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Comparison of estimates of global flood models for flood hazard and exposed gross domestic product: a China case study

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Supplement S1. Detailed Model Descriptions

S1.1 CaMa-UT

The CaMa-UT model follows the cascade model structure consisting of the JRA-25 global climate forcing, the MATSIRO-GW global hydrological model (GHM) and the CaMa-Flood-v3.6.2 global river routing model.

S1.1.1 Global Climate Forcing

The JRA-25 global climate forcing reanalysis dataset (Onogi et al., 2007) with Global Precipitation Climatology Project (GPCP) precipitation correction covers the period 1979 to 2010. The reanalysis dataset aims to improve data quality in Asia. The 6-hour forecast of total precipitation is claimed to perform the best between different reanalysis datasets, especially in the tropics (Onogi et al., 2007). The horizontal resolution of the dataset is 100 km and the vertical resolution is 50 km. The JRA-25 dataset is only used by the CaMa-UT model in this comparison.

S1.1.2 Global Land Surface Model

The MATSIRO-GW GHM (Koirala et al., 2014) estimates the runoff from the soil to river by calculating the energy and water flux between land surface and atmosphere (energy and water balance). The original MATSIRO is complemented with the integration of water table dynamics, resulting in the MATSIRO-GW model. The GHM runs at 1 degree resolution with an hourly model time step for the 1979 to 2010 period. The evapotranspiration scheme uses bulk formula and the runoff scheme consists of infiltration and saturation excess in addition to groundwater flow. The snow scheme is solved using the energy balance. The daily runoff calculated by MATSIRO-GW is used to force the global river routing model CaMa-Flood.

S1.1.3 Global River Routing Model

River discharge and water level dynamics are simulated by the CaMa-Flood (version 3.6.2) model, in this comparison without the channel bifurcation scheme (Yamazaki et al., 2014b) and satellite-based river width parameters (Yamazaki et al., 2014a). CaMa-Flood discretizes river networks into unit-catchments. The water level is derived from water storage for each unit catchment in 0.25 degree grid boxes using sub-grid topography parameters (Yamazaki et al., 2009). The parameters are extracted from the SRTM3 DEM and the HydroSHEDS river network and are used to represent floodplain inundation as a sub-grid process. The model uses the water level and local inertial flow equations to calculate the river discharge and flow velocity between upstream and downstream unit catchments prescribed by a river network map (Bates et al., 2010; Yamazaki et al., 2013) The local inertial flow equations explicitly represent the backwater effect. Mass conservation equations are used to update the water level for each unit catchment by considering the upstream input, downstream output and the local runoff input (Yamazaki et al., 2014b) . The time evolution of the water storage is calculated using the water balance equation.

S1.1.4 Flood Frequency Analysis

The flood frequency analysis extracts the annual maximum water levels for the unit catchments (0.25 degree grid box) from 1979 to 2010. The results are fitted with a Gumbel distribution to estimate the peak water level for a given return period.

S1.1.5 Downscaling Method

The estimated water level for a given return period is downscaled from a 0.25 degree resolution onto a SRTM3 DEM at 3 arc seconds or ~90m resolution. The flood depth is then calculated at a 1/200 degree resolution or ~18 arc seconds.

S1.1.6 Geographical Datasets

The CaMa-UT model uses the SRTM3 DEM and HydroSHEDS river network as its geographical input datasets. To increase flow connectivity between river channels and the surrounding floodplains the DEM is bias corrected. An algorithm is used to adjust the DEM based on a prescribed drainage network dataset (HydroSHEDS). Errors and obstacles that are removed consist of vegetation canopy, contamination of elevations by levees and water surfaces, sub-pixel sized structures, and random radar speckles (Yamazaki et al., 2012).

S1.1.7 Output

CaMa-UT outputs undefended fluvial hazard maps for multiple return periods (RP5, RP10, RP20, RP25, RP50, RP100, RP200, RP250, RP500, and RP1000) at 18 arc seconds resolution. The smallest modelled catchment area considered is drainage areas larger than a 0.25 degree grid box (~500km^2).

S1.2 GLOFRIS

The GLOFRIS GFM follows the cascade model structure. The PCR-GLOBWB GHM is forced with the EU-WATCH project global climate forcing dataset and is run with the DynRout global river routing model extension, and the inundation is downscaled using the GLOFRIS downscaling model.

