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Interactions between scientific uncertainty and flood management decisions: Two case studies in Colorado

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Abstract

Flood management policies in the United States rely on scientific information about the frequency and intensity of extreme precipitation and runoff. Yet, the available information is inherently uncertain because of the complexity of meteorological and hydrological processes. In mountainous areas, flood risk can vary greatly even within short distances depending on local climate, topography, soil characteristics, and land use. This paper describes two Colorado cases in which policy makers were presented with conflicting scientific estimates: revision of the Fort Collins floodplain map and modification of the Cherry Creek Dam. The case studies demonstrate that uncertainty can have substantial impacts on regulatory processes, public safety, and costs. The analysis considers the differing perspectives of various participants in the flood management processes, illustrating the interplay between uncertainties attributable to scientific issues and values issues. It suggests that attempts to provide a single "best" estimate do not necessarily meet the decision needs of all stakeholders. Conclusions indicate a need to improve communication about uncertainty when scientific estimates are provided to decision makers. Furthermore, in highly controversial decisions, it may be necessary to reframe the discussion to consider the values issues raised by scientific uncertainty.

Keywords: Floodplain management; Dam safety; Decision making; Uncertainty; Scientific information

1. Introduction

Uncertainty in scientific information has emerged as a major concern in environmental policy formulation. Holling (1995, p. 13) observes: "… knowledge of the system we deal with is always incomplete. Surprise is inevitable. Not only is the science incomplete, but the system itself is a moving target …." The public and policy makers look to science and engineering to provide deterministic solutions to technical problems; but scientists often disagree among themselves, and models and data analyses sometimes produce contradictory results (cf. Bradshaw and Borchers, 2000). Conflict resolution in the selection and implementation of management strategies is a political process, centered on values issues, often downplaying scientific and technical uncertainties. Arguments about scientific "facts" can easily become a cover for disagreements about values. Engineers cope with uncertainties as best they can; therefore unresolved questions may not be evident to policy makers (cf. Vick, 2002). Yet, the uncertainties can have profound implications affecting decision outcomes and, ultimately, the vulnerability and resilience of human and natural systems (cf. Pielke and Conant, 2003; Holling, 1995).

Flood management in the United States is supported by a large body of respected scientific data and research on meteorology and hydrology, much of it developed by federal agencies over the past 60 years for use in water management, flood control, and agriculture. Yet, even in the well-researched field of flood hazards, uncertainty in scientific estimates is unavoidable. The potential accuracy of floodplain maps and flood forecasts is limited by a number of factors, including natural variability in the

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physical environment, limitations in engineering calculations and judgments, future social and economic conditions, and surprises such as changes in terrain during extreme flood events.

In the US, federal guidelines establish minimum criteria governing flood mitigation measures. The criteria are based on historical precedents in engineering practice and continue to be debated by experts (see Wright, 2000; NRC, 2000; Dubler and Grigg, 1996). Fixed design values often give a misleading impression of certainty to the public and policy makers. For example, unambiguous delineation of the 100-year floodplain is required to enforce floodplain regulations, but estimates of the discharge, depth, and coverage of the 100-year flood contain considerable uncertainty. In recent advice to the public, the Federal Emergency Management Agency (FEMA) acknowledges the uncertainty in floodplain maps, stressing that risk levels are continually changing and that citizens may need to protect themselves against extreme floods even when their property is outside the mapped floodplain (TSARP, 2002). Similarly, dam safety standards are based on an estimate of the Probable Maximum Flood (PMF), but the estimate can differ substantially depending on the scientific methods used (see NRC, 1994; Jarrett and Tomlinson, 2000).

Estimates of the magnitude and frequency of extreme precipitation are especially uncertain in mountainous areas because of highly variable precipitation patterns, sparsely distributed weather stations, and short data records. In particular, scientists have questioned the accuracy of meteorological and hydrological information used for flood management in the state of Colorado and throughout the Rocky Mountain region (Jarrett and Costa, 1988; Jarrett, 1993; Grimm et al., 1995; Jarrett and Tomlinson, 2000). In several recent Colorado cases, disputes about which scientific estimates should be used have entered into policy debates.

Through the analysis of two cases in the Front Range region of Colorado's Rocky Mountains, this paper highlights how scientists and policy makers deal with the inevitable uncertainties in flood risk estimation and management and presents some of the practical and public implications of how uncertainty is accounted for. In both communities, citizens and policy makers were confronted with uncertain and contradictory hydrometeorological information and asked to make flood management decisions. The resulting political processes illustrate the interplay between scientific uncertainty and underlying disagreement about values and risks.

