Exploring the Concept of Cumulative, Probabilistic Flood Hazard Maps

Maryellen Hearn[1] and Verena Maleska[2]
[1]Erasmus Mundus Flood Risk Management Master Candidate; [2]Diploma Hydrologist, Germany

1. Introduction

This paper examines the potential to improve flood risk understanding through a proposed elaboration of a commonly used tool: the flood hazard map.

Despite the advancements in flood hazard uncertainty quantification in academia, the distributed (i.e. per pixel) representation of uncertainty in a flood hazard map has not found its way into mainstream practical application. Traditionally, and usually still today, flood hazard maps present deterministic flood model results (Smemoe et al., 2007; Merwade et al., 2008; de Moel et al., 2009). This means that, for a particular flood event (such as the 1% annual flood), there is one hard boundary representing where the flood is estimated to reach (flood extent), and each pixel within that boundary may represent one result value for depth, velocity, or other characteristics of the flood. Often multiple recurrence intervals are taken into account (such as the 0.2%, 0.5%, and 1% floods), depending on the purpose and resources available (Martini and Loat, 2007). Relying on these deterministic maps for practical use, however, assumes that the uncertainty of the model results is so limited that it need not be represented visually. While recognizing that different practical situations require different flood risk communication approaches (Morss et al., 2005), this paper proposes a mapping approach to be used when deterministic maps are insufficient.

This paper will begin with an illustration of a flood hazard map of the probability of flooding not only for multiple recurrence intervals (such as the 100-year event or 1% annual chance event), but also incorporating a probabilistic (i.e. non-deterministic) representation of multiple types of uncertainty. It will then briefly cover sources of uncertainty in flood hazard modeling and why they are particularly critical to represent in a map. Next follows the elaboration of the approach to include cumulative probability (i.e. probability of flooding over a multi-year period) and its potential to further improve risk communication. After considering the balance of complexity and simplicity, this paper will conclude with brief reflections on the broader implications for the interface between scientific research and practical implementation.

2. An Illustration of a Probabilistic Hazard Map for Practical Use

Flood hazard is one of the primary components of flood risk. According to the UN Office for Disaster Risk Reduction, a hazard is defined as "A potentially damaging physical event, phenomenon or human activity, which may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation." (UNISDR, 2004). A flood hazard map should, therefore, present the *probability* (often conveyed with a recurrence interval or annual chance) of a flood of a particular *magnitude* (in terms of extent, depth, velocity, or other characteristics). Typically, flood hazard model results are then combined with vulnerability data for the analysis of flood risk.

Imagine that the sample map in Figure 1 were to represent the probability of flooding at least 3 inches in the next 25 years, based on a) multiple annual chance floods (for example, a 0.2%, a 0.5% and a 1% chance flood), b) multiple sets of roughness values to represent friction of the channel and floodplain, and c) multiple climate projections. Home buyers might consult it in making decisions about where to live and whether or not to buy flood insurance. Local planners might consult such a map for considering areas for development or protection. Emergency management staff might consult it in planning emergency routes and updating the local emergency management plan. Insurance and reinsurance professionals could consult it in the estimation of premiums. Engineers and flood risk project managers might consult it for the purpose of planning grey and green infrastructure and other mitigation measures.

An example of a basic methodology (to be embedded within the standard modeling process) for creating such a probabilistic map to account for uncertainty could include:

1. Determine which components of the particular model in question are the most sensitive, i.e. a sensitivity analysis, which is standard for good modelling practice in general (van Waveren et al., 1999).

