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PROBLEMS OF CLIMATE VARIABILITY AND UNCERTAINTY IN FLOOD HAZARD PLANNING FOR THE COLORADO FRONT RANGE

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1. INTRODUCTION

Since the creation of the U.S. National Flood Insurance Program (NFIP) by Congress in 1968, extensive efforts have been made to reduce the impacts of flooding through floodplain mapping and improved community planning. In the last two decades, the Federal Emergency Management Agency (FEMA) has made substantial progress in motivating states and local governments to participate in NFIP. By 2001, over 19,000 communities were involved. In each NFIP community, a Flood Insurance Study is undertaken to analyze flood hazards in the community and prepare a Flood Insurance Rate Map (FIRM). The FIRM is intended to be the basis for floodplain management, mitigation, and insurance activities under NFIP.

Many of the existing floodplain maps have become seriously outdated as communities have grown and floodplain conditions have changed. FEMA acknowledges that, nationwide, nearly two-thirds of its flood maps are over 10 years old and “reflect outdated flood hazard data because watersheds and floodplains have changed faster than FEMA could afford to prepare updated maps” (FEMA 2002a). FEMA has initiated a Map Modernization Program to update the FIRMs and convert them to a digital format that will simplify their distribution, usage, and future revisions. In Colorado, goals of map modernization are to reduce the average age of the state’s FIRMs from over 13.6 years to 6 years or less and to develop flood hazard maps for many unmapped flood prone communities (Browning et al. 2002).

FEMA prescribes extensive requirements and guidelines that their “Flood Hazard Mapping Partners” (state and local agencies and study contractors) must follow in mapping and regulating floodplains. Acceptable methods and models are strictly specified, designed to create uniform levels of protection throughout the U.S. Assessments of flood risk are based on estimates of discharge, velocity, and depth in a "design flood", which is usually defined as the 100-year (1% probability) flood, although individual communities may choose to fund a higher level of protection for themselves. Many of the methods were developed by the U.S. Army Corps of Engineers and the U.S. Geological Survey in the 1970s and early 1980s and have received only minor additions and revisions since that time.

Flood discharge in the 1% annual chance flood is the basis for the hydrologic and hydraulic analyses that determine base flood elevation, floodplain boundaries, and other risk-related variables such as depth and velocity. Thus, uncertainty in the flood discharge estimates used as input to hydraulic models is a fundamental source of uncertainty in the resulting floodplain maps and vulnerability assessments.

Methods of riverine floodplain mapping recommended by FEMA indicate strong preference for use of historical streamgage measurements to estimate flood discharge (FEMA 2002b). Even on gaged streams, however, the existing streamflow data often violate the assumptions of flood frequency analysis (Thomas 2002). For ungaged, unregulated streams, regression equations developed by USGS are recommended to estimate discharge. However, standard errors of the regression estimates for the Colorado Plains region, which includes the Front Range, vary from 204% to 306% (Vaill 2000), partly because of insufficient

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data. Rainfall-runoff models frequently are used to estimate peak stream discharge because of the high spatial and temporal variability in Colorado precipitation. There is considerable evidence that the meteorology of extreme storms in Colorado is not adequately accounted for in standard hydrologic methods and models.

To provide information that is useful for flood hazard mapping and vulnerability assessments, the atmospheric science community needs information about decision making processes in floodplain management, use of weather and climate information, and problems perceived by users. This project is intended to help bridge the gap between users and providers of weather and climate information by (1) investigating the constraints that tend to prevent acceptance of new methods, (2) suggesting how new scientific information can be introduced into the floodplain management structure, and (3) enhancing the understanding and use of flood-related climate information by the many groups involved in floodplain management in the Colorado Front Range, including local officials and floodplain administrators, private consultants, state and regional flood control authorities, and federal agencies.

