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Flood hazard identification and mapping program (FHIMP): Technical Bulletins and Uncertainty in Flood Mapping

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ABSTRACT

Flood mapping is a critical tool for risk and emergency management, yet it is unavoidably subject to uncertainty arising from natural variability, data scarcity, analytical limitations, and natural variability. This paper examines uncertainty in flood mapping and its implications for decision-making. It outlines the sources of uncertainty and quantification methods, such as probabilistic approaches and sensitivity analyses. A case study of sensitivity demonstrates how parameter variability and calibration data validity influence peak flows, and flood hazard delineations. Best practices for communicating uncertainty to technical and non-technical audiences emphasize clarity, transparency, and the use of visual tools to convey confidence levels. Finally, strategies for managing uncertainty include a method to assess uncertainty and periodic map updates to account for climate change and evolving land use. By identifying the sources of uncertainty, quantifying this uncertainty, and communicating it via into flood mapping products, practitioners can create an appropriate degree of confidence in results and guide informed decision-making.

KEYWORDS: flood hazard, flood mapping, hydrometrics, hydrometeorology, uncertainty, sensitivity analysis, probability, communication

1 INTRODUCTION

As part of the federally funded Flood Hazard Identification and Mapping Program (FHIMP), Environment and Climate Change Canada (ECCC) acts as technical advisors on provincial and territorial flood mapping projects, advances the science of flood mapping, and provides guidance on best practices. This guidance is offered in the Federal Flood Mapping Guidelines Series and the Federal Flood Mapping Technical Bulletins Series (the Technical Bulletins). These Technical Bulletins complement the Federal Flood Mapping Guidelines Series by addressing specific flood mapping topics in more detail.

Currently a single Technical Bulletin is available: Geomorphic Considerations in Flood Mapping. Work is currently underway on a few more, including:

1. Flood Data Collection
2. A Framework for Review and Update Cycle of Flood Maps
3. Pluvial Flood Mapping Guidance
4. Uncertainty in Flood Mapping
5. Wave Hazards

This paper explores the Technical Bulletin on Uncertainty in Flood Mapping in more detail. Generally, the development of a flood hazard map involves three sequential steps (Figure 1):

1. Selection of the design flood flow,
2. Hydraulic modelling of floodwater elevation calculations from these design flood flows, and
3. Mapping and estimation of spatial flood extent from the hydraulic model results.

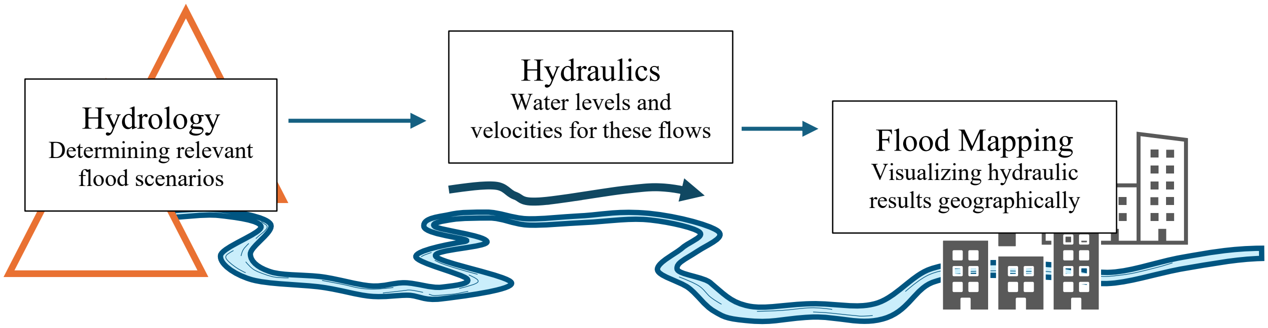

Figure 1: Potential Framework for Uncertainty by Workflow Step. Adapted from KWL (2024)

Each step relies on data, analysis, and assumptions, each with its own uncertainty. It is impossible to precisely measure all these processes in detail, to measure the quantity of every fluctuation. Therefore, flood maps are unavoidably subject to uncertainty. This uncertainty accumulates as calculations and decisions from the previous step are used, as shown below in Figure 2.

