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Review

Comprehensive Flood Risk Assessment: State of the Practice

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Abstract: A comprehensive assessment of flood hazards will necessitate a step-by-step analysis, starting with hydrometeorological examinations of runoff and flow, followed by an assessment of the vulnerability of those at risk. Although bodies of knowledge about these topics are large, flood risk assessments face data challenges such as climate change, population growth, and shifting land uses. Recent studies have provided comprehensive reviews of advances in the water sciences arena, and in a complementary way, this paper reviews the state of the practice of assessing flood risk, include flood scenarios, hydrometeorology, inundation modeling, flood frequency analysis, interrelationships with water infrastructure, and vulnerability of people and places. The research base for each of these topics is extensive. Some of the tools in these areas, such as hydrologic modeling, have research advances that extend back decades, whereas others, such as numerical weather prediction, have more room to evolve. It's clear from all studies that data is crucial along the progression from atmospheric conditions to the impact on flood victims. How data are provided and shared and how they are used by stakeholders in flood risk reduction continue to evolve. Improved availability of data and uses of emerging tools of data science and machine learning are needed to assess and mitigate flood risks. Continued the development of key tools is also required, especially to improve the capability to assemble them effectively on user platforms.

Keywords: flooding; forecasting; modeling; risk assessment; vulnerability; weather prediction

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1. Comprehensive Flood Risk Assessment

It is often reported that flooding poses the greatest risk among natural hazards, and floods continue to plague prone regions, as well as to occur periodically in unexpected ways [1]. The World Economic Forum's Global Risks Report 2023 identified natural disasters and extreme weather as among the greatest risks facing the planet, and that with better early warning systems, significant savings in lives and damages are possible [2]. Such warning systems will require accurate and reliable data for decision support to inform tools for forecasting, planning and design, regulatory controls, and post-event studies. The assembly of required data for these applications to support flood risk assessment poses formidable challenges, especially for a comprehensive approach to determine risks of increasing flood impacts on people and places. Experience shows that collecting all data on one platform is especially challenging, whether they are used for forecasting or longer-range planning, design, and post-event studies. These studies will continue and require periodic renewal because changes in climate, land uses, and the socioeconomic status of vulnerable areas keep occurring.

For flood risk assessments to be comprehensive requires analysis at critical points where risk is increased or decreased, from weather conditions and initial precipitation to control points, and eventually to points of vulnerability where victims are affected by floods. Flood risk is sometimes taken to mean the chance of flooding, but a complete view includes the hazard, the potential damages, and the vulnerability of the people or places who can be harmed. The starting point is hydrometeorology, but a comprehensive approach to risk assessment involves more steps to identify where interventions will be most effective in reducing flood damages on an overall basis. Each step in the sequence of critical points requires analysis to determine either the likelihood of damaging events or the vulnerability of targets, as they are exposed to threats and protected by infrastructure and or nonstructural programs.

Although flood risk assessment tools have large bodies of knowledge, their effectiveness is challenged by increasing threats due to climate change, population growth, and shifting land uses, among other driving forces. Flood exposure persists in developed regions [3] and in low-income settings it increases due to lack of effective responses [4]. Climate change is a special challenge because it can diminish the value of experience with past events for assessing risk [5]. It can be associated with dependent phenomena such as sea level rise, modified weather regimes that change snowmelt floods to more extreme rain-on-snow events, and to other hydrologic changes such as more extreme rainfall. Shifting land uses and geomorphological forms also pose challenges from forecasting to planning [6]. Although flood risk reduction strategies have shifted from structural to integrated non-structural measures, risk factors must still be assessed from initial storm events through the chains of causes and effects. The goal of this paper is to develop a comprehensive view of these causes and effects, beginning with hydrometeorology and extending through hydrological phenomena to eventual economic, social, and environmental impacts. By taking such a comprehensive view, an overall picture of the state of the practice of flood risk assessment can be presented so that opportunities for improvement are evident.

The core of flood risk assessment toolsets is in the water sciences arena, which has an extensive knowledge base. Its concepts, challenges, and future research directions were reviewed in a recent state-of-the-art paper with some 250 references about advances in flood science, including risk management [7]. These many facets of flood knowledge require involvement of multiple disciplines, including climate scientists, engineers, hydrologists and other geoscientists, statisticians, geographers, economists, behavioral scientists, and lawyers. These contributions were reviewed in another comprehensive paper that reported a bibliometric analysis of the evolution and prospects of flood risk assessment [8].

The bibliometric analysis showed increasing attention to resilience, with land planning, risk perception, and flood warning having fewer papers. Global warming was a dominant topic for riverine and coastal floods. Economic assessment and social impact analysis seemed promising, along with data science and remote sensing data. The authors found that most papers were in environmental sciences, then water resources, then meteorology and atmospheric science, with a few in geology, engineering, mathematics, and other fields. As always, such classifications can be problematic. For example, the field of water resources is explained as the "the area that manages flood risks and applies prevention measures," whereas engineering is a separate category, despite its role in managing flood risks.

This paper builds on the previous reviews to emphasize synthesis statements by flood authorities and science agencies about the state of the practice of how the research has been implemented for use in flood risk assessment. Most references about national practices in this paper are from examples in the United States, with acknowledgement of the parallel practices in other countries. No attempt has been made to compare national flood or weather offices or the tools they use for forecasting, modeling, and related flood risk management tasks. Implementation of flood risk assessment methods and flood forecasting methods are evolving across the world, but with some differences due to approaches unique to specific countries [9]. Research advances and implementation as toolsets are evident in higher income regions, but lower income regions suffer a lack of data as well as barriers to implementing the most advanced technologies. The international community is seeking ways to transfer technologies to these regions in ways that will facilitate their implementation.

