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Geomorphic response of a mountain gravel-bed river to an extreme flood in Aberdeenshire, Scotland

Abbreviated Title: Geomorphic response of severe flooding on the River Dee

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This study uses the 2015 ‘Storm Frank’ flood on the River Dee, Aberdeenshire, to assess the impact of extreme events on river dynamics. The Storm Frank flood caused significant local morphological change that was concentrated in the middle portion of the 140 km long river and overall net degradation that primarily occurred through lateral adjustment processes. Although the flood did not cause widespread change in channel planform, bank scour resulted in channel expansion and lateral migration as well as widespread aggradation on existing gravel beds. The HEC-RAS and CAESAR-Lisflood models were used to determine the impact of morphological changes from the Storm Frank flood on a series of future hypothetical floods. The results show that inundation is highly influenced by the degree of morphological change for moderate floods, but not for high magnitude ones. In-channel scour and bank erosion can lead to an increase in channel capacity, thereby decreasing inundation. Conversely, where conveyance capacity is decreased by aggradation, flood risk inherently increases. The impact of these changes was great for a 5-year return period flood, but minimal for a flood of magnitude comparable to Storm Frank’s. Our modelling results also reveal the inundation model is sensitive to the grain size and channel bed roughness input parameters, as these parameters impact flow discharge and flood hydraulics. Accurate determination of sediment parameters and degree of morphological change is therefore critical in flooding modelling and flood hazard management.

Supplementary material: Table 1 - Peak discharge and rainfall during the 2015 Storm Frank storm at each gauge station on the River Dee. Table 2 - parameters used in the hydrological model CAESAR-Lisflood. Table 3 – Sediment budget statistics of each DEM of difference threshold.

Floods, and in particular extreme floods, are significant geomorphic events that influence the form and dynamics of rivers (Attal, 2017; Baynes *et al.*, 2015; Bennett *et al.*, 2014; Turowski *et al.*, 2009; Yager *et al.*, 2012). The role that sediment plays in influencing the behaviour of rivers during extreme flood events is a key control on flood risk. For example, Turowski, *et al.* (2013) document two distinct sediment-related behaviours that occur during floods of different magnitudes, depending on the relationship between sediment supply and transport capacity. Under a ‘flood-depositing’ condition, large magnitude floods supply more sediment than can be transported, leading to aggradation. Conversely, sediment supply is smaller than the transport capacity and sediment is progressively being evacuated during small, high-frequency events. In a ‘flood-cleaning’ scenario, aggradation occurs during small, high-frequency floods, while the transport capacity exceeds the sediment supply in large magnitudes floods. In this scenario, sediment slowly aggrades over time, creating an ‘alluvial overprint’ from low-magnitude, high frequency events, until an extreme event flushes the sediment

down reach. These two types of behaviours have the potential to influence future inundation extent due to the changes in bed height and channel geometry leading to changes in water conveyance capacity (Stover & Montgomery, 2001; Korup *et al.*, 2004; Lane *et al.*, 2007).

Recent research has highlighted the significance of channel geometry on flood risk through field observations and conceptual and numerical models (Stover & Montgomery, 2001; Pinter & Heine, 2005; Lane *et al.*, 2007; Neuhold *et al.*, 2009; Carling *et al.*, 2013; Slater *et al.*, 2015 Guan *et al.*, 2016). Lane *et al.* (2007) emphasise the importance of sediment delivery and in-channel sedimentation on flood risk mapping. Based on surveys of the Upper Wharfe (Yorkshire), they demonstrate that over a 16 month period of measured in-channel sedimentation, a 1 in 0.5 year flood cause about half of the increase in inundation extent that was simulated to arise from (40 years of) climate change. However, local-scale changes in the channel form and sediment characteristics (such as grain size distribution and, in turn, hydraulic roughness) resulting from an extreme flood have somewhat gone unexplored in relation to flood risk. Changes in grain size and roughness following an extreme flood can significantly affect flow velocity and stage, influencing conveyance capacity and bed morphology (Nicholas, 2003; Staines & Carrivick, 2015; Guan *et al.*, 2015).

Many studies propose that morphological changes from extreme flooding are key in influencing local inundation and future flood risk (e.g., Stover & Montgomery, 2001; Pinter and Heine, 2005; Lane *et al.*, 2008), yet these factors are seldom included in hydrological models. To test how flood-induced morphological changes influence the severity of subsequent flood events, a case study of the geomorphic changes that occurred in the River Dee (Aberdeenshire, UK) following the 30th December 2015 ‘Storm Frank’ flood is conducted. A combination of field based and terrain analyses is used to investigate the geomorphic response of the River Dee to the severe flood. To test how changes in bed elevation and grain size from the flood influence the flow hydraulics of a subsequent flood event, a combination of two hydrological models are used.

The three research questions this paper asks are:

- 1) What are the controlling factors on sediment flux along the River Dee?
- 2) What geomorphic changes occurred during the Storm Frank flood?
- 3) How do the channel geometry changes influence inundation of future floods?

1. Study Area

1.1 Catchment description

The River Dee, Aberdeenshire, Scotland (Figure 1), rises on the plateau of Braeriach in Cairngorm Mountains at a height of approximately 1,200 meters, the highest source of any major river in the British Isles (Cooksley, 2007). The river flows 140 km eastwards to the North Sea at Aberdeen and drains a catchment area of approximately 2,100 km². Land use ranges from heather moorland and woodlands in the upper reaches, to agriculture and grasslands in the lower reaches.

