Advancing global flood hazard simulations by improving comparability, benchmarking, and integration of global flood models

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Abstract

In recent years, a range of global flood models (GFMs) were developed, each utilizing different process descriptions as well as validation data sets and methods. To quantify the magnitude of these differences, studies assessed the performance of GFMs on the continental and catchment level. Since the default models set-ups resulted in locally marked deviations, there is a clear need for further and especially more standardized research to not only maintain credibility, but also support the application of GFM products by end-users. Consequently, we here outline the basic requirements and challenges of a Global Flood Model Validation Framework for more standardized model validation and benchmarking in the hope of encouraging the much needed debate, research developments in this direction, and involvement of science with end-users. By means of the framework, it is possible to streamline the data sets used for input and validation as well as the validation approach itself. By subjecting GFMs to more thorough and standardized methods, we think their quality as well as acceptance will increase as a result, especially amongst end-users of their outputs. Otherwise GFMs may only serve a purely scientific purpose of continued model improvement but without practical use. Furthermore, we want to invite GFM developers to make their models more integratable which would allow for representation of more physical processes and even more detailed comparison on a model component basis. We think this is pivotal to not only improve the accuracy of model input data sets, but to focus on the core of each model, the process descriptions. Only if we know more about why GFMs deviate, are we able to improve them accordingly and develop a next generation of models, not only providing first-order estimates of flood extent but supporting the global disaster risk reduction community with more accurate and actionable information.

1. Introduction

Economic damage and casualties due to flooding increased remarkably in recent decades. Due to a combination of factors, such as population growth, urbanisation, and a changing climate, flood risk will continue to rise world-wide (Ceola et al., 2014; Munich Re, 2010; Winsemius et al., 2016). Thus, the implementation of improved flood risk management, as well as efficient adaptation and mitigation measures are required and, more fundamentally, a better understanding of the processes driving flood events. With most riverine flood events simultaneously impacting multiple neighbouring countries and catchments (Jongman et al., 2014), declining availability of observed discharge data on the one hand, and increasing computational power on the other hand, the benefit of using global flood models (GFMs) was recognized as a key tool in tackling these challenges. Hence,

hence their development and application increased rapidly in recent years (Bates et al., 2018; Ward et al., 2015).

All available GFMs are fit for the purpose of modelling global flood hazard and risk and validated to some extent during their development and dissemination. Yet, they all inherently have, depending on their governing processes and structure, distinct properties, strengths, and weaknesses. Since validation data, period, and location are usually not consistent between GFM description studies, model differences do not directly become visible while in fact they can result in locally remarkable deviations when compared with each other (Bernhofen et al., 2018; Trigg et al., 2016).

In contrast to GFMs, global hydrologic models (GHMs) are regularly compared, for instance their routing scheme (Zhao et al., 2017) or simulated runoff (Beck et al., 2017). Such model intercomparison projects are a great way to narrow the above-mentioned knowledge gap, let alone the stimulus for intensified scientific collaboration and exchange. Consequently, GFMs are behind in terms of collaborative testing as lack of more consistent and regular comparison, hampering a better understanding of the discrepancies in model outputs. This epistemic uncertainty could, we postulate, lead to problematic model equifinality as results may agree only coincidentally.

A better understanding of why and where each model may or should be used is, however, pivotal. Discerning not only a model's strengths, but also its uncertainties, limitations, and differences with respect to other models is a central pillar to put model outputs into perspective and increase their credibility. By virtue of a transparent comparison process with other models, individual model developers can see more clearly how to improve their own data sets and process representation where they may see these lacking.

Since the relative accuracy would become more tangible, the meaningfulness and applicability of each model for end-users would increase too. Various workshops aimed at bringing together researches and practitioners provide evidence that there is a growing demand for more transparency and better overview of GFMs as well as their characteristics and uncertainties (Global Flood Partnership, 2016, 2017; Willis Towers Watson, 2018). This is particularly important for non-expert users of model outputs who rely on a clear understanding of the appropriateness and limitations in order to use the data appropriately (Trigg et al., 2016; Ward et al., 2015).

So, what are some possible ways forward? First, to facilitate obtaining the required understanding, an easily accessible yet demanding validation and benchmarking framework could create a meaningful starting point. That this idea timely is shown by similar developments towards a framework for operational flood risk management (Alfieri et al., 2018) as well as from the above-mentioned need of end-users to get a better grasp of model properties. Second, models are in almost all cases closed systems where output is produced based on the input provided and the subsequent model steps executed. While this works well for default model applications, it hampers the model's extension and integration with new features, modules or even other models. In times of continued model integration, however, bridges with other models should be built if more (physical and non-physical) processes influencing flood hazard are required.

In the remainder of this article, we first present a range of state-of-the art GMFs and outline their specific properties. Second, we assess the different validation data sets, periods, and locations of these GFMs as published in peer-reviewed papers to supplement our call for streamlined validation approaches. Subsequently, we sketch a possible design of a Global Flood Model Validation Framework for model validation and benchmarking. Last, motivation and possible approaches to advance the openness and integration capability of GFMs is presented. The article is ended with conclusions, ideas on how to implement the presented ideas and recommendations for further improvement of comparability and applicability.

2. Current global flood models

Currently the most fully developed and openly accessible state-of-the-art GFMs are CaMa-Flood (Yamazaki et al., 2011), GLOFRIS (Winsemius et al., 2013), JRC (Dottori et al., 2016), CIMA-UNEP (Rudari et al., 2015), as well as the Fathom model (formerly SSBN; Sampson et al., 2015) and the ECMWF model (Pappenberger et al., 2012). These models can be divided into two main categories of GFMs, depending on the flow derivation modelling steps taken (Figure 1).

It must be noted that there is also a number of private or national CAT models that include global flood hazard ("catastrophe models"), each also having its own properties, modelling cascades, and evaluation procedure and criteria. Obtaining information about these CAT models is, however, complicated due to the protection of Intellectual Property (IP) rights and competitive commercial advantage. The following comparison therefore represents only the most open models and may need updating in the future if these commercial models become more transparent.