The paper begins with an explanation of flood risk locations and scenarios and continues with discussions of hydrometeorology and hydrology in the water cycle, their interrelationships with water infrastructure, and points of vulnerability of people and places. The emphasis in this paper is on the implementation of research and uses language focused on how our tools are used for purposes of flood risk reduction. This is different from the bibliometric analysis mentioned previously, which focuses on the disciplinary topics of areas such as environmental sciences, water resources, meteorology, and atmospheric science [8]. To the furthest extent possible, synthesis papers are cited, rather than individual studies or cases. These are intended to lead the reader to useful initial sources to gain overviews of the topics.

2. Flood Risk Locations and Scenarios

Flood threats cascade through the water cycle with many interrelationships, including among atmospheric conditions, precipitation, runoff, flow or surge, and exposure of victims. The locations where negative consequences may occur include local urban areas, river basins, and coastal zones. Risk is also affected by performance of conveyance infrastructure for stormwater and stream systems, as well as barriers provided by dams, levees, and surge protection barriers. The effectiveness of management programs such as flood forecasting, warning, and flood insurance also affects risk, and the vulnerability of victims and places affects it as well. For example, elderly or immobilized people will normally be the most vulnerable and subject to multiple health hazards. Vulnerability of places depends on building stock and protections such as flood proofing. Flood forecasting is especially important because its accuracy and timeliness are directly related to the time and opportunities that victims have available to avoid damages [9].

Although it is generally thought that flood risk is increasing, the dimensions of search increases are not well defined. For example, climate change may create more intense rainfall but not necessarily increase annual peak floods maximums. Moreso, the extent to which disasters occur will be affected by adaption measures that may mitigate negative consequences. For example, in a study of flood exposure in 37 European countries since 1870, the authors found increases in areas inundated and numbers of persons affected, but there were also decreases in fatalities and declines in annual financial losses in recent years. The authors suspected that frequent flooding was underreported, which may have biased the results [3]. It seems apparent that declines in fatalities and financial losses will follow patterns of economic development where more affluent areas are able to protect people and property better than in the past. Furthermore, financial losses in lower income areas will show lower levels than in the more affluent areas for the simple reason that property values are lower.

The points where risk assessments are needed can be identified by location with reference to exposure to different types of floods. As shown in Figure 1, the different types of floods occur in riverine and coastal locations, as well as in cities with stormwater management issues can be grouped as riverine floods, coastal floods, and urban floods, respectively, with subcategories such as flash floods and minor and major stormwater events, among others. Additionally, compound events such as coastal and riverine floods together can occur. The figure illustrates rainfall over the watershed that will affect the riverine and urban locations. Snowmelt is a major flood driver in some scenarios as well. The storm surge will be determined by wind conditions, which often occur in conjunction with storms, such as tropical storms and hurricanes.

The sequence of risk assessment tools required in a comprehensive approach from weather conditions and initial precipitation to points of vulnerability where victims are affected by floods is illustrated by Figure 2. At the beginning, atmospheric circulation models, satellite data, and downscaling methods support numerical weather prediction and provide data to support runoff modeling. Precipitation models using atmospheric data, along with historic statistics, provide data on extreme rainfall that leads to runoff, which can impact local flood victims in urban areas or other victims through stream flooding. Other hydrologic data such as temperature and snow conditions must be considered to determine impacts of snowmelt on flooding. Runoff models, and feed information to hydraulic models, which indicate flow velocities and depths of water at various points along stream systems. Infrastructure systems and control structures such as dams and levees may be provided to mitigate flood damages, and they can also be at risk of failures that create dam break or levee breach flooding. Non-structural measures such as the use of flood mapping, land use management, and flood insurance are also intended to mitigate effects of flooding. The extent of potential consequences will depend on the vulnerabilities of people and places, as well as the effectiveness of the barriers. Coastal flooding risks are determined by similar variables, beginning with wind, surge hydraulics, vulnerability, and barriers. Each of the tools along this sequence has its own research base and literature, often with different researchers working on them.