The River Dee is a classic example of a highland mixed bedrock-alluvial river; it is relatively unmodified with no major hydro schemes, although its banks have been engineered in places for fishery purposes and flood defence in the lower reaches. The underlying bedrock comprises resistant metasedimentary and igneous rocks formed during the Grampian and Caledonian orogenies between ~1000 and 420 Ma (Hall, 1991; Gordon *et al.*, 2006; Barron *et al.*, 2011). The channel is characterised by straight, meandering and braided patterns with large active lateral and mid-channel gravel bars. The glacial deposits that were left from the last glacial maximum now provide source material for reworking by the river (Maizels, 1985), with glaciofluvial sand and gravel deposits forming ridges, mounds and terraces in the valley.

1.2 Storm Frank flood

The winter of 2015 was an exceptionally stormy month for the UK with December 2015 being the wettest month on the historical record (Met Office, 2003). Due to the persistent rainfall in early December, soils became over-saturated and river flows across the UK increased, with record flows observed in many northern catchments of the UK (Barker *et al.*, 2016; Soulsby *et al.*, 2017). Of the three named storms in December 2015, ‘Storm Frank’ on the 29th and 30th was particularly severe in northeast Scotland. As a result of torrential rainfall on saturated soils in the mountainous upper catchment (Soulsby *et al.*, 2017), the River Dee exceeded the previously recorded maximum flood discharge recorded in 1937 (Marsh *et al.*, 2016). A mean of 70 mm of rain was recorded throughout the catchment during the storm, with over 100 mm falling in the headwaters. A peak discharge of approximately 1360 m³/s was recorded on December 30th, 2015 (Figure 2; Supplementary material Table 1) at the SEPA Woodend gauging station (Figure 4). This peak flow had an estimated return period of over 200 years, or an annual exceedance probability of less than 0.5% (Marsh *et al.*, 2016). Although comparison is uncertain, the Storm Frank flood event is likely to have been the largest since the 4th August 1829 ‘Muckle Spate’ flood which had a similar estimated annual recurrence interval (NERC, 1975).

The storm resulted in considerable flooding of and damage to property. In the town of Ballater alone, over 200 homes were flooded and farmland was extensively damaged through bank erosion and the deposition of overbank gravel deposits. Between Braemar and Ballater, a section of the A93 main trunk road by Abergeldie Castle was eroded away and road bridges were damaged throughout the valley.

2. Methodology

Our evaluation of the impact of the Storm Frank flood on the dynamics of the River Dee uses a combination of datasets obtained through fieldwork, topographic analysis, and hydrodynamic modelling. The controls on sediment entrainment in the fluvial network was determined through fieldwork and by utilising the hydrological model HEC-RAS (Section 2.1). Topographic analysis combined with field observations were used to characterise the geomorphic response of the river to the extreme flood event (Section 2.2). To test how changes from the Storm Frank flood could potentially affect subsequent flood flows and extents, hydrodynamic modelling of a series of flood events was conducted using HEC-RAS and CAESAR-Lisflood (Section 2.3). Two models are used for this study as a means of validation: comparing the outcomes of a 1D flow model (HEC-RAS) with that of a more comprehensive 2D hydraulic flow and landscape evolution model (CAESAR-Lisflood) allows us to assess the sensitivity of flood extent to the modelling platform used. This is crucial, as many organisations use simple 1D flow models such as HEC-RAS for flood risk mapping.

We explore the impact of Storm Frank on the flood extent of subsequent floods in two scenarios: a flood of similar magnitude as Storm Frank’s (return period > 200 years) and a higher probability, five-year return interval flood (Figure 3). The latter will have a lower impact than the extreme flood in terms of extent and morphological change, but it will happen more often, making it as relevant for planning. The analysis focused on the river between the Linn of Dee and the suburb of Peterculter, Aberdeen (Figure 1).

2.1 Sediment entrainment

At any point along the river, the shear stress combined with the sediment supply of a given flood govern erosion and deposition on the bed (Montgomery & Buffington, 1997). Shear stress increases with channel gradient and depth and decreases as channel width increases. This analysis focused on whether the discharges generated by the Storm Frank flood were capable of entraining the median grain size (D_{50}) of the sediment exposed on gravel bars. This percentile is of particular interest as the motion of grains of this size is expected to result in significant modification of the channel bed (Jansen, 2006).

Shields (1936) introduced a dimensionless parameter that defined the relationship between the fluid's forces and the gravitational forces keeping a grain of a specific size immobile:

$$\tau_{D_{50}}^* = \frac{\tau_b}{(\rho_s - \rho)gD_{50}} \quad (1)$$

where $\tau_{D_{50}}^*$ is the dimensionless shear stress for the specified grain size D_{50} , τ_b is the boundary shear stress (in Pascal), ρ_s is the sediment density ($\sim 2650 \text{ kg/m}^3$ for crustal rocks), and ρ is the fluid density (1000 kg/m^3 for water). When the flow overcomes the forces keeping the grain in place, the grain starts moving: the dimensionless shear stress at the point of incipient motion is known as the critical Shields stress (τ_c^*). A number of critical Shields stress values have been reported, which typically range from 0.03 to 0.06 for gravel-bed rivers (Buffington & Montgomery, 1999); the central value of 0.045 was chosen as the threshold for entrainment for this study.

