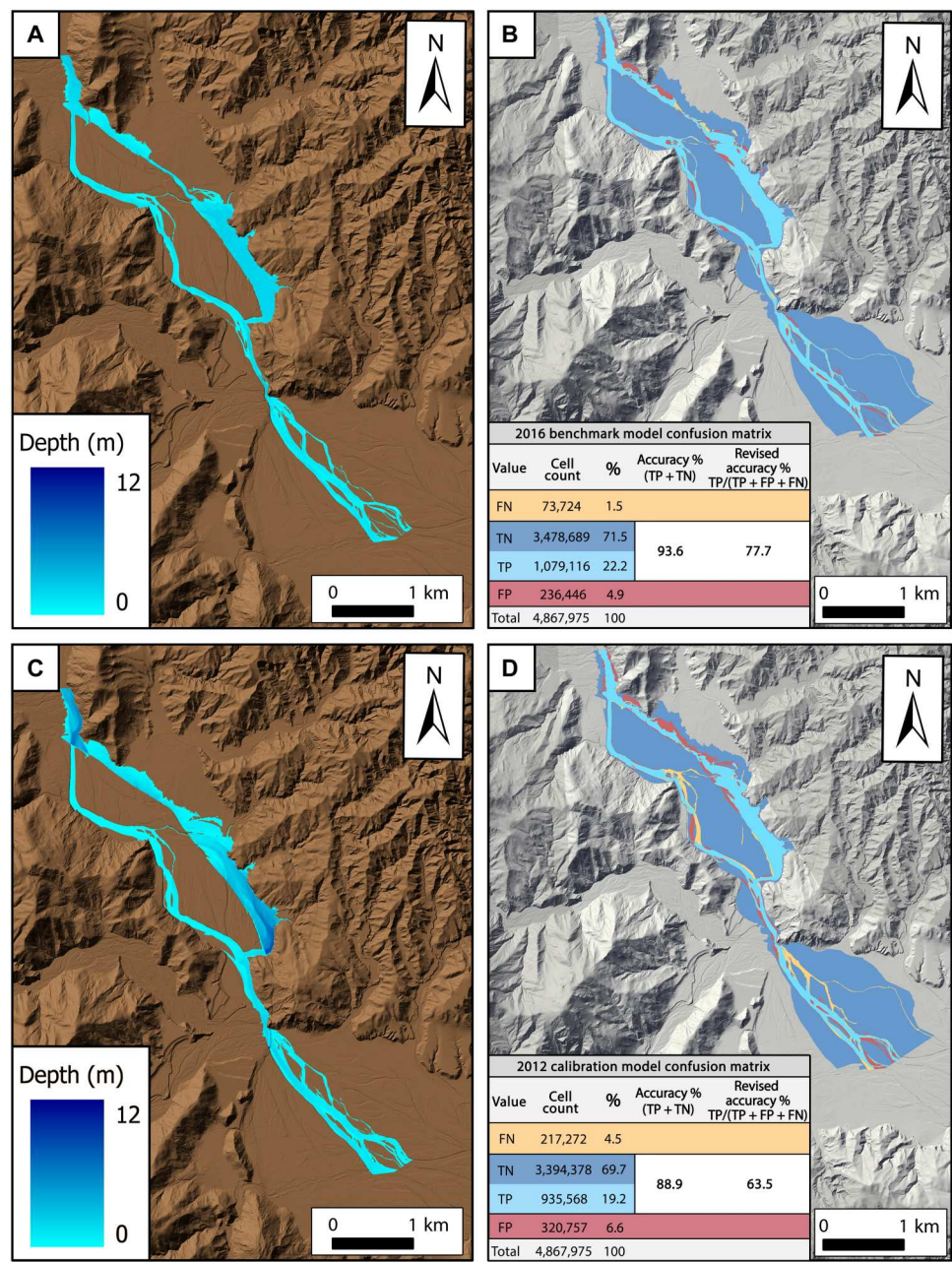


Fig. 3. HEC-RAS benchmark and calibration model accuracy assessment. (A) Benchmark HEC-RAS model results using lidar acquired within 2 months of the 2016 Papatea fault rupture. The flow regime is run as a forced steady-state plan over a period of 12 hours using event flow conditions of $187\text{ m}^3\text{ s}^{-1}$. (B) Accuracy assessment of the benchmark model when applying a contingency table confusion matrix approach. True-positive (TP) and true-negative (TN) values reflect areas where the model and classified aerial imagery agree that cells are wet (true positive) or dry (true negative) to provide an initial estimate of model accuracy, while false-positive (FP) and false-negative (FN) values reflect areas where the model results and classified aerial imagery do not align. The floodplain boundary is demarcated on the basis of the river valley geomorphology and generates many values in the “true-negative” category, creating a (floodplain) bias toward higher accuracy scores within the model. The true floodplain extent is inherently uncertain; therefore, revised accuracy scores address uncertainty within the model using the $F(1)$ equation (see Materials and Methods), which equitably address both underprediction or overprediction within the model (59). (C) Calibration model results when an identical flow regime is applied to a pre-event (2012) DEM modified with a synthetic fault scarp reflective of Papatea fault displacement. (D) Contingency table accuracy assessment results for the calibration model.