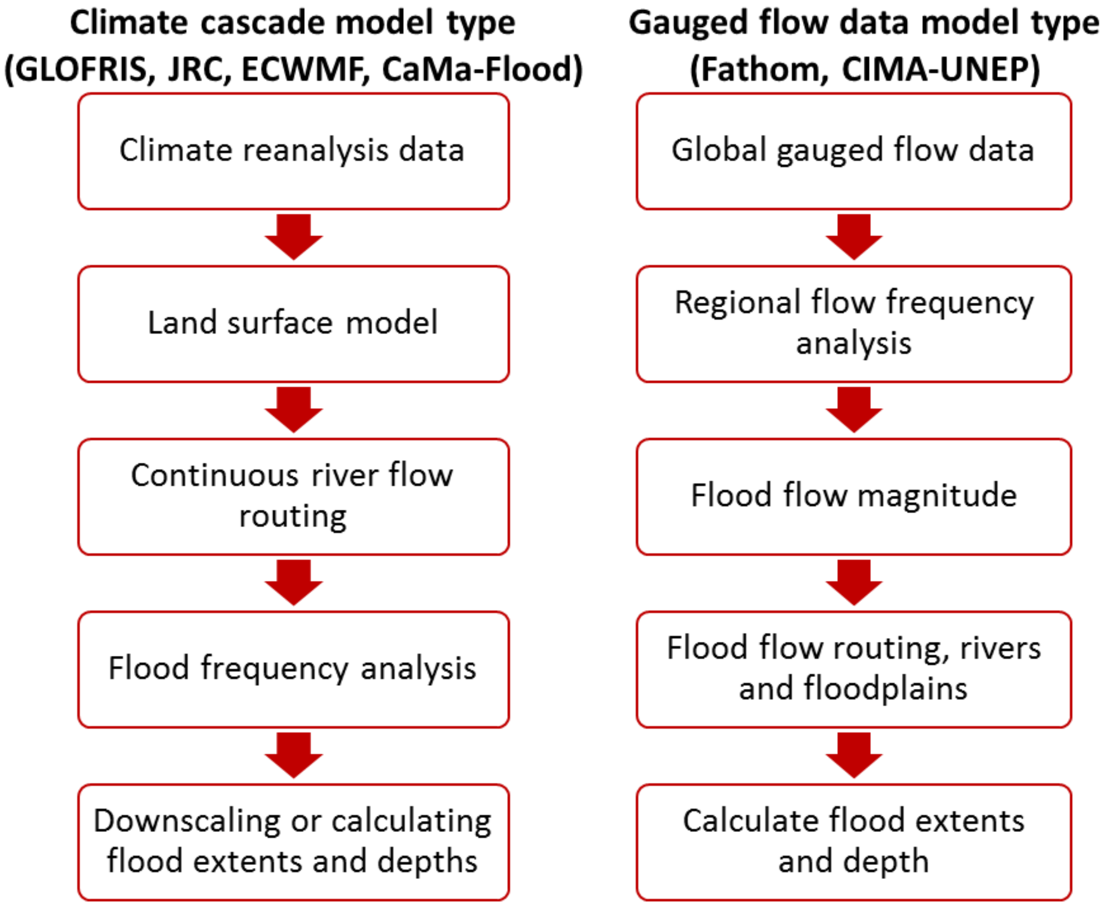

Figure 1: Modelling steps required for the two sub-categories of global flood models; modified from (Trigg et al., 2016)

The differing operations at various model stages result in a range of modelling approaches, each one using its own input data, method of calculating floodplain inundation, and spatial resolution. For instance, GLOFRIS runs at a 30 arc-min spatial resolution before post-processing and downscaling to 1 km, whereas the Fathom model yields output directly at 90 m globally. Such discrepancy in spatial resolution is possible because the models simulate processes with different scaling potential (Bierkens et al., 2015). As a result, the models perform differently in these scale-dependent processes. For example, GFMs employing a land surface or hydrologic model excel in simulating processes such as open water evaporation and groundwater infiltration. Contrariwise, the routing schemes of land surface or hydrologic models (typically the kinematic wave approximation) are less sophisticated and therefore lack important discharge dynamics which can be obtained from models employing higher-order approximations of full shallow water equations.

Notwithstanding the differences, all models are applied regularly and used to inform policy-makers about flood hazard and risk. GLOFRIS, for example, is applied within the World Resources Institute (WRI) Aqueduct tool, projecting current and future flood risk across the entire globe (World Resources Institute, 2018). The JRC model is applied as part of the Global Flood Awareness System GloFAS (Alfieri et al., 2013), and the Fathom model was recently used to compare flood risk with Federal Emergency Management Agency (FEMA) estimates across the continental United States (Wing et al., 2018). CIMA-UNEP was applied for estimating current and future flood risk for the Global Assessment Report (GAR) of the United Nations Office for Disaster Risk Reduction (Rudari et al., 2015; UNISDR, 2015).

3. META study: validation of GFMs

Before employing a GFM for flood hazard and risk assessments, ideally it should undergo thorough testing and validation. Due to the wide range of available observation data sets and depending on the model period as well as study area opted for, all GFMs may obtain good validation results, yet without providing any insight into performance relative to other GFMs. To get a grasp of the differences in model validation, we here detail the various data sets, periods, and locations used for the above-mentioned models.

As Table 1 shows, the spread in validation (or benchmarking) data sets used is tremendous. Partially, this can be explained by the particular moment of model publication and the availability of data sets at that time. It also shows that most GFMs are validated against inundation extent, but only a few compare simulated discharge and water surface elevation with observations, although these aspects are important for flood risk management as well. Besides, the river basins used for model validation differ widely between studies as does the number of scientific reports documenting the model development over time.

Trigg et al. (2016) showed that the GFMs listed in Chapter 2 agree only for around a third of simulated flood extent in Africa. Since there can only be one actual realization of inundation at a time, this finding shows that a successful individual validation of models without comparison may be misleading with respect to the accuracy of the resulting inundation maps.

Together with the lack of congruency in model validation, the results from Trigg et al. (2016) bolster the above-made claim that, to really get an idea of why model results deviate and to eventually learn from each other, more standardized validation and benchmarking procedures could be useful.

4. Establishing a Global Flood Model Validation Framework

To facilitate standardized validation and benchmarking of models and their results, a framework facilitating these steps is needed. A first step towards more systematic benchmarking was set with the GLOFRIM framework by Hoch et al. (2017) which allows for forcing different hydrodynamic models with identical hydrologic output. Yet, it can only mark a first proof-of-concept since much more functionality would eventually be needed. Some key tasks of a Global Flood Model Validation Framework would be, amongst others, to provide a front-end where users can upload model results as well as a back-end to not only execute validation and benchmarking autonomously but also store validation and benchmarking results (Figure 2). Besides, the framework should provide input data sets to be used for each GMF run.