S1.2.1 Global Climate Forcing

The EU-WATCH global climate forcing dataset is a derivative of the ERA-40 reanalysis dataset with GPCP and CRU corrections at 0.5 degree resolution (Weedon et al., 2011). The EU-WATCH dataset is further bias-corrected with monthly Global Precipitation Climatology Centre (GPCC) precipitation and covers the 1980 to 2015 time period. The dataset highlights the importance of evaporation within the water cycle and generates precipitation, temperature and radiation outputs at 6-hourly time steps.

S1.2.2 Global Land Surface Model

The PCR-GLOBWB model is run at a 0.5 degrees (0.25 degrees is now available) and calculates the water energy balance with a daily time step to simulate daily river discharge and flood volume (Ward et al., 2013). The global hydrological model calculates the evapotranspiration scheme using the Penman-Monteith formulation. The snow scheme is calculated by the degree-day method. An advanced feature of the PCR-GLOBWB model is the subgrid parameterization of surface runoff, interflow and baseflow. These 3 components combined form the total specific runoff of a cell.

S1.2.3 Global River Routing Model

The Dynrout extension of the PCR-GLOBWB model is a dynamic river routing scheme. The discharge is calculated using the kinematic wave approximation of the Saint-Venant Equation (Beek et al., 2011) at daily time steps. For each time step the model checks if the volume of water stored in the river is above bank-full discharge. If this is the case, the overbank flow is routed across the floodplain, separating river flow from overbank flow dynamically (Ward et al., 2013). During routing, the floodplain is subject to open water evaporation. For the routing the Mannings coefficient is set to 0.04 for channels and set to 0.10 for floodplains. The Dynrout extension does not model the backwater effect at river convolutions.

S1.2.4 Flood Frequency Analysis

For each grid cell, the output of the global river routing model is used to extract annual maxima flood volumes for the period 1980 to 2015. The Gumbel distribution is fitted and flood volumes for the selected RPs are calculated (Ward et al., 2013). The flood volume represents the amount of water potentially residing outside the river banks (Winsemius et al., 2013).

S1.2.5 Downscaling Method

The estimated flood volumes from the flood frequency analyses are downscaled and converted into inundation depth flood hazard maps using the GLOFRIS downscaling module (Winsemius et al., 2013). The downscaling method converts the flood volumes calculated at 0.5 degrees for the different return periods into high resolution (30 arc seconds or ~1km) hazard maps. This is done by first assuming that 2-year RP volumes do not lead to overbank flooding. These volumes are then subtracted from the total volume of the higher return periods. The downscaling module calculates the water level above the water level of the river within a 0.5 degree pixel. The upstream cells are then evaluated on their surface elevation above the downstream cells river channel elevation. If the upstream elevation is lower, the water level is imposed over this cell. This is done iteratively with steps of 0.1 m of water level. The process is mass conservative because it ensures that the water volume is the same as the global hydrological model output whilst selecting 1 km river pixels within the 0.5 degree pixels.

S1.2.6 Geographical Datasets

GLOFRIS uses the HydroSHEDS derived SRTM30 DEM and river network as its geographical input datasets.

S1.2.7 Output

GLOFRIS outputs undefended fluvial hazard maps for multiple return periods (RP5, RP10, RP25, RP50, RP100, RP250, RP500, and RP1000) at 30 arc seconds resolution. The smallest modelled catchment areas are equal to or above river Strahler order 6.

S1.3 JRC

The JRC model follows the cascade model structure although in a slightly different manner than the other cascade models in this study. The ERA-Interim global climate forcing dataset is used as input for the HTESSEL GHM. Next, the output is passed through the LISFLOOD-Global groundwater and river routing model. Combined, HTESSEL and LISFLOOD-Global perform the hydrological simulations for the Global Flood Awareness System (GloFAS). Flood frequency analysis is used to derive annual discharge maxima from the GloFAS stream flow simulations. The resulting data is then downscaled to a 30 arc second river network. Next, the 2D-hydrodynamic flood model CA2D performs local flood simulations along predetermined flood points. The flood hazard maps are created by merging the flood simulations for these flood points.

S1.3.1 Global Climate Forcing

The ERA-Interim climate forcing dataset covers the period 1980 to 2013. The dataset contains 6-hourly gridded estimates of 3D meteorological variables and 3-hourly estimates of a large number of surface parameters at 80 km horizontal resolution (Alfieri et al., 2012). The precipitation dataset has been bias-corrected with the GPCP v2.1 dataset. The output consist of precipitation, temperature and radiation variables (Balsamo et al., 2015).