forms as avulsion flow back-pools, and the water surface rises before floodwater overcomes the FSB to merge back into the parent Waiau Toa/Clarence River channel. The calibration model yielded a spatial accuracy of ~89% with an adjusted spatial accuracy of 63.5% (Fig. 3D). Lower spatial accuracy relative to the benchmark can be partially explained by natural river channel changes within the valley between 2012 and 2016, and the development of additional braid bars south of Corner Hill following the 2016 Papatea fault rupture (35), which is not present in the 2012 DEM. More overland flow was observed in the calibration model, which may relate to infiltration in the hours after the event, and thus a loss of accuracy when compared to imagery taken many hours later. By comparison, the benchmark model is less affected because lidar collection occurred at a time when a shallow channel had already begun to incise along portions of the fault scarp.

Behavioral and water depth differences between the benchmark and calibration model can be attributed to the absence of fault scarp barriers in the 2016 DEM. A National Institute of Water and Atmospheric research (NIWA) river survey completed in late December 2016 obtained several water depth profiles across channel localities near Glen Alton Bridge (fig. S1). Comparison of modeled water depths to these data confirms that the calibration model water depths are more indicative of real-world conditions than those in the benchmark model (fig. S2).

Assessing flood hazard from FIRA

Because the calibration model yielded reasonable accuracies compared to the benchmark model and observed data, we considered whether FIRA hazard in our reach could have been characterized before the 2016 event with some constraints on fault displacement and flow regimes. Five deformed pre-earthquake DEMs (Table 1) were combined with a five flow regimes, producing 25 scenario models. The results can be partitioned into four categories, ranging from little impact on river behavior through to complete avulsion of all Waiau Toa/Clarence River flow (Fig. 4). Of the 25 modeled scenarios, the lowest displacement and flow scenario was the only model to produce negligible change to the pre-event hydrology other than a minor scarp-parallel increase in water depth.

Table 1. Synthetic fault scarp displacement parameters. Values used to create the synthetic fault scarp modifications to the pre-event (2012) DEM. Values are derived from a vertical-to-horizontal (V:H) ratio of 1.4:1, and are broadly applicable to the Priam’s flat section of the Papatea fault (14), and checked against a static value of rake. *Italicized* throw and horizontal displacement values are the most representative of real-world displacement vectors measured near the northernmost fault scarp barrier (14). **Bold** values are broadly representative of the fault parameters along the northernmost 5 km of the Papatea fault (34).

Synscarp fault parameters				
Vertical throw (m)	Horizontal displacement (m)	Rake (°)	Dip (°)	Dip direction (°)
1	0.7			
3.5	2.5			
5	3.6	64	76	229
6.5	4.6			
7.8	3.9			

Nine scenarios resulted in back-pooling, and water elevation increases near FSB localities without avulsion. Partial avulsions occurred in nine other scenarios, wherein flow routes both into the existing channel, and overland along the fault scarp. Seven scenarios resulted in a full avulsion along the fault scarp, with complete abandonment of the parent channel (Fig. 5).

Scenario models with ~1.0 m of vertical throw fail to produce avulsions at any discharge. Increasing the vertical throw to 3.5 m results in noticeable pooling upstream of the FSB, and the activation of local anabranching channels within the braid plain as discharge values increase. Flow regimes exceeding 400 m³ s⁻¹ overwhelm all local channels, triggering partial avulsions. Increasing fault offset progressively reduces the flow rate required to trigger an avulsion. For example, ~5.0 m of vertical displacement causes avulsion when combined with a flow regime similar to that of November 2016. At maximum displacement, full avulsion occurs at every tested flow value except the highest. The scenario models indicate that had displacement on the Papatea fault been ~1.3 m higher in 2016, a full avulsion of the Waiau Toa/Clarence River would have occurred even in mean annual flood conditions.

DISCUSSION
Applications to hazard analysis and planning

The concept of an avulsion threshold proposes that increasing instability within a river system primes it for an avulsion. In a primed state, rivers at or near this threshold are more sensitive to avulsion-triggering events (24). Every reach has a unique avulsion threshold, yet FIRA modeling provides a powerful tool to constrain the fault offset and flow conditions that would trigger an avulsion. Given steady flow conditions and unchanging sediment dynamics, Waiau Toa/Clarence River FIRA scenario modeling (Fig. 5) shows the lowest displacement scenario of ~1.0-m vertical and ~ 0.7-m lateral failing to generate a FIRA event at any tested discharge. As fault throw increases, the discharge required to trigger an avulsion event decreases until ~6.5 m of vertical offset results in an avulsion at any discharge. Fault offset is thus the primary independent factor driving avulsion behavior, and without seismic surface displacement, avulsions do not occur at any modeled discharge. Nevertheless, flow regime is an important variable that influences the threshold for avulsions. At lower throw values (3.5 to 5.0 m), no avulsion occurs in annual low or mean annual flow regimes. Increasing the discharge from mean annual flow to flood conditions triggers partial avulsions even when throw is held constant. This observation implies that, although FIRA may not occur at the time of the earthquake, faulting may instead prime the system for an avulsion at higher discharge (24). Floods are the most common trigger of river avulsion (24, 25), and the relationship between the fault displacement and discharge has important implications when considering flood hazards in other locations. FIRA events are capable of producing both rapid and delayed alterations to the flow and flood patterns within affected rivers. Populations near fault-river intersections need to be aware that rivers can change course instantaneously following large earthquakes or in the days or weeks following when flow conditions are sufficient to trigger a delayed avulsion.