The first case is Fort Collins, where a 1997 flood disaster motivated the community to re-evaluate its design rainfall and re-draw its floodplain maps. The second case concerns Cherry Creek Dam upstream of Denver, where widely varying estimates of maximum flood potential have led to public controversy and may mean millions of public dollars spent for raising the height of a dam.

This paper is unusual in the flood management literature, because it intentionally draws attention to the scientific discrepancies and their implications for risk management debates and policy decisions. Previous discussions on uncertainty in the underlying scientific information used in flood management have taken place primarily in engineering journals and technical reports (cf. USACE, 1996; NRC, 2000). However, a serious cross-disciplinary dialog is necessary to ensure thoughtful consideration of appropriate risk assessments by scientists, policy makers, and communities at risk. The limitations of our scientific knowledge of hydrology and meteorology are not "political" per se, but the necessary interpretations of flood probabilities and the PMF lead to different policies with vast public safety implications. The case studies illustrate the "certainty gap" between what decision makers want and need and what science can provide. They demonstrate the need to rely on expert judgment when science is uncertain, and show the ensuing conflict when experts disagree. Finally, they show the variety of decision makers affected, with different information needs and responses to risk and uncertainty, suggesting that attempts to provide a single "best" estimate do not necessarily meet the decision needs of all stakeholders.

2. Methods

This study uses an exploratory case study approach (Yin, 1994) to focus on how uncertainty in hydrometeorological information interacts with flood management decisions. In accord with Yin's (1994) recommendations, two well-documented cases within the same geographic region were chosen to represent distinct aspects of flood management. That is, the two cases represent different types of flood management decisions (floodplain management and dam safety), involve use of different types of meteorological information (precipitation frequencies and maximum precipitation), and involve decisions at several levels of government (local, state, and federal). For each case study, the authors interviewed the government official responsible for facilitating the decision process; i.e., the local Floodplain Manager in the first case and the federal Project Manager for the dam in the second case. The case study descriptions rely on those and other interviews (described in the next paragraph), as well as published reports, official correspondence, and records of public meetings, all of which are cited herein. The two officials have read and approved the case study descriptions.

To understand the context of the case studies, the authors conducted semi-structured interviews and discussions with 12 practitioners and scientists (including the two officials above) who have either a key role in flood management or significant knowledge about the topic. Table 1 provides summary information about the interviewees, who were selected to represent a variety of professional responsibilities, areas of expertise, and levels of government. Open-ended questions were designed to

Table 1
Interview subjects

Position	Number of subjects	Jurisdiction
Floodplain manager for a Colorado city	2	Local
Engineer, urban flood control	1	Metropolitan area
Engineer, state flood protection	1	State
Engineer, Federal Emergency Management Agency	1	Federal
Engineer, US Army Corps of Engineers	1	Federal
Hydrometeorological consultant	2	Private sector
Scientist	1	State
Scientist, National Weather Service	1	Federal
Scientist, US Geological Survey	1	Federal
Flood policy expert	1	University
Total	12	

gather qualitative data on what technical information is used in flood management, what participants know about the uncertainty in the information, and how uncertainty affects flood policies and management. A list of questions was prepared for each interviewee based on his or her professional responsibilities and areas of expertise. Questions for floodplain management professionals covered flood experiences, decision-making processes in floodplain management at local, state, and federal levels, and methods of using weather and climate information and dealing with uncertainty in that information. Questions for scientists focused on their scientific specialties, with emphasis on the role of uncertainty in the information they provide or use. Notes were taken during the interviews, often by several researchers, and promptly transcribed.

To supplement the interviews, the regulatory context in which flood management decisions occur was examined through extensive study of government documents, including federal and state guidelines for floodplain management and dam safety, scientific and engineering reports, FEMA Flood Insurance Studies for Colorado communities, and reports of expert advisory panels.

Members of the research team also attended two annual meetings of the Colorado Association of Stormwater and Floodplain Managers and one meeting of the US Association of State Flood Plain Managers (ASFPM). During these several-day events, team members held discussions with floodplain managers, engineering consultants, and representatives of government agencies who provided useful insights into the concerns of flood management professionals and the discrepancies between official guidelines and actual practice. Additional insights were obtained through observation at public meetings on local flood issues in Boulder, CO. Ideas suggested by these casual conversations and observations were later investigated more thoroughly in interviews and by examining public documents.

The case studies, interviews, and documents were obtained over a period of several years as part of a study on uncertainty in the meteorological information used for flood management in Colorado (Morss et al., 2005). Analysis of the interviews and documents initially focused on the use of scientific information by stakeholders, including policy-making bodies, technical advisers, and government agencies. The case studies were used to investigate the influence of uncertainty in decision making, focusing on stakeholders' responses to uncertainty, and interactions within and among groups of stakeholders. The results show that scientific and technical uncertainty is integrally entwined with uncertainty due to values and other issues (Hall and Davis, 2001).