In its proposed form, the framework would be designed to only detect differences in simulated flood hazard. Since all GFMs employ different ways of how to determine risk by accounting for exposure and vulnerability, these aspects should be compared at a later stage as well. We here, however, focus on the physical modelling side of flood risk to keep the scope of the study and proposed framework manageable. Moreover, many end-users such as insurance companies do have their own exposure and vulnerability maps and rely on hazard estimates for risk assessments.

By means of the framework, it would not only be possible to provide standardized input and validation data, but also to clearly define model boundary conditions. Using identical data will improve the comparability of model validation as this is currently done independently, using different validation data products, time periods, and study areas as shown in Chapter 3.

Testing Elements

We think it would be essential to test the models for the specific primary aspects listed below, yet this may be extended or altered if needed at any stage:

A. *Inundation extent*. A key output needed, for instance, by re-insurers to define flood-prone areas and determine premiums for portfolio exposure that intersects with the flood extent.
B. *Inundation depth*. Model output required by many risk assessments to assess potential damage via a depth-damage curve.
C. *Discharge hydrograph*. This is the fundamental driver of the out-of-bank flood processes.

By subjecting the GFMs to a thorough comparison and streamlining their input boundary conditions, the impact of the following secondary model aspects can also be tested:

D. *Forcing/Input data*. Assessing its impact is paramount to understand to which extent GFM accuracy is defined by model design or input/forcing data, something not covered by the study of Trigg et al. (2016).
E. *Regionality*. Here referred to as a model's ability to perform in certain regions, differing in their meteorological, geographical, and other properties. Also, this could include an assessment whether GFMs perform well only for large rivers and where the threshold lies in the accurate representation of inundations along smaller reaches.

Testing Challenges

Before establishing the framework, several decisions have to be made and existing challenges addressed, as Alfieri et al. (2018) also pointed out. These decisions require but are not limited to the following list:

a) *Test location*. First, is should be clear which river basins are ought to be used. As shown in Table 1, most major river basins were already used for validation and thus it would be sensible to use one of them. "Classic" examples are the Amazon and Ganges-Brahmaputra basin as they both represent large low-lying floodplain areas where inundations occur regularly. The former is an indicator of performance in simulating large river flood extents while the latter is particularly relevant from a flood risk perspective due to a large population exposure. To be able to test for regionality, the chosen basins should also differ in their meteorological, geographical, and hydrological properties. Besides, only reasonably large catchments should be used to ensure that all models can sufficiently represent the processes despite differences in spatial resolution. As models and observations improve in resolution, the testing catchment testing scale can be adjusted appropriately.

b) *Forcing data*. Despite most model forcing data being openly accessible, a clear decision has to be made which dataset shall be used. For models based on meteorology (e.g. GLOFRIS or the JRC and ECMWF models), recent global forcing data such as ERA-Interim or ERA5 should be provided (Berrisford et al., 2011; ECMWF, 2018). In case derivatives such as flood wave hydrographs are required (e.g. Fathom, CIMA-UNEP), pre-processed data should be made available. In all cases, the data must be downloadable via the front-end of the framework.

c) *Downstream boundaries*. Even though not all GFMs can accommodate dynamic sea levels as downstream boundary condition, we recommend that in an initial approach this should be activated to facilitate comparison across default models settings. For advanced comparisons, the effect of changing downstream boundaries can be studied as well by de-activating them or, analogously, account for them once model development allows for it.

More challenging, validation data must be provided which meets the demands for state-of-the-art flood hazard modelling. State-of-the-art in this context also means that all validation data sets used must explicitly address possible uncertainties in observations. Hence, these additional aspects should be considered:

d) *Discharge data.* Required to validate the models' skill to simulate discharge dynamics. Depending on the chosen test locations, different sources may be available, either global data sets or from local authorities. In case of the Amazon, for example, discharge data can be retrieved from ORE-HYBAM (ORE-HYBAM, 2018). One of the few global data bases of observed discharge is maintained by the Global Runoff Data Centre, currently containing data for around 1300 stations (GRDC, 2018). To provide robust validation results, sufficiently long time series must be available. For those models simulating specific return periods only, corresponding discharge values should be derived from observations.

e) *Inundation maps.* Data ranging across various locations world-wide must be available, preferably open access remotely sensed satellite products to maintain global comparability. Since image quality may be hampered by cloud cover (Bernhofen et al., 2018), this step may require some pre-processing. Alternatively, already pre-processed maps may be used, for example from the AquaMonitor (Donchyts et al., 2016). Also, maps from the Dartmouth Flood Observatory (http://floodobservatory.colorado.edu/), the GIEMS data set (Papa et al., 2010; Prigent et al., 2007) or from Tellman et al. (2017) can be used. For those models simulating inundation extent for specific return periods, inundation maps for actual events with corresponding return periods should be used as much as possible for validation, possibly building upon recent methods (Giustarini et al., 2015; Huang et al., 2014).

f) *Water levels.* To guarantee a globally uniform approach, satellite products should be used, for example ICESAT, ICESAT 2, ENVISAT or SWAT once available. The locations used for validation and benchmarking should be chosen such that potential vertical inaccuracies are limited. Again, the data must be carefully selected and pre-processed, for example to remove measurements affected by land or vegetation signals, to streamline the entire validation and comparison process.

In a nutshell, the proposed framework's objectives are threefold: (1) provide forcing data, (2) validate and benchmark model results, and (3) store reference model output per GFM (Figure 2). Once the user-performed simulation runs with the provided forcing data, results can be uploaded via a front-end to the framework's back-end. Here, both validation and benchmarking will be performed. For the validation, we suggest the following metrics: (i) for inundation extent, the hit ratio H, the false alarm ratio F, and the critical success index C; (ii) for discharge, the coefficient of determination r^2, the Kling-Gupta-Efficiency KGE (Gupta et al., 2009), and the root mean square error RMSE; (iii) for surface water elevation, RMSE. Since these objective functions are only a recommendation, a definite choice should only be made after both developers and end-users agreed on common standards meeting their expectations and needs. This requires involvement of potential end-users in the development of the framework.

To perform the necessary operations, employing the increasing power of cloud computing could be a viable option. For benchmarking purposes, the model results will be stored in cloud-optimized format (for example cloud-optimized GeoTIFF; COG) and version-controlled according to the version number of tested GFM in a reference data repository, hence containing the most recent outputs of GFMs and allowing for tracking the impact of model developments on output. The reference observation data sets will then be used to apply the same objective functions. Once all steps are successfully executed, the resulting validation and benchmark statistics will be made available to the user via the front-end again.

