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Key Points:
- Estimates of flood risks can be strongly biased by bathtub hazard modeling
- Physics-based modeling reduces flood risk bias compared to bathtub modeling and is now feasible globally
- Short-format, high-impact journals have contributed to "climate hype" stemming from biased bathtub modeling studies

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Flooding is Not Like Filling a Bath

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Abstract Damage and disruption from flooding have rapidly escalated over recent decades. Knowing who and what is at risk, how these risks are changing, and what is driving these changes is of immense importance to flood management and policy. Accurate predictions of flood risk are also critical to public safety. However, many high-profile research studies reporting risks at national and global scales rely upon a significant oversimplification of how floods behave—as a level pool—an approach known as bathtub modeling that is avoided in flood management practice due to known biases (e.g., >200% error in flood area) compared to physics-based modeling. With publicity by news media, findings that would likely not be trusted by flood management professionals are thus widely communicated to policy makers and the public, scientific credibility is put at risk, and maladaptation becomes more likely. Here, we call upon researchers to abandon the practice of bathtub modeling in flood risk studies, and for those involved in the peer-review process to ensure the conclusions of impact analyses are consistent with the limitations of the assumed flood physics. We document biases and uncertainties from bathtub modeling in both coastal and inland geographies, and we present examples of physics-based modeling approaches suited to large-scale applications. Reducing biases and uncertainties in flood hazard estimates will sharpen scientific understanding of changing risks, better serve the needs of policy makers, enable news media to more objectively report present and future risks to the public, and better inform adaptation planning.

Plain Language Summary Numerous studies of flood risks under climate change, such as changing sea levels and flood hydrology, assess exposure by assuming that projected water levels for oceans and rivers extend horizontally across the land surface. However, this represents a significant over-simplification of flooding that can strongly bias estimates of flood exposure (e.g., a factor of two error). Of particular concern is that biased results sometimes feed into climate hype from the news media, which can undermine public trust in climate science. Data and models suited to more complete modeling of flooding are presented.

1. Introduction

The effect of gravity on any still liquid open to the atmosphere is to produce a horizontal free surface, or one with the slightest of curvature based on earth's radius. This property has proven useful for centuries. For example, legend holds that Archimedes of Syracuse (c. 287–212 BC) estimated the volume of a gold crown from the displacement of a level pool, and later deduced that the gold was diluted with silver (Biello, n.d.). To this day, still liquid volume changes (e.g., in a tank or reservoir) are handily estimated by multiplying changes in water levels with surface area. However, once the fluid is set in motion, the free surface is displaced and is no longer horizontal. Floods involve waves of moving water displaced from the horizontal, and the free surface displacement is influenced by the interaction of gravity, friction, pressure gradients and inertia.

Much research to date focused on understanding and estimating flood risks at large spatial scales (e.g., metropolitan, national, global) has relied upon the assumption that floods behave as a level pool (Hooijer & Vernimmen, 2021; Kulp & Strauss, 2019; Ohenhen et al., 2024; Strauss et al., 2012, 2021). For coastal studies, level pool models (also termed bathtub or planar models) extrapolate extreme ocean water heights over land to estimate flooded areas (Poulter & Halpin, 2008). For inland studies, stream heights are horizontally extrapolated over floodplains using tools such as the Height Above Nearest Drainage (HAND) method (Nobre et al., 2011). Both approaches are much easier to implement than physics-based models, and the ease of bathtub modeling makes it possible for many researchers to quickly estimate flooding over large spatial scales. Yet flooding is not like filling a bath, and such approximations effectively ignore how the laws of motion and hydrologic budgets affect what land could be inundated and/or flooded. Continued use of level pool approximations in flood risk research