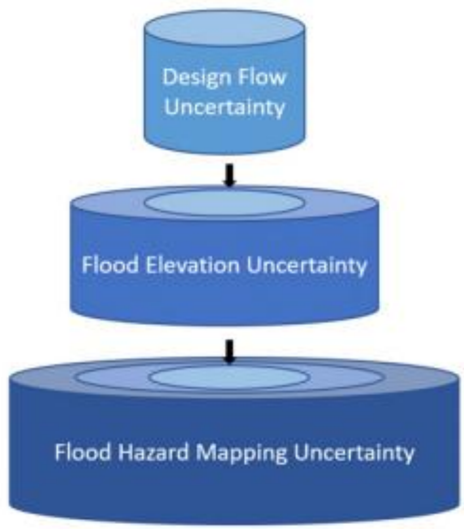

Figure 2: How uncertainty can propagate through the flood mapping process and potentially have additive impacts, increasing the potential uncertainty of the final flood hazard map. (MacHydro, 2023)

To address this uncertainty, it must first be understood and characterized. Then this uncertainty must be effectively communicated, as flood mapping is in-and-of-itself a communication tool. Finally, the uncertainty can be managed, limited, and accounted for.

2 UNDERSTANDING UNCERTAINTY

Uncertainty refers to limitations both in the accuracy and the confidence of results due to incomplete, imperfect, and unknown information, measurements, and analysis. It has several common characteristics:

- Uncertainty may be *quantifiable* or *unquantifiable*. Quantifiable uncertainty can be measured and expressed as a relative or absolute measure. Unquantifiable uncertainty may stem from elements that may change in the future or where there is insufficient information or understanding to adequately account or characterize the uncertainty.
- Uncertainties may be *reducible* (e.g. through more or better data collection or study) or *irreducible* (e.g. cannot be reduced by any means available at the time the knowledge is required).
- There may also be unknowable uncertainties, which cannot reasonably be anticipated or quantified.

Uncertainty is an unavoidable component of flood mapping. It must therefore be understood and managed, which requires an appreciation of both where it stems from (sources of uncertainty) and the relative impact of that uncertainty on the final output (quantifying uncertainty and sensitivity analysis).

The first step to understanding uncertainty in a study is to set an optimization goal (i.e. an objective function) for the analytical technique used (e.g. flood frequency analyses, synthesized data records, hydrologic, and/or hydraulic modelling). This defines the acceptable tolerance between the simulated and observed series. Then determine if a bias correction is required to meet this tolerance, then run the model again until no further correction is necessary.