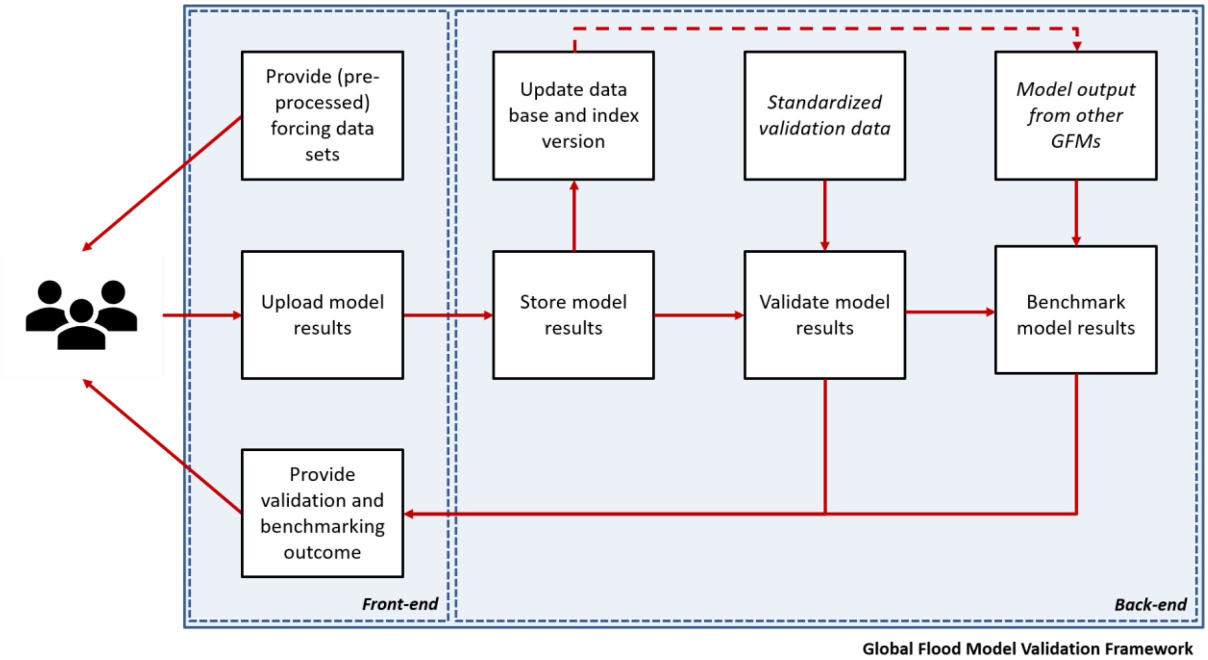

Figure 2: Conceptual design of a cloud-based Global Flood Model Validation Framework for model validation and benchmarking as well as maintaining a reference data base

The framework and data could be hosted by a neutral institution or other body, for instance within the Global Flood Partnership (GFP) which already collected first experiences with a common tool for operational flood risk management (Alfieri et al., 2018). Alternatively, such a framework could be hosted under the umbrella of the upcoming Global Risk Assessment Framework (GRAF) which aims at implementing a range of models and with a particularly end-user orientation (UNISDR, 2018).

We are aware that setting up such a framework requires both financial and time resources. Yet, we believe that once validation and benchmarking of GFMs is streamlined, they will benefit by reducing uncertainty associated with model output and its application. Using centrally provided data would also enhance the reproducibility of model output, as work flows and data use would become more transparent. We are confident the efforts made will eventually pay off as model output uncertainty will be reduced while scientific discourse will be improved, leading to better informed decisions and reduced economic damage and casualties.

5. Opening the black box of model code

With the scientific funding bodies increasingly requiring research to be openly available, most (unfortunately not all) GFMs can be downloaded freely, advancing the usability and impact of the models. However, even with open code and model output availability, most models follow a “black box” modelling approach of reading input data, executing a prescribed and model dependant set of processes, and thereafter providing output data (Figure 1). Such approaches, nonetheless, pose a major limitation to making GFMs more integratable, intuitive, and interactive due to the lack of process accessibility. However, we consider process integration as key to better comparability as well as future improvements, and thus think that global flood hazard simulations can greatly benefit from opening the black box.

Admittedly, the integration of different models is not rocket science and was already achieved. Models can, for instance, use the output of model A as forcing for model B (Biancamaria et al., 2009; Lian et al., 2007; Schumann et al., 2013). Such offline-coupling, however, increases overall computation time and may yield large intermediate files. Other forms of coupling entail online-coupling where the exchange of variables during model execution and without intermediate files is hard-coded (Sutanudjaja et al., 2017; Viero et al., 2014). Clearly, such bespoke model coupling is fit for bespoke purposes, yet it lacks the flexibility to be easily altered for other applications or to be extended with other models or only parts thereof.

To facilitate interactive and intuitive model coupling as well as to avoid "integronster", i.e. models whose combined code is hard to disentangle and uncertainties are hard to trace (Voinov and Shugart, 2013), the Basic Model Interface (BMI; Peckham et al. (2013)) provides a powerful and flexible tool to exchange model information via an (user-defined) interface script (Figure 3) without the need of integrating actual model code into one overarching model.

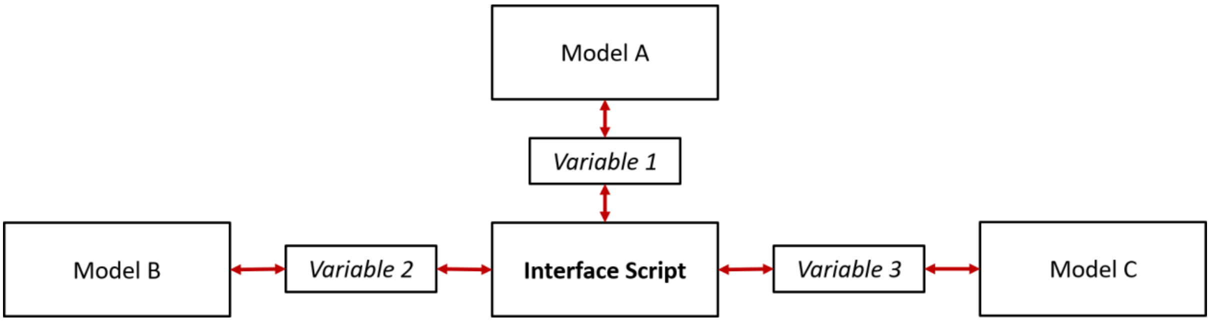

Figure 3: Schematic of coupling models as well as exchanging model information via BMI and a central interface script

The different models can for example be hydrologic or hydrodynamic models and exchange variables such as runoff or inundation depth, respectively. Yet, also other models could be linked up such as coastal or crop growth models or even non-physical models such as agent-based models.