This report focuses on uncertainty in the information available for floodplain management in Colorado and constraints that inhibit use of new data and methods. It is based on interviews and discussions with floodplain management professionals, examination of Flood Insurance Studies for several Colorado communities, and a review of documents published by FEMA and the Colorado Water Conservation Board. Discussions took place at conferences of the Association of State Flood Plain Managers (ASFPM, June 2002) and the Colorado Association of Stormwater and Floodplain Managers (CASFM, September 2002). Interviews were conducted with the following individuals: Alan Taylor, Floodplain and Wetlands Coordinator, City of Boulder (2/26/02 and 3/8/02); Marsha Hilmes-Robinson, Floodplain Administrator, City of Fort Collins (4/1/02); Kevin Stewart, Manager, Information Systems and Flood Warning Program, Urban Drainage and Flood Control District of the Denver metropolitan area (5/1/02); and Mike Grimm, Hazard Mapping Division, FEMA (7/24/02).

2. CLIMATE AND FLOODS IN THE COLORADO FRONT RANGE

Most of Colorado's population is located in the Colorado Front Range (CFR) where the foothills of the Rocky Mountains meet the plains. The area has experienced rapid population growth during the past 30 years. Large numbers of tourists are drawn to canyon communities in the region, often adjacent to uncontrolled and ungaged streams. The semiarid climate of the CFR tends to lead to public complacency regarding flood risk. Yet, because of the steep terrain, streams respond rapidly to localized intense thunderstorms. The primary threat is flash flooding, characterized by a rapid increase in water depth and velocity, little warning time, and significant risk to life as well as property. The Big Thompson flood of 1976, which resulted in about 140 deaths, was a wake-up call to policy makers that prompted increased efforts to manage floodplains and develop warning systems (Gruntfest 1987).

Rapid population growth and urbanization along the CFR, along with construction of dams, pipelines, irrigation ditches, detention ponds, and other structural measures for flood control and water supply, has changed the response characteristics of many watersheds. This means that even when historical streamflow data are available, they may not be representative of how the same stream would respond to the same rainfall today. For these reasons, the design flood is often constructed by developing a "design rainfall" standard, usually the estimated 100-year precipitation, which is then entered into a hydrologic model to generate estimates of peak streamflow.

Flash floods are of particular concern as a threat to both lives and property. They are common in Colorado from mid-July through October due to the frequency of convective storms, involving intense rainfall of short duration. Thus, design rainfalls usually are stated in terms of the amount of precipitation falling in a short time period (commonly 2-3 hours). However, floods causing the greatest property damage in Colorado usually occur between May and August and are caused by widespread sustained rainfall over a period of several days, sometimes including flash flood episodes. Figure 1 shows locations and damage levels of Colorado's most damaging floods, as listed in the *1999 Colorado Flood Hazard Mitigation Plan* (Kistner and Assoc. 1999). Although the largest damages occurred in population centers along the Front Range, most of the associated storms involved widespread rainfall and many inflicted damage in the plains as well.

A comprehensive list of extreme storms in Colorado since 1864 was developed by McKee and Doesken (1997), with the goal of capturing the largest storms ever observed in or near the state. Through analysis of hourly and daily precipitation records, they developed a list of 328 extreme storms, then identified those which were roughly equivalent in intensity to the storm that caused the Big Thompson Flood of 1976 (Table 1). Of the nine Colorado storms listed in Table 1, seven caused major damage (the exceptions are 1938 and 1981 storms that apparently did not strike developed areas). McKee and Doesken concluded, "exceptionally heavy precipitation events similar to the Big Thompson flood, although rare in a specific sense, can actually be expected to occur somewhere in the state about once in any 10-20 year period" (p. 32). Furthermore, "by far the greatest propensity for such storms is along the eastern base of the Rocky Mountain foothills" (p. 28). Thus, the McKee and Doesken analysis indicates that the state's region of highest population, the Front Range, also has the highest likelihood of extreme precipitation.