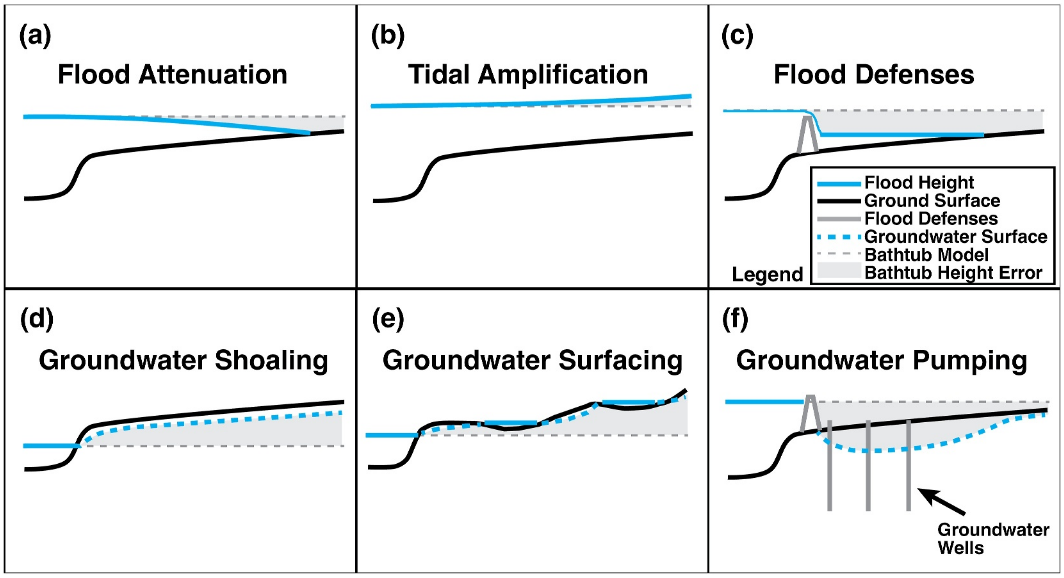

Figure 1. Examples of the limitations arising from bathtub modeling include the inability to capture: (a) flood attenuation from the effects of event dynamics and friction on flood spreading, (b) tidal amplification associated with the resonance of ocean tides within coastal embayments (e.g., Gallien et al., 2011), (c) flood defenses such as levees and flood walls that may overtop during an extreme event but still restrain the degree of inland flooding (e.g., Sanders et al., 2023), (d) shoaling of the groundwater table and (e) surfacing groundwater from the combined influence of rising sea levels and changing hydrologic budgets (Befus et al., 2020), and (f) pumping of groundwater within lands below sea level to mitigate inundation by rising groundwater.

introduces unacceptable levels of uncertainty in the form of bias and threatens the credibility of climate change science among policy makers and the public.

2. How Bathtub Modeling Fails

Flooding occurs with a range of spatial and temporal scales which bear directly on impacts and risks. Episodic, short-lived flooding that occurs during extreme events contrasts with permanent inundation brought on by rising mean sea level and groundwater levels (Flick et al., 2012). The former is driven by extreme weather events and/or infrastructure failures and introduces shocks to communities in the form of property damages and health and safety risks, followed by a cycle of recovery. On the other hand, the latter is driven by long-term changes in sea levels, lake levels, and groundwater levels and presents a state change with no potential for return.

Errors in level-pool estimation of episodic flooding stem directly from their ignorance of dynamics and hydrologic budgets. For example, episodic floods do not have unlimited time to propagate across extensive floodplains before the tide turns or the flood wave peaks (Figure 1a), and water starts to drain back out of the system because pressure gradients have reversed. Flood heights can also amplify within coastal embayments (Figure 1b) from tidal resonance (Gallien et al., 2011) and low lying land behind flood defenses may be inundated in bathtub models when in reality there is no hydraulic connection to these areas. Didier et al. (2019) caution that coastal flood depths may be overestimated by 100% using bathtub modeling versus dynamic modeling, Vousdoukas et al. (2016) report errors in coastal flood extent exceeding 200%, and Barnard et al. (2019) document a 300% difference in exposed population using dynamic versus bathtub modeling. For the case of inland flooding, errors of up to 4 m in the estimation of flood water levels have been documented, and the accuracy of flood extent estimates can be less than 50% (i.e., worse than a random classification) (Gutenson et al., 2023; Hocini et al., 2021; Johnson et al., 2019). Level-pool estimation of (permanent) inundation based on coastal water levels is also problematic because inundation may result from emerging groundwater (Figure 1d) or inland ponding (Figure 1e) which are sensitive to hydrologic budgets (Befus et al., 2020). Some limitations of bathtub modeling relative to the projection of both flooding and inundation are illustrated in Figure 1.

Table 1
Results From Selected Studies Which Compare Dynamic, Physics-Based (Hydraulic) Models to Static, Bathtub (Level-Pool) Models

Reference	Flood type	Event	Bathtub model CSI	Hydraulic model CSI	Bathtub relative accuracy
Hocini et al., 2021	Inland	France, 2018	0.52	0.78	67%
		France, 2010	0.59	0.81	72%
Wing et al., 2019	Inland	USA, 2017	0.41	0.66	62%
Gallien, 2016	Coastal	US, 2014	0.13	0.71	18%
Ramirez et al., 2016	Coastal	France, 2010	0.31	0.50	62%
		USA, 2012	0.52	0.47	111%
		Myanmar, 2008	0.46	0.49	94%
Vousdoukas et al., 2016	Coastal	France, 2010	0.25	0.50	50%
Bates et al., 2005	Coastal	UK, 1938	0.11	0.91	12%

Note. The Critical Success Index (CSI) quantifies the match between modeled flood extents and those observed during the given flood events, where one is a perfect fit and 0 is no match whatsoever. Bathtub relative accuracy refers to the proportional similarity in skill bathtub models have compared to hydraulic approaches (i.e., 100% = identical skill in both methods).

