AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL070260

Key Points:

- First continental-wide long-term event-continuous 2-D flood inundation computations
- At-a-station discharge records do not directly translate to flood hazard
- There is a need to rethink flood hazard assessment globally

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Citation:
Schumann, G. J.-P., D. Stampoulis, A. M. Smith, C. C. Sampson, K. M. Andreadis, J. C. Neal, and P. D. Bates (2016), Rethinking flood hazard at the global scale, *Geophys. Res. Lett.*, *43*, 10,249–10,256, doi:10.1002/2016GL070260.

Received 1 JUL 2016
Accepted 21 SEP 2016
Accepted article online 24 SEP 2016
Published online 9 OCT 2016

Rethinking flood hazard at the global scale

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Abstract Flooding is governed by the amount and timing of water spilling out of channels and moving across adjacent land, often with little warning. At global scales, flood hazard is typically inferred from streamflow, precipitation or from satellite images, yielding a largely incomplete picture. Thus, at present, the floodplain inundation variables, which define hazard, cannot be accurately predicted nor can they be measured at large scales. Here we present, for the first time, a complete continuous long-term simulation of floodplain water depths at continental scale. Simulations of floodplain inundation were performed with a hydrodynamic model based on gauged streamflow for the Australian continent from 1973 to 2012. We found the magnitude and timing of floodplain storage to differ significantly from streamflow in terms of their distribution. Furthermore, floodplain volume gave a much sharper discrimination of high hazard and low hazard periods than discharge. These discrepancies have implications for characterizing flood hazard at the global scale from precipitation and streamflow records alone, suggesting that simulations and observations of inundation are also needed.

1. Introduction: Context and Motivation

1.1. Context

Flooding is a natural process that sustains ecosystems around the globe, but at times floods can have devastating effects on society and the environment at the cost of many billions of dollars annually [*Hirabayashi et al*., 2013] and significant loss of life. Flood risk, which is projected to increase in the future [*Arnell and Gosling*, 2014], is the product of flood hazard and asset exposure, and hence, accurate estimation of magnitude and timing of floodplain variables such as flow depths and velocities during flood events is of great importance. Yet at present these variables are largely ignored when inferring flood risk at the global scale, and instead, flood risk is most often treated as synonymous with streamflow observations [*Milly et al*., 2002] and simulations [*Hirabayashi et al*., 2013; *Ward et al*., 2014] or even precipitation extremes [*Pall et al*., 2011].

In reality, the transformation from rainfall to runoff is highly nonlinear, as is the subsequent transformation from river runoff to floodplain water depths. The physical processes involved in the latter transform can only be represented realistically by hydrodynamic models [*Neal et al*., 2012a; *Bates et al*., 2010] that can resolve flood inundation in two dimensions. Until recently, continental- and global-scale applications of such models have been limited by two main factors: first, globally available floodplain topography has vertical errors of several meters which is incompatible with inundation modeling [*Schumann et al*., 2014b] and second, traditionally two-dimensional hydrodynamic models are computationally expensive to run over large scales [*Neal et al*., 2012b; *Schumann et al*., 2013]. Furthermore, traditionally, flood modeling has looked at spatially distributed discharge and water levels rather than inundation volume, the reason being that discharge and water levels are comparatively easy to record at point locations and so can serve as calibration and validation of flood models while floodplain volume is difficult to measure and requires computations of 2-D hydrodynamics.

Considerable advances in numerical code and computational power are now enabling scientists to model floodplain hydrodynamics at the global scale with resolutions that may render flood hazard simulations meaningful at the local level (3 arc sec or even 1 arc sec are becoming feasible [see, e.g., *Sampson et al*., 2015; *Dottori et al*., 2016]). Except for these few notable examples, other attempts to roll out models on a continental to global scale exist but most often predict at a point discharge with relatively little attention to accuracy at the inundation model grid scale actually required [*Fekete et al*., 2002; *Thielen et al*., 2009; *Alfieri et al*., 2013; *Pappenberger et al*., 2012; *Brakenridge et al*., 2012; *Winsemius et al*., 2013]. Typical grid resolutions of continental- or global-scale models dealing with flood inundation processes are in the order of a few tens of square kilometers or solve floodplain dynamics in subgrid parameterization [*Yamazaki et al*., 2011; *Pappenberger et al*., 2012; *Paiva et al*., 2011, 2013; *Mateo et al*., 2014], which may miss important local variations in topography and thus may not resolve inundation pattern details necessary to understand associated risks locally. As outlined in *Schumann et al*. [2013], other studies use hydrodynamic models [e.g., *Paiva et al*., 2013] but employ a simple fill operation for the floodplain with prediction of storage volume only. Since those models lack floodplain hydraulics, they cannot reproduce inundation area dynamically. *Mateo et al*. [2014] simulated subgrid floodplain dynamics at ~10 km (5′) resolution with subsequent downscaling to ~2 km but only over a limited area basin scale. Studies that looked at forecasting at the basin scale applied either only hydrologic models [e.g., *Mendoza et al*., 2012; *Gouweleeuw et al*., 2005; *Werner et al*., 2005] or data-based approaches [e.g., *Romanowicz et al*., 2008; *Liong et al*., 2000] with consequently no detail on flood inundation patterns.

