10. Arze del Granado, F. J., Coady, D. & Gillingham, R. *World Dev.* **40,** 2234–2248 (2012).
11. Clements, B., Coady, D., Fabrizio, S., Gupta, S. & Shang, B. *Econ. Energy Environ. Policy* **3,** (2014).
12. Rao, N. D. *Energy Sust. Dev.* **16,** 35–43 (2012).
13. *Implementing Energy Subsidy Reforms: Evidence from Developing Countries* (World Bank, 2012); http://dx.doi.org/10.1596/978-0-8213-9561-5
14. *Energy Subsidy Reform: Lessons and Implications* (IMF, 2013); http://www.imf.org/external/np/pp/eng/2013/012813.pdf
15. Alkire, S. *World Dev.* **30,** 181–205 (2002).
16. Drèze, J. & Sen, A. *An Uncertain Glory: India and Its Contradictions* (Princeton Univ. Press, 2013).
17. Jakob, M. & Hilaire, J. *Climatic Change* http://dx.doi.org/10.1007/s10584-015-1406-2 (2015).
18. Jakob, M. *et al. Nature Clim. Change* **4,** 961–968 (2014).
19. *World Development Indicators* (World Bank, 2014); http://go.nature.com/Oo93Bg
20. *World Telecommunication/ICT Indicators Database* 18th edn (ITU, 2014); http://www.itu.int/en/ITU-D/Statistics/Pages/publications/wtid.aspx
21. Pachauri, S. *et al. Environ. Res. Lett.* **8,** 024015 (2013).

Acknowledgements
We thank S. Pachauri, N.D. Rao and J. Stecker for helpful comments and suggestions.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to M.J.

COMMENTARY:

Usefulness and limitations of global flood risk models

Philip J. Ward, Brenden Jongman, Peter Salamon, Alanna Simpson, Paul Bates, Tom De Groeve, Sanne Muis, Erin Coughlan de Perez, Roberto Rudari, Mark A. Trigg and Hessel C. Winsemius

Global flood risk models were developed to identify risk hotspots in a world with increasing flood occurrence. Here we assess the ability and limitations of the current models and suggest what is needed moving forward.

Global flood risk models (GFRMs) are now a reality[1–7]. More and more, these 'quick and not so dirty' methods[8] are being put to use by an increasing range of practitioners and decision-makers. The adoption of the Sendai Framework for Disaster Risk Reduction[9] and the Warsaw International Mechanism for Loss and Damage Associated with Climate Change Impacts[10] have made these efforts even more essential.

However, GFRMs have their limits compared with local-scale models[11], and there is often a mismatch between their actual ability and the envisaged use by practitioners. Modellers and users need to critically assess this discrepancy. We provide perspectives drawing from practical applications of global river flood risk models (Table 1), demonstrating the accomplishments in these examples, as well as limitations and gaps between user 'wish lists' and model capabilities. We present a research agenda to address these issues and reduce the gaps.

Applications in risk management

The global assessment reports (GAR)[4] of the United Nations Office for Disaster Risk Reduction provide a high-level platform for distributing global natural hazard risk data, including floods, which has proved instrumental in advocating for disaster risk management (DRM) internationally. Risk is framed as a 'contingent liability'; if a country allows future risks to accumulate, it effectively undermines its own potential for future socioeconomic development. This has paved the way for a more quantitative approach in the Sendai framework compared with the previous Hyogo Framework for Action, setting quantitative risk-reduction targets that are now being developed into measurable indicators.

GFRMs have been applied by the World Bank and the Global Facility for Disaster Reduction and Recovery to inform national-level DRM. Following Nigeria's devastating floods in 2012, a post-disaster needs assessment recommended strengthening flood resilience. In response, the World Bank Africa Disaster Risk Management team began developing a National Flood Risk Management Implementation Plan. At the time, little local or national information was available to assess flood risk. Within weeks, the GLOFRIS model[5,6] (Global Flood Risk with IMAGE Scenarios) was used to provide flood risk maps per state. These were used in dialogues to engage stakeholders and identify risk hotspots requiring further localized research. Building on this success, a first-cut state-level flood risk assessment was commissioned for World Bank's Europe and Central Asia region, including climate and socioeconomic projections. These rapid assessments in data-scarce countries have been useful in internal World Bank Group discussions and will be used in the near future to inform discussions with governments in the region.