Within the context of model benchmarking, implementing the BMI functionalities into GFMs may facilitate forcing them with identical data and, in turn, more standardized validation and benchmarking. The applicability of the BMI concept was shown by applying the GLOFRIM framework to benchmark different hydrodynamic models (Hoch et al., 2017) as well as different schematizations of the same hydrodynamic model (Hoch et al., 2018).

Unfortunately, none of the above mentioned GFMs currently contains any BMI functionality (or anything like it). Since the implementation of a BMI is non-invasive, we think more efforts should be directed towards advancing the accessibility of model processes and variables. In the long term, this would, besides supporting model validation and benchmarking, allow for a plug-and-play design where applicants can create their "own" GMF depending on their study specific needs and would also facilitate more efficient modelling efforts.

Conveniently, the proposed framework can help in identifying which components of which models excel. For example, if benchmarking results indicate that Model A may profit from more physical groundwater modelling, such a module from another Model B could be added and forced with variables from Model A, for instance surface water depth. Besides, output from other non-GFM models could be employed such as sea levels from a tide and surge model (Model C) which would even further increase the number physical processes representable (Figure 3).

We are aware that this would not only require opening the black box, but possibly also developers' minds. Besides, possible issues with IP rights may have to be solved first. Still, we are confident that such inter-active model functionalities can become a core element of advancing model validation and benchmarking across scales and processes, as they may result in new and promising research possibilities.

6. Conclusion and recommendations

Many GFMs found application in policy tools or operational systems but are still not well compared and consequently differences are not well understood. However, we think that this is pivotal for increased acceptance of GFMs by end-users and thus the existing different approaches to simulate inundation data require a more thorough and streamlined validation and benchmarking procedure.

GFMs were validated with a wide range of data sets for various time periods in numerous river basins all over the World. While the data used for validation is to some extent related to the date of model publication and the data availability at that time, the fact that all models are validated "successfully" for non-identical settings may lead to the misleading conclusion that all model perform equally well. Additionally, it does not support a clear conclusion as to why results differ between GFMs.

Due to the range in validation approaches, we see great potential for models to improve by comparing with and learning from others. Therefore, we sketch a Global Flood Model Validation Framework serving multiple purposes. First, it provides identical model forcing. Second, it validates simulated discharge, inundation extent, and surface water elevations. Third, it serves as a repository and version-control of GMF output and thus also allows for benchmarking output from different models and model versions. By establishing such a framework, we can ensure that, despite all independent model development trajectories, the same data and criteria are applied for assessing model output.

Since the framework can only streamline external factors, there will probably still be deviations in model results due to differences in internal model structure, processes, and parameterization. This is perfectly acceptable as the proposed framework is not meant to converge all GFMs, but rather as a testing and learning environment for researchers to improve usability and acceptance by end-users.

By means of the framework, insights could be provided in the upsides and downsides of each tested model design. If the framework is applied for more river basins and hydrologic conditions, it would furthermore be possible to identify where and under which circumstances each model performs best. Such knowledge can, in turn, be beneficial when it comes to communicating model strengths and limitations to policy and decision makers and provides them with a tool to identify which GFM may be most appropriate for a project or application in a specific region. Besides, the insights gained may be used to better point towards model shortcomings that could benefit from adopting methods implemented in better performing models.

For models to profit further from such insights, it could be necessary to open up the default “black box” of model processes. While a standard comparison framework may be sufficient for default applications of the models, implementing functions to allow for accessing and exchanging model variables could facilitate integrating components from other GFMs to improve model performance. Moving away from a black box approach may stimulate the benchmarking and comparison of GFMs as assessments could be performed at an unprecedented level of detail and flexibility, allowing ranking of the importance of different elements of GFMs. For example, the same spatially varying hydrologic output could be applied to all models, reducing the number of factors influencing model deviations. Vice versa, it could be possible to provide a clearer picture on how the routines calculating hydrologic forcing may differ by applying one routing scheme to all models designs. Ultimately, the GFMs would move closer together without abandoning their specific properties, and uncertainties surrounding flood hazard outputs could be reduced greatly.

We are aware that the presented framework and the required openness about model performance may discourage contributions from private CAT models. Nevertheless, we are convinced that an independent validation and benchmarking framework can be beneficial for the private sector too, as (a) data providers could present their results from commercial CAT models in a broader context, and (b) data users could first analyse which products fits their needs best before purchasing a flood product. We hope that thorough benchmarking of inundation maps becomes the new normal, eventually requiring vendors to improve their services and consequently resulting in better risk estimates for end-users. From a technical point of view implementing the CAT models into the proposed framework would be relatively straightforward as they essentially employ the same technology and input data types as the open scientific models. A major requirement for those model developers would of course be that outcomes are not necessarily made publicly available.

While the here proposed Global Flood Model Validation Framework focusses on differences in model design and associated differences in model output, more steps should be taken to improve the comparability and consequential uptake of GFMs. First, the nomenclature of model variables and components differs greatly between models, hampering the traceability of model work flows. By using more standardized terminology, for example the standard names proposed by the Community Surface Dynamics Modelling System (https://csdms.colorado.edu/wiki/CSDMS_Standard_Names), comparing GFMs would become easier, particularly for non-expert users. And second, comparability, inter-operability, and usability of model outputs would be greatly supported by agreeing on clear standards for files, for instance based on the guidelines of the Open Geospatial Consortium (http://www.opengeospatial.org/). Third, it is necessary that all GFMs (as for models in general) provide easily comprehensible description of how they work and what their outputs represent.

To establish a full comparison between GFMs, exposure and vulnerability data should be compared as well. Since these data layers are not based on a modelling cascades, the proposed Global Flood Model validation and benchmarking framework may not be the right means. Nevertheless, we think that further investigation is needed to better understand to which extent differences in simulated risk assessment outputs are dependent on hazard, exposure or vulnerability. Eventually, the three pillars of risk could be compared altogether. Such an extensive intercomparison project would help greatly to advance the current state of GFMs and to identify new research possibilities.