1.2. Motivation

Recent advances in computational resources, terrain data sets [*Baugh et al*., 2013; *Sampson et al*., 2015], and progress in more speed-efficient hydrodynamic model codes [*Bates et al*., 2010] now allow application of this type of model at continental and global scales [*Sampson et al*., 2015; *Yamazaki et al*., 2011; *Ward et al*., 2015; *Dottori et al*., 2016]. However, to date only discrete return period flows have been simulated with advanced hydrodynamic schemes, or continuous time series simulations have been performed but at subgrid resolution lacking detail in floodplain topography. Here we present event-continuous long time series of inundation simulated at high enough spatial resolution to resolve the necessary topographic variations that govern floodplain flow paths. This is important because the probability of exceeding a particular discharge may not be the same as the probability of exceeding a particular floodplain water depth, which is a result of the nonlinear relationship between flow depths and discharge created by complex floodplain topography.

As a first contribution of this type, we present initial results of a long time series (1973–2012) flood inundation simulation at high spatial resolution over an entire continent. We anticipate the results to demonstrate the importance of floodplain hydrodynamics at this scale and expect to identify a new standard for assessing flood hazard and thus risk at the global scale. We are aware that this poses a considerable challenge which, however, needs to be addressed, if we want to improve prediction of global-scale flood inundation hazard. Long time series of continuous event-based simulations of spatial patterns of inundation would provide key information about the flood record and nonlinearities between discharge and inundation depths, which has implications for how hazard and risk should be assessed. This then also allows better means to project the future as well as enable event-specific hindcasting, nowcasting, and forecasting at a continental to global scale

2. Methodology

We use a computationally efficient two-dimensional hydrodynamic model (LISFLOOD-FP [*Bates et al*., 2010]) which employs a novel subgrid channel formulation [*Neal et al*., 2012a] to generate a continental-scale flood inundation climatology for Australia covering a 40 year period (1973–2012). The model was built from freely available Shuttle Radar Topography Mission (SRTM) data, which was corrected for vegetation canopy height using a global ICESat-1 canopy data set [*Simard et al*., 2011], and channel bathymetry was estimated within the model code [*Neal et al*., 2012a; *Andreadis et al*., 2013]. More detail on the necessary preprocessing of the SRTM topography can be found in *Schumann et al*. [2013]. All rivers that drain a catchment area greater than 10,000 km^2 were explicitly represented in our model, and significant flow contributions from smaller tributaries were accounted for as additional inflow points along those major rivers. The model also includes lakes and reservoirs from the Global Lake and Wetland Database [*Lehner and Döll*, 2004]. Reservoirs and channels were filled with an average condition water level before starting computations and were handled implicitly within the model's hydrodynamic scheme, without any operational rules or sudden water releases; in other words, the model used the same hydrodynamic scheme everywhere, including across the surface of lakes and reservoirs. Also important to note is that currently, the flood inundation model does not account for agricultural, industrial, or other water withdrawal not already captured by a stream gauge. We believe this to be important mainly during low flow conditions when floodplain inundation approaches zero rather than during high event flows that we are attempting to reproduce correctly in this study. All this will of course impact results, and more research is needed to understand how to correctly implement reservoir operations and water withdrawal in hydrodynamic models. We assume that our simple approach represents a best first effort which should be confirmed by our model validation.