With advances in numerical algorithms[12], new global datasets[13], and high-performance computing, it is now possible to develop global flood hazard models at 100 m resolution that solve hydrodynamic equations. An example is the SSBN-flow model[14], which has been used for national flood hazard mapping in Belize as part of the World Bank Caribbean Risk Information Programme. The Government of Belize will use the nationally consistent, indicative flood hazard maps to support decision-making in spatial and infrastructure planning, particularly for housing and roads, from national to enumeration area scales. This approach has considerably enhanced the quality of flood information, which was

© 2015 Macmillan Publishers Limited. All rights reserved

previously unavailable. Implementation challenges included model validation against limited local data in Belize, and managing user expectations on model capabilities. Example data from the SSBN-flow model for Africa can be found in Fig. 1.

Since an ultimate DRM aim is to manage (and reduce) risk, users are logically eager to start using GFRMs for designing flood management strategies. The current generation of models is beginning to provide such functionality. For example, the Aqueduct Global Flood Analyzer allows users to assess on-the-fly how much risk could be avoided per country, state, or river basin, if flood protection standards were increased, for example, by building dykes or levees. This functionality includes analysing the effectiveness of those strategies under future climate conditions, helping to integrate DRM into broader discussions on climate change adaptation[15].

The Sendai framework[9] emphasizes the importance of early warning systems in DRM. This requires global flood forecasting, and (near) real-time monitoring systems, such as GloFAS (Global Flood Awareness System)[16], GFMS (Global Flood Monitoring System)[17], and Dartmouth Flood Observatory. The potential use of these systems for triggering DRM actions prior to flood events instead of *ex post* disaster recovery is being tested by Uganda Red Cross, together with German Red Cross and Red Cross Red Crescent Climate Centre. In northeastern Uganda, where no local flood models exist, a forecast-based financing system has been established to trigger *ex-ante* actions based on GloFAS forecasts. These are large-scale actions, such as distributing water purification tablets in entire villages, appropriate for the high false-alarm rates and low spatial resolution inherent in global flood models.

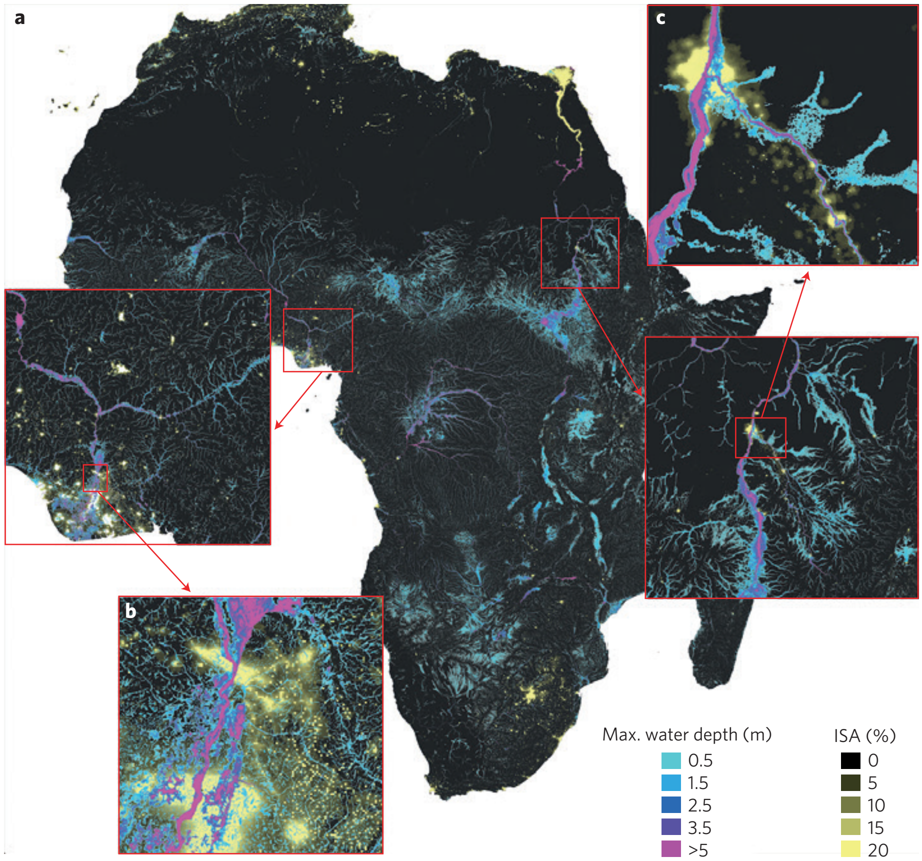

Figure 1 | Example hazard data from a global flood model, overlaid on impervious surface area (ISA) data[27] as an indicator of exposure. The hazard data shown here are from the SSBN global flood model[14], and show 1-in-100-year maximum flood depth for: **a**, all of Africa; **b**, River Niger at Onitsha, Nigeria; and **c**, Blue Nile at Omdurman, Sudan.