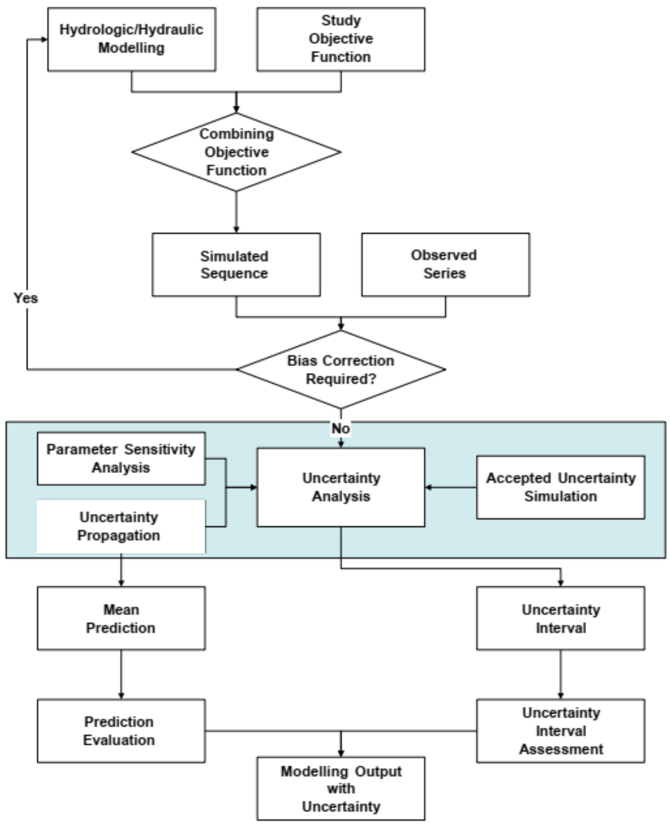

Figure 3: Uncertainty workflow of hydrologic and hydraulic modelling (NRCan and ECCC, 2023)

Then perform a sensitivity analysis or Monte Carlo simulation of the model's output for each non-constant parameter. Adjust each parameter and compare the results to determine each parameter's relative impact. These analyses/simulations will produce a mean prediction with an uncertainty interval (e.g. the average value of design flood events with confidence limits or min/max differences of different analyses).

2.1 Sources of Uncertainty

The *Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation* (NRCan and ECCC, 2023) classifies uncertainty into four characteristics categories based on the origin of that uncertainty:

1. **Natural or intrinsic uncertainty** from the inherent randomness of natural processes, which varies over time and space. This natural uncertainty is difficult to reduce and quantify as the data is irreproducible. Examples include changes to bathymetry/topography (e.g. due to erosion), and/or natural physical processes (e.g. weather patterns, heterogeneity in soil hydraulic conductivity).

2. **Data uncertainty** from measurement errors, instrumentation errors, inconsistencies and non-homogeneity of the data, data handling, and inadequate representativeness of data over time and space. This data uncertainty is reducible with better or increased measurements. Examples include spatial/temporal data availability (e.g. proximity of monitoring stations, data gaps), data quality, accuracy and precision (e.g. measurement/instrument error, data handling), and/or climate change projections (e.g. availability of projections for key parameters, reliance on interpretation/analysis, changing flood mechanisms).
3. **Calculation uncertainty** from the inability of a mathematical technique or model to accurately represent the true physical behaviour of the natural world. The technique or model may be poorly or incompletely specified, or the phenomena modelled has instabilities and non-linearities which are not reflected in the modelling approaches. For example, historic flood event classification (e.g. rainfall, snowmelt, or rain-on-snow), choice of statistical distributions within a frequency analysis, model choices and associated limitations (e.g. 1D vs. 2D hydraulic models), and/or processing hydraulic models to develop flood maps (e.g. interpolation of a river flood profile)
4. **Parameter uncertainties** from inaccurately assessed parameter values in the test or calibration data, due to limited numbers of observations, and statistical imprecision. Examples include the selection of most-fitting frequency distribution parameters, the abstraction of physical properties such as sediment grain size, or hydraulic roughness, and/or assumptions made due to limited availability of data.

These categories of uncertainties are interdependent and overlap. The overlap of these interdependencies reduces the overall uncertainty. An example of the interdependence is how natural uncertainty impacts the measurement of water levels, which in turn reduces the certainty of the parameter valuation. Having uncertain values for the parameters inherently makes the model uncertain.