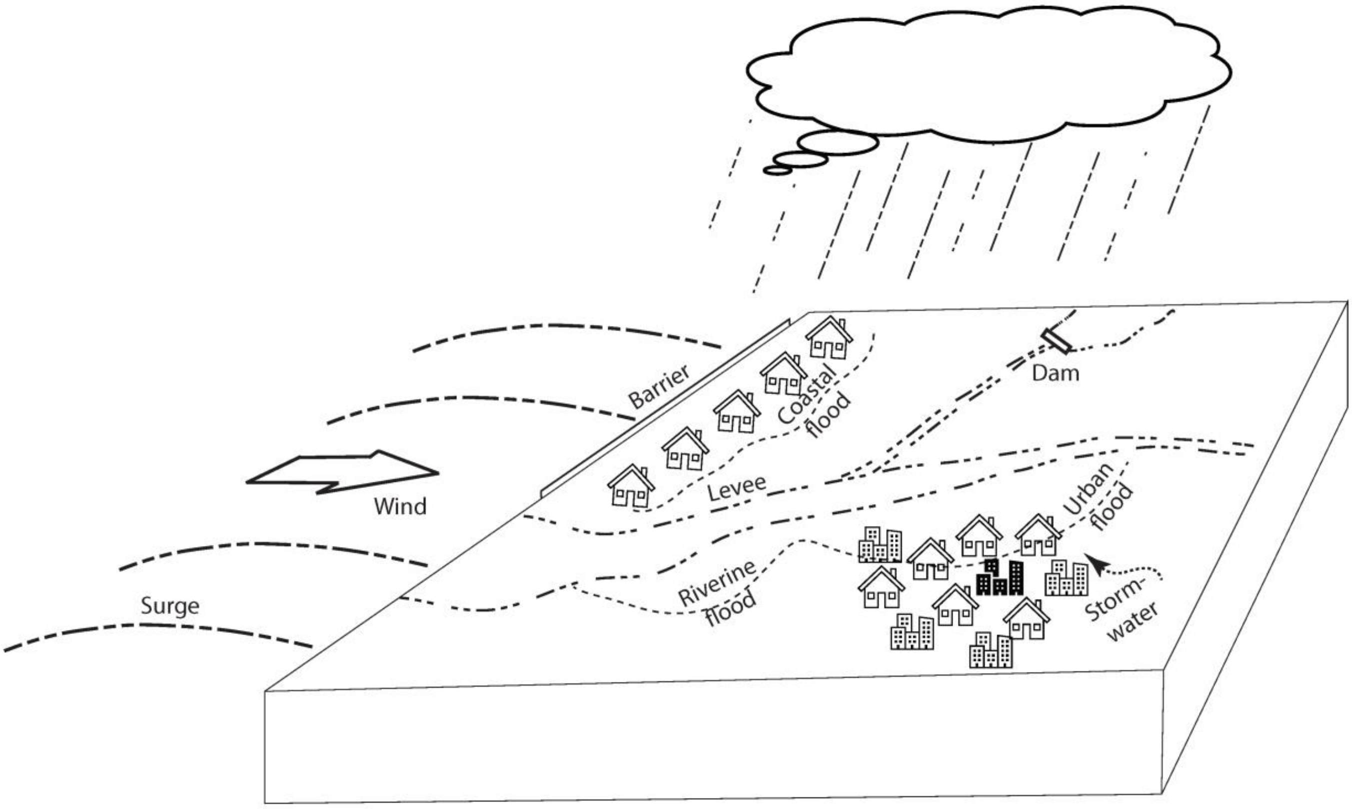

Figure 1. Reference diagram showing locations of riverine and coastal flood risks.

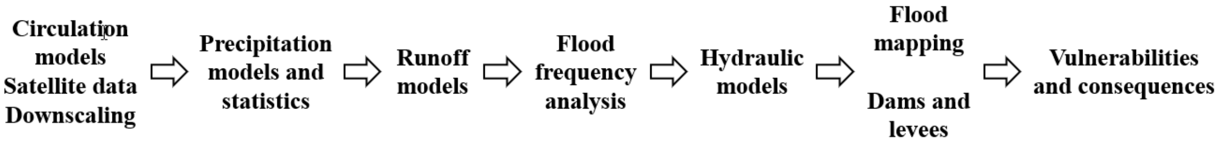

Figure 2. Sequence of data and analysis for comprehensive flood risk assessment.

The scenarios of flood risk assessment where these tools are used occur at small, medium, and large scales, and the analyses require somewhat different approaches [10,11]. At small scales, the usual situations involve urban stormwater, small watersheds, or site-based dam or levee safety. The medium scale involves river or coastal floods, which are also evident at large scales, such as the scenario where regional flood policies are to be determined. At all three scales, flood risk assessments are used for flood forecasting, as well as planning, design, and post-flood forensic analyses of causes. These assessments can address degrees of flood risk from the nuisance level [12] up through disastrous events [13].

3. Hydrometeorology and Flood Risk

Hydrometeorological data and models for flood risk assessment begin with numerical weather prediction, which provides information for purposes such as flood forecasting and warning systems. With satellites providing remotely sensed data and advances in simulation modeling, the data and predictions continue to improve, and people are accustomed to reliable overall weather forecasts. Numerical weather models solve equations of the physical laws of atmospheric dynamics. The larger the scale and need to incorporate variability of spatial extent, time period, and modeling of specific phenomena, the more the computational power needed, and supercomputers serve weather service centers to provide forecasts at increasingly smaller scales as computational power increases. Forecasts are needed for small-to-large geographic scales and from short-to-long timescales. The smaller areas and shorter time spans pose the most challenges, but they are very important in providing time for potential victims to prepare [14].

After flood risk assessments draw precipitation data from numerical weather prediction studies, they can inform integrated modeling studies where climate predictions and statistical data are forcing functions for hydrologic runoff and streamflow models [15] used to inform forecasting, planning and design, or forensic studies of flood disasters. In the U.S., the focus of integrated platforms is in programs of the Advanced Hydrological Prediction Service (AHPS), which is a recent development of the National Weather Service [16]. The AHPS is a platform to organize a suite of forecast products to display the magnitude of floods at different time scales. Most water-level data in the AHPS is from the gages of the United States Geological Survey (USGS) [17], with additional information as available also used. The USGS has operated the system of stream gages for more than 100 years and is the main source of flood data in the nation. The data are organized and delivered to Weather Forecast Offices and River Forecast Centers, which run hydrologic models to create displays on AHPS web pages for used by different parties.