Active faults intersect rivers at >26,000 known locations worldwide (Fig. 6). (36, 37). All plate boundary margins on land therefore host possible FIRA sites, although some of the most notable historical examples have occurred in intracontinental settings (e.g., New

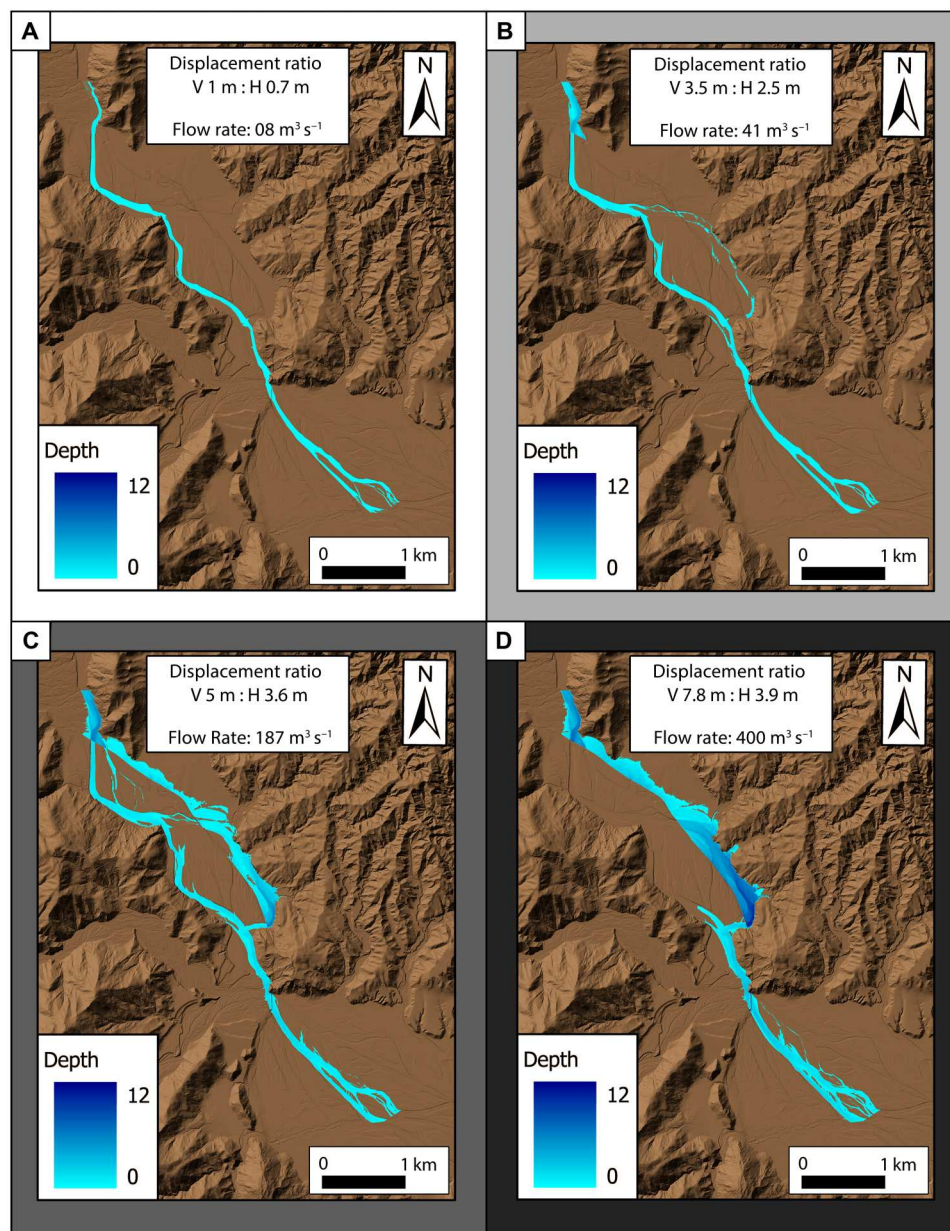


Fig. 4. HEC-RAS scenario modeling categories. Twenty-five scenarios were modeled by combining five displacement regimes and five flow regimes. Results of the scenario models can be broadly partitioned into four main categories. (A; white) Little change in river behavior or morphology other than negligible water depth increases near the fault. (B; light gray) Mild to moderate changes in river behavior, with water depth values increasing near FSB localities as water begins to pool against the scarp and form a local backwater. Local antecedent anabranching braid channels are activated as flow values increase; however, no avulsion of flow occurs outside of the established braid plain. (C; dark gray) A partial avulsion of flow occurs, wherein some flow escapes from the main braid plain to flow along the fault scarp. Flow obstruction near FSB locations drives water depth increases as an extensive backwater forms upstream of the fault. (D; black) River flow is fully obstructed by the fault scarp, causing a full avulsion, accompanied by large water depth increases upstream of the FSB.