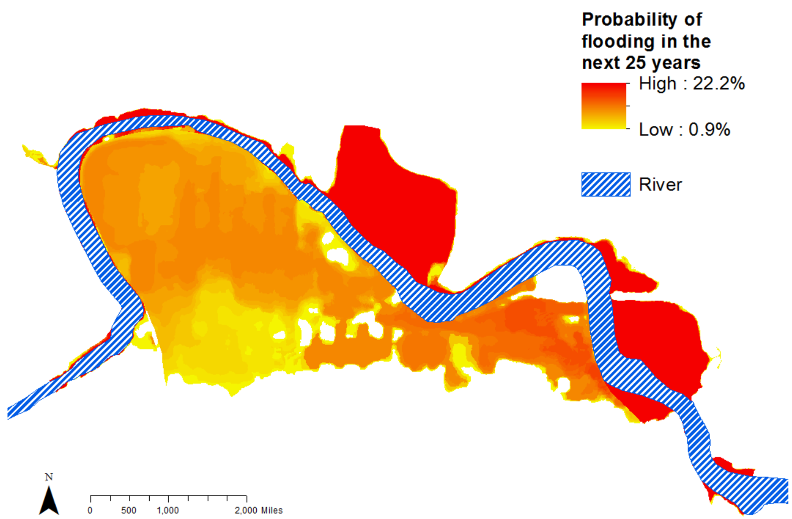

Figure 1: Probability of flooding in 25 consecutive years.
This figure is a mockup using fake data solely for purposes of illustrating the mapping concept introduced in this paper, not the model or data.

2. Perform multiple simulations of flood hazard, varying the most sensitive variables within a feasible range to represent their uncertainty. For this example, assume a single model's output is a grid of pixels showing 0 for a prediction of "no flood", 1 for "flood". A depth threshold may be applied as part of this process, if desired (e.g. only areas predicted to have a maximum depth of at least 3 inches of water will have a value of 1, all others have a value of 0).
3. For each return period, add all of the simulation result files together per-pixel and divide by the total number of simulation files (i.e. calculate mean value by pixel). This represents the probability that each pixel will be inundated for that return period, considering the most sensitive sources of uncertainty. The result map will be a grid with probabilities ranging from 0 to 1.

3. Uncertainty of Flood Hazard Modeling and its Representation in Maps

Numerous types and sources of uncertainty can contribute to variable flood hazard model results. Quantification of epistemic uncertainty appears frequently in the literature around flood hazard modeling. Epistemic uncertainty is uncertainty due to lack of information, and is often juxtaposed with aleatoric uncertainty, which is due to randomness (Der Kiureghian and Ditlevsen 2009, Oden et al., 2010). Examples of sources of epistemic uncertainty in a flood hazard model include input and output data errors, model structure, methods, and related assumptions. Many studies focus on the uncertainty of the hydrodynamic model input data, especially channel/floodplain friction (Manning's *n*), magnitude of water flow (e.g. peak discharge of the 1% annual chance event), and topography (e.g. errors in elevation data), as well as the interdependency of these variables (Aronica et al., 2002; Cook and Merwade, 2009; Kalynapu et al., 2011; Jung et al., 2014; Jung and Merwade, 2015; Faghih et al., 2017;). Smemoe et al (2007) propose an approach using varied input data for hydrologic and hydraulic models to produce a continuous map of flood probability, and they demonstrate that such an approach would better reflect state of the art engineering capabilities while potentially reducing the number of disputes and map change orders (within the context of the U.S. National Flood Insurance Program, or NFIP).

The quantification and prediction of global climate change and its variable local impacts are increasingly of interest for flood hazard and risk modeling as well. While a tremendous scientific effort has greatly increased our understanding of and projections for climate change on global and regional levels, uncertainty regarding precise, long-term temperature and hydrological trends remains (IPCC, 2014). In terms of categorization, Refsgaard et al. (2013) claim that there are elements of epistemic uncertainty, but also aleatoric uncertainty (such as the initial conditions of the climate models) within climate change modeling. Flood hazard and flood risk modeling under various climate projections has been conducted on various geographic scales and using a variety of scenario and ensemble approaches (Dankers and Feyen, 2008; Hirabayashi et al., 2013; Ward et al., 2014; Alfieri et al., 2016;).

When presenting flood hazard in a map, not representing uncertainty may limit the understanding of the hazard and related risk. Maps present information in a visually engaging manner, and, generally speaking, people are less critical of maps than of some other forms of communication (Monmonier, 1996). As Mark Monmonier proposed in the book *How to Lie with Maps*, maps are necessarily only able to provide a partial representation of reality, and it is up to the map maker to determine the most important components and how to include them (1996). Therefore, the effect of a map (i.e. the impression it leaves on the audience and how it affects their decisions) depends on the assumptions made by the map maker, not to mention the audience members' backgrounds.