Although forecasting systems such as the AHPS are established and operational, research and development continue to improve them with next-generation global models such as the Model Prediction Across Scales (MPAS) system to enable transition from global to regional scales for downscaling to inform flood forecasts more effectively [18]. MPAS links atmospheric, oceanic, and land data for climate and weather studies [h] and can be used with the Weather Research and Forecasting (WRF) Model for numerical weather prediction. The WRF model links data and a computational software for applications across scales. It has a large user community and is used for real-time forecasting [19].

As numerical weather prediction methods and tools improve, they will help flood forecasters and provide spinoff benefits for planning, design, and forensic analysis. The state of the practice depends on the effectiveness of the scientists and system developers to incorporate research findings. In the case of research on general circulation models, an extensive body of literature explains advances in the global climate models and downscaling for use at appropriate locations. Although research advances continue, challenges occur when spatial scales of the models are not as fine as users require and when model outputs may be biased by observational data [20]. The challenges for small areas and short time durations provide a major direction for research.

4. Expected Extreme Precipitation

Whether they are used for forecasting, planning and design, or forensics, expected values of extreme precipitation are needed for applications at different scales and time intervals. The links between extreme precipitation and flooding involve different scenarios, from frequent-to-rare floods and for diverse locations. Some evidence suggests that although extreme precipitation is increasing, flood magnitudes are decreasing on an overall basis, even while very rare floods are increasing in frequency [21].

The users of precipitation data can rely on numerical weather prediction to forecast precipitation or use statistics of historical data, depending on the scenario of flood risk assessment. Numerical weather prediction will yield values of expected rainfall totals and, in some cases, the duration of storms. The National Weather Service [22] has a program for Quantitative Precipitation Forecasting (QPF) with time windows from 6-h up. These can be used for river flood forecasts where spatial scales are not too sensitive to accuracy of the time distribution of the rainfall, and they will have limited utility for small scales such as urban stormwater flooding. The state of the practice of QPF depends, of course, on the technologies for numerical weather prediction explained above.

Advances in use of radar have improved QPF for nowcasting, and methods continue to evolve, ranging from simple to complex and expensive. Nowcasting generally means to forecast local conditions from the present time to 6 hours ahead. This requires addressing diverse weather conditions such as convective weather phenomena involving local to mesoscales and short time periods. Researchers have developed various methods to correlate data sources to improve the short-term forecasts. These are important to improve resilience against threats such as flash floods in streams or sudden urban flooding. A summary of the state of the practice has been provided by the World Meteorological Organization (WMO), with emphasis on providing guidance for emerging programs [23]. The guidelines explain the WMO approach to develop an integrated Data-processing and Forecasting System (DPFS) to help national meteorological and hydrological services implement nowcasting systems.

The only way to provide needed high-resolution spatial coverage for short-term forecasts is by use of remote sensing with operational radar systems but implementing these can be challenging in the low-income settings around the world. In response, the WMO is part of an initiative to deploy low-cost weather instrumentation for developing countries.

Nowcasting methods vary from simple extrapolation of radar precipitation echoes to more sophisticated systems that combine different outputs and computational models leading to creation of expert systems that different streams of data. These use automated tools and systems to the extent possible to address short time periods. Of course, user-supplied heuristics must be an integral part of nowcasting.

For planning, design, and forensics, the need is for statistics of historical data to indicate expected point precipitation. These statistics were assembled some 60 years ago when the NWS published Technical Paper 40, which was the first precipitation atlas for the U.S. [24]. The program now produces the U.S. Climate Atlas [25], and other countries have similar efforts such as The Climate Atlas for Europe [26] and various national and transnational climate atlases in Europe [27]. These are evolving into climate portals that include spatial information about climate change.

The NWS also supports NOAA Atlas 14, which provides a portal for regional estimates of extreme precipitation based on the 1-in-NN chances of being exceeded in a year as needed for infrastructure planning and design, as well as for regulations, modeling, and analysis [28]. Data from the Atlas can be accessed via the portal with the Precipitation Frequency Data Server [29]. Atlas 14 is funded cooperatively by users, and plans are for complete national coverage assuming stationary time series, with extension later to include non-stationarity as dictated by the users. Needs to update this Atlas were identified in a 2018 report by the U.S. Advisory Committee on Water Information, which has an Extreme Storm Events Working Group. It recommended improvements in areal reduction factors, design storms, and confidence intervals.

Methods for statistical analysis of extreme precipitation in the U.S. continue to advance, but climate change effects continue to challenge the validity of expected values for use in flood frequency estimates [30]. In parts of the world with scarce or missing data, statistical information will be more difficult to assemble, and other methods to estimate expected extreme precipitation are still needed. The best approach will combine local precipitation data that are available with remote sensing data such as from the Tropical Rainfall Measuring Mission (TRMM) [31].

5. Runoff Modeling

The prediction of catchment response is essential for flood forecasting and is also needed in planning and design, as well as forensics [32]. The tools of flood hydrology used for the prediction and flood routing were already advanced by the 1960s [33,34], but they depend on data availability, which is an issue in many regions [35]. Now, the earlier tools have been incorporated into advanced integrated software packages that are available commercially and through open source [36]. The US Geological Survey [37], Agricultural Research Service [38], US Army Corps of Engineers [39], and Natural Resources Conservation Service [40] have separate software packages, each with a different history, but all simulate physical hydrologic processes of evaporation, transpiration, runoff, infiltration, and interflow to yield runoff estimates. National hydrologic centers and research institutes in other countries have similar model packages.