3. SOURCES OF UNCERTAINTY

The notion of a "100 year" or "1% annual probability" flood creates considerable confusion. Experts tend to dismiss such concerns as a misunderstanding of probability on the part of laypeople. However, there is good reason to further investigate the validity of estimated flood probabilities. One reason for possible misrepresentation of flood risk is that estimates of flood probabilities at a particular location are used with the assumption that they represent only the natural variability in streamflow at that location, but often they contain substantial additional uncertainty.

Risk assessment literature draws a useful distinction between variability and uncertainty (Cullen and Frey 1999, Morgan and Henrion 1992). *Variability* is inherent in natural systems; it can be measured but generally cannot be reduced. In the case of floods, it is the result of variations in the incidence of weather events. Estimates of future precipitation and flood discharge are based on historical precipitation and streamflow data under the assumption that climate and land surface characteristics are reasonably stable.

In contrast, *uncertainty* results from lack of information. Its magnitude is difficult to measure, but it can be reduced through increased knowledge and improved data. For example, flow data are generally available only for larger streams and precipitation data may be available only at a substantial distance from the location of interest. In Colorado, high spatial and temporal variability in summer precipitation leads to a high degree of uncertainty in flood risk estimates that are based on distant monitoring sites or short data collection periods. Expanded networks of precipitation monitors and streamgages can reduce the uncertainty in discharge estimates that results from spatial variations in rainfall. For example, additional data are presently being collected in some urban areas for use in ALERT flood warning systems but, as yet, have been little used in the upgrading of floodplain maps.

Changes in land surface characteristics caused by human activities or natural processes introduce additional uncertainty, which can be resolved by updating the floodplain analyses on a timely basis. With planning horizons on the order of 30 years, floodplain managers face further uncertainties associated with future land use changes, climate variability, and possible future climate changes.

4. RESPONSES TO UNCERTAINTY

Colorado floodplain administrators give a variety of reasons for not trusting the federal Flood Insurance Rate Maps (FIRMs) as planning tools. They see absurdities in the maps (such as "air walls" where the mapping process arbitrarily ended). They experience floods that are much more frequent than a 100-year recurrence but are not in mapped floodplains. If a severe flood occurs, it can be much more extensive than the 100-year floodplain shown on their maps. Maps rapidly become outdated in areas of rapid development. The cities of Boulder and Fort Collins have funded development of their own flood hazard maps, which contain substantially more information than the FIRMs developed by FEMA.

The *Colorado Flood Hazard Mitigation Plan* encourages communities to adopt local ordinances that are more stringent than state or federal criteria, especially in areas with older maps that may not reflect the current hazard: "Because many existing floodplain maps are out of date, caution should be exercised when utilizing them for regulations.

Conservative safety factors are highly recommended" (Kistner and Assoc. 1999, p. D-4).

To compensate for inadequacy of the maps, floodplain managers adopt strategies that provide an extra margin of safety. Examples given by those we interviewed are: (a) using conservative modeling assumptions (such as assuming peak rainfall over the entire city at the same time, zero soil permeability, and/or full build-out of the area); (b) adopting extra freeboard requirements for elevation of buildings in the floodplain; (c) adding locally-defined floodplains that are not included in FEMA maps; and (d) using a 0.2% annual probability flood (i.e. 500-year, instead of the regulatory 100 year flood) as the basis for defining floodplains. Thus, when risk estimates are considered highly uncertain, conservative strategies intended to maximize safety may lead to unnecessarily strict regulations in some locations but inadequate protection in others.

In selecting the appropriate level of risk protection, FEMA guidelines recommend protecting against floods with more than a 1% annual chance of occurrence. Protection against rarer, more severe floods is assumed to not be cost-effective. Some floodplain management staff express a need to look more carefully at the risks to particularly vulnerable facilities outside of mapped 100-year, and even 500-year, floodplains because of the unpredictability of flows in the most extreme flood events.