2.1.1 Bar sediment surveys

The surface grain size distribution of exposed bars was measured by placing a 50 m fibreglass measuring tape lengthwise along the gravel bar, with each pebble measured at 50 cm intervals (Kellerhals & Bray, 1971; Attal *et al.*, 2015). The intermediate (*b*-axis) was measured to the closest millimetre. This method is advantageous in mountainous streams that transport coarse material (cobble to boulder size) and was found to provide an adequate representation of the sediment grain size at the reach scale (Wolman, 1954; Sloan *et al.*, 2001; Van den Berg & Schlunegger, 2012; Bekaddour *et al.*, 2013). Wolman (1954) found that sampling the intermediate axis of 100 clasts was sufficient in providing a reliable median grain size value, but authors have argued that higher stone counts are needed to accurately characterise the tails of the distribution (e.g., 16th and 84th percentiles) (Rice & Church, 1996).

21 gravel bar sites from the Lui confluence to Aberdeen were sampled, yielding a total of 2,100 grain measurements. The values of the D_{50} (median grain size) and D_{84} (84th percentile) were estimated from the combined measurements at each field site. This study assumes the pre- and post-storm grain size distribution are comparable, as there is no pre-flood grain size data for the whole river. It is likely however; the Storm Frank flood may have affected sediment grain size; we will explore this possibility with one of our modelling scenarios using CAESAR-Lisflood.

2.2 Morphological change analysis

The morphological response to the Storm Frank flood was quantified utilising the DEM of Difference (DoD) technique. This approach is a key tool for detecting fluvial morphological change and determining sediment budgets (e.g. Brasington *et al.*, 2003; Fuller *et al.*, 2003; Wheaton *et al.*, 2010; Williams *et al.*, 2011). A DoD is the result of subtracting the elevations of an older DEM from the elevations of a newer DEM on a cell by cell basis. The older, 'pre-flood' dataset in this study is primarily based on an aerial lidar survey undertaken in March 2011 with a 1 m resolution. The newer 'post-storm' lidar flyover was undertaken in April 2016 and has a spatial resolution of 0.25 m that was resampled to a 1 m resolution. The negative elevation changes represent areas of erosion (surface lowering), while positive changes indicate deposition (surface raising). An estimate of the net sediment budget of the river was calculated by totalling the volume of erosion and deposition that occurred over the specified time period.

To account for the uncertainty of the source DEMs in the detected elevation changes, we follow the probabilistic approach described by Wheaton *et al.* (2010). A threshold for detection U_{crit} (m) is used to quantify the uncertainty of the DoD by defining a confidence interval such that:

$$U_{crit} = t \sqrt{SDE_{new}^2 + SDE_{old}^2} \quad (2)$$

where SDE_{new} (m) and SDE_{old} (m) are the standard deviations of error of the new and old DEMs, and t is the chosen confidence interval (Brasington *et al.*, 2003; Lane, Westaway and Hicks, 2003; Wheaton *et al.*, 2010). Confidence intervals of 100%, 70%, and 50% were applied, yielding detection thresholds of 10, 30, and 50 cm respectively. Changes detected below the given threshold of detection were disregarded in the analysis.

It is important to consider that (1) the lidar does not penetrate deep into water and (2) the two lidar datasets were not collected immediately before and after Storm Frank. The wetted channel bed topography in the DEM is thus not accurate, creating a large uncertainty in the resulting DoDs and sediment budget. However, as the lidar was captured at times of comparable low discharge, any large elevation change detected is considered a reliable indicator of change. The time between the two lidar datasets were captured (from 2011 to 2016) also creates an uncertainty in the detection of direct geomorphological changes; the sediment budget represents a five-year budget rather than exclusively from the Storm Frank flood. During those years, the only significant flood occurred in August 2014 ('Ex-Hurricane Bertha') with a peak discharge of 665 m/s² at Woodend (half of Storm Frank's). This flood may have caused morphological changes. However, we will consider that most large elevation changes are the results of the Storm Frank flood, due to its exceptional magnitude. Some signatures of the flood were also erased through bank engineering and the removal of overbank sediment deposits before the 2016 lidar survey. Aerial photos of the river from between 2010 and 2015 (0.25 m resolution) were analysed and compared to the 2011 DEM. The comparison shows very little geomorphic change between the time the first lidar data were captured and Storm Frank. Aerial photographs at 0.1 m resolution acquired concurrently with the 2016 lidar survey were also compared with 2015 aerial photos to validate the geomorphic changes from the Storm Frank flood as detected in the DoD.

2.3 Hydrodynamic modelling: flood extent and sediment mobility

2.3.1 HEC-RAS

The impact of the extreme flood event on subsequent flood risk was initially evaluated using a simple steady state one-dimensional hydraulic model, the Hydrological Engineering Center's River Analysis System (HEC-RAS). The HEC-RAS steady flow model is based on the one-dimensional energy equation where the total energy at any given location along the river is equivalent to the sum of the potential and kinetic energies and losses through friction (Hydrologic Engineering Center, 2018). We refer the reader to Brunner (2016) for the full numerical equations for one-dimensional water surface profile calculations. HEC-RAS is a widely used steady flow model that has been successfully applied in river basins similar to this study (Bekaddour *et al.*, 2013; Jansen, 2006; S. N. Lane *et al.*, 2007; Miller & Cluer, 1998).

