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Reconstructing flash flood magnitudes using 'Structure-from-Motion': A rapid assessment tool

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SUMMARY

Accurate records of flash flood magnitudes are required to inform flood forecasting and planning. However, whilst a distributed flood survey is desirable to capture spatial heterogeneity in peak water surface elevation, the field time required for a distributed survey often limits the spatial coverage of such reconstructions. For the first time, we demonstrate the application of Structure-from-Motion (SfM) with Multi-View Stereo (MVS) to reconstruct the magnitude of a flash flood. This approach required only standard digital photographs and ground control points, took only ~30 min in the field, and can be embedded within existing protocols easily. We validated the method against a conventional dGPS survey in three stages: (i) comparison of topographic data revealed that SfM was accurate to within 0.1 m; (ii) high water marks extracted from the SfM model were within 0.25 m of those surveyed in the field with no consistent over or under-estimate; (iii) peak discharge reconstructed from a two-dimensional hydraulic model was within the range of more conventional estimates. With low uncertainty in our terrain model and our reconstructed flood water surface, we highlight the added value of the SfM approach for incorporating reach scale spatial variability into hydraulic reconstructions.

1. Background

Flash floods are defined as sudden-onset floods of peak discharge far in excess of normal river flows. They are typically of limited areal extent, exhibit rapid response times and arise from localised, intense convective rainfall events. Flash floods can be extremely destructive (Lumbroso and Gaume, 2012) and hazardous to human life; Barredo (2007) estimated that flash floods were responsible for 40% of flood-related deaths in Europe between 1950 and 2006. With increasing levels of development in flash flood prone areas, the potential repair cost to infrastructure also increases. This increased hazard may be exacerbated in the near-future as increased temperatures under projected climate change intensify the hydrological cycle (Huntington, 2006), thereby increasing the frequency and severity of flash floods.

Accurate field observations of flash flood magnitude enable: (i) characterisation of the response of particular catchments to extreme rainfall events (Marchi et al., 2010); (ii) insight to the controls on flash flood processes; and (iii) information to be gained that is pertinent to flood-frequency analyses. In turn, these calculations and knowledge can aid future flood forecasting and planning. While establishment of rainfall radar networks has improved our ability to make distributed estimates of rainfall (although some uncertainties remain; e.g. Villarini et al., 2014), obtaining accurate estimates of flash flood magnitude is challenging. Direct measurements of peak discharge are logistically impossible in the vast majority of cases and stage-recording devices are typically absent for the areas experiencing highest flows. Where stage monitoring does take place, the destructive nature of extreme flash-flood events can damage the device. In any case, should flood stage data be retrievable, the recorded level is likely to require unreliable extrapolation from existing stage–discharge rating curves. There is consequently a paucity of systematic observation data of peak flood discharge. While, at a broader scale, remote sensing methods such as synthetic aperture radar and interferometric methods may be able to retrieve surface water extent and potentially depth from airborne and spaceborne platforms (e.g. Mason et al., 2012; García-Pintado et al., 2013), field-based post-flood analysis is an extremely common requirement for flood discharge estimates.

Post-flood analysis must include distributed flood surveys to adequately characterise an event because of the localised nature of rainfall and runoff generation, transmission losses and the resulting spatial heterogeneity of flash flood magnitudes (e.g. Bull et al., 1999; Hooke and Mant, 2000). A range of methods exist

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to obtain post-flood peak discharge estimates; Gaume (2006) and Gaume and Borga (2008) highlight the need to develop a robust, standardised method for calculating these estimates. Given the large uncertainties inherent in any post-flood analysis and multiple sources of error, Gaume (2006) emphasises that measurement of multiple cross-sections in a single reach and examination of the coherence of the estimates is essential.

Extracting channel cross sections and estimating flood stage from trash lines (or a crest-stage recorder) and application of one-dimensional flow equations remains the most common method of estimating flash flood discharge (e.g. Bull et al., 1999; Gaume and Borga, 2008; Sandercock and Hooke, 2010). Yet even with careful data collection and thorough validation, Gaume and Borga (2008) suggest that an uncertainty bound of 30–50% be applied to any estimated flash flood peak discharges in headwater catchments. There are many sources of uncertainty inherent in post-flood analysis. These include: (i) difficulty in interpreting high water marks (for example, a locally high water mark may arise from the presence of an obstacle in the flow or superelevation on a meander bend, or trash lines may form on vegetation temporarily bent by flow); (ii) estimation of channel roughness required for hydraulic equations; (iii) the sensitivity of estimates to the slope value used; and (iv) the use of post-flood surfaces to estimate peak flow on the assumption that subsequent geomorphological change can be ignored.

Considering (ii) above, various guidance documents exist to facilitate the estimation of a roughness coefficient (typically Manning's n). Issues include bed forms, sediment load, obstructions, unsteady flow, variability in channel planform and the presence of flexible vegetation. Lumbroso and Gaume (2012) detail a thorough account of the limitations of using Manning's equation to estimate flash-flood discharge and, following Grant (1997), suggest that supercritical flow in mobile-bed channels cannot be sustained over reaches >20 m as interactions between channel hydraulics and bed configuration inhibit sustained supercritical flow. Thus, it is reasonable to revise any discharge estimates that produce supercritical flow down to discharge resulting in a maximum Froude number of 1. This approach highlights the past systematic over-estimation of flash-flood peak discharge and has been applied in the recent Europe-wide HYDRATE initiative (Borga et al., 2011).