S1.3.2 Global Land Surface Model(Dottori et al., 2016)

The output of the ERA-Interim dataset is used to force the HTESSEL GHM (Balsamo et al., 2009). HTESSEL estimates the surface water and energy fluxes, as well as the temporal evolution of soil temperature, moisture contents and snowpack conditions (Dottori et al., 2016). HTESSEL uses the energy balance and the Penman-Monteith equation for the evaporation scheme. The runoff scheme consists of the variable infiltration capacity and the Darcy equations. The snow scheme is modelled using the energy balance (Balsamo et al., 2009). The model is run at 0.1 degree resolution with an hourly time step. The outputs consist among others of surface and sub-surface runoff.

S1.3.3 Global River Routing Model

The HTESSEL model is not capable of simulating horizontal water fluxes along the river channel and as a result LISFLOOD-Global is used to model groundwater flow in addition to river routing. LISFLOOD-Global is a 1-D channel routing model, run at 0.1 degree resolution and is executed using the kinematic wave equations. The surface and sub-surface runoff output from HTESSEL is passed through the LISFLOOD-Global river routing model. The river parameters like channel gradient, Mannings coefficient, river length, width and depth were estimated from the digital elevation model, the river network and the upstream area (Alfieri et al., 2012). The Mannings coefficients range from 0.2 for forested area to 0.04 for river channels. The river routing model is capable of simulating transmission losses in arid and semi-arid regions.

S1.3.4 Flood Frequency Analysis

Daily annual maxima of discharge are extracted for each grid element of the GloFAS river network and are fitted with a Gumbel distribution to estimate discharge warnings at a range of RPs (Alfieri et al., 2012; Dottori et al., 2016).

S1.3.5 Downscaling Method

The stream flow information (daily and extreme discharges) is downscaled from a 0.1 degree resolution to a higher resolution of 30 arc seconds or ~1km. The downscaling is spread over “flood points” that are regularly spaced 10 km apart along the 30 arc seconds river network. The “flood points” are then linked to a section of the 0.1 degree river network in order to assign discharge hydrographs. The downscaled daily and extreme discharges are then processed to create synthetic flood hydrographs for each flood point based on local peak discharge, flow duration and time of concentration (Dottori et al., 2016).

S1.3.6 Flood Inundation Model

The “flood points” assign areas for flood simulation with the 2D hydraulic model CA2D. This flood simulation is executed using the semi-inertial formulation of the shallow water equations with a local time step algorithm. The flood inundation modelling uses a sub-grid approach for representing the main river network, which is composed of a channel and a flood plain fraction, each one with a different elevation and area. The CA2D model uses a D8 flow connection where a cell is connected to 8 instead of 4 cells (Dottori and Todini, 2011). The Mannings coefficient or roughness values are derived from land use information from the Global Land Cover 2000 dataset at 30 arc second resolution. After all the local flood simulations are executed for the flood points, the flood maps are merged together to create flood hazard maps.

S1.3.7 Geographical Datasets

The JRC model uses the HydroSHEDS DEM and Drain Direction map for river basins below 60 degrees north. Channel bed elevations are based on the lowest elevation values of the 3 arc second void-filled SRTM DEM included in the 30 arc second river network cell. This is an averaging method that smooths out random errors. The channel width is taken from the Global River Width Database (Yamazaki et al., 2014a). The DEM for flood simulations is corrected using the global vegetation height dataset (Simard et al., 2011). No correction is applied for urban areas.

S1.3.8 Output

The JRC model outputs undefended fluvial hazard maps for multiple return periods (RP10, RP20, RP50, RP100, RP200, RP500, and RP1000) at 30 arc seconds. The modelled river network includes rivers with an upstream drainage or catchment area larger than 5000 km^2.

S1.4 ECMWF

The ECMWF model follows the cascade model structure. The global flood hazard maps are based on the ERA-Interim/Land dataset, this is a combination of a global climate forcing dataset in conjunction with a GHM. The meteorological fields of the ERA-Interim reanalysis force the HTESSEL GHM, the same model used by JRC. The daily runoff from the model forces the CaMa-Flood global river routing model, the same routing model as the CaMa-UT model. A flood frequency analysis is applied to extract the annual maxima of river discharge for each return period. The same downscaling method as CaMA-UT is applied.