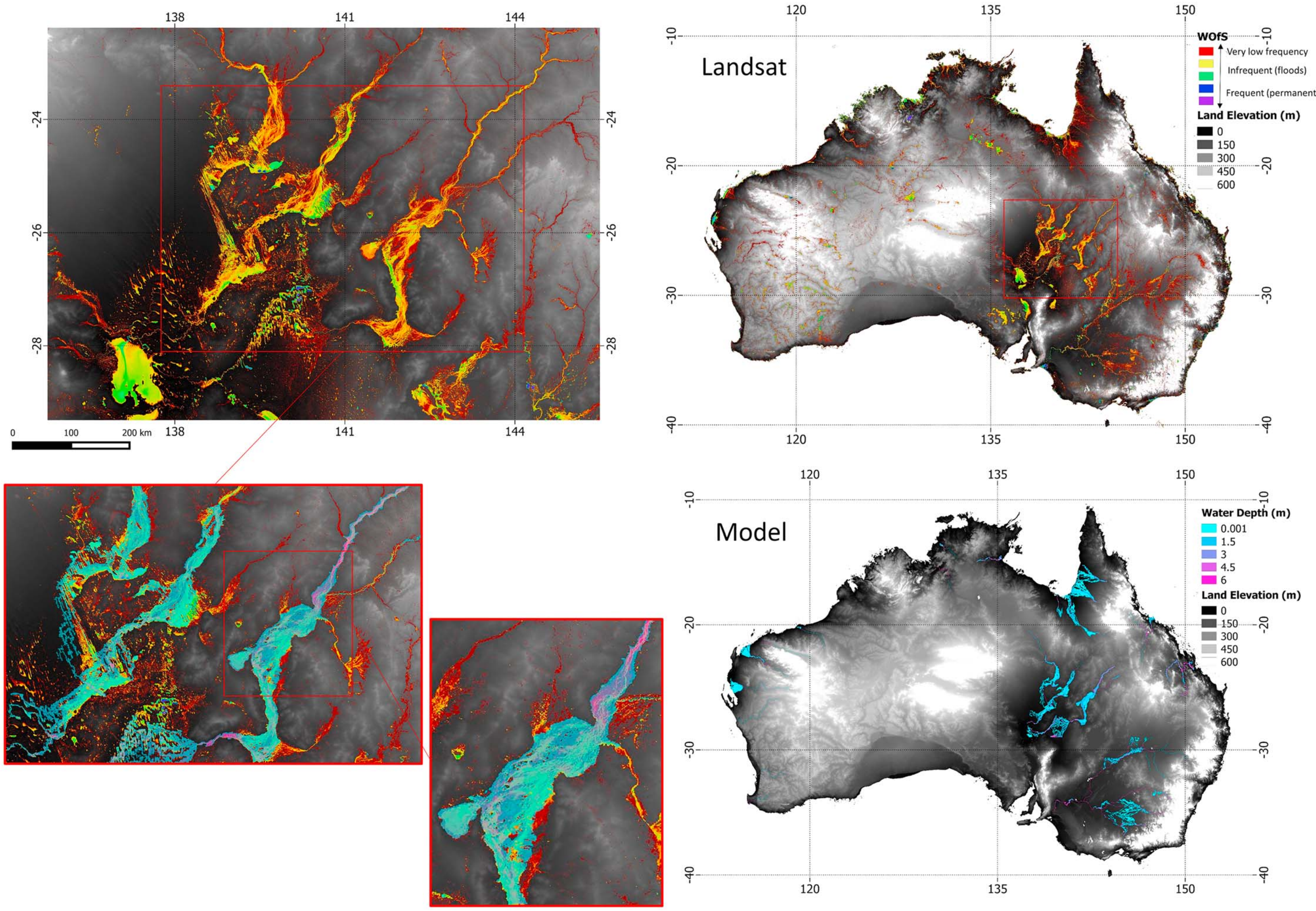

Figure 1. (top row) Number of times water was detected between 1987 and 2014 by Landsat 5 and 7. Frequently observed water (such as permanent lakes and reservoirs) is shown in purple and blue, down through green to infrequently observed water (such as floods) in yellow, and finally to very low percentages in red. ©Geoscience Australia. (bottom row) Overlay map showing maximum inundation depth over the 40 year model simulation downscaled onto the 90 m SRTM-DEM on top of the 28 year Landsat observations (note that for this comparison, the Landsat data were aggregated to the same resolution as the downscaled model output).