2.2 Quantifying Uncertainty

A wide range of possible methods and approaches for uncertainty quantification exist, requiring a different amount of effort. Therefore, the practitioner should select the uncertainty quantification method that is appropriate for their level of required precision, the resources available, and the requirements of the end users and decision makers. Quantification methods are discussed in greater detail in *Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation (NRCan and ECCC, 2023)*, *Guidelines for Communication of Uncertainty in Flood Maps (KWL, 2024)*, and *ECCC Uncertainty in Floodplain Mapping (MacHydro, 2023)*. Some methods include the following:

- Uncertainty allowances and/or relative magnitudes based on subjective judgement.
- Uncertainty estimates based on multiple measurements and/or reported data accuracies for inputs.
- Uncertainty estimates based on multiple analysis approaches for a given item (for example, by determining river flood design flows using two different methods and comparing the results).
- Best estimates and upper and lower bounds developed for all uncertainty components and propagated through the analysis to determine corresponding flood mapping results for the best estimate and reasonable upper and lower bounds (i.e. three sets of results for a given event).
- Analytical techniques, which involve a derivation of the exact probability density function and/or statistical moments of a model as a function of several stochastic variables. (Yung, 2011)
- Approximate techniques involve probabilistic assessment based on a broad spanning sensitivity analysis, such as a Monte Carlo simulation. These approach assigns probability distributions for the range of values considered in the sensitivity analysis and then runs multiple simulations where the values for each of the parameters being varied is selected randomly based on their probability distributions. (Yung, 2011) Sensitivity analyses are discussed in more detail below.

Ideally, uncertainty assessments should also state items which cannot be quantified.

2.3 Sensitivity Analysis and Case Studies

A sensitivity analysis involves changing the model input parameters by a set amount, then examining how those changes affect the model's output. The parameters that are selected to be varied are sources of uncertainty. Once these parameters have been selected, the model is run repeatedly, increasing or decreasing a parameter each time, and the subsequent changes to the results (i.e. water levels, velocities, flooding extents, and depths) are recorded while holding all other parameters constant. Once all parameters have been run, a list is prepared with the parameter causing the largest response of the results first. This technique highlights the input parameters that will most significantly change the results, and therefore the input parameters to pay particular attention to during model calibration.

In 2024, CBCL and Associated Engineering conducted a sensitivity analysis on the flood mapping process completed for one flood study in Nova Scotia, and another in British Columbia (CBCL, 2025). The focus of this analysis was to examine the impact of the variability of parameter selection on the resulting flows, water levels and flood maps.

The study concluded that the most sensitive parameters affecting the estimated peak flows included, in order: the source calibration event, the maximum overland flow parameter, IDF data source, discretization level of sub-catchments, soil hydraulic conductivity, and hyetograph distribution (Figure 5 below). It is noted that these findings may be limited to watersheds with rainfall-dominated runoff responses.

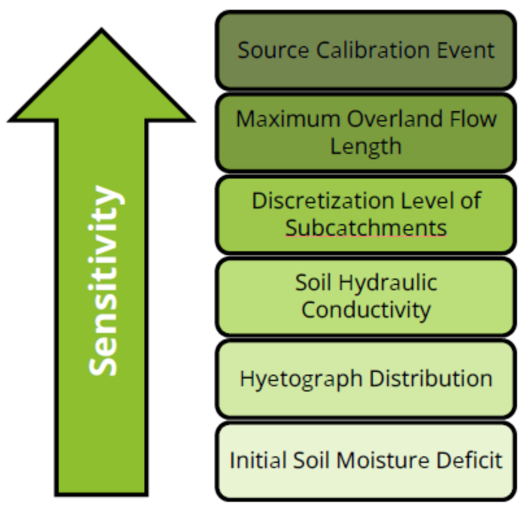

Figure 4: The Most Sensitive Hydrologic Input Model Parameters (CBCL, 2024)

This study also revealed that the highest sensitivity of flood extents was less focused on how calibration parameters were selected, but rather more focused on the validity of the calibration data in the first place. The study therefore recommended prioritizing the identification of a representative flow gauging station, the selection of a suitable flow calibration event and in turn, the identification of a suitable climate station that recorded the rainfall that generated the peak flow used for calibration, and then the selection of a suitable design rainfall event data source and distribution. These aspects, admittedly, are highly dependent on the availability, quality and suitability of flow gauging and climate station data to represent of the local hydrologic processes.