The models have diverse uses such as mapping floodplain areas or studying the incidence of flooding in different locations and conditions, including post-wildfire scenarios. They can predict flood events or be used for continuous simulation. They are most useful for smaller catchments and in urban stormwater studies where land uses and assumed rainfall patterns have more certainty than they do in larger basins. For larger basins, statistical analysis of historical floods is commonly used because the spatial heterogeneities of watersheds and rainfall patterns create uncertainty in results [41]. As an illustration, consider a large watershed with several tributaries of significant size that is fed by many small streams. The geomorphic characteristics of such basins will be diverse, and their lack of spatial homogeneity prevents accurate prediction of runoff for different storm characteristics [42].

Inland stream systems have clearly defined catchment boundaries that determine runoff, which is needed as the input to hydraulic models and for estimating flood inundation for risk assessment, damage estimation, and floodplain mapping. Catchment boundaries differ by scale of the watershed, and in the U.S., a system of Hydrologic Unit Codes has been developed to provide a classification system [43]. There is no global standard to classify watershed sizes, which provide a discussion topic to improve the comparability of flood risk assessment practices among countries. To illustrate the variation of catchment sizes, Table 1 shows watersheds from an average of 40 square miles to regions covering several states.

Table 1. Classification of watersheds and river basins.

Name	Level	HUC * Digits	Number in U.S.	Average Area, Square Miles	Average Area, Square km
Region	1	2	21	177,580	285,788
Subregion	2	4	222	16,800	27,037
Basin	3	6	352	10,596	17,052
Subbasin	4	8	2149	700	1126
Watershed	5	10	22,000	227	365
Subwatershed	6	12	160,000	40	64

* HUC is Hydrologic Unit Code.

The distinction between small watershed hydrology and flood prediction in larger basins is important in flood risk assessment. Although there is no standard definition of a small watershed, data in Table 1 suggest that a 12-digit sub-watershed is small, but much smaller watersheds require analysis in some applications. The 12-digit HUC with an average area of 40 square miles corresponds to the scale of a medium city of 5000 people per square mile and 200,000 people. An example of the largest level would be the Missouri River Basin above St. Louis with more than 500,000 square miles in the region.

A fine-grained watershed model will include characteristics of very small watersheds because larger ones lack homogeneity. Even 12-digit HUC watersheds are sufficiently heterogeneous in land characteristics not to be treated as homogeneous hydrologic units for simulation modeling.

For local situations, the 12-digit HUC watersheds can be subdivided. For example, a 40-square-mile watershed could be decomposed to one-square-mile units, and these could be further divided into smaller units. The widely used Rational Method to compute stormwater runoff is usually limited to 200 acres (80 Ha), so a one-square-mile watershed would include slightly more than three of these. At the very small scale, the drainage area of a city block, say 5 acres, could be served by a single drainage pipe and be the unit for a calculation of runoff. Even a roof area at around 1500 square feet (140 m^2) is tributary to drains and can be analyzed in a similar way [44].

If spatially uniform storms of different magnitudes were superimposed on the watershed, then an accurate unit hydrograph could be derived. However, the reality is that heterogeneous storm patterns are imposed on diverse geomorphic patterns and invalidate this approach for larger watersheds. However, some progress has been made through the storm catalog method.

This was demonstrated in a complex region by combining records of radar rainfall fields with stochastic storm transposition methods in the Baltimore Metropolitan area, which has complex terrain with Chesapeake Bay to the east, mountainous terrain to the west, in addition to urbanization [45]. Storm transposition is a common method for use in studying various "what if" scenarios of flood likelihood [46,47].

One challenge to modeling is prediction of flooding after fire, which has become a more common problem due to climate change and drought [48]. As an example, the Colorado Water Conservation Board, which has statewide responsibility for flood risk planning, has studies in several fire-scarred watersheds and is conducting studies to apply the HEC HMS simulation program to develop an improved understanding and develop guidelines that can be used in the State of Colorado and similar western areas [49].

Regardless of the approach to modeling runoff, challenges will persist, particularly those related to changes in land use and climate. As research continues, it will be important to incorporate it into products that will be appropriate for the time and area scales needed for flood risk reduction. Providing these products will continue to be a public private endeavor, where government-sponsored research can be disseminated by public agencies or incorporated into commercial products [50].

6. Flood Frequency Analysis

The concept of flood frequency analysis provides an integrated mechanism to estimate the magnitude and likelihood of maximum instantaneous peak flows for flood risk assessment [51]. To improve communication among public and private stakeholders, uniform and consistent methods can help. Although metrics for flood frequencies are well-known among professionals, communicating with the public continues to be challenging, particularly when non-stationarity is involved [52].

In response to the need to address statistical complexity and recognizing the need for a consistent approach, federal agencies have produced a set of Guidelines for Determining Flood Flow Frequency known currently as "Bulletin 17C" [53]. The predecessors of Bulletin 17C extend back to 1967, when the U.S. Water Resources Council published Bulletin 15, "A Uniform Technique for Determining Flood Flow Frequencies," which recommended use of the log-Pearson Type III distribution to annual peak flow data. This distribution is a flexible distribution that can be fit to series with differing skew and other statistical parameters. With several parameters, it was deemed to be more appropriate than other extreme value distributions such as the log-normal or Gumbel.