More efforts should be taken to advance our understanding of GFMs and their differences. With our proposed validation and benchmarking framework together with greater model accessibility, we see great potential for future model developments as well as an increased number of GFM applications and hope that model comparison will play a more significant role in future flood hazard modelling studies.

Tables

Table 1: Overview of validation data sets of discharge, inundation extent, and water surface level (WSL) as used in various scientific studies of GFM development

GFM	Study	River basin	Period	Validation data sets		
				Discharge	**Extent**	**WSL**
CaMa-Flood	Yamazaki et al. (2011)	Amongst others: Amazon, Congo, Brahmaputra, Rhine, Ob	*Varying per basin*	GRDC[1]	SAR imagery (Hess et al., 2003); GIEMS (Prigent et al., 2007)	---
	Yamazaki et al. (2012)	Amazon	2003-2005	ANEEL[2]	GIEMS (Prigent et al., 2007)	Envisat RA-2
	Yamazaki et al. (2013)	*Global maps used*	1991-2000	GRDC	---	---
	Yamazaki et al. (2014)	Mekong	2001-2005	Inomata and Fukami (2008); MRC[3]	---	MRC[3]
GLOFRIS	Winsemius et al. (2013)	Ganges-Brahmaputra	1961-1990	---	DFO[4]	---
JRC	Dottori et al. (2016)	Tocantins, Severn, Thames, Elbe, Po, Niger, Indus, Ganges, Mekong, Irrawaddy	2000-2013		DFO ;UNOSAT	---
		Amongst others : Rhine, Danube, Columbia, Thames, Colorado, Yukon		Local observations, based on (Hirpa et al., 2016)		---
CIMA-UNEP[5]	Rudari et al. 2015)	Colombia, Germany and Thailand	---	Amongst others: GRDC, RivDIS[6]	DFO	---
Fathom	Sampson et al. (2015)[7]	Bow River, North Saskatchewan, Red Deer; Severn, Thames	*Comparing return periods*	---	Alberta State Government; JRC model	---
	Wing et al. (2017)[7]	Conterminous United States	*Comparing return periods*	---	FEMA[8], USGS[9]	---
ECMWF	Pappenberger et al. (2012)[7]	*Various major catchments on all continents*	*Comparing return periods*	---	Flood hazard maps as used by UNISDR	---

[1] GRDC, Global Runoff Data Centre

[2] ANEEL, Agencia Nacional de Energia Electrica

[3] MRC, Mekong River Commission

[4] DFO, Dartmouth Flood Observatory

[5] Development and validation of the CIMA-UNEP model was not published in peer-reviewed scientific journals

[6] RivDIS, Global River Discharge Database

[7] both studies only performed benchmarks with inundations maps from other inundation models or databases for given return periods

[8] FEMA, Federal Emergency Management Agency

[9] USGS, United States Geological Survey

References

Alfieri, L., Burek, P., Dutra, E., Krzeminski, B., Muraro, D., Thielen, J. and Pappenberger, F.: GloFAS-global ensemble streamflow forecasting and flood early warning, Hydrology and Earth System Sciences, 17(3), 1161–1175, doi:10.5194/hess-17-1161-2013, 2013.

Alfieri, L., Cohen, S., Galantowicz, J., Schumann, G. J.-P., Trigg, M. A., Zsoter, E., Prudhomme, C., Kruczkiewicz, A., Coughlan de Perez, E., Flamig, Z., Rudari, R., Wu, H., Adler, R. F., Brakenridge, R. G., Kettner, A., Weerts, A., Matgen, P., Islam, S. A. K. ., de Groeve, T. and Salamon, P.: A global network for operational flood risk reduction, Environmental Science & Policy, 84(March), 149–158, doi:10.1016/j.envsci.2018.03.014, 2018.

Bates, P. D., Neal, J., Sampson, C., Smith, A. and Trigg, M.: Chapter 9 - Progress Toward Hyperresolution Models of Global Flood Hazard A2 - Michel, Gero BT - Risk Modeling for Hazards and Disasters, pp. 211–232, Elsevier., 2018.

Beck, H. E., van Dijk, A. I. J. M., de Roo, A., Dutra, E., Fink, G., Orth, R. and Schellekens, J.: Global evaluation of runoff from 10 state-of-the-art hydrological models, Hydrology and Earth System Sciences, 21(6), 2881–2903, doi:10.5194/hess-21-2881-2017, 2017.

Bernhofen, M., Whyman, C., Trigg, M. A., Sleigh, P. A., Smith, A. M., Sampson, C. C., Yamazaki, D., Ward, P. J., Rudari, R., Pappenberger, F., Dottori, F., Salamon, P. and Winsemius, H. C.: A first collective validation of global fluvial flood models for major floods in Nigeria and Mozambique, Environmental Research Letters, 2018.

Berrisford, P., Dee, D. P., Poli, P., Brugge, R., Fielding, K., Fuentes, M., K\r allberg, P. W., Kobayashi, S., Uppala, S. and Simmons, A.: The ERA-Interim archive Version 2.0, ERA Report Series, (1), 23, 2011.

Biancamaria, S., Bates, P. D., Boone, A. and Mognard, N. M.: Large-scale coupled hydrologic and hydraulic modelling of the Ob river in Siberia, Journal of Hydrology, 379(1–2), 136–150, doi:10.1016/j.jhydrol.2009.09.054, 2009.

Bierkens, M. F. P., Bell, V. A., Burek, P., Chaney, N., Condon, L. E., David, C. H., de Roo, A., Döll, P., Drost, N., Famiglietti, J. S., Flörke, M., Gochis, D. J., Houser, P., Hut, R., Keune, J., Kollet, S., Maxwell, R. M., Reager, J. T., Samaniego, L., Sudicky, E., Sutanudjaja, E. H., van de Giesen, N., Winsemius, H. C. and Wood, E. F.: Hyper-resolution global hydrological modelling: What is next?: "Everywhere and locally relevant," Hydrological Processes, 29(2), 310–320, doi:10.1002/hyp.10391, 2015.

Ceola, S., Laio, F. and Montanari, A.: Satellite nighttime lights reveal increasing human exposure to floods worldwide, Geophysical Research Letters, 41(20), 7184–7190, doi:10.1002/2014GL061859, 2014.

Donchyts, G., Baart, F., Winsemius, H., Gorelick, N., Kwadijk, J. and van de Giesen, N.: Earth's surface water change over the past 30 years, Nature Climate Change, 6, 810, 2016.