Challenge for risk management

Of course, GFRMs are no panacea. A question regularly posed by users is what the exact risk is for a particular community, street, or asset. Such questions highlight the apparent mismatch between the resolution and accuracy of GFRMs and the detail of information required for local-level decisions. The accuracy of flood hazard maps is dependent on the quality of the elevation data (digital elevation models; DEMs) used. Although a near-global DEM of 30 m resolution is now available[18,19], flood hazard map accuracy at such scales remains limited due to a number of factors, including: accuracy of boundary conditions used to force inundation models (for example, meteorological data)[5]; limitations in knowledge of river geomorphology (for example, river profiles and roughness); and the accuracy of DEMs themselves[20]. To estimate risk at such detailed scales, local data on exposure (how many people, buildings, and other elements are located in harm's way) and vulnerability (how susceptible are those exposed elements to flooding) are also required. Obtaining detailed information on exposure and vulnerability at the global scale remains an open challenge.

While GFRMs are used to assess the effectiveness of DRM strategies at the large scale, the granularity of the input data means that they cannot be used to design individual DRM measures. For example, while we can assess damages avoided by protecting a country against a 100-year flood, we cannot use GFRMs to design the actual measures needed to achieve this. In the example of dykes, questions regarding location, height, material, and so forth, cannot be answered using GFRMs. These limitations must be clearly communicated to users at all stages of engagement, to avoid mismatches in expectations down the line. A key challenge is the lack of data on flood management strategies already in place. Flood management has already played a strong role in reducing vulnerability to flooding[21]; ignoring this leads to gross overestimates of risk[5].

In addition, emergency responders require flood risk information in terms of the potential impacts of a flood event, which is currently not contained in global flood forecasting and monitoring systems. At present, most of these systems only provide physical flood thresholds, based on statistical analyses of predicted riverflow, since detailed global flood hazard modelling in near real-time remains a daunting task.

Research agenda

A priority for increasing GFRM accuracy is an improved representation of fundamental physical and socioeconomic processes leading to flood impacts. For hazard

© 2015 Macmillan Publishers Limited. All rights reserved

Table 1 | Links to models, tools, and programmes discussed in the text.

Model, dataset or programme	Link
World Bank Caribbean Risk Information Programme	www.charim.net
Aqueduct Global Flood Analyzer	www.wri.org/floods
GloFAS	www.globalfloods.eu
GFMS	http://flood.umd.edu
Dartmouth Flood Observatory	http://floodobservatory.colorado.edu/Archives/index.html
WorldDEM	http://www.geo-airbusds.com/worlddem/
OpenStreetMap	www.openstreetmap.org
InaSAFE	http://inasafe.org/en
Global Assessment Report Risk Data Platform	http://risk.preventionweb.net

modelling, we need better elevation data[20]. While the recently released 30 m DEM[19] has improved horizontal resolution substantially, it did not improve the vertical accuracy required to improve global inundation models. An exciting commercial initiative towards such an improvement is WorldDEM, which is to feature a large increase in vertical accuracy. Efforts have been undertaken to yield river-width data at the global scale[13], but more data are needed on other key geomorphological aspects, not to mention the presence of anthropogenic features in hydraulic systems, such as dykes and levees.

But without profoundly improved representations of exposure and vulnerability, gains from improved hazard modelling will not filter through to improved risk estimates. At present, GFRMs use simple aggregated land-use data to represent exposure, such as 'urban area' per cell, and vulnerability is commonly represented by a handful of depth-damage functions. These assumptions ignore huge spatial heterogeneities in exposure and vulnerability[22]. An exciting initiative that could revolutionize GFRMs is OpenStreetMap (OSM), a global crowdsourced database of buildings and infrastructure. OSM is being used to support local DRM worldwide[23]. A challenge for the global risk modelling community is to find smart ways to harness this wealth of object-based exposure data for GFRMs.