Because our study examines only two US cases in depth, the results cannot be extended to broad generalizations about the use of scientific information in flood management decisions. In addition, the case studies are limited by a lack of direct information from elected officials and private citizens, whose views are represented only if mentioned in the interviews, meeting reports, or official correspondence. Nevertheless, the analysis of the case studies within the broader US flood management context generates some interesting insights and raises several issues for exploration in future research.

The remainder of this paper is organized as follows. Section 3 provides background information on the study region and the relevant federal guidelines and technical practices used in floodplain mapping and dam design. Section 4 summarizes the case studies. Section 5 presents an analysis of issues raised by the case studies. The concluding section brings together some key insights derived from the analysis.

3. Background

3.1. Study region

The study was conducted in Colorado's Front Range region,[1] where the foothills of the US Rocky Mountains meet the plains (Fig. 1). The region houses over 80% of the state's residents, and its population increased by 50% between 1980 and 2000, accompanied by rapid suburban development.

Colorado's climate is strongly influenced by its topography (cf. Doesken et al., 2003). The Front Range is situated on the east side of the Rocky Mountains, where elevations rise abruptly from about 1500 m where the plains meet the foothills to high ranges with peaks over 4000 m. Annual precipitation generally increases with

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[1] The Colorado Front Range region consists of 12 counties (Adams, Arapahoe, Boulder, Broomfield, Denver, Douglas, El Paso, Elbert, Jefferson, Larimer, Pueblo, and Weld), with 81.7% of the state's population, according to US Census Bureau estimates for 1 July 2000.

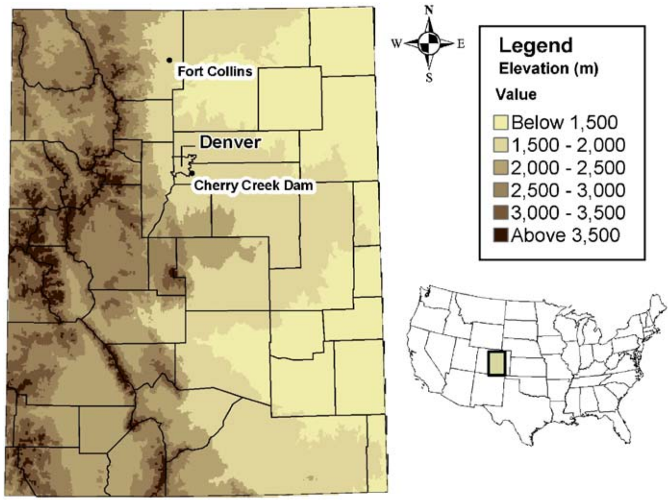

Fig. 1. Front Range region of Colorado, with case study locations.

elevation, but is also influenced by the orientation of mountain ranges and the effects of local topographic features. Thus, large weather variations occur within short distances. The high mountains receive their greatest precipitation in the form of winter snow, with the major snowmelt runoff occurring in May and June. In contrast, the eastern plains receive most of their precipitation during the warm season, April through September. Thunderstorms are common during spring and summer in the plains and foothills, creating severe flood hazards. In steep mountain canyons, streams respond rapidly to localized intense thunderstorms.

Highly variable rainfall patterns, a paucity of rain and stream gages, and short gage record lengths in Colorado make it particularly difficult to accurately estimate the probabilities of extreme precipitation and predict flood events. A serious threat is flash flooding, characterized by a rapid increase in water depth and velocity, little warning time, and significant risk to lives and property. More sustained flooding also occurs. Indeed, floods causing the greatest property damage in Colorado usually have involved widespread sustained rainfall over a period of several days, sometimes including flash flood episodes (Kistner and Associates, 1999).

3.2. *Floodplain maps and precipitation frequency*

In the US, floodplain maps developed by FEMA contractors meet the legal requirements for identifying the regulatory floodplain in a community. These widely used flood management tools are the basis for floodplain management, mitigation, and insurance under the National Flood Insurance Program (NFIP) for communities throughout the nation. The regulatory floodplain depicted on the map represents the area that would be inundated by a "design flood", usually defined as the 100-year flood (i.e., the flood discharge that has a 1% chance of being exceeded in any given year). Some floodplain maps also show the inundation area of the 500-year flood (which has a 1 in 500, or 0.2%, annual chance of exceedance).

Floodplain maps become seriously outdated as communities grow and floodplain conditions change (Burby, 2001). In response, FEMA has initiated the Map Modernization Program, a five-year plan to upgrade the nation's flood map inventory. Goals are to provide maps and data in digital form, openly accessible via the Internet, enabling officials at all levels of government to assess risks using geographic information systems (GIS) technology and increasing public awareness of flood hazards (FEMA, 2004, 2005a).