Three sets of data are required for the HEC-RAS steady flow model: 1) channel geometry data, 2) basin characteristics, and 3) flow data. Geometric data and basin characteristics were extracted using the HEC-GeoRAS tool extension in ESRI's ArcMap (Ackerman, 2009). Detailed water surface profiles were extracted from a series of cross-sections using a standard GIS environment on the pre-storm 2011 lidar, from the Linn of Dee to Aberdeen at 150 m intervals. To represent variability of hydraulic roughness, each land use theme (i.e. river, woodlands, grassland, and heather) was given a Manning's roughness coefficient based on Chow (1959) and Phillips and Tadayan (2006).

The discharges for the Storm Frank flood were initially modelled on the older 2011 'pre-storm' DEM to simulate the peak inundation extent of the flood (Run 1A; Figure 3). A subsequent flood with the same discharge was then modelled on the more recent 2016 'post-storm' DEM (Run 2A; Figure 3). The two simulated floods were then compared to determine how the channel geometry changes impact inundation of a subsequent extreme flood of similar magnitude.

The boundary shear stress τ_b (refer to Section 2.1) for the Storm Frank flood was computed for each extracted cross-section and given a grain size value from the closest sampled bar site. The Shields stress exerted on the channel bed for the D_{50} at each site was then calculated using Equation 1. At any location along the river where $\tau_{D_{50}}^*$ exceeds 0.045, sediment transport is inferred, and channel erosion is expected. Conversely, if $\tau_{D_{50}}^*$ is less than 0.045, sediment is considered immobile and deposition is predicted on the channel bed.

2.3.2 CAESAR-Lisflood

CAESAR-Lisflood (Coulthard *et al.*, 2013) is a landscape evolution model (LEM) that combines the hydraulic flow model Lisflood-FP (Bates *et al.*, 2010) and the CAESAR geomorphological model (Coulthard *et al.*, 2002; Van De Wiel *et al.*, 2007) for the simulation of erosion and deposition in drainage basins over a range of timescales. The more comprehensive two-dimensional landscape evolution model CAESAR-Lisflood is used in this study for its capability of modelling sediment transport of multiple grain sizes at regional scales. The CAESAR model is able to model landscape evolution by shifting water and sediment across topography according to fluvial erosional and depositional processes and slope processes. The integration of the CAESAR and Lisflood-FP models allows the flow algorithm to be completely based on the Lisflood-FP flow model while incorporating the sediment transport equations used in CAESAR. The improved CAESAR-Lisflood model has been proven to be highly performant in landscape evolution modelling, sediment transport of multiple grain sizes, and fluvial erosion and deposition processes (e.g. Howard *et al.*, 2016; Lim *et al.*, 2016; Hancock *et al.*, 2017). Further details on the model computations are given in Coulthard *et al.* 2013.

As with HEC-RAS, the Storm Frank flood was initially modelled on the older 2011 ‘pre-storm’ DEM (Run 1B) and the 2016 ‘post-storm’ DEM (Run 1C) (Figure 3). The five-year recurrence interval flood was then modelled on the ‘pre-storm’ DEM (Run 2B) and ‘post-storm’ DEM (Run 2C) (Figure 3) to examine if changes related to Storm Frank affect flood risk of higher probability flows.

As the lidar pulse cannot penetrate water, flood-induced changes within the wetted perimeter which may influence subsequent inundation are not captured in Runs 1C and 2C. CAESAR-Lisflood can be used to predict channel bed changes that may have occurred during the flood and complement the DoD results (Run 1B). The Wilcock & Crowe (2003) sediment transport law was chosen for calculating fluvial deposition and erosion, as their formula was considered more appropriate for the wide range of grain sizes measured in the field. For the model, eight bedload grain sizes and their proportions according to the Wentworth (1922) class scale were used in the model and distributed evenly across the modelled reach. Each sediment size at the bar survey sites was classified as boulder, cobble, gravel, etc., and the average size of each class was input into the model. (See Supplementary material, Table 2, for full list of model parameters).

The outputs CAESAR-Lisflood generate are the water level at each given time step, an updated elevation raster based on simulated bed erosion and deposition, and the reach distribution of D_{50} in the top layer from the modelled flood. As an alternative to the 2016 ‘post-storm’ DEM, the new simulated elevation raster of the channel was used to determine how changes in the channel bed influence a subsequent flood (Run 2D; Figure 3). The predicted erosional and depositional changes of the model were compared with the original DoD for validating the channel changes and sediment budget output by CAESAR-Lisflood.

2.3.4 Variations in channel roughness

Although the discharge and channel geometry are key controls on inundation extent and depth, a less explored control is roughness variability due to grain size differences. Studies have demonstrated the significance of Manning’s roughness (n) on bed morphology and peak flow in hydrological modelling (Nicholas, 2003; Carrivick, 2007; Stains and Carrivick, 2015). Changes to roughness factors

following an extreme flood event may influence water velocity and in turn, conveyance capacity and stage. To test this hypothesis and the model's sensitivity to such parameters, the resulting D_{50} surface layer derived from the CAESAR-Lisflood output of the Storm Frank flood (Run 3D; Figure 3) was used to determine the spatial variation in channel roughness (Strickler, 1923):

$$n = 0.047D_{50}^{\frac{1}{6}} \quad (3)$$

The model with the forecasted variation in bed roughness was then compared to the CAESAR-Lisflood run with a constant channel bed Manning's roughness coefficient (Run 2C). This experiment explores how a grain size and roughness change from an extreme flood could influence a subsequent flood event and future flood hazards. The difference in the flood models is used to determine how sensitive the model output is to grain size and roughness parameters, therefore allowing assessment of whether grain size changes need to be considered to make reliable flood inundation predictions.