Madrid and Rann of Kutch earthquake examples above). Roughly 10% of global active fault-river intersections are located in New Zealand, where floods are one of the most common and costly natural hazards, and where ~675,500 of the resident population occupies flood hazard zones (38–40). Across most of the country and many regions globally, climate change is expected to increase the frequency and intensity of extreme rainfall events (39, 41–43). There is considerable uncertainty around how these changes will

alter the magnitude of future flooding events; however, extreme rainfall is the primary driver of flooding within New Zealand, and increases in extreme rainfall events in some regions may result in more frequent floods (39). Global flood risk is also likely to alter, with one climate change model predicting that global flood risk may increase by ~187% by 2050. The frequency of 100-year floods is expected to roughly double across ~40% of the globe, affecting ~450 million people living in flood-prone areas (43). The

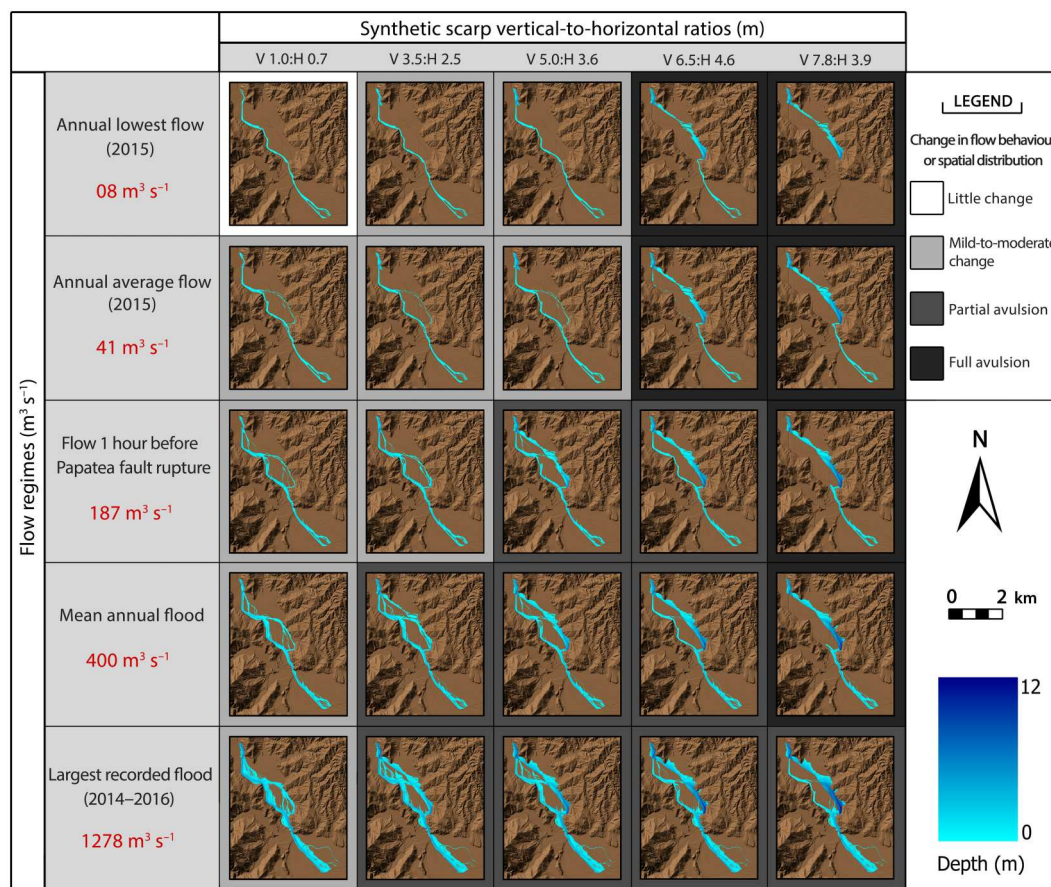


Fig. 5. Waiau Toa/Clarence River HEC-RAS scenario model results. Twenty-five Waiau Toa/Clarence River FIRA scenario models were produced in HEC-RAS using a pre-event (2012) DEM modified to reflect five different displacement values. Hanging-wall vertical uplift and lateral translation is determined by the vertical-to-horizontal (V:H) ratios listed at the top of each column. The five displaced DEM's were combined with five individual flow regimes (found to the left of each row) to assess the interactions between variable offset scenarios and flow rates. Flow values were calculated using Glen Alton Bridge gauge data provided by Environment Canterbury, providing flow rate measurements from early 2014 to 1 hour before the 2016 Kaikōura earthquake (fig. S4). The exception is the mean annual flood (MAF) value, which was instead calculated during previous flood modeling work within the Waiau Toa/Clarence River valley (35). Results are partitioned into four main categories (white, gray, and black colored frames; see Fig. 4 for full descriptions).

likelihood of fault ruptures occurring within flooded river systems may thus be heightened in some regions of the world.