An enhanced ability to quantify channel topography and other characteristics (e.g. vegetation density) can therefore be of use in obtaining more reliable estimates of channel roughness. Yet, moving beyond cross-sections to Digital Elevation Models (DEMs) often requires time-consuming land surveying using a dGPS or geodimeter (e.g. Hooke and Mant, 2000; Hooke, 2007; Sandercock and Hooke, 2010) or more recently a Terrestrial Laser Scanner (Ballesteros Cánovas et al., 2011) which would entail a full day in the field at each study reach. Greater knowledge of the reach geometry also overcomes issues outlined in (i) above as localised estimates of maximum flood stage can be interpreted within the wider geomorphological context. This can even be advantageous when observed super-elevation on the outside of a meander bend can be related to the bend geometry and flow velocity, providing a check on estimated velocities. Such super-elevation, along with analysis of morphological and sedimentological characteristics of deposits can also help diagnose whether the flow is fluvial, hyper-concentrated or debris flow, requiring different flow models in each case (though see Prochaska et al. (2008) for an demonstration of limitations of applying the forced vortex equation to debris flows).

Perhaps more importantly, DEMs can be used to run hydraulic models to match the estimated water level and observe the discharge at which the closest fit is achieved. This is seen as the best approach to flash flood discharge estimation (Gaume, 2006) for a number of reasons. Application of two-dimensional hydraulic models based on the shallow water equations improves on one-dimensional step-backwater approaches as typical features of a high-magnitude flood event including rapidly varied flow, non-uniform velocity, secondary flow, super-elevation of the water surface on the outside of bends, simultaneous inundation of multiple channels, flow around islands, etc., can be incorporated into the analysis (Carrivick, 2006; Tayefi et al., 2007). Form roughness can be incorporated directly where high-resolution bed topography is available. Two-dimensional depth-averaged hydraulic models are well-established in studies of lower-magnitude floods (e.g. Lane and Richards, 2000) and flash floods (e.g. Ballesteros Cánovas et al., 2011) and have even been applied to simulate high-magnitude outburst floods (e.g. Denlinger et al., 2002; Carrivick, 2006) and lahars (Carrivick et al., 2009). Many comparisons of 1D and 2D approaches demonstrate convincingly the improved representation of flood hydraulics offered by 2D hydraulic models and greater reliability of simulations (e.g. Tayefi et al., 2007; Cook and Merwade, 2009) although others suggest they are broadly equivalent in some cases (e.g. Horritt and Bates, 2002). Enhanced availability of remotely sensed topographic data over the last decade has led to further acceleration of high resolution 2D hydraulic models (Bates, 2012); however, it should be noted that in the case of flash floods, which can modify reach morphology considerably, the use of post-flood topography is a limitation for both 1D and 2D approaches, and may affect their comparison.

Structure-from-Motion (SfM) has the potential to offer the best of both worlds: high-resolution detailed 3D topography of entire river reaches suitable for 2D hydraulic models using non specialist survey equipment and requiring a minimum of field time (similar to that needed for a single cross-section with a geodimeter) (Fonstad et al., 2013). When coupled with dense Multi-View Stereo (MVS), Structure-from-Motion can produce high resolution fully 3D terrain models with centimetre precision requiring only a consumer-grade digital camera.

In short, SfM requires as input a number of images of the same scene. 'Keypoint' features that are invariant to changes in scale and orientation are detected in each image and a distinctive description applied to each (Lowe, 2004). Correspondences between these keypoints in different images are made and then refined to include only geometrically consistent matches (see Snavely et al., 2008). Bundle adjustment is then used to reconstruct simultaneously 3D scene structure, camera positions and orientations (extrinsic calibration), and often intrinsic camera calibration parameters. This SfM process results in estimated camera locations and parameters and a sparse point cloud. From this information, the second step of MVS is then implemented to produce a much denser point cloud (Furukawa and Ponce, 2010) which is later scaled and georeferenced.

SfM-MVS has only recently been applied to geoscience problems and, given the convenience offered, is rapidly gaining momentum in its uptake (e.g. Westoby et al., 2012; James and Robson, 2012; Javernick et al., 2014; Lucieer et al., 2014; Woodget et al., 2014). Outside of the geosciences, other recent applications of SfM include documenting archaeological sites (e.g. De Reu et al., 2014; McCarthy, 2014) and providing 3D digital content for cultural preservation (e.g. Koutsoudis et al., 2014).

2. Aim

The aim of this paper is to demonstrate the application of Structure-from-Motion (with MVS) coupled with two-dimensional depth-averaged hydraulic modelling to reconstruct peak discharge of a flash flood event (described in Section 3). Several methods (described in Section 4) are used to validate the SfM-approach in three stages; (i) the SfM-derived DEM is compared with dGPS