In the context of the current discussion, the assumption under question is whether or not uncertainty is important enough to include in a flood hazard map itself. In a review of flood mapping practices across twenty-nine European countries, de Moel et al. (2009) observe that incorporating both climate change effects and the related uncertainties of flood risk management into mapping practices, could be "an important driver for spatial planners and investors […]." The results of Vause's (2013) interviews with members of two English Flood Action Groups echo this sentiment, suggesting that the inclusion of uncertainty in flood mapping can facilitate more informed decision-making.

4. Potential for Improved Communication of Flood Risk

The communication of the probability of extreme flood events has been an ongoing challenge, particularly in terms of a) model result uncertainty and b) terminology around extreme events (e.g. return periods, annual chance). Smemoe et al. (2007) examine the first of these (model result uncertainty), demonstrating that, given model uncertainty and natural variability, no single line could be a sufficiently accurate representation of the 1% floodplain boundary, as it is represented today in FEMA flood maps. The authors recognized that there may be institutional barriers to shifting toward a more probabilistic approach, at least within the context of the U.S. NFIP insurance rates, but that the technical capacity already exists (Smemoe et al., 2007).

Regarding terminology around the risk of extreme events, a recent study on flood risk map communication in Edinburgh sheds some light. Strathie et al. (2015) found that the return period terminology (e.g. "1 in 200 year flood") and the annual chance terminology (e.g. "0.5%" or "1 in 200 chance that flooding will occur at least once in *any given year*") received the lowest median perceived risk rates. This means that, compared to descriptions of the same risk level using cumulative terms (e.g. 11.8% chance of flooding at least once *in 25 years*), participants felt safer, less at-risk, when using the return period and annual chance terminology. Though participants indicated that they *preferred* the statements reflecting the annual chance, the objective comprehension test suggested that more participants *understood* the cumulative statements.

Could cumulative, probabilistic flood hazard maps help the public and decision makers overcome some of the challenges of understanding flood risk uncertainty and terminology? The algorithm from Section 2 detailed how to produce a probabilistic map that represents uncertainty due climate projections, roughness parameters, and the method for calculating the discharge of the peak event, but it also represented multiple extreme flood events on the same map in terms of cumulative probability (also shown in Figure 1). In reality this enhancement leaves the map image itself unchanged, but alters the probability labels in the legend. The algorithm could be amended with the following additional steps:

4. Select the period for accumulation, and weight each set of return periods accordingly. For example, assume the return periods to be included are 0.2%, 0.5% and 1% annual chance. The 1% chance flood has a 99% chance of not occurring in any given year, so the chance of it not occurring in 25 consecutive years would be 77.8% (99% to the power of 25). This means the likelihood of having a 1% chance or greater flood in 25 years is 22.2% (100% - 77.8%). Doing the same for the 0.2% and 0.5% chance floods, their respective likelihood of occurrence in 25 years will be 4.9% and 11.8%. Multiply each return period probability map (from step 3) by the likelihood of occurrence.
5. Combine the grids from step 4 using a tool which, for each pixel, maintains the maximum value of all of the input grids. For example, if a pixel is represented as having 4% probability of inundation in 25 years on one grid and 7% probability on another grid, the resulting map will represent the pixel as a 7% probability of flooding in 25 years.
6. Finally, for the purposes of audience understanding, it may be wise to overlay a grid or polygon which that covers the river itself, to avoid it being represented as a 22.2% chance of flooding. In theory, this is similar to including a 100% (or almost 100%) annual chance flood in the analysis

along with the 0.2%, 0.5%, and 1%.