Although FIRA events represent a relatively small compounding factor to background flood hazard, they come with potentially disastrous consequences. Given the near instantaneous change in boundary conditions caused by fault deformation, land not previously considered to be flood prone can be inundated in the seconds, minutes, and hours following fault surface rupture. At a high level, FIRA risk may be greatest near tectonically active range fronts and adjacent basins, such as in the Himalayan foreland, where access to water resources and arable land drive development and sustain large populations (44, 45). If large single-event slip on fault(s) were to destabilize flood protection measures or divert flow from established courses via paleochannels (e.g., Fig. 1), the impacts on adjacent settlements and critical infrastructure immediately following earthquakes could be extreme. Even so, stable continental regions must not be excluded when considering FIRA hazard. Historical case studies demonstrate that large displacements are possible even within the low-relief, tectonically quiescent settings characteristic

of stable continental regions and can therefore disrupt the course of low-gradient rivers (8).

Our modeling approach provides a means to assess FIRA hazard within a semi-deterministic framework. The well-constrained physics of this problem in terms of river hydraulics and fault rupture behavior means that possible FIRA events can be characterized before future earthquakes and so can be used to guide flood hazard management and land-use planning. Single-event displacements and fault kinematics can be measured from site investigations and paleoseismic trenches. Flow regimes can be measured directly or calculated using established probabilistic methods (46, 47). Even in its current form, which ignores the longer time scale complications of post-earthquake sediment dynamics, this modeling approach allows planners to define avoidance zones or implement mitigation measures that could reduce exposure of people and property to "likely" or "maximum credible" FIRAs in their immediate aftermath. It is crucial that improved flood risk assessment be undertaken in areas vulnerable to seismic deformation and that up-to-date tectonic, hydraulic, and topographic data be used to inform

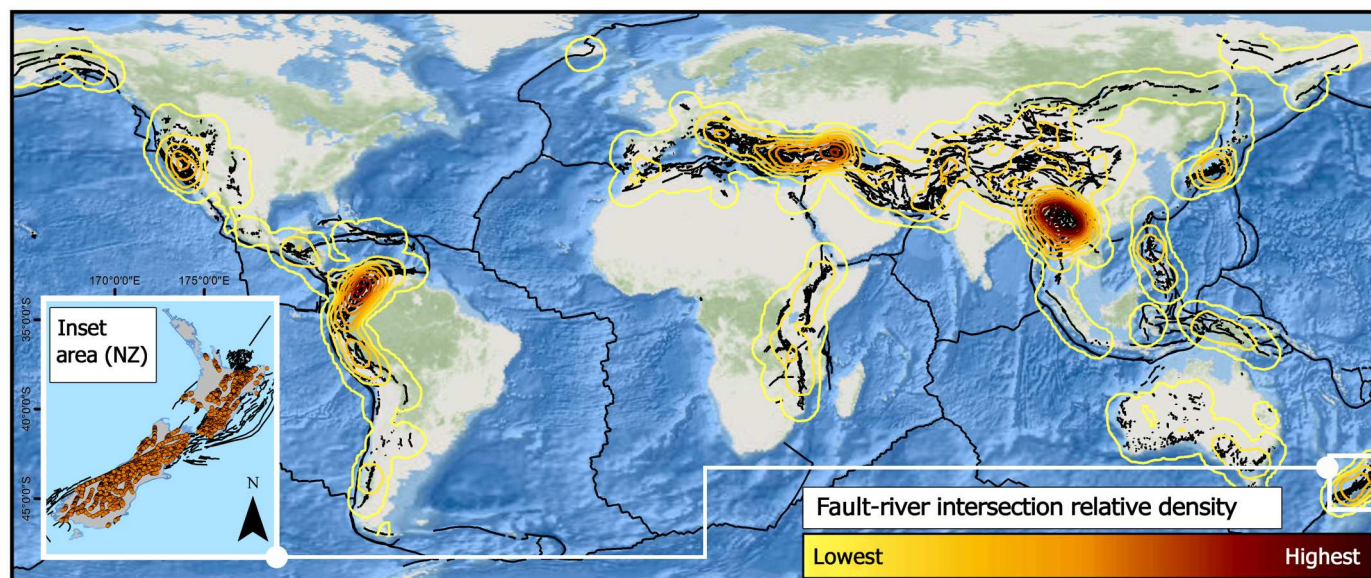


Fig. 6. Relative density of global fault-river intersections. Contours reflect the density of points where active faults from the GEM Global Active Faults Database [black lines; (37)] intersect rivers (36) within a tolerance of 30 m. While not all fault-river intersections are capable of producing FIRA, the map shows that they are ubiquitous across plate boundaries and many stable continental regions. Intersections are particularly abundant in convergent plate settings, where rivers facilitate the transport of eroded material from actively uplifting, and in many cases, fault-bounded mountains. In New Zealand alone (inset), there are >2000 fault-river intersections (orange dots).

probabilistic models combining fault displacement hazard analysis with flood hazard and risk models.