FEMA floodplain maps and regulatory standards focus on reducing property damage, but Colorado floodplain managers are also concerned with the danger of injury or loss of life in flash flood situations. The City of Boulder commissioned a study of flood depths and velocities at which people are unable to stand up, using the results to define "high hazard" zones on floodplain maps based on the product of Depth x Velocity (Abt and Wittler 1988; Alan Taylor, personal communication 2/26/02). The approach also has been adopted by the City of Fort Collins (Marsha Hilmes-Robinson, personal communication 4/1/02).

5. LEARNING THE HARD WAY

A severe flood in 1997 in Fort Collins, CO, illustrates the impact of uncertainty in estimates of extreme precipitation. The city of Fort Collins is located at the base of the Rocky Mountains in northern Colorado. A history of severe floods in the region led the city to develop a comprehensive floodplain management program in the 1980s (Grimm 1998). It took a record storm to convince policy makers that the city's "design rainfall" had been substantially underestimated.

In July 1997, Fort Collins was hit by the heaviest rains ever documented over an urbanized area in Colorado (Grigg et al. 1999). Some peak discharges greatly exceeded estimated 500-year flows. The resulting flood disaster left 5 people dead, 54 injured, 200 homes destroyed, and 1,500 homes and businesses damaged. Lessons learned from that flood intensified floodplain management efforts in Fort Collins. Re-estimation of the 100-year "design precipitation" rate based on new data suggested the rate should be increased by 27% (Doesken and McKee 1998; Charlie and Doehring 2000). This increase, adopted by the City Council in 1999, substantially increased the extent of the 100-year floodplain (Marsha Hilmes-Robinson, personal communication 4/1/02). This decision produced considerable public outcry and left public officials concerned about the political implications of increased accuracy in flood probabilities.

This flood offers important lessons about assessment of flood risk. Grigg et al. (1999) conclude that recurrence intervals do not communicate risk effectively and that planning for normal storms (2- to 100-year events) is not enough. Furthermore, "the 100-year or 500-year floods are only reference values ... more extreme events are quite possible." They point out that the flood "exhibited unusual rainfall and dramatic runoff and provided a wakeup call that current practice in assigning return periods to such extreme events needs to be reviewed" (p. 261).

6. BARRIERS TO THE USE OF NEW SCIENTIFIC INFORMATION

It seems clear that better information about Colorado climate and the meteorology of extreme storms could improve the accuracy of flood risk estimates in the Colorado Front Range. At the same time, there are substantial barriers to the use of such information within the structure of floodplain management in the U.S. We reviewed FEMA documents and questioned floodplain management professionals and private consultants to identify factors that tend to prevent acceptance and use of new scientific information and methods. The following factors were identified.

(1) Lack of consideration of meteorological variability and uncertainty. The focus of FEMA's Map Modernization Program is on improved hydrologic and hydraulic modeling, including higher-resolution elevation mapping. Improvement of meteorological information is not explicitly mentioned.

Our discussions with contractors who serve as FEMA's Mapping Partners indicate that the uncertainty in precipitation estimates used as input to the hydrologic models is largely ignored. However, these hydrologists and engineers recognize that there is a high degree of oversimplification introduced by 1-dimensional hydrologic models that ignore temporal and spatial variability in precipitation. Some express frustration at the constraints imposed by FEMA requirements, but lack the information and resources needed to pursue alternative methods.

(2) Resistance to introduction of new methods and recalculation of risk levels. FEMA provides a list of approved methods and models, and requires extensive documentation, justification, and review of any methods used that are not on their list. Although FEMA guidelines permit use of non-standard methods under special circumstances, engineers and other consultants who serve as study contractors indicate that this is a daunting and time-consuming process they prefer to avoid. Therefore introduction of new methods is actively discouraged.

On the other hand, Mike Grimm of FEMA's Hazard Mapping Division explains that NFIP is community-based. An important consideration in whether FEMA approves a new estimate of 100-year discharge is whether the local community is willing to defend the new method and the revised estimate (M. Grimm, personal communication, 7/24/02).