In many of the world's most 'risky' places, such as rapidly urbanizing deltas, flood hazards are the result of the interaction of river discharge and coastal sea levels. We therefore need to move towards an integration of river and coastal flood risk modelling to accurately assess risk in these places. The improvements described above would help with this, but it would also require developing dynamical global tide and storm surge models, and linking these with river flood models. Further gains in granularity, accuracy, and model speed could be made by nesting local flood models within global models. Such nesting has a long tradition in global climate modelling[24], and could offer GFRMs the advantage of gaining more detail in areas where it is required.

Urgent efforts are required to develop databases showing current flood management worldwide. A database of flood protection standards per country is expected shortly, providing a valuable first step. Moving forward, the community requires information on which specific measures are taken and where, in terms of not only structural measures, but also non-structural measures such as flood zoning, building codes, and insurance. We could learn from crowdsourcing successes in other fields, such as OSM, by using such platforms to develop crowdsourced databases on the location and height of protection measures such as dykes and levees. Such a database could play an important role in monitoring DRM and climate change adaptation efforts.

Global-scale flood forecasting and monitoring systems need to go beyond the provision of solely information on exceedance above physical flood thresholds. Emergency responders require information on forecasted flood impacts, and should be able to link their action thresholds to global-scale flood forecasting and monitoring systems. Connecting the offline global flood risk information from GFRMs to global flood forecasting and monitoring systems is a key to further increasing the usability of both of these model families.

The effectiveness of risk information in supporting DRM is largely contingent on how the information is communicated and its timely availability. When a disaster occurs, information is required immediately — there is no time for lengthy periods to commission new studies, carry out new simulations, analyse and present results, and so forth. A range of tools has recently been developed to communicate risk in a clear and effective way. One example is InaSAFE, an open-source tool for impact assessment, now used extensively to support decision-making at national and sub-national levels in Indonesia and elsewhere. Successes like InaSAFE and the Aqueduct Global Flood Analyzer emphasize the demand for translating complex flood risk data into interactive and actionable information. While a first push in this direction is being made, further developments are required.

Not only should information be actionable, its (deep) uncertainties should be estimated and transparently communicated. At present, there is clear frustration regarding the lack of guidance from modellers on the reliability and uncertainty contained in model results. A better representation of uncertainty may lead to better decision-making[25]. Techniques to communicate and visualize uncertainty in relation to decision-making already exist, such as adaptation pathways[25], but such novel techniques still need to be made fit for use with GFRM outputs.

Addressing this research agenda is a daunting task for any single organization. It requires interdisciplinary research, close collaboration with user communities, and grounding in a wider context of DRM and climate change adaptation. Launched in 2014, the Global Flood Partnership provides a platform for organizations involved in global flood risk, early warning, and observation to collectively identify and address challenges[26]. As a bottom-up, voluntary partnership, it allows direct knowledge transfer from centres of excellence in global flood risk modelling to users, including hydrological and emergency management authorities, humanitarian response organizations, international development banks, and the private sector. Harnessing the knowledge and drive of this network should help us push towards a new generation of actionable GFRMs for contributing to real-world DRM and climate change adaptation. ❐

Philip J. Ward[1,], Brenden Jongman[1,2], Peter Salamon[3], Alanna Simpson[2], Paul Bates[4,5], Tom De Groeve[3], Sanne Muis[1], Erin Coughlan de Perez[1,6,7], Roberto Rudari[8], Mark A. Trigg[4] and Hessel C. Winsemius[9] are at [1]Institute for Environmental Studies (IVM), VU University Amsterdam, 1081HV Amsterdam, The Netherlands. [2]Global Facility for Disaster Reduction and Recovery, World Bank Group, Washington DC 20433, USA. [3]European Commission, Joint Research Centre, 21027 Ispra,*

© 2015 Macmillan Publishers Limited. All rights reserved

*Italy. [4]University of Bristol, Bristol BS8 1SS, UK. [5]SSBN Flood Risk Solutions, Cardiff CF10 4AZ, UK. [6]Red Cross Red Crescent Climate Centre, 2521 CV The Hague, The Netherlands. [7]International Research Institute for Climate and Society, Columbia University, New York, New York 10964, USA. [8]CIMA Research Foundation, 17100 Savona, Italy. [9]Deltares, 2629 HV Delft, The Netherlands. *e-mail: philip.ward@vu.nl*