On the floodplain, the model simulated flow paths and inundation variables at 1 km resolution, which were subsequently downscaled onto the 90 m SRTM-DEM (digital elevation model) using a mass-conservative downscaling algorithm [*Schumann et al*., 2014c] (Figure 1). The model was forced using daily gauged flows. Downstream boundary conditions were imposed using as a normal depth flow condition the thalweg gradient, and reservoirs and lakes were filled before the simulation was run and were implicitly regulated by the hydrodynamics of the model during simulation as noted earlier. Since seasonal evaporative water loss is significant in some regions of Australia, we also used interpolated and gridded observed mean monthly evaporation fields from the Australian Bureau of Meteorology to simulate evaporation from open water as implemented by *Neal et al*. [2012a]. We also wish to note that in the present study we simulated flooding primarily in large river catchments and their lowland floodplains, and although we accounted for flow contributions of smaller tributaries along the main stream networks, we omitted rainfall-runoff contributions from smaller and steeper upland basins as well as direct rainfall onto the simulated floodplains. Although accounting for this may be nontrivial in some locations and is possible with current state-of-the-art hydrodynamic modeling approaches [see, e.g., *Sampson et al*., 2015], such processes are commonly omitted in most flood inundation simulations.

It is well known that wide-coverage satellite imagery is suitable for assessing the skill of large-scale flood models and here we calibrated floodplain inundation accuracy using a historic Landsat 2 image of the

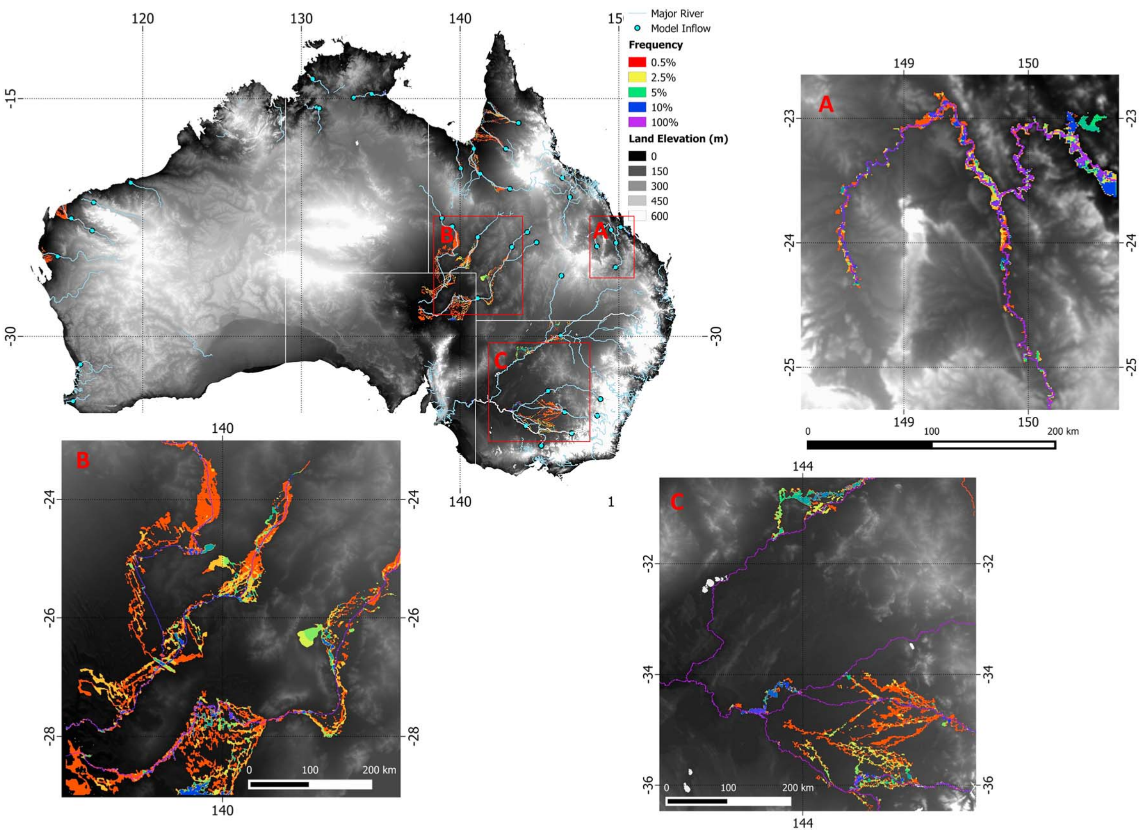

Figure 2. Map of Australia showing frequency of simulated inundation over 40 years (1973–2012) going from red to green (below 5% of the time inundated), through blue (>10%) to purple (rivers and reservoirs). Major rivers and model inflow locations (discharge stations and additional inflow locations) are also shown.