3 Results and Discussion

3.1 Downstream evolution of sediment grain size

The substrate material is was found to be sub-rounded to rounded, suggesting either a relatively long distance of transport or recycling of already (at least partly) rounded material. The presence of rounded material close to the headwaters and the widespread exposure of glacial sediment (e.g., till) across the catchment suggest a strong recycling component. A wide range of particle sizes was found on the 21 gravel bars (Figure 4). The largest D_{84} and D_{50} were both found at the Deecastle site (D12) with the smallest at Braemar Castle (D4). The largest grain size value of 1200 mm was measured downstream at Upper Blackhall (D16), where large boulders have been sourced from the adjacent hillslope. From the source, the D_{50} fines rapidly downstream to Braemar with an abrupt coarsening near Ballater, then there is a weak downstream fining trend towards the river's outlet. Similar patterns are seen in the D_{84} : there is no discernible trend overall, though there is a slight downstream fining to Braemar, and again a weak downstream fining trend towards the outlet.

Due to the absence of a clear downstream trend, variations in sediment mobility and river behaviour will likely be driven by changes in stream power, associated mostly with changes in channel gradient. In the steeper reaches, high shear stress and stream power will most likely lead to bed erosion paired with lateral bank erosion (although limited by bedrock), as a high probability for transport will be expected. On the contrary, flatter reaches will be dominated by bank erosion and channel migration due to sediment armouring and often greater sensitivity of banks and floodplains. A bed with a highly armoured layer may be more resistant to bed erosion, and bank scour will likely be the response during high flow events rather than bed degradation. These hypotheses are tested in section 3.3.

3.2 Geomorphic response to the Storm Frank flood

In common with other studies, the geomorphic responses on the River Dee were spatially variable in both magnitude and style (e.g. Sholtes et al., 2018; Thompson & Croke, 2013). The most notable locations that exhibited channel planform change or extreme elevation changes (e.g. more than 1 m) are identified in Figure 5. The reaches that exhibited the greatest morphological changes are 1) between Inverey and Braemar, 2) between Abergeldie Castle and Kincardine O'Neil, and 3) at Drumoak. Dominant morphological changes primarily occurred through lateral adjustment where scoured and filled banks resulted in channel expansion and lateral migration. Major deposition can be seen on gravel bars, as well as on the floodplain where high water levels led to the deposition of overbank sediment (Figure 6).

Despite the magnitude of the flood and large amount of damage to infrastructure, the only significant changes in planform developed locally where the river altered its course due to the excess gravel deposits and bank erosion, as can be seen in Figure 6. Over the entire study area, changes are detected

in 29% (10 cm threshold DoD) to only 2% (50 cm threshold DoD) of the channel and floodplain (Supplementary material, Table 3), with nearly 60-70% of the total volume eroded having been redeposited within the study area (Figure 7) suggesting the river is relatively stable. Despite variation in the absolute volumes of deposition and erosion, the total net volume difference is negative in each threshold and the patterns of erosion and deposition remain similar. The total net volume difference of about -602,200 m³ to -349,550 m³ (Figure 7) may represent sediment that was exported out of the estuary at Aberdeen. However, it is important to consider the limitations of the DoD, as part of the excess volume may have gone undetected on the channel bed (due to the lidar's inability to penetrate water), or may have not been captured due to the minimal level of detection (e.g., thin layers of gravel and sand deposited on the floodplain). Although the budget appears erosional, the DoD approach does not allow changes within the wetted portion of the active channel to be assessed, limiting our ability to determine whether the different sections of the river are 'flood-cleaning' or 'flood-depositing'. Nonetheless, this simple approach gives a reliable visual and quantitative assessment of the major morphological changes that occurred above water level (banks, bars and floodplain) during the Storm Frank flood.

As the DoD does not accurately capture bed elevation changes, a modelled 'post-storm' DEM was reconstructed with CAESAR-Lisflood and compared to the DoD (Figure 8) to assess the model's capability in predicting sediment transport, and re-create potential in-channel changes. The general trend of the modelled channel changes is highlighted by channel bed aggradation and high levels of bank erosion, and generally comparable morphological changes that are captured in the lidar DoD, in particular in places where significant changes were detected in the lidar DoD (Figure 8). However, as can be seen in Figure 8, significant differences elsewhere are clear, which may simply be due to the fact that the model will predict changes across the whole channel, when the lidar DoD captures only changes in the non-submerged parts.