Dottori, F., Salamon, P., Bianchi, A., Alfieri, L., Hirpa, F. and Feyen, L.: Development and evaluation of a framework for global flood hazard mapping, Advances in Water Resources, 94, 87–102, doi:10.1016/j.advwatres.2016.05.002, 2016.

ECMWF: ERA5 Documentation, [online] Available from: https://software.ecmwf.int/wiki/display/CKB/ERA5+data+documentation (Accessed 9 March 2018), 2018.

Giustarini, L., Chini, M., Hostache, R., Pappenberger, F. and Matgen, P.: Flood hazard mapping combining hydrodynamic modeling and multi annual remote sensing data, Remote Sensing, 7(10), 14200–14226, doi:10.3390/rs71014200, 2015.

Global Flood Partnership: The Global Flood Partnership Conference 2016 - Linking global flood information with local needs, Joint Research Centre, Ispra, Italy. [online] Available from: https://gfp.jrc.ec.europa.eu/sites/default/files/2017-06/GFP_2016_outcomes_final.pdf (Accessed 19 July 2018), 2016.

Global Flood Partnership: The Global Flood Partnership Conference 2017 - From hazards to impacts, Ispra, Italy. [online] Available from: https://gfp.jrc.ec.europa.eu/sites/default/files/2017-12/JRC_Technical_Report_GFP_2017_outcomes_final.pdf (Accessed 19 July 2018), 2017.

GRDC: GRDC Composite Runoff Fields v1.0, [online] Available from: http://www.grdc.sr.unh.edu/ (Accessed 9 March 2018), 2018.

Gupta, H. V, Kling, H., Yilmaz, K. K. and Martinez, G. F.: Decomposition of the mean squared error and NSE performance criteria : Implications for improving hydrological modelling, Journal of Hydrology, 377(1–2), 80–91, doi:10.1016/j.jhydrol.2009.08.003, 2009.

Hess, L. L., Melack, J. M., Novo, E. M. L. M., Barbosa, C. C. F. and Gastil, M.: Dual-season mapping of wetland inundation and vegetation for the central Amazon basin, Remote Sensing of Environment, 87(4), 404–428, doi:10.1016/j.rse.2003.04.001, 2003.

Hirpa, F. A., Salamon, P., Alfieri, L., Pozo, J. T., Zsoter, E. and Pappenberger, F.: The Effect of Reference Climatology on Global Flood Forecasting, Journal of Hydrometeorology, 17(4), 1131–1145, doi:10.1175/JHM-D-15-0044.1, 2016.

Hoch, J. M., Neal, J. C., Baart, F., van Beek, R., Winsemius, H. C., Bates, P. D. and Bierkens, M. F. P.: GLOFRIM v1.0 - A globally applicable computational framework for integrated hydrological-hydrodynamic modelling, Geoscientific Model Development, 10, 3913–3929, doi:10.5194/gmd-10-3913-2017, 2017.

Hoch, J. M., Winsemius, H. C., Van Beek, L. P. H. and Bierkens, M. F. P.: Benchmarking flexible meshes and regular grids for large-scale fluvial inundation modelling, Advances in Water Resources, 2018.

Huang, C., Chen, Y. and Wu, J.: Mapping spatio-temporal flood inundation dynamics at large river basin scale using time-series flow data and MODIS imagery, International Journal of Applied Earth Observation and Geoinformation, 26, 350–362, doi:http://dx.doi.org/10.1016/j.jag.2013.09.002, 2014.

Inomata, H. and Fukami, K.: Restoration of historical hydrological data of Tonle Sap Lake and its surrounding areas, Hydrological Processes, 22(9), 1337–1350, doi:10.1002/hyp.6943, 2008.

Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J. C. J. H., Mechler, R., Botzen, W. J. W., Bouwer, L. M., Pflug, G., Rojas, R. and Ward, P. J.: Increasing stress on disaster-risk finance due to large floods, Nature Climate Change, 4(4), 1–5, doi:10.1038/NCLIMATE2124, 2014.

Lian, Y., Chan, I.-C., Singh, J., Demissie, M., Knapp, V. and Xie, H.: Coupling of hydrologic and hydraulic models for the Illinois River Basin, Journal of Hydrology, 344(3–4), 210–222, doi:10.1016/j.jhydrol.2007.08.004, 2007.

Munich Re: Topics Geo, natural catastrophes 2009: analyses, assessments, positions, Munich Reinsurance Group, Munich, Germany., 2010.

ORE-HYBAM: HYBAM ORE-South America, [online] Available from: http://www.ore-hybam.org/index.php/eng/Data/Station-Access-Maps/HYBAM-ORE-South-America (Accessed 19 July 2018), 2018.

Papa, F., Prigent, C., Aires, F., Jimenez, C., Rossow, W. B. and Matthews, E.: Interannual variability of surface water extent at the global scale, 1993-2004, Journal of Geophysical Research Atmospheres, 115(12), 1–17, doi:10.1029/2009JD012674, 2010.

Pappenberger, F., Dutra, E., Wetterhall, F. and Cloke, H. L.: Deriving global flood hazard maps of fluvial floods through a physical model cascade, Hydrology and Earth System Sciences, 16(11), 4143–4156, doi:10.5194/hess-16-4143-2012, 2012.

Peckham, S. D., Hutton, E. W. H. and Norris, B.: A component-based approach to integrated modeling in the geosciences: The design of CSDMS, Computers and Geosciences, 53, 3–12, doi:10.1016/j.cageo.2012.04.002, 2013.

Prigent, C., Papa, F., Aires, F., Rossow, W. B. and Matthews, E.: Global inundation dynamics inferred from multiple satellite observations, 1993–2000, Journal of Geophysical Research, 112(D12), D12107, doi:10.1029/2006JD007847, 2007.

Rudari, R., Silvestro, F., Campo, L., Rebora, N., Boni, G. and Herold, C.: IMPROVEMENT OF THE GLOBAL FLOOD MODEL FOR THE GAR 2015. [online] Available from: https://www.preventionweb.net/english/hyogo/gar/2015/en/bgdocs/risk-section/CIMA%20Foundation,%20Improvement%20of%20the%20Global%20Flood%20Model%20for%20the%20GAR15.pdf (Accessed 8 June 2018), 2015.

Sampson, C. C., Smith, A. M., Bates, P. D., Neal, J. C., Alfieri, L. and Freer, J. E.: A high-resolution global flood hazard model, Water Resources Research, 51, 7358–7381, doi:10.1002/2015WR016954, 2015.