Murrumbidgee River (Murray-Darling basin) flood event in mid-October 1975. The flooded area was extracted from the satellite image using the Normalized Difference Water Index [*McFeeters*, 1996], and as a fit metric, we computed the Receiver Operating Characteristic (ROC) curves [*Schumann et al*., 2014a] between the imaged and the simulated flooded area from plausible model parameterizations [*Neal et al*., 2012a]. The best model parameterization achieved a ROC performance value of 0.81, with 1 denoting a perfect fit (for inverting channel bathymetry within the model based on channel width and discharge relationships, the bathymetry coefficient value as defined in *Neal et al*. [2012a]: 0.55; Manning's n value for channel friction: 0.04).

The model was calibrated in the Murray-Darling basin, which is a temperate region, but we assumed a spatially and temporally uniform friction value across different climate regions, an assumption which represents a nonnegligible source of uncertainty. However, we validated the performance of the calibrated model over a large inundated floodplain area (~17,000 km^2) in SW Queensland, a region with very different river geomorphology and climate, which should at least partly verify the above assumption. Here we used the maximum inundated area as extracted from a 28 year record of Landsat images [*Mueller et al*., 2016] and compared that to the maximum computed by our model (Figure 1), which gives a predicted correct (flooding) statistic [*Schumann et al*., 2009] of 89.6% and an area in error of 10.9%. Note that we highly constrained the easily predictable "dry/dry" score for map overlay operations.

3. Results and Implications

Simulating floodplain inundation over 40 years using daily gauged flow rates allows us to build a database of model output variables, such as flood depths, inundated area (Figure 1), as well as floodplain water volume changes and frequencies of inundation as shown in Figure 2. Such a continental database of high-resolution (90 m or finer) flood hazard variables has unprecedented value for a large number of socioeconomic sectors,

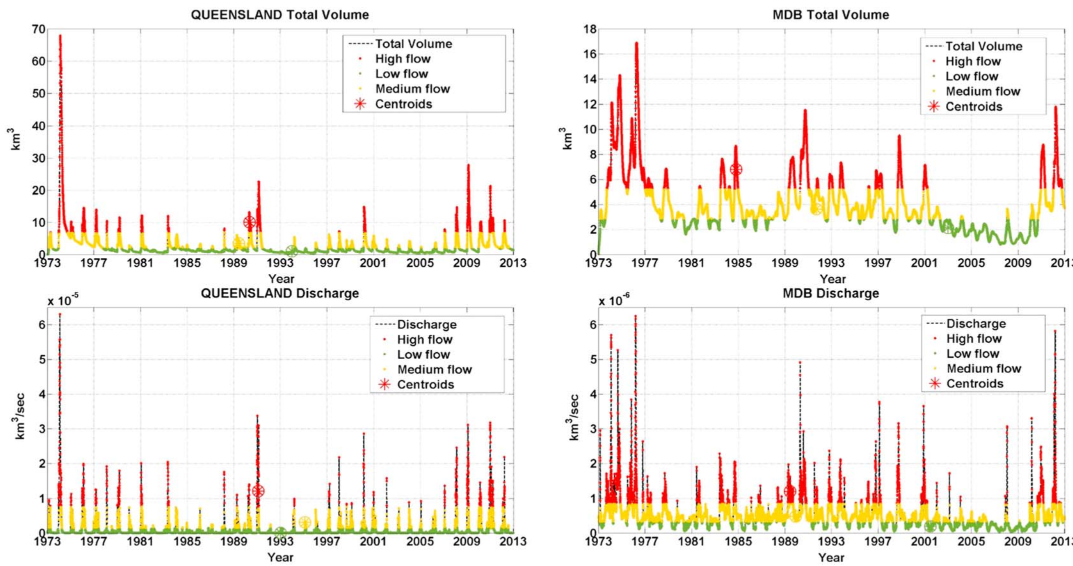

Figure 3. Plots showing the sequence of low, medium, and high flows from the 40 year model run for (left column) the Queensland area and (right column) the Murray-Darling basin (MDB). Results are illustrated for both the total volume of (top row) inundation and (bottom row) at-a-station discharge.

science, and applications including flood disaster management, response, and resilience. This is significantly different from flood hazard estimated from the return period of extreme discharge because it is based on a historical record. This also allows comparison with high-resolution long-record observations as we have presented here and as presented in *Brakenridge and Anderson* [2006].