S1.4.1 Global Climate Forcing

The ERA-Interim climate forcing dataset covers the period from 1980 to 2013. The dataset contains 6-hourly gridded estimates of 3-D meteorological variables and 3-hourly estimates of a large number of surface parameters (Alfieri et al., 2012). The horizontal resolution is 80 km and the precipitation dataset has been bias-corrected with the GPCP v2.1 dataset. The output consist of precipitation, temperature, and radiation variables (Balsamo et al., 2015).

S1.4.2 Global Land Surface Model

The HTESSEL model is not capable of simulating horizontal water fluxes along the river channel and as a result LISFLOOD-Global is used to model groundwater flow in addition to river routing. LISFLOOD-Global is a 1-D channel routing model, run at 0.1 degree resolution and is executed using the kinematic wave equations. The surface and sub-surface runoff output from HTESSEL is passed through the LISFLOOD-Global river routing model. The river parameters like channel gradient, Mannings coefficient, river length, width and depth were estimated from the digital elevation model, the river network and the upstream area (Alfieri et al., 2012). The Mannings coefficients range from 0.2 for forested area to 0.04 for river channels. The river routing model is capable of simulating transmission losses in arid and semi-arid regions.

S1.4.3 Global River Routing Model

River discharge and water level dynamics are simulated by the CaMa-Flood (version 3.6.2) model, in this comparison without the channel bifurcation scheme (Yamazaki et al., 2014b) and satellite-based river width parameters (Yamazaki et al., 2014a). CaMa-Flood discretizes river networks into unit-catchments. The water level is derived from water storage for each unit catchment in 0.25 degree grid boxes using sub-grid topography parameters (Rudari and Silvestro, n.d.)(Yamazaki et al., 2009). The parameters are extracted from the SRTM3 DEM and the HydroSHEDS river network and are used to represent floodplain inundation as a sub-grid process. The model uses the water level and local inertial flow equations to calculate the river discharge and flow velocity between upstream and downstream unit catchments prescribed by a river network map (Bates et al., 2010; Yamazaki et al., 2013). The local inertial flow equations explicitly represent the backwater effect. Mass conservation equations are used to update the water level for each unit catchment by considering the upstream input, downstream output and the local runoff input (Yamazaki et al., 2014b) . The time evolution of the water storage is calculated using the water balance equation.

S1.4.4 Flood Frequency Analysis

The flood frequency analysis extracts the annual maxima water levels for the unit catchments (0.25 degree grid box) from 1979 to 2010. The results are fitted with a Gumbel distribution to estimate the peak water level for any return period.

S1.4.5 Downscaling Method

The estimated water level for a given return period is downscaled from a 0.25 degree resolution onto a SRTM3 DEM at 3 arc seconds or ~90m resolution. The flood depth is then calculated at a 1/200 degree resolution or ~18 arc seconds.

S1.4.6 Geographical Datasets

The ECMWF model uses the SRTM3 DEM and HydroSHEDS river network as its geographical input datasets. To increase flow connectivity between river channels and the surrounding floodplains the DEM is bias corrected. An algorithm is used to adjust the DEM based on a prescribed drainage network dataset (HydroSHEDS). Errors and obstacles that are removed consist of vegetation canopy, contamination of elevations by levees and water surfaces, sub-pixel sized structures, and random radar speckles (Yamazaki et al., 2012).

S1.4.7 Output

The flood hazard maps of the ECMWF model consist undefended fluvial hazard maps for multiple return periods at 18 arc seconds resolution. The available return periods are: RP5, RP20, RP25, RP50, RP75, RP100, RP500, and RP1000. The smallest modelled catchment areas consist of drainage areas larger than a 0.25 degree grid box (~500km^2).

S1.5 CIMA-UNEP

The CIMA-UNEP model follows the gauged flow model structure without downscaling methods and with global climate forcing and global hydrological model corrections. An extreme value statistical analyses are performed based on a global river discharge dataset. From this dataset a regionalized flood frequency analysis is conducted using the index flood method to compute extreme discharge values ("index discharge") around the globe. Regression techniques are used to extrapolate the extreme discharge values to areas where there is no or insufficient gauged data. To improve the regression and assess where there are insufficient observations the EC-Earth global climate forcing dataset is used to force the Continuum GHM as a correction. After the determination of the discharge quantiles, the results are passed through a simplified hydraulic flood model (global river routing model) to create the flood hazard maps.