We note modeling frameworks used to estimate episodic flooding typically distinguish between flood hazard drivers and flooding itself. That is, a set of data and/or models is used represent the flood hazard drivers (the water mass inputs to a simulation, or *boundary conditions*) such as rainfall, storm surge, waves, groundwater levels, mean sea level change, subsidence, while a separate model (termed a *flood inundation model*) captures the distribution of flooding itself considering these boundary conditions, topography, infrastructure, and other factors. Bathtub models represent an option for this second step, though may be driven by boundary conditions of varying form and complexity.

Bathtub modeling is especially biased in urban areas where both episodic flooding and permanent inundation are modulated by flood defenses (Figure 1c), drainage infrastructure and pumping (Figure 1f). Moreover, fine-scale topographic features, such as elevated roadways or traffic dividers, exhibit influence over the spatial distribution of flooding. Accurate modeling of urban flood hazards generally calls for the use of fine-scale topographic data (<10 m resolution) and explicit treatment of urban drainage infrastructure, and ignorance of these features can lead to significant overprediction of flood impacts (Gallien et al., 2014, 2018). Recent research has shown that models with differing levels of resolution and representation of infrastructure may generate estimates of exposed properties and populations that differ by a factor of two or more, and differences in flood hazard distributions can lead to erroneous assessments of flood risk hot spots and inequalities in flood exposure by social groups (Schubert et al., 2024).

Table 1 summarizes the findings of key studies in technical journals where both bathtub and dynamical models were systematically benchmarked against observations of real flood events. All studies compute the Critical Success Index (CSI), a measure of fit between observed flood inundation extents and their simulated analogs. It penalizes both under and over prediction errors, producing a similarity score between 0 and 1, where one is a perfect match. These benchmarking studies convincingly evidence the effect of ignoring physics, with bathtub models consistently failing to outperform a random classification (i.e., they have CSI <0.5). Fleischmann et al. (2019) suggest that a CSI in excess of 0.65 (for inland floodplains) is when a model starts to have local relevance, and therefore produces useful and useable results when applied in impact analyses.

3. Recommended Methods to Model Flooding

Flood management professionals have long relied upon physics-based flood inundation modeling to support planning and design needs, and there is a wealth of available software to support modeling studies at local scales—typically the scale of river reaches and individual coastal embayments. However, software developed for local-scale modeling studies is cumbersome if not impossible to apply at metropolitan and larger scales due to data needs and computational bottlenecks. Driven by needs within the insurance and financial services industries to have comparable estimates of risks at national and global scales, and the needs of governments to coordinate adaptation planning across regions, new classes of large-scale, physics-based flood inundation models have emerged over recent years to align with the availability of data and resources for modeling. First, continental-scale models take advantage of global data sets characterizing topography (Hawker et al., 2022), land use, flood defenses (Scussolini et al., 2016) and hydrology (Do et al., 2018). Schemes that resolve the physics of flooding have now been deployed across continental or larger domains for both inland (Dottori et al., 2022; Sampson et al., 2015; Yamazaki et al., 2011) and coastal (Bates et al., 2021; Eilander et al., 2023; Vousdoukas et al., 2016) studies, permitting an understanding and communication of flooding risks with greater fidelity and confidence than recent simplistic studies using bathtub approaches. Moreover, recent work by Wing et al. (2024) demonstrates the availability of data globally to support physics-based flood inundation modeling for a range of climate scenarios. Second, regional-scale models take advantage of more detailed data that is often available within the metropolitan regions of more developed nations, including fine-scale (<5 m) topographic data and flood infrastructure data. Examples of regional-scale models include PRIMo (Kahl et al., 2022a; Sanders & Schubert, 2019), and 3DI (Stelling, 2012), and SFINCS (Leijnse et al., 2021), all of which use a multi-grid data structure to limit the computational bottlenecks that arise from physics-based modeling of flooding at fine-scale (<5 m) over regional (O (10^3-10^4) km^2) domains. Increasing spatial resolution and more detailed data subsequently offers the potential for greater accuracy at finer scales, while studies have also highlighted the need for more validation data (Schubert et al., 2024). In summary, physics-based flood inundation modeling is now feasible from local to global scales, and a wide range of methods have been developed to match the availability of data and needs for precision. For a more thorough review of physics-based flood inundation modeling methods, the reader is referred to Bates (2022).