Insights from our site-specific scenario models could help inform regional FIRA hazard assessment or identify sites for more detailed investigation. Regional assessments are complicated by event- and site-specific factors such as (i) antecedent topography and fault orientation controls the routing of flood waters over the landscape and thus whether flow will dechannelize or spillover into the post-quake channel (48) (ii) variability of fault kinematics between avulsion events, (iii) actual location of surface rupture relative to mapped fault traces (49), (iv) continuous reworking of floodplains and migration of channels since the last survey date, and (v) precise flow conditions at the time of rupture. It would nonetheless be informative to consider the physical variables influencing relative hazard to identify and prioritize sites for more detailed investigation and modeling.

The potential for overbank flow and dechannelization upstream of an FSB, and thus relative FIRA hazard, is dependent on the characteristics of the backwater that forms after faulting. Higher backwater surface elevations over a longer reach maximize the potential for overbank flow and eventual avulsion (5). A prior study on retrogradational avulsions using sediment transport models and observations of natural avulsions demonstrated that dechannelization is dependent on backwater evolution upstream of a channel blockage. Whether a particular reach avulses or “heals” in response to a sediment blockage is determined by the slope of the reach, the discharge, and the ratio of the blockage height to bankfull normal flow depth of the channel (5).

At its simplest, the potential for overbank flow (F) at an FSB is a function of the throw (T), discharge-dependent normal depth (D_Q ; see Supplementary Text for further information on how D_Q was established), and bankfull normal depth (D_N ; herein defined as the

mean annual flood depth)

$$F = \frac{T + D_Q}{D_N} \quad (1)$$

$F > 1$ will result in the water surface exceeding the bank elevations at the FSB. When T is large, even small normal flow depths (for a given discharge) may spill overbank, and when $T = 0$, normal flow depths at or above mean annual flood levels will also result in overbank flow.

To investigate the relationship of these variables at our site (Fig. 5), we plotted F versus discharge for the 25 scenario models presented in Fig. 5. In general, the propensity for avulsion and abandonment of the pre-quake channel increases with increasing F (Fig. 7). Partial and full avulsions are associated with $F > 2$ in the Waiau Toa/Clarence River reach (Fig. 7). Greater discharges appear to sustain flow in the pre-quake channel at increasing values of F , leading to a higher threshold for full avulsion at the largest discharges considered. More data are needed to fully describe this trade off, yet it is consistent with work previously done on retrogradational avulsions, wherein higher discharges result in reduced backwater height relative to flow depth, consequently reducing overbank flow (5).

In reaches of equal slope, F may serve as a reasonable first-order indicator of relative FIRA hazard. If throw is known (e.g., paleoseismic investigations), and D_Q can be measured at reference discharges, then F can be estimated and compared to values from other reaches. The specific threshold of ~ 2 for our reach is likely site specific and unlikely to hold in other locations but may nonetheless serve as a useful reference.

In practice, more work will be required to operationalize this approach to regional hazard assessment. Although using F is appropriate for our site and represents the 1D geometry with the most potential to restrict flow, it assumes an upstream-facing fault

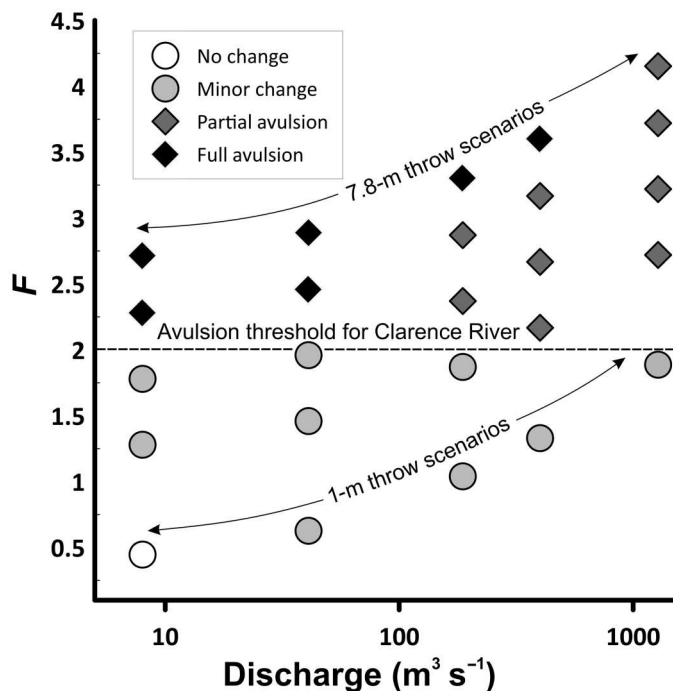


Fig. 7. Plot comparing the potential for overbank flow (F) versus discharge for the 25 Waiau Toa | Clarence river scenario models. In general, the likelihood of avulsion and parent channel abandonment rises with increasing F (Eq. 1). In reaches of equal slope, F may be a good indicator of relative FIRA hazard. Partial and full avulsions are associated with $F > 2$ in the Waiau Toa/Clarence River reach. Higher discharges seemingly sustain some flow in the pre-quake parent channel at increasing values of F , elevating the threshold at which a full avulsion occurs. This effect may be related to the backwater surface elevation increasing relative to flow depth in these scenarios, thus raising the water surface elevation to a point where flow can access the displaced pre-event parent channel (5).

scarp with primarily vertical displacement. Scarps that form oblique or parallel to a channel may require a 2D approach. In addition, we only consider fault throw because the amount of lateral offset on the Papatea fault is negligible compared to the width of the braid plain. In narrow channels with large lateral offsets, an “effective throw” or cross-sectional area change should be considered. Critically, our analysis is limited to one reach and therefore cannot account for the influence of slope in determining relative hazard. Changing slope will influence the distance over which a backwater gets established, and the relationship we present here will need to be adjusted to incorporate varying slope. Physics-based modeling following the approaches used to model retrogradational avulsions (5) could address this gap but would need to account for immobile (over short time scales) fault scarp-shaped obstructions in the channel. Last, observations from natural fault-river intersections immediately following surface-rupturing earthquakes are required to test the robustness of F (Fig. 7) in determining relative FIRA hazard.