S1.5.1 Global Gauge Dataset

The global gauge dataset used in the CIMA-UNEP model consists of more than 8000 stations around the world (Rudari and Silvestro, n.d.). The data stems from various sources and contains various compilations of national and regional datasets. Long-term mean monthly discharge is acquired from the Global Runoff Data Centre (GRDC, Germany) and is complemented with the datasets R-ArcticNET, RivDIS v1.1, Monthly Discharge Data for World Rivers (DE/FIH/GRDC and UNESCO/IHP) and more.

S1.5.2 Regional Flood Frequency Analysis

The temporal resolution of the river discharge data of the global gauge dataset is downscaled to daily data before use in the regional flood frequency analysis, using an autoregressive approach (Rebora et al., 2006). After temporal downscaling a regionalized flood frequency analysis is conducted using the index flood method to compute extreme discharge values ("index discharge") around the globe. The CIMA-UNEP model uses regression techniques on geomorphological and climatological variables to extrapolate the extreme discharge values to areas where there is no or insufficient gauged data. The generalized extreme value distribution is fit for each site to estimate the quantiles associated with different return periods (Rudari et al., 2015).

S1.5.3 Global Climate Forcing and Global Hydrological Model Correction

The addition of the EC-Earth Global Climatic Model version 3 (Johnston et al., 2012) and the Continuum GHM improves the extrapolation of gauged data through climatological variables by assessing where there are not enough observations (Silvestro et al., 2013). EC-Earth is used to reproduce present climate statistics with a 3 hour time step covering the period 1960 to 2012 at a 1.125 degree resolution. Precipitation and temperature are bias corrected based on the observed quantities of the CHIRPS dataset, which covers the period 1981-2012 (Rudari et al., 2015). The meteorological fields produced by the EC-Earth model force the Continuum model. The model time step is 3 hourly at 3 arc second resolution, similar to the DEM resolution. The energy balance is solved explicitly for each cell with the force-restore equation, solving the evapotranspiration scheme. The runoff scheme separates channel and hillslope flow. Snow is simulated with mass conservative equations (Silvestro et al., 2013, 2015).

S1.5.4 Global River Routing Model

After the determination of the discharge quantiles the results are passed through a simplified hydraulic flood model (global river routing model). The model generates a cross section of a specified width for each stream section. These cross sections are used to extract elevation data from the DEM in order to create specific stage discharge functions using the Manning's equation (Rudari et al., 2015). The resulting functions calculate the river stage from peak flow estimates for each return period. The corresponding flooded area is generated for each stream section and combined into flood hazard maps based on the DEM. The river routing model uses a variable Manning's roughness coefficient along each cross section and is determined on the basis of the land use map provided by the Glob Cover dataset. The model allows for the simulation of braiding rivers and accounts for the backwater effect.

S1.5.5 Geographical Datasets

The CIMA-UNEP GFM uses a reconditioned SRTM3 (version 4.12) DEM and HydroSHEDS river network. The reconditioning is performed by recombining the HydroSHEDS dataset with the original point of the DEM using the TOPODEM interpolation technique. This method uses an iterative finite difference interpolation technique. TOPOGRID is used to connect drainage structures and to correct the representation of ridges and streams for the river network (Rudari et al., 2015).

S1.5.6 Output

The CIMA-UNEP model is the only model that has a level of flood protection built in, which cannot be removed. Flood protection is integrated by creating defense ellipsoids around large cities, the size of which is dependent on the GDP. All flooding within this ellipsoid is removed in post-processing and follows the assumption of total flood protection up to a 200 year return period. The CIMA-UNEP flood hazard maps are fluvial only and the available return periods are: RP25, RP50, RP100, RP200, RP500 and RP1000. The acquired resolution of the flood hazard maps is ~32 arc seconds resolution or ~1km. It is important to note that the native output is at 3 arc seconds. The river network size considered includes rivers with an upstream drainage or catchment area larger than 1000km^2.