As noted earlier, presently at large scales, the standard procedure to infer flood occurrence probabilities and associated flood risk is to use instantaneous river discharge measured at a station [*Milly et al*., 2002; *Ward et al*., 2014]. Here we examined the relationship between floodplain water volume, inundated area, and station discharge at continental scale to assess how flood risk is estimated in each case. Grouping station discharge and floodplain volume into “low,” “medium,” and “high” flows over the entire simulation time (Figure 3) revealed that explicitly representing the floodplain will give a much better discrimination of, and smoother transition between, high hazard and low hazard periods than discharge. Floodplain volume consequently defines periods of extremes (i.e., floods and droughts) much more sharply and with higher fidelity than discharge. The partitioning was done with the nonhierarchical *k*-means clustering algorithm: three mutually exclusive clusters were defined by minimizing the distance (sum of absolute differences) between data points in each cluster. The centroid of each cluster (shown in the plots for each group) is given by the data point that minimizes the distance to all other data points in that cluster.

Comparing the statistical distribution of the 40 year streamflow record for major rivers in Australia to that of the associated floodplain inundation volume and area (simulated by our model) highlighted substantial differences. The probability of occurrence assigned to a given flow is significantly different (around 10% at $p < 0.01$) to that of the corresponding floodplain volume, and this effect is consistent across regions. However, differences between flow and the associated flooded area are much larger and vary considerably with changes in regional floodplain topography (20%–30% for the events selected here; see Figure 4). This has important implications when inferring flood hazard, and therefore risk, from station discharge data alone, since the probability of occurrence assigned to station discharge for one event is not the same as the inundation volume probability of that event and that difference is even more pronounced for inundated area probability. Estimation of flood hazard therefore requires the use of two-dimensional hydrodynamic models that correctly capture the nonlinear influence of floodplain topography on the evolution of inundation.

We have demonstrated that accounting for the hydraulic effect of (Australia’s) floodplains can lead to significant differences in flood estimation. In fact, using station discharge on its own can lead to important overestimation of flood hazard. Unsurprisingly, inundation area has a strong nonlinear relationship with discharge and is governed by constraints and changes in floodplain topography. The results shown here are unprecedented at this spatial scale and record length and highlight the importance of global flood