3.3 Shear stress and morphological change during the Storm Frank flood

Using the output of the HEC-RAS model, we compare the magnitude of morphological change and bed shear stress during the Storm Frank flood. Predicted shear stress values range from 3 to 425 N/m² (Figure 9). Shear stress in excess of 100 N/m² should be characterised by 'catastrophic' river change according to Magilligan (1992). Just over 80% of the study area is estimated to have experienced sediment transport during the Storm Frank flood, based on the Shields stress applied to the median grain size D_{50} , therefore potentially resulting in significant modification of the channel bed. Reaches with large morphological change were typically located in non-bedrock constrained valleys with steep slopes and high shear stress values. For instance, the alluvial reaches between Abergeldie Castle and Ballater that experienced significant change, had shear stresses typically greater than 150 N/m² and slopes ranging from 0.005 to 0.01 m/m. However, although the Linn of Dee knickpoint had the largest predicted shear stress value, no change was detected in the lidar DoD, as the river is constrained in a narrow bedrock chasm. At sites where the Shields stress value was below 0.045, the boundary shear stress was also relatively low (typically < 60 N/m²), suggesting transport is primarily controlled by slope rather than changes in grain size. For example, the channel segments with slopes ranging from 0.001 to 0.003 m/m near Braemar had a Shields stress lower than 0.045 and experienced little to no geomorphic change.

The relationship between shear stress and geomorphic change highlights two distinct behaviours in stream evolution. In steep confined reaches, high shear stress results in bed erosion paired with lateral bank erosion (although limited by bedrock), whereas flatter, less confined reaches are dominated by gravel bar aggradation with channel migration. This pattern is similar to those observed in other river systems (Sholtes et al., 2018; Thompson and Croke, 2013). The imbalance between sediment flux and transport capacity results in a mixed erosional-depositional system where steep reaches are conditioned by supply-limited processes and flat reaches by transport-limited processes.

Our inability to capture changes in the submerged portions of the channel does not allow comparison of local erosional or depositional budgets to local Shields stress values. Nevertheless, it is important to note that morphological changes expressed in the DoD are associated with both erosion and deposition within many reaches (Figure 6), suggesting the Shields approach is too simplistic to capture dominant sediment behaviour at the reach scale. Other factors not considered could have determined geomorphic response. Given the magnitude of the flood and morphological change in places, it is possible that ‘non-Newtonian’ flow conditions characterised by high fluid densities and turbulence occurred, that locally amplified sediment transport rates (Costa, 1984). Moreover, the presence of engineering and riparian land use characteristics, factors that determine the planform development of the Dee (Maizels, 1985), could have further influenced responses.

3.4 Impact of extreme events on future flood risk

Flooding from the Storm Frank flood is predicted to be extensive, with a total area of inundation of approximately 26 km² and inundation of the entirety of the floodplain in many localities (e.g. Figure 10). Areas particularly prone to flooding in the model are the towns of Braemar, Ballater and Dinnet, where water is predicted to extend over 600 meters across the floodplain. Inundation of the Storm Frank flood using the HEC-RAS and CAESAR-Lisflood models (Run 1A and Run 1B) are presented in Figure 10A. There is a lack of data on the exact flood extent of Storm Frank. However, trash lines surveyed on the ground and in some cases visible in the 2016 aerial photos show a good fit to the modelled flood extent, except for two locations where the trash lines appear in the middle of the modelled flood extent. The HEC-RAS and CAESAR-Lisflood runs are extremely similar, varying in area by only 6%. This agreement suggests the equations used are consistent and that the choice of algorithm is not necessarily crucial for processing flood extent: a 1D model performs as well as a full 2D hydrodynamic model. This is particularly reassuring as most studies, if not all, give preference to one model for determining inundation.

An extreme flood with the same discharge was applied on the post-flood DEM to assess the impact of the Storm Frank morphological changes on flood extent for a flood of similar magnitude (Run 2A and Run1C). The runs predict extremely similar inundation extents to the ‘pre-storm’ runs, varying by less than 1%. (Figure 10B). The overall similarities between the two model’s flood extents are spatially coherent across the whole study area, despite the documented channel changes. For extreme floods, the floodplain geometry may be more important in controlling flood extent than the channel bankfull geometry.

In contrast, when modelling the flood extent for a five-year return period event, we observe a change in inundation extent between the model using the ‘pre-storm’ DEM (Run 2B) and the model using the ‘post-storm’ DEM (Run 2C). Total inundation from Run 2B to Run 2C decreased by 6% and an area of approximately 1.15 km² was left dry, that was previously inundated. The redistribution of sediment and in-channel scour led to an increase in channel capacity, resulting in a reduction of inundation area (Figure 11). Although there is some aggradation in the inside of the meander at Abergeldie Castle (Figure 11A), bank erosion increased channel width by approximately 15 meters, increasing the total channel cross-sectional area. The increase in channel cross-sectional area increased the local flood conveyance capacity, decreasing flood stage, and allowed the subsequent flood to remain within the channel banks.

Unlike the model runs on the lidar ‘post-storm’ DEM (Run 2C), the model run on CAESAR-Lisflood simulated bed changes (Run 2D) displays an increase in inundation compared to the five-year flood under the ‘pre-storm’ conditions (Run 2B). The total river wide area of inundation under the simulated DEM is predicted to increase by 12% (or 2.23 km²) compared to the run with ‘pre-storm’ conditions, which drastically contrasts with the outcome of Run 2C. This likely results from the fact that the lidar DoD cannot detect any changes in the submerged parts of the channel, resulting in many areas appearing unchanged, whereas CAESAR-Lisflood will predicts erosion and deposition across

the entire channel (see contrast between Fig. 8a and 8b, in particular in eastern half of the image). Bed aggradation decreased the height between the channel bed and bankfull stage, increasing maximum inundation for the same magnitude flood (Figure 12). The rise in bed elevation decreased channel cross-sectional area, resulting in a decrease in local conveyance capacity. The implication of such an increase for a higher probability flood is of concern for residential areas within or close to active floodplains. The model predicts that aggradation occurs throughout the whole study area, therefore increasing flood risk for the whole river system.