Bulletin 15 was superseded by Bulletin 17 in 1976 as "Guidelines for Determining Flood Flow Frequency" to add methods for outliers, use of historical information, and regional skew data. Bulletins 17A and 17B came later with additional methods, and the history is traced in reference [53]. Now, Bulletin 17C has incorporated new research-based methods and represents the state of the practice in the U.S. of determining flood frequencies. Non-stationarity is now addressed, although it still represents the greatest challenge to use of historical information in fitting distribution functions to flood frequencies. In addition to the basic method, it includes methods to use data from intervals between annual maximums and about low flood outlier data.

Bulletin 17C recommends that several categories of flood frequency information be used, to include gaging data, historical information, paleoflood and botanical data, regional information to estimate skew coefficients, comparison with similar watersheds, and runoff computations from precipitation. It alerts the analyst to watch for data issues such as measurement errors, random events, trends, persistence, mixed populations, watershed changes, and climate variability. Finally, the guidance recommends consideration of accumulated risk, going beyond annual probabilities. The guidance document defines risk as the probability that one or more events will exceed a given flood magnitude within a specified period of years. In other risk studies, this is usually considered as the likelihood of an event, where risk also considers the vulnerability and consequences. In any event, the guidance recommends computing this accumulated risk (or likelihood of one or more events in a period of years), rather than reporting only the annual probability.

The guidelines do not include a method to consider uncertainty in estimates, but it could be added after additional research [54]. Regardless of the method used in flood frequency analysis, results can be uncertain due to unknown factors, including limited data, non-stationarity, and other factors. A case in point was an effort by a committee of the National Research Council to develop a reliable estimate of flood frequencies on the American River near Sacramento, California [55]. Challenges encountered by the committee led it to report how different data types should be used in estimating flood frequencies, consistent with those included later in Bulletin 17C.

Coastal surge is analogous to catchment runoff in that it produces flood flow. Rather than precipitation, the wind determines the quantity and timing of flood flows. Flood risk assessment in the wind-driven events involves different hydrological parameters than those required for modeling of surface runoff. For that reason, coastal surge models have their own research community that is separate from hydrology modeling. The models are discussed briefly in the next section.

The importance of flood risk modeling is crucial, as it encompasses much more than just the narrow local economic impact. In fact, it can even have a global impact on the supply chain [50]. By integrating hydrologic and hydraulic models with economic models, and considering the supply chain, we can demonstrate how the economic consequences of disasters propagate and impact regions and nations in varying manners, based on their geopolitical and income status.

7. Conveyance Models

Similar to runoff models, sophisticated hydraulic conveyance models are available as tools to simulate stream flow, depths, and velocities in flood areas. The models involved from early developments in open channel hydraulics [56], fluid mechanics, and wave travel via unsteady flow for flood routing [57] to integrated models simulated on the computer. For example, prior to the 1960s, for a typical steady flow analysis of flood depths, a channel analysis would be based on computation of backwater curves. Flood routing might use a tool such as the Muskingum method to consider unsteady flow, but the advent of computers enabled the solution of the Navier–Stokes equations for unsteady flow using partial differential equations.

Hydraulic models for flows in channels and stormwater systems are now available in software packages for unsteady flow with 1-D and 2-D simulations based on equations of motion. Similar to runoff models, success in applying them depends on data and mapping more than on technical methods. Predicting floodplain inundation using 2-D models is computationally expensive, and direct prediction of detailed floodplain hydrodynamics in real time is still not a common practice in an operational flood forecasting system [58].

Hydraulic models work well when appropriate data are available, but this represents a challenge due to changing riverine and morphological conditions, including topography, land uses, and the bathymetry of reservoirs, lakes, and ponds [59]. These problems are particularly challenging in the preparation of flood maps. As discussed in the next section, maps are core parts of flood risk management program and will require accurate depiction of flood depths and velocities in floodplains. In a simple and static situation, a channel flow depth could be extrapolated across a topographic surface to enable delineation of the floodplain. However, situations are dynamic and when flow paths and land use changes are made, sustaining accurate mapping becomes more challenging.

Some consistency in applying hydraulic models is needed in floodplain mapping, and to provide it, the USACE Hydrologic Engineering Center River Analysis System (HEC-RAS) has been adopted by the US Federal Emergency Management Agency as an integrated software package for analysis of floodplain hydraulics [60]. Without standardization of this nature, different models might yield confusing results and make regulatory control more difficult.

Accounting for hydraulic interactions is important because stream pathways are interconnected, and measures taken in one place may affect other places. The interactions are complex and the distribution of risk across watersheds is often difficult to identify [61]. For example, in a major court case, the US Court of Federal Claims held the Army Corps of Engineers responsible for flood damage to farmland when it implemented mandated environmental responses to its flood control policies on the Missouri River [62].

Storm surge flooding has worsened due to sea level rise and other climate-related forces [63]. In coastal storm surge, the wind delivers the energy that drives the water inland after reaching the shore. Suites of ocean circulation and wave models are used to simulate the timing and magnitude of storm surge. Different models are used, such as coupled surge and wave models involving ocean simulation and wave spectrum analysis [64,65]. The models are used in different ways for local applications, such as in Rhode Island's STORMTOOLS suite of numerical models, maps, and other aids for users to identify hazards along the state's coastlines [66]. Coastal surge is also dependent on sea level rise, which is another dimension of the perils posed by climate change.