Schumann, G. J.-P., Neal, J. C., Voisin, N., Andreadis, K. M., Pappenberger, F., Phanthuwongpakdee, N., Hall, A. C. and Bates, P. D.: A first large-scale flood inundation forecasting model, Water Resources Research, 49(10), 6248–6257, doi:10.1002/wrcr.20521, 2013.

Sutanudjaja, E. H., van Beek, L. P. H., Wanders, N., Wada, Y., Bosmans, J. H. C., Drost, N., van der Ent, R. J., de Graaf, I. E. M., Hoch, J. M., de Jong, K., Karssenberg, D., Lopez Lopez, P., Peßenteiner, S., Schmitz, O., Straatsma, M. W., Vannametee, E., Wisser, D. and Bierkens, M. F. P.: PCR-GLOBWB 2.0: a 5 arc-minute global hydrological and water resources model, Geoscientific Model Development Discussions, 2017.

Tellman, B., Sullivan, J., Doyle, C., Kettner, A., Brakenridge, G. ~R., Erickson, T. and Slayback, D. ~A.: A Global Geospatial Database of 5000+ Historic Flood Event Extents, AGU Fall Meeting Abstracts, 2017.

Trigg, M. A., Birch, C. E., Neal, J. C., Bates, P. D., Smith, A., Sampson, C. C., Yamazaki, D., Hirabayashi, Y., Pappenberger, F., Dutra, E., Ward, P. J., Winsemius, H. C., Salamon, P., Dottori, F., Rudari, R., Kappes, M. S., Simpson, A. L., Hadzilacos, G. and Fewtrell, T. J.: The credibility challenge for global fluvial flood risk analysis, Environmental Research Letters, 11(9), 094014, doi:10.1088/1748-9326/11/9/094014, 2016.

UNISDR: Global Assessment Report on Disaster Risk Reduction, Making Development Sustainable: The Future of Disaster Risk Management, Geneve., 2015.

UNISDR: Putting science to work for resilience, [online] Available from: https://www.unisdr.org/archive/58772 (Accessed 23 July 2018), 2018.

Viero, D. P., Peruzzo, P., Carniello, L. and Defina, A.: Integrated mathematical modeling of hydrological and hydrodynamic response to rainfall events in rural lowland catchments, Water Resources Research, 50(7), 5941–5957, doi:10.1002/2013WR014293, 2014.

Voinov, A. and Shugart, H. H.: 'Integronsters', integral and integrated modeling, Environmental Modelling & Software, 39, 149–158, doi:10.1016/j.envsoft.2012.05.014, 2013.

Ward, P. J., Jongman, B., Salamon, P., Simpson, A., Bates, P. D., de Groeve, T., Muis, S., de Perez, E. C., Rudari, R., Trigg, M. A. and Winsemius, H. C.: Usefulness and limitations of global flood risk models, Nature Climate Change, 5(8), 712–715, doi:10.1038/nclimate2742, 2015.

Willis Towers Watson: Insights from the Willis Re Flood Club: the weaknesses and strengths of flood modelling, Willis Towers Watson Wire [online] Available from: https://blog.willis.com/2018/06/insights-from-the-willis-re-flood-club-the-weaknesses-and-strengths-of-flood-modelling/ (Accessed 19 July 2018), 2018.

Wing, O. E. J., Bates, P. D., Sampson, C. C., Smith, A. M., Johnson, K. A. and Erickson, T. A.: Validation of a 30 m resolution flood hazard model of the conterminous United States, Water Resources Research, 53(9), 7968–7986, doi:10.1002/2017WR020917, 2017.

Wing, O. E. J., Bates, P. D., Smith, A. M., Sampson, C. C., Johnson, K. A., Fargione, J. and Morefield, P.: Estimates of present and future flood risk in the conterminous United States, Environmental Research Letters, 13(3), doi:10.1088/1748-9326/aaac65, 2018.

Winsemius, H. C., van Beek, L. P. H., Jongman, B., Ward, P. J. and Bouwman, A.: A framework for global river flood risk assessments, Hydrology and Earth System Sciences, 17(5), 1871–1892, doi:10.5194/hess-17-1871-2013, 2013.

Winsemius, H. C., Aerts, J. C. J. H., van Beek, L. P. H., Bierkens, M. F. P., Bouwman, A., Jongman, B., Kwadijk, J. C. J., Ligtvoet, W., Lucas, P. L., van Vuuren, D. P. and Ward, P. J.: Global drivers of future river flood risk, Nature Clim. Change, 6(4), 381–385, 2016.

World Resources Institute: Aqueduct Global Flood Analyzer, [online] Available from: http://floods.wri.org (Accessed 8 March 2018), 2018.

Yamazaki, D., Kanae, S., Kim, H. and Oki, T.: A physically based description of floodplain inundation dynamics in a global river routing model, Water Resources Research, 47(4), 1–21, doi:10.1029/2010WR009726, 2011.

Yamazaki, D., Lee, H., Alsdorf, D. E., Dutra, E., Kim, H., Kanae, S. and Oki, T.: Analysis of the water level dynamics simulated by a global river model: A case study in the Amazon River, Water Resources Research, 48(9), 1–15, doi:10.1029/2012WR011869, 2012.

Yamazaki, D., De Almeida, G. a M. and Bates, P. D.: Improving computational efficiency in global river models by implementing the local inertial flow equation and a vector-based river network map, Water Resources Research, 49(11), 7221–7235, doi:10.1002/wrcr.20552, 2013.

Yamazaki, D., Sato, T., Kanae, S., Hirabayashi, Y. and Bates, P. D.: Regional flood dynamics in a bifurcating mega delta simulated in a global river model, Geophysical Research Letters, 41(9), 3127–3135, doi:10.1002/2014GL059744, 2014.

Zhao, F., Veldkamp, T. I. E., Frieler, K., Schewe, J., Ostberg, S., Willner, S., Schauberger, B., Gosling, S. N., Schmied, H. M., Portmann, F. T., Leng, G., Huang, M., Liu, X., Tang, Q., Hanasaki, N., Biemans, H., Gerten, D., Satoh, Y., Pokhrel, Y., Stacke, T., Ciais, P., Chang, J., Ducharne, A., Guimberteau, M., Wada, Y., Kim, H. and Yamazaki, D.: The critical role of the routing scheme in simulating peak river discharge in global hydrological models, Environmental Research Letters, 12(7), 075003, doi:10.1088/1748-9326/aa7250, 2017.