Complementing the studies by Stover and Montgomery (2001), Pinter and Heine (2005), Lane et al. (2007), Rickenmann et al. (2016), and Guan et al. (2016), this study demonstrates that bed aggradation and bank erosion exert a major influence on future inundation. In-bank scour during extreme floods may increase the channel's cross-sectional area and local conveyance capacity, resulting in smaller overbank flows. Conversely, bed aggradation leads to a decrease in channel cross-sectional area and stage height, resulting in greater inundation. Such local changes can have an impact further downstream: an increase in local conveyance capacity will lead to more water being delivered downstream, potentially reducing downstream flood attenuation and leading to flooding in areas that would have remained dry otherwise. A decrease in local conveyance capacity would have the opposite effect. We do not observe any of these downstream effects in both scenarios: flood extent overall decreases across the whole study area in Run 2C, and it increases overall in Run 2D, suggesting consistent changes in channel cross-section area across the whole length of the River Dee in each scenario (increase in Run 2C and decrease in Run 2D).

This analysis presumes that the morphology established during the extreme flood persists until the next flood event occurs. The potential role of lower magnitude 'background' events in reshaping the channel in the period between floods has not been considered, as smaller floods may erode aggraded material, infill scoured areas, and adjust river back into equilibrium. However, our results show that, in the context of the Dee, the legacy of the extreme flood events seems to be preserved in the form of changes in channel geometry which directly affect inundation associated with floods of greater probability.

3.5 Model sensitivity to sediment parameters

Although it is common practice to vary Manning's coefficient according to surface type (channel bed, grass, forest, etc.), changes in the spatial distribution of grain size and roughness in the channel bed are somewhat disregarded in hydraulic modelling, as many studies assume a constant grain size and Manning's coefficient within the river channel (e.g. Miller and Cluer, 1998; Bradbrook *et al.*, 2004); Hancock *et al.*, 2017). In this section, we test the model's sensitivity to a variable grain size and Manning's coefficient within the river, and its resulting impact on flow resistance. Demonstrated in Figure 13, the run with a spatially varying Manning's coefficient in the channel (Run 3D) is compared to one that has a spatially constant Manning's coefficient (Run 2B). Compared to the five-year flood with constant Manning's coefficient, variations in channel roughness allowed the flood to stay almost completely in-bank along the entire river. The change in roughness increased peak discharge by 5%. Note that in this case, the variable roughness predicts greater roughness (coarser sediment) in the main channel, with lower roughness in secondary branches and floodplain (Figure 13A), but that the predicted Manning's coefficient ($n = 0.015$ to 0.035 , Run 3D) is everywhere smaller than for the case with constant coefficient ($n = 0.039$, Run 2B). This explains the lower flood extent despite greater peak discharge (greater flow velocity).

The sensitivity of the model to a change in roughness reveals variations in grain size and roughness could have a significant influence on flood inundation. This is particularly true of rivers transporting a wide range of grain sizes (up to boulder size), as these will be more susceptible to surface grain size (and therefore roughness) changes following an extreme event. A constant channel Manning's

roughness or grain size may not be appropriate to model the evolution of flood inundation in dynamic rivers.

4 Conclusion

In this study we assessed the morphological changes on the River Dee associated with an extreme flood event, and its potential impact on subsequent hypothetical flood events. The 2015 Storm Frank flooded a total area of approximately 27 km² and resulted in an overall export of sediment associated mainly with channel scour and lateral bank erosion. The morphological response to the flood was spatially variable. Locations of significant morphological change at < 1 km reach scales were primarily concentrated within the middle part of the river (50 – 90 km) between Abergeldie Castle and Kincardine O’Neil. Dynamic channel segments were typically located in areas of high shear stress and steep slopes within sections of the valley not constrained by bedrock. Significant bank erosion and gravel bar deposition was localised, suggesting the river is relatively resilient to extreme flooding. 80% of the river was predicted to have undergone sediment transport, but the relationship with geomorphic response was complex suggesting other factors were important. Vegetation, land use, and human influences such as bank engineering should be assessed in the future to determine how these controls potentially influence channel response at the reach scale.

Hydraulic modelling of a five-year return flood indicates that channel aggradation or scour related to previous floods is a key control on future flood projections. Where bankfull channel width is increased by lateral bank scour, inundation extent decreases and local channel conveyance capacity is enhanced. However, a decrease in local flood inundation extent and local bankfull stage may increase flood hazards downstream by decreasing flood attenuation, facilitating conveyance of water downstream. Where changes are dominated by bed aggradation, inundation increases and maximum inundation (constrained by the valley width) may be reached at lower stage heights, increasing local flood risk. A test run of the flood model’s sensitivity to channel’s roughness also indicate that variable grain size potentially affects flood inundation extent due to its influence on flow velocity and flood conveyance. This result indicates that further assessments of the spatial distribution of sediment grain size within the channel are needed: a constant channel Manning’s coefficient may not be appropriate to model projections of flood risk in dynamic river systems.