Model calibration based on alternate hydrologic parameters values did not greatly change the estimates of peak flow, reinforcing the finding that the most significant source of uncertainty is the precipitation and flow data that is used for model calibration and design hyetograph generation.

Similar to peak flow, for a given measured rainfall, and gauged flow to calibrate to, using different sets of parameter adjustments in the calibration process had minor impacts to the resulting flood extents, so long as the modelled hydrograph closely represented the measured hydrograph, notably the peak flow.

3 COMMUNICATING UNCERTAINTY

The goal of communicating uncertainty in flood mapping is to help end users appreciate how results and conclusions might vary in different circumstances, enabling them to interpret results with an appropriate level of confidence. Clear communication of the limitations and uncertainties in flood mapping is critically important because these maps may result in planning, regulatory and legal ramifications, but can also be used by the larger public to help understand the personal risk to them.

Communication approaches range from limited information/quantification (acknowledgement and qualitative commentary) to very detailed analysis and quantification, including mapping specific uncertainty outcomes.

Communicating uncertainty in a way that is accurate, scientifically defensible, and broadly accessible involves balancing objectives that sometimes conflict. Flood maps should be communicated in a way that best serves both their ultimate purpose and intended audience, where appropriate communication may look different depending on both.

The most important piece of information communicated within flood hazard maps is flood inundation extent (and potentially depth). A major limitation of current flood maps is that flood inundation levels are usually binary (i.e., they show a single inundation stage). While this creates the impression that a high degree of certainty is imbued within that single line, significant uncertainty exists within this precise inundation level: adjacent areas on either side of the inundation line may share a similar flood hazard and a single line may give a false sense of precision that does not exist. Specifically, flood hazard exists as a gradient around the presented inundation extent, even though very few flood hazard maps present it as such. This gap could undermine public trust in flood hazard maps, especially if the design flood flow occurs and inundates beyond the single flood line contained within the flood hazard map. This highlights the importance of clearly communicating key assumptions within the analysis to the public (for example, which design flow was selected to calculate the inundation level).

Effective communication of uncertainty should strive first and foremost to convey the desired information in a way that is easily understandable by the intended audience. For instance, public communication and other non-technical products (such as a public flood map) should prioritize clarity and key messages over more technical details (which could be provided in an accompanying technical document). Communication should be done using clear and simple language and information regarding the analysis should also be presented in a 'tiered' format that accounts for the level of detail needed by a specific audience.

Uncertainty should be presented in a way that highlights which limitations exist as well as what conclusions can still be made despite this uncertainty. Visual communication, such as the presentation of a 'gradient' around the flood inundation level, should be clearly defined. Including this information in the final mapping product communicates that inundation levels are not binary but rather contain a range of probable values due to uncertainties in the methodology that decision makers and other members of the public must consider. By comparison, technical documents require comprehensive information detailing study assumptions and methods used to determine uncertainty. Details regarding methods used to define flood maps, as well as major assumptions made, should be readily available. At a minimum, study results and interpretation should be accompanied by a statement of sources of uncertainty, and the limitations in the final product.

4 MANAGING UNCERTAINTY

The effort required to assess uncertainty in flood mapping depends on the type of assessment, and to efficiently use limited resources, the uncertainty assessment process should be defined at the project outset. The aspects of uncertainty of most concern to the map users should be targeted.