Future model refinement and applications

Our models focus on the relationship between fault displacement and instantaneous flooding and therefore disregard sediment dynamics. That is, our models are applicable strictly in the minutes to hours following a fault rupture, when sediment dynamics are unlikely to contribute to avulsion. Future investigations into FIRA

events may wish to examine river and fault displacement interactions across longer time frames, which would require consideration of evolving floodplain topography and channel migration and/or bed aggradation. In catchments where coseismic landslide debris is connected to channels, the availability of additional sediment must be taken into account and may confound these models. As noted previously, bathymetric data would improve model precision and are required to accurately model sediment dynamics. The destruction of the Glen Alton Bridge gauge following the Papatea fault rupture took with it the ability to constrain river behavior in the hours following the earthquake. The lack of reliable post-quake flow data led us to enforce a steady flow regime, where the discharge remains fixed throughout the modeled period. This approach could have influenced overland flow predictions within the benchmark and calibration models but proved useful for scenario modeling when attempting to quantify whether a FIRA event would initiate in the minutes to hours following fault offset. Future iterations of this model may instead utilize an unsteady flow regime, wherein flow varies with time based on hydrograph inputs. This approach would allow for an analysis of how flood waves may influence avulsions over fault-displaced landscapes and would almost certainly influence the patterns of wetting and drying within the model.

Implications for landscape evolution and neotectonics

FIRA events offer a snapshot of how tectonic and fluvial processes interact on short time scales. Some of the most notable and well-studied faulted landscapes on Earth host displaced or beheaded channels, offset terraces, and fault-bounded wetlands (7, 11, 15, 16, 50). These depositional environments are important for understanding seismic hazard and fault behavior. For example, the ~8000-year on-fault paleoseismic record for the plate-bounding Alpine fault in New Zealand relies on a schematic model of sedimentation due to intermittent ponding along a scarp (16, 51). In this model, the fault scarp dam contributes to the formation of a “tectonic hydrosere”—a wetland environment consisting of couplets of swamp and fluvial sediments deposited during different stages of the seismic cycle. Geochronology of these sediments yields the average recurrence of surface-rupturing earthquakes, informing both time-independent and time-dependent seismic hazard (52). Similar depositional models are used in paleoseismic investigations in a range of settings, including sag ponds and intermittent streams on strike-slip systems (e.g., San Andreas fault) (53) and deflected drainages along normal faults (e.g., Wasatch fault) (54).

It is worth questioning how paleoseismic records in these environments could change if sense of slip, single-event displacement, or discharge varies over time. The evolution of fault-bounded wetlands in single events, and thus their utility in paleoseismic record keeping, depends on nonstatic variables such as flow and/or variable fault kinematics and displacements [e.g., (55)]. For example, our scenario models demonstrate that it is possible for hydrological changes and associated post-seismic deposition to occur long after fault rupture, when discharge is sufficient to cause an avulsion—thus skewing the timing of earthquakes interpreted from the stratigraphic record toward artificially younger ages. The spatial extent and longevity of flooding will vary between events. Over time and subjected to erosion and deposition, geological archives might miss some of the detail that recent case studies capture. FIRA models may thus provide a pathway toward improving

interpretations of paleoseismic records and understanding how earthquakes contribute to landscape evolution over short time scales (56). For any site, a range of offset and flow regimes could be modeled to determine (i) the flow regime at which natural over-bank flooding occurs; (ii) the minimum offset and discharge values that allow the stream to maintain a consistent course, with no substantial avulsions occurring; and (iii) the offset values that cause impoundment of stream flow, wherein the development of a fault-proximal wetland and clastic sedimentation is most likely to occur.

Rivers and faults interact on a range of time scales. We demonstrate that the spatial extent of coseismic river avulsion and flooding due to surface faulting are reliably reproduced using a hydrodynamic model. In addition, with up-to-date high-resolution topography, coseismic flood hazard scenarios can be characterized before earthquakes using synthetic deformation constrained by paleoseismology and some knowledge of river flow regimes. The success of these models in reproducing the observed avulsion behavior is important because the concepts are applicable to other regions. While fault rupture-induced avulsions are potentially destructive coseismic hazards, this work highlights the fact that the associated flood extents are predictable and thus mitigable. Synthetic displacement and flow models may also be useful for evaluating the fidelity of fault-proximal paleoseismic records that rely on schematic relationships between fault offset and stream discharge. The results therefore detail the interplay between tectonic and fluvial processes with single-event resolution that is commonly lost in prehistoric events.