Balancing Barriers of Complexity and Simplicity

Albert Einstein was attributed with the quote "Make it as simple as possible, but no simpler," which resonates also in statistician Arnold Zellner's re-interpretation of the KISS principle ("Keep It Sophisticatedly Simple") (Zellner, 2002). This sentiment, also referred to as "Occam's razor", has influenced scientific endeavor at least as far back as the fourteenth century, when William of Occam first proposed such a principle of parsimony (Young et al., 1996). As with most good advice, this principle has many interpretations in practice.

Some might say that the algorithm detailed in Sections 2 and 4 is too complex. Creating a cumulative, probabilistic flood hazard map could be considered a costly burden, both in time and resources (such as data and storage capacity), particularly when overloaded staff are already working on tight budgets. However, there are tools available today, for free or for purchase, with which a limited version of the process would be feasible on a small scale, assuming previous modeling experience and perhaps limited programming skills to speed the process. On a larger scale, the basic technologies and techniques are available, but combining them into an efficient, user-friendly format would require enough demand to make it worth the effort.

Others might argue that the algorithm is far too simplistic. The process could be criticized for obscuring the true level of uncertainty in flood hazard modeling. However, the proposed process is an attempt to fulfill responsibilities a) as a mapmaker, to highlight the most important components of the system for audience understanding, and, perhaps more importantly b) as a modeler, to recognize that the absence of uncertainty in a flood hazard map is, in many cases, too simple to adhere to the advice of Einstein, Zellner, and William of Occam. The alternative (i.e. providing a deterministic map) should be considered a more significant offense than a reasonable attempt to recognize the most sensitive variables through probabilistic model results.

6. Conclusions

The approach to flood hazard mapping outlined in this paper integrates Smemoe et al.'s (2007) approach to representing epistemic uncertainty in flood maps, de Moel et al.'s (2009) call for representation of climate projections in flood hazard mapping, and the concept of presenting flood hazard maps in terms of cumulative probability, as examined by Strathie et al. (2015). Not *every* source of uncertainty would be visually represented (though the related assumptions should accompany the map). However, this map tells a significantly richer story than a deterministic, annual chance flood hazard map.

Part of the inspiration for this approach was to align flood hazard uncertainty communication with that of familiar communication methods. For example, people appear to be accustomed to precipitation forecasts delivered as a probability (e.g. percent chance of rain) for a given time range (e.g. the next 24 hours). Rather than checking the weather to decide whether to bring an umbrella, one might consult the cumulative, probabilistic flood map to make a decision about purchasing flood insurance or investing in flood risk mitigation measures.

This paper explores one potential approach to improving the understanding of flood risk. Looking to the future, this paper is also intended to encourage the exchange of knowledge, perspectives, and ideas between researchers and practitioners, and to provoke further discussion on two principle questions: a) could cumulative, probabilistic flood hazard maps make risk communication more effective for individual and community-wide decision-making? and b) does the process described in the paper strike the appropriate balance between comprehensiveness and simplicity? Should this, or another technique, satisfy both of those requirements, the follow-up question is: whose role should it be to enable and support the integration of such maps into practical applications, and how?

6. References

1. Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., de Roo, A., Salamon, P., Wyser, K., Feyen, L., 2016. Global projections of river flood risk in a warmer world. Earth's Future.

2. Aronica, G., Bates, P. D., Horritt, M. S., 2002. Assessing the uncertainty in distributed model predictions using observed binary pattern information within glue. Hydrological Processes 16, 2001-2016.

3. Cook, A., Merwade, V., 2009. Effect of topographic data, geometric configuration and modeling approach on flood inundation mapping. Journal of Hydrology 377 (1), 131-142.

4. Dankers, R., Feyen, L., 2008. Climate change impact on flood hazard in Europe: An assessment based on high-resolution climate simulations. Journal of Geophysical Research: Atmospheres 113 (D19).

5. de Moel, H. d., Alphen, J. v., Aerts, J., 2009. Flood maps in Europe – methods, availability and use. Natural Hazards and Earth System Sciences 9 (2), 289-301.

6. Der Kiureghian, A., Ditlevsen, O., 2009. Aleatory or epistemic? Does it matter? Structural Safety 31 (2), 105-112.

7. Faghih, M., Mirzaei, M., Adamowski, J., Lee, J., El-Shafie, A., 2017. Uncertainty estimation in flood inundation mapping: an application of nonparametric bootstrapping. River Research and Applications.

8. Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., Kanae, S., 2013. Global flood risk under climate change. Nature Climate Change 3 (9), 816-821.

9. IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.

10. Jung, Y., Merwade, V., 2015. Estimation of uncertainty propagation in flood inundation mapping using 1-D hydraulic model. Hydrological Processes 29, 624-640.

11. Jung, Y., Merwade, V., Kim, S., Kang, N., Kim, Y., Lee, K., Kim, G., Kim, H. S., 2014. Sensitivity of subjective decisions in the glue methodology for quantifying the uncertainty in the flood inundation map for Seymour reach in Indiana, USA. Water 6, 2104-2126.

12. Kalyanapu, A., Judi, D. R., Mcpherson, T. N., Burian, S. J., 2011. Monte Carlo-based flood modelling framework for estimating probability weighted flood risk. Journal of Flood Risk Management.

13. Martini, F., Loat, R., 2007. Handbook on good practices for flood mapping in Europe. European Exchange Circle on Flood Mapping (EXCIMAP), Paris/Bern.

14. Merwade, V., Olivera, F., Arabi, M., Edleman, S., 2008. Uncertainty in Flood Inundation Mapping: Current Issues and Future Directions. Journal of Hydrologic Engineering 13 (7), 608-620.

15. Monmonier, M., 2014. How to Lie with Maps. University of Chicago Press.

16. Morss, R. E., Wilhelmi, O. V., Downton, M. W., Gruntfest, E., 2005. Flood Risk, Uncertainty, and Scientific Information for Decision Making: Lessons from an Interdisciplinary Project. Bulletin of the American Meteorological Society 86 (11), 1593-1601.

17. Oden, T., Moser, R., Ghattas, O., 2010. Computer Predictions with Quantified Uncertainty, Part I. SIAM News 43 (9), 1-3.

18. Refsgaard, J. C., Arnbjerg-Nielsen, K., Drews, M., Halsnæs, K., Jeppesen, E., Madsen, H., Markandya, A., Olesen, J. E., Porter, J. R., Christensen, J. H., 2013. The role of uncertainty in climate change adaptation strategies—a Danish water management example. Mitigation and Adaptation Strategies for Global Change 18 (3), 337-359.

19. Smemoe, C. M., Nelson, E. J., Zundel, A. K., Miller, A. W., 04 2007. Demonstrating floodplain uncertainty using flood probability maps. Journal of the American Water Resources Association 43 (2), 359-371.

20. Strathie, A., Netto, G., Walker, G., Pender, G., 2015. How presentation format affects the interpretation of probabilistic flood risk information. Journal of Flood Risk Management.

21. UN International Strategy for Disaster Reduction, 2004. Living with Risk: A Global Review of Disaster Reduction Initiatives. United Nations Publications.

22. van Waveren, R.H., Groot, S., Scholten, H., van Geer, F.C., Wösten, J.H.M., Koeze, R.D., Noort, J.J., 1999. Good Modelling Practice Handbook. STOWA/Rijkswaterstaat-RIZA.

23. Vause, R., Aug 2013. End-User Specific Flood Uncertainty Mapping: Effective Map Design from the Perspective of the English Public. Master's thesis, Technical University of Dresden.

24. Ward, P.J., van Pelt, S.C., de Keizer, O., Aerts, J.C.J.H., Beersma, J.J., van de Hurk, B.J.J.M., te Linde, A., 2014. Including climate change projections in probabilistic flood risk assessment. Journal of Flood Risk Management 7 (2), 141-151.

25. Zellner, A., 2002. Simplicity, Interference and Modeling: Keeping it Sophisticatedly Simple. Cambridge University Press, Ch. Keep It Sophisticatedly Simple, pp. 242-262.

Author Contact Information:

Maryellen Hearn, Erasmus Mundus Flood Risk Management Master Candidate; Email: maryellen.hearn@mailbox.tu-dresden.de, m.hearn@wateryouthnetwork.org