8. Infrastructure and Management Programs to Reduce Flood Risk

As shown on Figure 2, flood risk assessment must consider multiple stages across a sequence from atmospheric conditions to the points where victims are vulnerable.

Flood risk depends on the effectiveness of barriers provided by infrastructure or management systems such as forecasting, flood warnings, and flood plain land use control. Infrastructure systems are dams and levees, stormwater collection, and conveyance systems. Flooding can also be caused by breaks in underground pressure pipes, so risk should consider their likelihood of failure. Flood risks depend on original integrity and current condition of the infrastructure components. Dam safety programs are in place to require periodic condition inspections. Levee ownership and condition pose many management problems, and stormwater systems are expensive, invisible, and easy to neglect. Operational management systems are used for reservoir control and for stormwater systems operation.

Management program effectiveness affects vulnerability and is part of the assessment equation. Floodplain mapping is essential for floodplain regulation, zoning, and establishment of insurance premiums. To prepare maps, the outputs of hydrologic and hydraulic models are combined with topographic information, building stock, and other land use models to create inundation estimates to indicate flood damages.

The importance of floodplain maps to the U.S. National Flood Improvement Program has been recognized continually, and several assessments of it have been completed, leading to recommendations to remedy shortcomings [67,68]. Their evolution required the advances in hydrologic and hydraulic models that are evident today, and mapping is also dependent on the accuracy and granularity of data for land uses and topography. Flood maps still involve multiple uncertainties, mainly due to hydrologic and land use data limitations.

Technological advances in flood mapping are impressive, including hydrologic and hydraulic models, digital elevation models (DEMs), and geographic information system. Data limitations will impair each category but involving methods of data science provide new possibilities to identify and correct errors through cross comparison of estimation methods. Machine learning will be a core technology to advance these methods [69,70]. It can be applied, of course, across all flood risk assessment categories such as modeling, effectiveness of flood warning, and vulnerability of victims [71]. In the case of flood mapping, its use is to correlate available data to optimize the probability that accurate estimates are made.

As flood mapping becoming more automated, the accuracy and availability of digital elevation models become more important, especially in data-poor regions [72,73]. The accuracy of the DEMs continues to improve, both as a result of increasing granularity of map observations and use of statistical procedures to extrapolate, interpolate, and test elevation data. With advances in artificial intelligence applied to flood risk assessment, DEMs will need to be dynamic to accommodate land use changes as they occur.

As a result of the uncertainties posed by climate change and land use evolution, design standards and flood mapping require continuing improvement [74,75]. Despite the utility of flood maps, many flood damages also occur outside of mapped areas, which continues to be of concern. Another serious issue in non-structural management programs is the difficulty of protecting properties that are subject to repetitive flooding. A method named “managed retreat” has been proposed to respond to this problem, meaning to remove at-risk properties on a selective basis [76]. This method illustrates a direct approach to managing vulnerability to reduce flood risks.

9. Vulnerabilities and Consequences

Each of the categories of economic, social, and environmental consequences involves its own set of vulnerabilities and suffers damages in different ways. A few decades ago, little data was available on the economic consequences of flood damage. Today much more data are available and flood damages can be estimated better, mainly to serve the insurance industry. They depend on building stock and type, location, and associated factors that affect vulnerability. Flood risk reduction continues to be challenged by land development, which changes location and vulnerability. Sea level rises in coastal areas increase threats and the risk of damaging consequences to vulnerable properties.

Social impacts dealing with special populations, poverty, housing, grief, and loss continue to be major concerns involving equity and justice of vulnerable populations [77]. Improving community resilience is important [78] and use of social media to manage flood preparedness is a promising tool [79]. Social impacts are difficult to classify and measure, and with many human issues in play, it is unlikely that a standard methodology or single index can be accepted. One study showed 24 indicators of variables divided into “physical exposure” and “resistance.” Physical exposure (9 indicators) was indicated by variables such as the percentage of an elderly population. Resistance had three categories: protection (3 indicators), reaction capacity (4 indicators), and coping capacity (8 indicators) [77]. The exposure variables fit into the “victims” category on Figure 2 and the resistance variables fit the “barriers” category, as shown. In that sense, the resistance variables are a combination of local emergency management and the capacity of the local area to respond to emergencies effectively. The integrated assessment tool Hazus, to be discussed in the next section, measures social vulnerability and impacts in terms of “direct social losses,” as indicated by displaced population and people seeking shelter [80]. In that sense, it lacks the granularity of the approach suggested by Tascón-González et al. [77], where characteristics of the people are measured by variables such as age, gender, disabilities, and similar metrics.

Environmental consequences of flooding can include erosion, siltation, and landslides, damage to vegetation and habitats, and contamination. Floods are a natural phenomenon, so the environment will normally absorb most of their impacts, although they may create significant environmental change. Flooding also has positive benefits to the environment such as nourishment of wetlands and flood plains [80].

10. Hazus: Development of an Integrated Risk Assessment Tool

Efforts have been made to assemble all elements of flood risk assessment into one platform. Under sponsorship of USFEMA, an integrated tool named Hazus has been developed to model risk of earthquakes, hurricanes, floods, and tsunamis [81,82]. Beginning in the 1990s and continuing for more than a decade, an engineering committee that included the writer guided development of the flood module of Hazus. The tool is distributed free as a GIS-based desktop program that includes inventories of building stocks and other datasets that contribute to assessment of flood risk. Hazus can assess physical, economic, and social impacts of floods for use in mitigation, recovery, preparedness, and response planning.