Generally, an uncertainty assessment process includes the following steps:

1. Identify and list anticipated sources of uncertainty (including data, parameters, assumptions, analysis, modelling) for all stages of the project. Include acknowledgement that there may be unknown uncertainties that are not identified.
2. Qualitatively rate all sources of uncertainty on two scales:
    a. the degree to which they are expected to affect the end results (i.e. sensitivity), and
    b. how well they can currently be addressed or accounted for.
3. Categorize these uncertainties into appropriate functional groups for analysis and communication, taking into account their relative sensitivity.
4. In collaboration with users and decision-makers, rank sources of uncertainty and assumptions in terms of how they affect their specific decisions, then collaboratively decide which uncertainties and assumptions to prioritize and the uncertainty quantification methods to be used. This should be completed before the data analysis and modelling step.
5. For the prioritized uncertainties, quantify, propagate, and analyze uncertainties in the process of producing the required flood maps.
6. Review the initial decisions taken under Steps 1-4 to confirm that the decisions remain appropriate in the context of the results.
7. Communicate uncertainty in project deliverables.
8. Evaluate the communication for efficacy and audience needs and adapt as appropriate for future communications.

Flood maps are useful to understand and mitigate flood risk, despite (and because of) the uncertainty. To improving this usefulness, explicitly state the required level of certainty, and understand that the data, models, and methods used do not have to be perfect to be useful.

4.1 Planning for Potential Change and Aging Flood Maps

As part of each flood mapping study, practitioners should review the intended scope and use of the flood maps in the context of ongoing and expected changes within the watershed and along the floodplain. Studies should identify an appropriate planning horizon for flood risk management that considers climate and land use changes expected (e.g., sea-level rise, changes in precipitation, and/or urbanization of natural areas). Precautionary factors of safety may be appropriate in situations where uncertainty is high.

Climate change is one of the largest considerations of future uncertainty in the flood mapping process. Climate change uncertainty is the combination of a cascade of uncertainties from various sources: emissions scenarios, climate models, downscaling and bias-correction methods, natural variability, statistical parameter estimation, and the applications methods that are being used to incorporate climate information as inputs. Because the approaches to incorporate climate change in flood mapping differ from jurisdiction to jurisdiction and analysis to analysis, a consistent approach should be considered to standardize and characterize uncertainty.

A major event like a major flood, ice jam, or storm surge event larger than the historical record used in any FFA (flood frequency analysis) for a flood hazard delineation could warrant a re-examination of the FFA. In addition, if the channel or infrastructure changes from the initial study, a new hydraulic analysis will indicate whether risks of inundation have increased, even if the hydrology remains essentially the same.

4.2 Technical Bulletin on Flood Map Updating

Many jurisdictions legislate a periodic re-assessment of flood hazard. The United Kingdom (UK Environmental Agency, 2019) requires a review every six years, and FEMA must assess the need to revise flood mapping every five years (Department of Homeland Security, 2017). ECCC is currently drafting guidance on the recommended time interval between flood map updates, based on academic and non-academic publications, articles, flood mapping reports, guidelines from other countries, and subject matter experts.

The recommended baseline for review and update of flood maps is 5 years. However, there are several circumstances that would trigger an unscheduled review, such as: new planning guidance that creates a substantial change in flood mapping methodology; identification of an error or inaccuracy in the existing flood map or study; or major terrain and structural alterations that would affect the results.

5 CONCLUSION

The following is a summary of notable considerations for uncertainty with flood mapping:

- **Uncertainty is unavoidable and should therefore be acknowledged and quantified**: While it may not be possible to completely identify, quantify, or remove all sources of uncertainty, there is still value in understanding, quantifying, and addressing uncertainty.
- **Maintain confidence in flood mapping through clear communication**: Communication of uncertainty is important for informed decision making and public awareness, but it must be carefully balanced against the need to maintain a reasonable level of confidence in the mapping results. Methods of communicating uncertainty therefore needs to create the appropriate level of confidence in results while acknowledging limitations.
- **Uncertainty increases over time, therefore managing uncertainty includes planning for change**: Updating flood maps reduces the uncertainty caused by gradual changes in the environmental factors, as well as those factors that increase uncertainty by the passage of time, or analytical techniques that are shown to increase certainty. Planning for future changes is therefore critical, and periodic reviews (typically every five years) and unscheduled updates triggered by major events can help maintain map reliability.

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