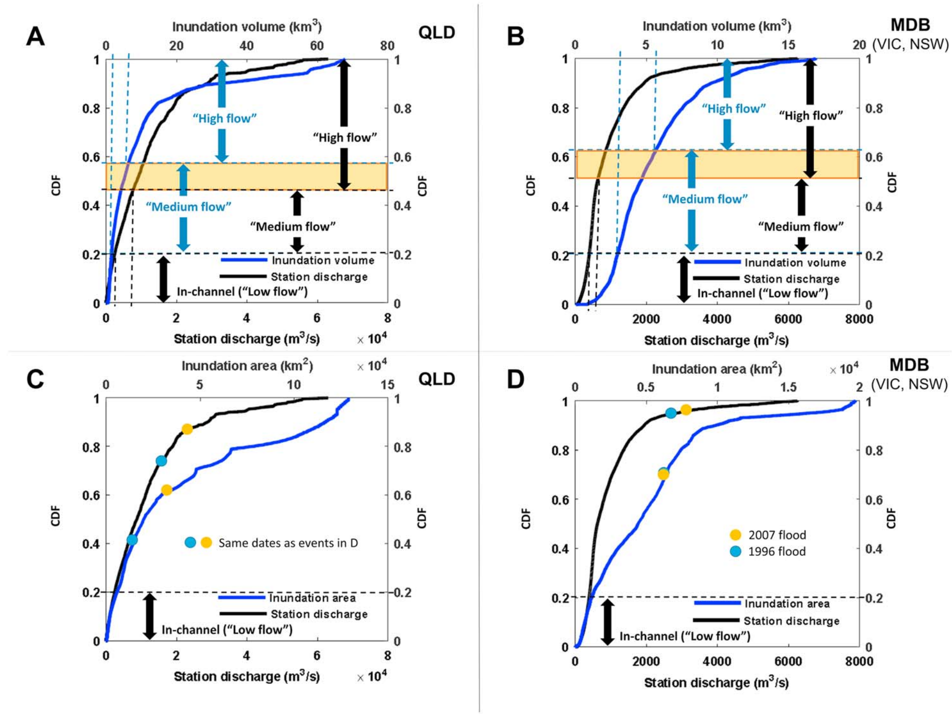

Figure 4. Cumulative distribution functions (CDFs) of station discharge (black line) versus (a and b) flood volume (blue line) and (c and d) inundated area (blue line) for Queensland (Figures 4a and 4c) and the Murray-Darling basin (Figures 4b and 4d). There is a significant difference ($p < 0.01$, two-sample nonparametric KS test) between all the distributions, meaning that the probability of occurrence assigned to station discharge for one event is not the same for inundation volume of that event and is even more different for inundated area. Probability differences (highlighted by the colored box) are around 10% for inundation volume and are consistent across regions but are much larger and vary considerably with changes in regional floodplain topology (20%–30% for the events selected here). Note that in Figures 4a and 4b the CDF cutoff value (dashed lines) represents the maximum class break value as assigned by the *k*-means clustering algorithm (cf. Figure 3).

inundation dynamics. There is hence a need to rethink current approaches to estimating flood risk at global scales, at least from the perspective of using flood inundation models.

Looking to the future, the continued expansion of cities located on river floodplains and coastal deltas due to population growth and migration will inevitably produce a significant increase in flood exposure [*Hirabayashi et al.*, 2013; *Jongman et al.*, 2012]. Economic losses will also increase [*Hallegatte et al.*, 2013] as people are lifted out of poverty, living standards rise, and a global middle class with western consumption patterns emerges. If current trends continue, then populations will grow, age, become more affluent, and migrate to zones of higher flood risk, and the need for approaches of the type presented in this paper will become even more pressing. Fortunately, there are considerable grounds for optimism concerning the skill of global flood risk estimates [see, e.g., *Ward et al.*, 2015]. This is a rapidly developing field, and, while much research is still needed, a revolution in flood modeling science is taking place that will in the future substantially enhance our ability to manage flood risk globally.

4. Conclusions

Here we present, for the first time, a continuous long-term simulation of floodplain water depths at continental scale and at a resolution that enables us to understand inundation dynamics regionally. Simulations of floodplain inundation were performed with a hydrodynamic model based on gauged streamflow for the Australian continent from 1973 to 2012. This allowed us to assemble a temporally continuous flood inundation time series. We found the magnitude and timing of floodplain storage to significantly differ from streamflow in terms of their distribution. Furthermore, floodplain volume gave a much sharper discrimination of high hazard and low hazard periods than discharge.

The aforementioned discrepancies demonstrate that global streamflow or precipitation alone may not be sufficient to infer flood hazard and risk, but instead, their combination with flow depths and inundated area through a continuous, event-based historical hydrodynamic simulation should complement these inferences. However, more efforts are still needed to achieve better accuracy of global DEMs which would improve our current ability to simulate floodplain inundation more accurately. This would also allow a more rigorous analysis of floodplain water volumes and thus a more credible applicability of the latter to local floodplain management.

We argue that long-term event simulations would be of great benefit to the fields of flood risk, emergency response (for looking at clustering of events), (re-)insurance markets (for looking at flood event losses), ecosystem services, and many others dealing with floodplain flows; however, the record length may likely be too short in some places, so caution should be used when interpreting the results.

Nevertheless, it can be deduced that the magnitude and cost of global flood risk may need to be reevaluated using true hydrodynamic simulations in floodplains.

Acknowledgments
All authors are in agreement of all aspects of the work published and confirm contribution. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). G. J-P. Schumann's time was supported by a NASA ESTO grant (14AIST14-0074). The authors would like to thank Shahar Janjua for assisting with the model validation during his internship. The authors also declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. Note that the data supporting the conclusions can be obtained from the corresponding author upon request.

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