Data sets included in Hazus are for physical damage to residential and commercial buildings, schools, critical facilities and infrastructure; economic loss, including lost jobs, business interruptions, and repair and reconstruction costs; social impacts of displaced households, shelter requirements, and populations exposed to floods; and cost-effectiveness of mitigation strategies such as elevating structures or retrofitting buildings.

Because Hazus combines many types of data, it uses some simplified approaches, but it represents a valid screening tool, and when used in conjunction with accurate local data, it can provide complex sets of vulnerability data to inform risk assessments. The user community of Hazus now includes around 40 groups in the U.S. The Hazus website describes some 18 success stories, one of which was a post-flood assessment of how successfully stronger floodplain regulations could have reduced flooding from the disastrous 2013 Colorado flood [83].

11. Conclusions

As flood hazards increase, assessing their risks becomes more important to flood forecasting, planning and policy, design, and post-flood studies. Risks involve much more than hydrologic issues, and comprehensive assessments must consider the points where their elements vary, including threats, consequences, and vulnerability of places and people. These occur along a sequence from climate forces to vulnerability of people and places. The state of the practice differs along this sequence and requires this longitudinal view to help identify where interventions will be most effective in reducing flood damages.

The state of the practice for the tools used in flood risk assessment can be summarized in eleven categories. Each category has an extensive research base, and some are advanced and others still evolving. The tool categories that seem more advanced are statistical analysis of precipitation, watershed and stormwater models, hydraulic models, and models to assess infrastructure integrity. Whereas additional research and development of these tools will help in flood risk assessment, their effectiveness will be dominated more by data availability and user skills than by technological advances. Tools that seem to be evolving are circulation models and satellite data, downscaling, flood mapping, and estimation of vulnerability and consequences. Each of these stands to improve data availability, so it seems that more work on them is justified. Flood frequency analysis is also evolving due to its status as an integrative tool of several others.

Circulation models and downscaling are the basis for the numerical weather prediction methods needed for flood forecasting to reduce risk by providing time to adjust to anticipated floods. The tools have spinoff benefits for planning, design, and forensic analysis and better understanding of weather dynamics can support tools for scenario development and testing of models and potential solutions. A large community of climate scientists works on circulation models, which are important in climate change policy as well as flood risk assessment. Although the models have high levels of complexity, a great deal of progress has been made, and they are being used increasingly in numerical weather models.

Statistics of extreme precipitation continue to be compiled and methods to extrapolate information using data science methods are improving. Data needs are extensive for magnitude, timing, and spatial variability, and the specter of climate change hangs over efforts to utilize the data to obtain reliable flood frequency estimates. Despite the challenges, values available from precipitation atlases such as those of the U.S. National Weather Service continue to improve and are widely used in flood risk studies.

Hydrologic methods continue to improve as they use knowledge bases that have evolved for decades. However, the heterogeneity of landscapes and watersheds creates data problems, and the non-homogeneous spatial nature of rainfall patterns continues to challenge runoff studies. This indication is that, although the mathematics of runoff models are important, without improved data, their potential for improvement is limited.

Tools to analyze flows in stormwater systems and channels have advanced to the point where software packages for unsteady flow analysis and even 2-D channel flow are available. Given the sophistication of these methods, further research about the mathematics of the equations of motion would seem to offer limited advances. Success in applying models depends more on data and mapping than on technical methods. Coastal surge models are also advanced, and results will be dependent on sea level rise, which is another effect of climate variability.

Infrastructure-related risks in riverine or stormwater systems depend mostly on integrity and condition assessment of the systems and barriers they provide. Dam safety will continue as a high-profile issue, and there are also many management problems related to levee ownership and condition. Stormwater systems do not always function well, and they are expensive, invisible, and easy to neglect.

Flood mapping is the end goal of inundation modeling because a valid map of flood level imposed on land areas determines the extent of flooding. Many flood damages occur outside of mapped areas, which continues to be of concern. As with other aspects of flood risk assessment, the most urgent need is for better data.

Flood risk reduction continues to be challenged by land development and climate change, which cause vulnerabilities to change. A few decades ago, scant data were available on the economic consequences of flood damage, but more data are available now, and flood damages can be estimated better. It depends on building stock and building type, which change with redevelopment. Flood insurance in coastal areas and repetitive flooding are of concern to risk managers. Social impacts and justice for vulnerable populations continue to be major issues in flood risk reduction, but it is difficult to assess them comprehensively.

The state of the practice of the eleven risk tools discussed shows mixed levels of development among them. Assembling them into integrated models such as Hazus offers possibilities to estimate risks rapidly on an approximate basis. Although results of such estimates will feature large uncertainty, they can indicate areas of risk concern that need policy attention, and in some cases, urgent action.

The flood risk community has many groups, each of which focuses on its own contributions. Working together, they form a vital interdisciplinary cluster with many accomplishments. Their work will continue, because assessing flood risks comprehensively and mitigating them will always be an unfinished work because too much change in nature and socioeconomic systems will continue.

A major conclusion from this state-of-the-practice review is about the importance of data all along the chain from atmosphere to flood victims. The issue is not only about the advancement in data management, although that is an urgent issue. It is about how the data are used by all parties involved in each phase of flood risk reduction, including the potential victims themselves. How data are provided and shared is evolving with social media, and such democratization of its availability will likely be a major trend in flood risk assessment.

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