4. Bathtub Modeling in Short-Format, High-Impact Journals Contributes to Climate Hype

Studies that rely on bathtub modeling are, perhaps paradoxically, most commonly found in short-format, high-impact journal publications and involve flood risk assessments at regional or larger scales (Fang et al., 2022; Hinkel et al., 2014; Hooijer & Vernimmen, 2021; Kulp & Strauss, 2019; Ohenhen et al., 2024; Strauss et al., 2012, 2021; Ward et al., 2017; Winsemius et al., 2013). Editors at high-impact journals typically screen submissions for evidence of scientific merit and policy relevance, and large-scale flood risk studies with national or international scope often "check the boxes" for manuscripts to continue for a scientific peer review—which is only afforded to a small minority of submissions at the most prominent journals. Researchers may justify use of bathtub modeling as an important first step to assess how flood risks are changing at large scales, or may erroneously assert that the scarcity of data justifies the simplification of flood physics (i.e., Table 1 documents systematic bias from bathtub models across inland and coastal applications). And depending on the peer reviewers, this may constitute an adequate justification for editors to enable subsequent publication of the paper. But when the work is then covered by major international news organizations such as *The Guardian* (Uteuova, 2021), *CNN* (Keefe & Ramirez, 2021) *BBC* (Amos, 2019), *Washington Post* (Dennis, 2022), and *New York Times* (Lu & Flavelle, 2019), the nuances and limitations of the modeling method—even those acknowledged by the researchers—can easily be lost in translation, and the research becomes vulnerable to *climate hype*. For example, on the basis of the bathtub modeling by Kulp and Strauss (2019), the *New York Times* (2019) published a piece confidently entitled "Rising Seas Will Erase More Cities by 2050, New Research Shows" containing wild assertions such as "Southern Vietnam could all but disappear," "Mumbai…is at risk of being wiped out," and "Basra…could be mostly underwater by 2050." And it is not only the news media who contribute to climate hype. For example, based on projections that less than 2% of the population of coastal cities would be impacted with flooding brought on by sea level rise and subsidence, Ohenhen et al. (2024) published a paper in the flagship journal *Nature* with the exaggerated title "Disappearing Cities on U.S. Coasts".

Conversely, flood risk studies using bathtub modeling would be a challenge to publish in highly regarded, long-format, disciplinary journals where reviewers are very likely to scrutinize modeling methods for innovation and fit compared to the state of the art. Importantly, disciplinary journals serve as a proving ground for the best methods to tackle large-scale studies of flood risk, and confidence in the modeling approaches applied in short-format, high-impact papers on flood risk can be increased with references to methodological papers in the leading disciplinary outlets. For many large-scale bathtub modeling papers in high-impact journals, this important step is missing.

Many social science scholars have argued that climate hype undermines public trust in science (Bogert et al., 2024; Master & Resnik, 2013). Minimally, we know that residents within at-risk areas are unlikely to trust

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projections of future flooding that are not grounded by their lived experiences such as with accurate hindcasts of historical events (Cheung et al., 2016; Houston et al., 2019; Sanders et al., 2020). Therefore, projections that cities "disappear", "are erased" or "are wiped out" surely raise skepticism, if not distrust, by residents, policy makers and scientists alike.

5. Trustworthy Predictions Needed for Transformative Adaptation

Flooding is worsening rapidly and increasingly threatens public safety and national economies (Smith, 2020; World Meteorological Organization, 2021). In the U.S., a recent report by the federal government suggests that flooding is now incurring costs that are 1%–2% of GDP, and these costs are likely to increase with rising sea levels and more intense storm systems brought on by a warming climate (Joint Economic Committee, 2024). Transformative adaptation including the restoration of natural infrastructure, better flood defenses, the relocation of significantly at-risk human activities, and the reshaping of cities for increased resilience is needed to stall and ultimately reverse these trends (Intergovernmental Panel on Climate Change, 2023). Crucially, accurate and trusted models of flood risk are needed to effectively engage impacted communities in adaptation processes and implement effective and equitable responses (Mach et al., 2022). The modeling process itself represents a mechanism to build understanding among stakeholders about trends in flooding and the effectiveness of available responses (Sanders et al., 2020). To this end, research studies that oversimplify flooding—such that simulated outputs are more challenging to trust within at-risk communities—pose a threat to transformative adaptation. We call on researchers, journal editors and reviewers to henceforth go beyond bathtub modeling and the level pool approximation in large-scale assessments of flood risk. Addressing this deficiency is paramount to the credibility of flood science and its application for transformative adaptation.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

There is no primary data, processed data or software involved in this study.

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