This study supports the concept that morphological channel changes from extreme flooding, even in a relatively stable mixed bedrock-alluvial river, have a significant influence on flood risk. As climate change is predicted to lead to increased extreme precipitation and flooding in Scotland by the 2050s (Werritty, 2002), accurate assessment of flood risk and hazards is crucial. Understanding sediment transport mechanics and channel bed evolution in mixed-alluvial bed rivers is therefore essential for evaluating the impacts of river flow regime changes driven by climate change.

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Figure 1. Location of the River Dee catchment in northeast Scotland and its simplified geology. (Source: EDINA Geology Digimap Service, <https://digimap.edina.ac.uk>).

Figure 2. Hydrograph of the River Dee at the SEPA Woodend gauging station (NO63482, 95613) and total daily rainfall from the 28th to 31st of December 2015. Discharge provided by SEPA in 15 minute intervals. Discharge of the Storm Frank flood rose to a peak of approximately 1360 m³/s. (Contains SEPA data © Scottish Environment Protection Agency and database right 2019. All rights reserved). Rainfall data provided by National River Flow Archive, 2019, <https://nrfa.ceh.ac.uk>, UK Centre for Ecology & Hydrology (UKCEH), Wallingford.

Figure 3. Flow chart describing the DEM and discharge input and output for each flood model run using HEC-RAS and CAESAR-Lisflood. A CAESAR-Lisflood simulated bed elevation DEM was input into Runs 2D and 3D. The output grain size layer in Run 1B was used in Run 3D to compare runs with a varying Manning's coefficient (n) on the channel bed and floodplain.

Figure 4. (a) Topographic map of the Dee catchment with location of each site where grain size measurements were taken. **(b)** The 50th and 84th percentile of the grain size distributions are represented with a conservative 10% uncertainty. Braemar (Br), Ballater (Bal), Aboyne (Aby), Banchory (Ban), and Aberdeen (Ab) are displayed at the top for reference. **(c)** Elevation profile of the Dee. The large knickpoint of the Linn of Dee is located 15 km upstream of Braemar.

Figure 5. Location of areas of high geomorphic channel change, detected in the DoD. Site C1, C2, and C3 are explored further in Figure 6.

Figure 6. Top: Aerial photos of the channel before Storm Frank at site C1, C2, and C3 (located on Figure 5), taken in 2015. (Updated: 29 October 2018, Getmapping, Using: EDINA Aerial Digimap Service, <https://digimap.edina.ac.uk>). Middle: DoD overlaying the top aerial photo, indicating where significant erosion (red) and deposition (blue) occurred during the flood. Bottom: Aerial photo taken after Storm Frank (April 2016).

Figure 7. Volumetric budget of the DEM of difference based on a 10, 30, and 50 cm morphological change threshold. Total volume of erosion varied from 1.81 - 0.61 km³, total volume of deposition was 1.21 - 0.26 km³, leading to a net erosional volume of -602,220 to -349,550 m³ (see Supplementary material, Table 3).

Figure 8. Example of comparison of **(a)** the DoD based on lidar data and **(b)** the modelled DoD from CAESAR-Lisflood at site C1.

Figure 9. (a) Predicted basal shear stress from the HEC-RAS simulation of the Storm Frank flood and **(b)** computed dimensionless Shields stress of the D_{50} utilising Equation 1. Where the Shields stress exceeds 0.045, sediment is predicted to be mobilised and erosion expected.

Figure 10. (a) HEC-RAS Storm Frank flood run (Run 1A) overlaid by the CAESAR-Lisflood Storm Frank flood run (Run 1B) on the pre-storm DEM with observed trash lines. **(b)** Comparison of the Storm Frank flood runs from HEC-RAS (Run 2A) and CAESAR-Lisflood (Run 1C) on the post-storm DEM. Location is just upstream of the Clunie Water confluence in Braemar, an area that is particularly prone to flooding.

Figure 11. (a) Changes detected in the DoD in the reach adjacent to Abergeldie Castle (Figure 1). **(b)** Five-year flood run on the pre-storm DEM (Run 2B). **(c)** Five-year flood run on the post-storm DEM (Run 2C). **(d)** Observed changes in channel cross-section due to erosion (red) and deposition (blue) during Storm Frank. Modelled water stage of the five-year flood is shown (dashed line) for Runs 2B (black) and 2C (grey).

Figure 12. (a) Changes detected in the modelled DoD near the River Gairn confluence, just upstream of Ballater. (b) Five-year flood run on the pre-storm DEM (Run 2B). (c) Five-year flood run on the simulated post-storm DEM (Run 2D). (d) CAESAR-Lisflood predicted changes in channel cross-section due to erosion (red) and deposition (blue) during Storm Frank (Run 1B). Modelled water stage of the five-year flood is shown (dashed line) for Runs 2B (black) and 2D (grey).

Figure 13. (a) Predicted effect of spatial variations in Manning's n coefficient due to spatial variations in grain size predicted in Run 1B on inundation extent. (b) Inundation extent prediction comparison of Run 2D with a constant channel bed Manning's coefficient of 0.039 (n) with the spatially variable channel bed roughness (Run 3D).

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