S1.6 Fathom

The FATHOM model follows the gauged flow model structure by applying a hybrid-clustering approach in conjunction with a flood-index methodology to global river discharge station datasets (Smith et al., 2015). Through these methods a regionalized flood frequency analyses is conducted to compute annual maxima (AMAX) discharge values. Simple design hydrographs are created based on AMAX discharge values in order to create flood hydrographs that are required to force hydrodynamic simulations. The hydrodynamic simulations are conducted with the sub grid variant of the LISFLOOD-FP global river routing model at a 30 arc second resolution. The water levels are than downscaled to 3 or 30 arc seconds, while preserving water surface elevation, to create the flood hazard maps (Sampson et al., 2015).

S1.6.1 Global Gauge Dataset

The FATHOM GFM derives its input from a global dataset of river discharge stations, sourced from 703 stations of the Global Runoff Data Centre (GRDC) and from 242 stations of the United States Geological Survey (USGS) stream gauge network (Smith et al., 2015). The first covers a discharge record from 1983 to 2002 and the second from 1807-2009. The stations used are representative of all hydro-climatic regions in the world.

S1.6.2 Regional Flood Frequency Analysis

The regional flood frequency analysis uses a hybrid-clustering approach in conjunction with a flood-index methodology to create global data coverage. The hybrid-clustering approach (Smith et al., 2015) uses catchment descriptors of climate class, upstream annual rainfall and catchment characteristics. The data from the global gauge datasets are first subdivided into the 5 main categories of the Köppen-Geigner climate classification (Kottek et al., 2006). The hybrid-clustering approach is then used to partition the gauging stations into homogeneous regions. The catchments are then pooled together based on a combination of Ward's algorithm and k-means clustering (Ramachandra Rao and Srinivas, 2006; Smith et al., 2015).

Using the flood-index method a regional flood frequency analysis is applied to each group of pooled gauges. The scale parameter is called the index-flood. From the estimation of the index-flood, the flood frequency curves are derived that represent the ratio of any given recurrence interval flood to the index-flood (Smith et al., 2015).

The AMAX discharge per pooling group, created by the above mentioned methods, are converted into flood hydrographs for the forcing of the hydrodynamic river routing. The conversion uses the rational method, where time of concentration is calculated with the Manning's equation to estimate routing velocity (Sampson et al., 2015).

Small channels with a catchment area smaller than 50 km2 use a different method because these channels are driven mainly by precipitation, this is the pluvial component of the flood hazard maps. A "rain-on-grid" method is used where flow is generated by raining directly on the DEM at a 3 arc second resolution instead of the 30 arc second resolution used for the regional flood frequency analysis. Instead of discharge data, Intensity-Duration-Frequency (IDF) relationships are used to estimate the duration, intensity and frequency of extreme rainfall. The method then follows the same data pooling approach that is used for the fluvial component.

S1.6.3 Global River Routing Model

The output of the regional flood frequency analyses in the form of flood hydrographs is the input for the sub grid variant of the LISFLOOD-FP global river routing model. LISFLOOD-FP uses the inertial formulation of the shallow water equations (Neal et al., 2012) for areas that are not steep or discontinuous in topography. The steep areas are simulated with a slope-dependent fixed-velocity 2D routing scheme (Sampson et al., 2013). The global river routing model simulations are conducted at a 30 arc second resolution.

S1.6.4 Downscaling Method

A downscaling method is used for the interpolation of a smooth water surface elevation between the centers of each 30 arc second cells, interpolating the water surface levels to a 3 arc second resolution. The water depths are re-calculated by comparing the 30 arc second DEM with the 3 arc second DEM. This downscaling method is surface water elevation preservative.

S1.6.5 Geographical Datasets

The FATHOM model uses the void-filled variant of the SRTM DEM at 3 and 30 arc seconds. Corrections are applied to the 3 arc second SRTM DEM, these corrections consists of a vegetation correction (Baugh et al., 2013; Simard et al., 2011) and an urban area correction (Elvidge et al., 2007) that uses urbanization to control a window filter. In addition, noise reduction using a feature preserving smoothing algorithm (Gallant, 2011) is applied. The mean of corrections for the 3 arc second DEM is used to correct the 30 arc second DEM to ensure consistency (Sampson et al., 2015).

S1.6.6 Output

the FATHOM model outputs undefended fluvial and combined (fluvial with pluvial) hazard maps for multiple return periods (RP5, RP10, RP20, RP50, RP75, RP100, RP200, RP250, RP500, and RP1000) at 3 arc seconds resolution. FATHOM does provide flood hazard maps with integrated flood protection, but these were not considered in this study. The upstream catchment area for the fluvial hazard maps under consideration is larger than 50 km^2.