References

1. Dilley, M. *et al. Natural Disaster Hotspots. A Global Risk Analysis* (The World Bank, 2005).
2. Hallegatte, S., Green, C., Nicholls, R. J. & Corfee-Morlot, J. *Nature Clim. Change* **3,** 802–806 (2013).
3. Hirabayashi, Y. *et al. Nature Clim. Change* **3,** 816–821 (2013).
4. UNISDR *Global Assessment Report on Disaster Risk Reduction. Making Development Sustainable: The Future of Disaster Risk Management* (United Nations International Strategy for Disaster Reduction Secretariat, 2015).
5. Ward, P. J. *et al. Environ. Res. Lett.* **8,** 044019 (2013).
6. Winsemius, H. C., Van Beek, R., Jongman, B., Ward, P. J. & Bouwman, A. *Hydrol. Earth Syst. Sci.* **17,** 1871–1892 (2013).
7. Ward, P. J. *et al. Proc. Natl Acad. Sci. USA* **111,** 15659–15664 (2014).
8. *Understanding Risk: Producing Actionable Information* (World Bank, 2015).
9. *Sendai Framework for Disaster Risk Reduction 2015–2030* A/CONF.224/L.2 (United Nations, 2015).
10. *Decision2/CP.19 Warsaw International Mechanism for Loss and Damage Associated with Climate Change Impacts* (UNFCCC, 2013).
11. Jonkman, S. N. *Nature Clim. Change* **3,** 1004 (2013).
12. Bates, P. D., Horritt, M. S. & Fewtrell, T. J. *J. Hydro.* **387,** 33–45 (2010).
13. Yamazaki, D. *et al. Water Resour. Res.* **50,** 3467–3480 (2014).
14. Bates, P. D., Smith, A., Sampson, C., Alfielri, L. & Neal, J. C. in *Am. Geophys. Union Fall Meet.* Abstract H33M-03 (AGU, 2014)
15. Mechler, R. *et al. Nature Clim. Change* **4,** 235–237 (2014).
16. Alfieri, L. *et al. Hydrol. Earth Syst. Sci.* **17,** 1161–1175 (2013).
17. Wu, H. *et al. Water Resour. Res.* **50,** 2693–2717 (2014).
18. Simpson, A. Better understanding disaster risk: a new dataset is set to make a difference. *World Bank Voices Blog* (24 September 2014); http://blogs.worldbank.org/voices/better-understanding-disaster-risk-new-dataset-set-make-difference
19. *ASTER GDEM* Version 2 (Land Processes Distributed Active Archive Center, 2015); https://lpdaac.usgs.gov/dataset_discovery/aster/aster_products_table/astgtm
20. Schumann, G. J-P., Bates, P. D., Neal, J. C. & Andreadis, K. M. *Nature* **507,** 169 (2014).
21. Jongman, B. *et al. Proc. Natl Acad. Sci. USA* **112**, E2271–E2280 (2015).
22. Jongman, B. *et al. Nat. Hazard Earth Sys.* **12,** 3733–3752 (2012).
23. Haklay, M., Antoniou, V., Basiouka, S., Soden, R. & Mooney, P. *Crowdsourced Geographic Information Use in Government* (Global Facility for Disaster Reduction and Recovery and World Bank, 2015); http://go.nature.com/CUxelq
24. Rummukainen, M. *WIREs Clim. Change* **1,** 82–96 (2010).
25. Haasnoot, M., Kwakkel, J. H., Walker, W. E. & Ter Maat, J. *Glob. Environ. Change* **23,** 485–498 (2013).
26. De Groeve, T. *et al. Bull. Am. Meteorol. Soc.* **96,** ES97–ES100 (2014).
27. Elvidge, C. D. *et al. Sensors* **7**, 1962–1979 (2007).

Acknowledgements

This project was funded by a VENI grant from the Netherlands Organisation for Scientific Research (grant no. 863.11.011). The findings are drawn from workshops and discussions between users and modellers at the Understanding Risk Forum in London, 2014, the European Geosciences Union General Assembly in Vienna, 2015, and the Global Flood Partnership annual meeting in Boulder, 2015. We thank the participants of these events for their valuable contributions. The Uganda Red Cross forecast-based financing pilot is funded by the German Federal Ministry for Economic Cooperation and Development. The World Bank Caribbean Risk Information Programme (www.charim.net) is financed by the European Union-funded ACP-EU Natural Disaster Risk Reduction Program and managed by the Global Facility for Disaster Reduction and Recovery.

© 2015 Macmillan Publishers Limited. All rights reserved