MATERIALS AND METHODS

Synthetic fault scarps are generated within a selected DEM based on an input fault trace, single-event displacement, average fault rake, dip, and average dip direction. We apply constant horizontal and vertical shifts—defined by the dip direction, rake, dip, and magnitude of slip—to every raster cell on the hanging wall side of the fault. This shift results in a vertical scarp in the DEM, which we deem sufficient for our modeling despite differing from observed 2016 scarp morphologies. Ordinarily, we might expect to apply an overall shift to the whole of the resulting deformed DEM to account for the relative motions of the footwall and hanging wall. However, on the Papatea fault, almost all of the absolute coseismic displacements were in the hanging wall, so we applied no overall shift.

The U.S. Army Corps of Engineers Hydrologic Engineering Centre's River Analysis System (HEC-RAS) was used to produce a 2D hydraulic model in which flow behavior was modeled across a period of 12 hours. Diffusion-wave equations were selected to solve for flow moving across a computational mesh draped atop the DEM, allowing the program to calculate water surface elevation for each individual cell. We used a hydro-processed 1-m DEM compiled from lidar acquired in late December 2016 to early January 2017 (57) to represent the post-event landscape in the benchmark model. The pre-event calibration model used a 1-m DEM (lidar acquired in 2012) modified with a synthetic fault scarp. Manning's n roughness coefficients were spatially allocated using a Land Resource Information Systems land cover layer (fig. S3), with values set in line with hydraulic modeling recommendations provided by the Christchurch City Council (58) and previous flood modeling work conducted in the area (35). Weather events within upper catchments caused high flow conditions within the Waiau Toa/

Clarence River in the days preceding the earthquake (35). Gauge data suggest that the flow was slowly declining in the hours preceding the fault rupture (fig. S4), with the last recorded Glen Alton Bridge measurement of $187 \text{ m}^3 \text{ s}^{-1}$ taken at 2300 hours (~1 hour before the earthquake). This was considered to be the closest approximation to event conditions at the time of fault rupture. A steady-state flow regime was enforced to examine the FIRA event in specific flow conditions and as it occurred in the minutes to hours following fault rupture. Were the model to be used to examine flow behavior across longer time scales, an unsteady approach using observed river discharge or a design hydrograph would likely be more appropriate.

Identical benchmark model parameters were used to assess a series of scenario models. "Static" fault parameters were allocated on the basis of values derived for the northernmost 5 km of the main Papatea fault strand (34); however, due to notable variability in dip along the fault, a dip value more representative of the dip values within Priam's Flat (Fig. 2) was selected (Table 1). We varied single-event displacement and flow regimes in the scenario models based on a range of geologically reasonable and previously reported values. Five single-event displacement values (Table 1) were used to create five unique DEMs used as the basis for hydraulic scenario models in HEC-RAS. Rake values were set using a vertical-to-horizontal ratio calculated from fault measurements taken within Priam's flat (14), giving a ratio of ~1:1.4. The exception is the highest value tested, which was taken from average values for the northernmost 5-km section of the main strand (34). Displacements were selected on the basis of the wide range of reported single event displacement values (SEDs) for the fault in trench and geomorphic studies (14, 34).

Five flow scenarios were modeled using Glen Alton Bridge gauge data (fig. S4). Recorded values span from 2014 to 2016, with annual lowest and mean annual flow conditions (8 and $41 \text{ m}^3 \text{ s}^{-1}$, respectively) allocated based on the only complete year of recording (2015). Gauge data values were used to set two additional flow scenarios, being conditions ~1 hour before the event ($187 \text{ m}^3 \text{ s}^{-1}$), and the largest recorded flood event ($1278 \text{ m}^3 \text{ s}^{-1}$) to occur throughout the entire 2014–2016 period. Mean annual flood conditions were set to $400 \text{ m}^3 \text{ s}^{-1}$ as per Waiau Toa/Clarence River flood modeling work completed in 2019 (35).

Accuracy assessment

The spatial accuracies of the benchmark and calibration models with properties matching those of the Kaikōura earthquake were assessed using contingency tables. Contingency tables compare the number of pixels that the model correctly or incorrectly predicts to be wet or dry (59) when compared against a raster of wet cells within classified aerial imagery taken the day of the event

$$PC = \frac{TP + TN}{TP + TN + FP + FN} \quad (2)$$

where PC is the spatial accuracy or "predicted correct"; TP and TN are true positives and true negatives, respectively; and FP and FN are false positives and false negatives, respectively (59). We also report a more conservative estimate of spatial accuracy accounting for floodplain bias, wherein many of the true-negative values (i.e., most of the floodplain) are unlikely to be wet. This approach compensates for over- and underprediction in both deterministic

and uncertain calibrations

$$F(1) = \frac{TP}{TP + FP + FN} \quad (3)$$

where $F(1)$ is the adjusted spatial accuracy (59).

Supplementary Materials

This PDF file includes:

Figs. S1 to S4

Supplementary Text

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Coseismic river avulsion on surface rupturing faults: Assessing earthquake-induced flood hazard

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