S1.7 JBA

The JBA model follows the gauged flow model structure without the use of regression or downscaling techniques. The global gauge dataset consists of precipitation time series that are used to calculate design rainfall and design flood magnitude with hydrological models. These statistics force the global river routing models to calculate the output for each cell of the flood hazard maps. The model has two methods that each use one of two global river routing models that depend on the size of modelled rivers, size and slope of the floodplain, type of flooding and availability of a bare-earth digital terrain model (DTM) or a digital surface model (DSM).

S1.7.1 Global Gauge Dataset

The JBA method uses two types of input datasets to force two flood frequency analysis (FFA) models depending on the river size or the type of floods (fluvial or pluvial) modelled.. The large rivers FFA model defines large rivers as having a catchment size >500 km^2. The input data in the form of rainfall data is provided by the Climate Research Unit (CRU). The CRU TS 3.2 dataset contains monthly time series of precipitation, daily maximum and minimum temperatures, cloud cover, and other variables covering the Earth's land areas for 1901-2011. The data set is gridded to a 0.5 degree resolution, based on analysis of over 4000 individual weather station records.

Small rivers and surface water are defined as being of catchment size <500 km^2. The Precipitation time series for these areas are derived from the Climate Forecast System Reanalysis (CFSR) precipitation dataset (Saha et al., 2010). This dataset has a higher temporal and spatial resolution, providing hourly rainfall totals on a 0.3 degree grid for the period 1979-2009.

S1.7.2 Flood Frequency Analysis

The FFA model for large rivers estimates river flow along the river network by applying an empirically based rainfall-runoff approach. This approach links design rainfall to design river flood magnitude for a range of return periods. The design rainfall is calculated for the watershed of each individual river section (i.e. drainage points are created at each confluence and the watershed of each point is delineated). There is an initial step of a spatial query between the 0.5 degree CRU data and each watershed boundary, to sum the monthly rainfall depth for each tile/part of tile for each watershed. This rainfall depth is then converted to a monthly rainfall volume per watershed. The empirical relationship to transform from rainfall to design flood peak (calibrated on observed river discharges) is applied to each watershed.

The FFA model for small rivers and surface waters generates design rainfalls for three storm durations (1, 3, and 24 hours) through extreme value analyses of the CFSR precipitation dataset. This results in 3 design rainfall totals for each return period at a 0.3 degree resolution. These are then smoothed and interpolated to create a continuous rainfall surface for each return period and storm duration. Where available, local Intensity-Duration-Frequency (IDF) curves and national rainfall statistics supplement the CFSR data and calibrate the rainfall estimates. The continuous rainfall surface is used to generate storm hyetographs for each model catchment.

S1.7.3 Global River Routing Model

The JBA method uses either the RFlow model or the JFlow model for the river routing, depending on the size of the rivers, size of the floodplain and the availability of a bare-earth digital terrain model (DTM).

The RFlow model is used when there is no bare-earth DTM available and uses a digital surface model (DSM). The model is a 1D model based upon normal depth calculations and custom 2D flood spreading tools. The inputs required are elevation data, the drainage network and river flow estimates at the upstream and downstream end of each watercourse section. Cross sections are drawn at interpolation points that are spaced between 200 m and 5 km apart. The Manning's equation is then used to estimate normal flood depth at each cross section, which is spread downstream with the 2D flood spreading tools.

The JFlow model is used for large rivers where a bare-earth DTM is available, for all small rivers, and for surface water flooding. An exception is that the JFlow model is also used for large rivers even if no DTM is available, if the rivers have a very flat or wide floodplain. The JFlow model is a full 2D hydrodynamic model that can be run in different configurations based on river size and flood type. For the modelling of large rivers, regularly spaced points are placed along the drainage network. At each point, a flood hydrograph is generated for each return period. The bankfull discharge is estimated and removed from the simulation. The remaining water volume is spread along the floodplain by calculating full shallow water equations.

Small rivers and surface water are simulated by the JFlow model using a direct-rainfall configuration. The design hyetographs created through the extreme value analysis are applied to an entire catchment as a blanket. Different runoff rates are applied across each catchment to reflect different land use and climate characteristics. Towns, cities and urban drainage systems are accounted for by removing the 5-year rainfall total from the flood simulations.