Floodplain managers indicate that it is difficult to get FEMA to allow additions to floodplain maps. However, Grimm explains that Digital FIRMs (DFIRMs) being developed through the Map Modernization Program will allow greater flexibility. A new FEMA policy allows communities to have both standard and enhanced flood map databases. The standard map shows current land use and is used to set flood insurance rates. The enhanced map can contain additional information to meet planning needs in the community. A common addition is "future conditions hydrology" to depict the impacts of expected development (FEMA 2002b). The community must provide the necessary technical information.

Changes in floodplain boundaries create public backlash and anger in local communities (as seen in the Fort Collins example above). Officials express reluctance to increase the level of risk protection, or to acknowledge uncertainty in floodplain calculations, because of potential public reactions.

(3) Reluctance to acknowledge uncertainty. In the policy context, clearly defined regulatory limits and uniform standards and methods are considered essential to provide clarity, create the perception of fairness, and discourage litigation. Policy makers tend to avoid acknowledging uncertainty in the scientific information on which regulations and standards are based.

However, in the face of incomplete and uncertain information, decision makers must determine how to balance the risks and demands within their communities. Our discussions indicate that floodplain managers and engineers tend to choose on the side of caution, particularly in communities that have recently experienced severe floods. On the other hand, the public and local officials in areas that have not experienced extreme floods are inclined to overlook or dismiss the flood risk in the face of more urgent needs and demands. For example, in the Pikes Peak Regional Building Department, a recent dispute between building officials and the floodplain manager over enforcement of floodplain regulations led to the forced resignation of the floodplain manager (Zubeck 2002).

It appears that some communities err on the side of caution, achieving a higher level of protection (lower level of flood risk) than is formally stated, while others balk at the costs and restrictiveness of effective mitigation and may fail to achieve stated levels of protection.

7. NEEDS FOR FUTURE RESEARCH

Although improved weather information is a high priority for flood warning systems in Colorado and dense monitoring networks now operate in some areas, little effort has been made to use this information in long term flood hazard planning. New data sources (such as ALERT raingage networks and NEXRAD radar rainfall data), coupled with more detailed analysis of long-term raingage data, could potentially improve estimates of extreme precipitation and flood discharge.

Rainfall attributes over the Colorado Front Range are affected by large-scale climate forcings, especially during summer. We intend to investigate whether estimates of flood risk variables can be improved through better understanding of relationships between climate/weather regimes and summer precipitation on a variety of temporal and spatial scales and whether summer season precipitation forecasts can be helpful in flood hazard planning.

With the current federal and state plans to update floodplain maps under FEMA's Map Modernization Program, this is an ideal time to provide improved meteorological analyses that might reduce uncertainty in the estimates of flood discharge in Colorado and other mountainous areas of the arid west.

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Table 1. Extreme rain events (> 10 inches) in Colorado. (Source: McKee and Doesken, 1997; Doesken and McKee, 1998)

Storm	Date	Max. Rain (Inches)
1. Pueblo / Penrose	June 2-6, 1921	6 - 12
2. Cherry Creek / Hale	May 30-31, 1935	12 - 24
3. N. Colorado Front Range	Sep. 2-3, 1938	6 - 10
4. Rye (S. Colo. Front Range)	May 18-20, 1955	6 - 13
5. Plum Creek	June 16-17, 1965	14 - 16
6. Big Elk Meadows	May 4-8, 1969	6 - 14
7. Big Thompson	July 31, 1976	12
8. Frijole Creek	July 2-3, 1981	8 - 16
9. Fort Collins, and	July 27-28, 1997	14.5
Pawnee Creek	July 29-30, 1997	15.1
Elsewhere in Rocky Mountain Front Range:		
10. Savageton, WY	Sep. 27-29, 1923	17
11. Gibson Dam, MT	June 6-8, 1964	16
12. Rapid City, SD	June 9, 1972	15

Figure 1. Locations of the most damaging floods in Colorado, 1864-1999. (Damage in millions of 1999 dollars.)