Output from both global river routing models are the maximum depth of flooding for each 30m cell for a range of return periods.

S1.7.4 Geographical Datasets

The JBA method uses Intermap Technologies Inc's NEXTMap WORLD30 Digital Surface Model (DSM) for China. The DSM provides global coverage at 1 arc second resolution. On a global scale, the JBA method uses a bare earth digital terrain model (DTM) in addition to the DSM. The JBA method derives the river network from elevation data and applies extensive validation and correction before use.

S1.7.5 Output

JBA Risk Management provides undefended fluvial and combined (fluvial with pluvial) hazard maps for multiple return periods (RP20, RP50, RP100, RP200, RP500 and RP1500) at 1 arc seconds resolution. JBA further provides a dataset of defences (largely for dense urban areas) that can be superimposed on the flood hazard maps to create a defended set of flood maps per return period. There is no minimum for the catchment size considered in the modelling domain.

S1.8 KatRisk

The KatRisk GFM follows the cascade model structure without the use of downscaling methods. The fluvial and pluvial components are modelled separately. The fluvial and pluvial flood components of the KatRisk model are forced with the ERA-Interim climate reanalysis dataset, daily gridded precipitation observations are provided by the CPC. The data are then used as input to the Topmodel rainfall-runoff model (global hydrological model). The outputs force two separate 2D-hydrodynamic river routing models, depending on the flood type. Flood frequency analysis (FFA) is used to derive the flood depth at 3 arc seconds. Both flood types are finally merged into combined hazard maps.

S1.8.1 Gauged Dataset and Climate Forcing

KatRisk uses the gridded daily precipitation observations provided by the US National Weather Service's Climate Prediction Center (CPC). Atmospheric variables used to estimate evapotranspiration are taken from the ERA-Interim climate forcing dataset. The ERA-Interim climate forcing dataset covers the period from 1980 to 2013. The dataset contains 6-hourly gridded estimates of 3-D meteorological variables and 3-hourly estimates of a large number of surface parameters (Alfieri et al. 2013). The horizontal resolution is 80 km and the precipitation dataset has been bias-corrected with the GPCP v2.1 dataset. The output consists of precipitation, temperature and radiation (Balsamo et al. 2015). The pluvial component uses historical rainfall data in conjunction with extreme value distributions to estimate rainfall intensity over each catchment for a series of return periods (10, 20, 50, 100, 200, 500 year).

S1.8.2 Global Hydrological Model

The above mentioned datasets are used to force the Topmodel global hydrological model (GHM). Topmodel is a rainfall-runoff model that assumes that local runoff can be described by local slope and upstream area. Groundwater tables and flow paths are described by surface topography. The evapotranspiration schemes use the Penman-Monteith equation and the snow scheme is solved using the degree day method. The daily runoff calculated by the Topmodel is used to force the global river routing models of KatRisk.

S1.8.3 Global River Routing

A unit hydrograph approach is used to model transport of water along the river network. Upstream and lateral inflow is treated as instantaneous input to a linear time-invariant model using the advection-diffusion equation as response function. Two parameters (wave celerity and diffusivity) are calibrated for each catchment.

The fluvial inundation is calculated with a 2D-hydrodynamic model that uses the shallow water equations. Upstream inflow is estimated from the river routing model and the model is run in steady state, recording final flood depths for each cell. The model uses a second-order finite volume scheme.

The pluvial inundation dynamics are calculated using a 2D-hydrodynamic storage cell model that uses the diffusive wave equations. The runoff from the rainfall-runoff model is distributed uniformly across a catchment and routed according to topography. In modeling the pluvial flow, the fraction of the precipitation that becomes surface runoff (as opposed to being absorbed by the soil or evaporating) is calibrated using historical river gauge data.

S1.8.4 Geographical Datasets

KatRisk has modified the SRTM3 HydroSHEDS DEM before use. The DEM is processed algorithmically and manually to remove above ground obstructions and artificial noise.

S1.8.5 Output

Katrisk provides undefended maximum flood depth hazard maps from pluvial and fluvial flooding for multiple return periods (RP10, RP20, RP50 RP100, RP200 and RP500) at 3 arc second resolution. There is no minimum catchment size considered in the modelling domain. For this study, only inundated areas with flood depths > 4 cm were considered in the flood hazard maps .

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