New maps will not solve all the problems of flood risk estimation in the US, however, because of the inevitable gaps in technical information. For example, FEMA recommends use of historical streamgage measurements to estimate the 100-year flood (FEMA, 2002). However, streamgage data are not available on many smaller streams, and in areas that have experienced rapid population growth or changes in water management, historical streamflow data are not representative of how a stream would respond to an extreme storm today. Therefore, floodplain maps are often constructed using a "design rainfall" standard, usually the estimated 100-year (or 1% annual chance) precipitation. The design rainfall is entered into a rainfall–runoff model to generate estimates of the 100-year flood discharge. Because summer convective thunderstorms produce intense rainfall of short duration, design rainfalls in the Colorado Front Range are usually stated in terms of the amount of precipitation falling in a short time period (commonly 2–24 h).

The design rainfall at a particular location is estimated from historical precipitation frequencies. The Precipitation Frequency Atlas of the Western United States (NOAA Atlas 2) (NWS, 1973) is the main source of precipitation frequency information used for floodplain and stormwater management in Colorado. NOAA Atlas 2 is primarily based on only 22 years of precipitation data (from 1948 to 1970); thus, its estimates of 100- or 500-year precipitation contain substantial uncertainty. A new precipitation frequency atlas (NOAA Atlas 14), based on improved statistical methods and enlarged data sets, has been developed for parts of the US but does not include the Rocky Mountain region (Bonnin et al., 2003).

3.3. *Dam safety and probable maximum precipitation (PMP)*

US federal dam safety guidelines classify dams located upstream from populated areas as "high hazard" (ICDS, 1998, Section IIIB). For many years, guidelines have recommended that high-hazard dams be designed to withstand the largest flood-induced forces that can be expected during their lifetime (NRC, 1994; Graham, 2000). Safety requirements for dam and spillway design are based on estimates of the PMF, the worst-case flood scenario considered reasonably possible in a particular drainage basin.[2] The US Army Corps of Engineers (USACE) designs its high-hazard dams to pass a PMF without overtopping the embankment (USACE Omaha Dist., 1999c).

The PMF is estimated using the PMP, a worst-case rainfall scenario at a given location.[3] PMP calculations use historical data from extreme storms that have occurred nearby within a meteorologically similar region. However, estimation of the PMP involves many subjective decisions. For example, transposition of storms in areas of complex topography requires expert judgment, even within short distances, because of differences in orography and moisture availability (NRC, 1994).

PMP estimates for the western US have gradually been changed through a series of studies by the National Weather Service (NWS). Revised PMP estimates for the Rocky Mountain region east of the Continental Divide were published in Hydrometeorological Report 55A (HMR 55A) in 1988 (Hansen et al., 1988). HMR 55A provides "generalized" regional PMP estimates, smoothed to give location-specific estimates. "Site-specific" PMP analyses can improve the estimates by accounting for specific topographic features of a basin that might be overlooked in a generalized regional study. For several Colorado reservoirs, the generalized PMP estimates have been questioned, and the NWS or expert hydrometeorological consultants have carried out site-specific PMP analyses for particular basins (e.g., NWS, 1995; Tomlinson and Solak, 1997; Solak, et al., 2000).

Revised calculations of PMP and PMF have raised questions on the safety of many older dams in the US. Estimates of the cost of modifying existing US dams to accommodate the PMF vary widely, but are in billions of dollars (Graham, 2000; Lave et al., 1990). The subjective nature of PMP and PMF calculations, the inconsistency in protection levels achieved, and the extremely high costs of meeting PMF criteria have prompted challenges to PMF-based methods (discussed in Section 5.3.3).

4. Description of case studies

Concerns about the accuracy of hydrometeorological estimates used in flood management have led the Colorado Water Conservation Board (CWCB) and several local governments in Colorado to initiate new hydrometeorological studies.[4] Two case studies illustrating how decision makers dealt with uncertain scientific information are described here. In the Fort Collins case, the community questioned the standard precipitation frequency estimates provided in NOAA Atlas 2 and developed its own estimates for use in revising its floodplain map. In the Cherry Creek Dam case, state and local governments and local citizens questioned the PMP estimates provided by the NWS and the expensive dam modifications proposed by the USACE. Both cases are ongoing, as the two communities continue on the path of managing their flood risk in an evolving scientific, societal, and political environment. This section summarizes events in the two case studies up to the time of our analysis (through February 2005). The following section discusses issues raised by the case studies.

4.1. *Fort Collins: re-estimation of the 100-year design rainfall*

The city of Fort Collins is located at the base of the Rocky Mountains in northern Colorado (Fig. 1). A history of severe floods in the region led the city in the 1980s to develop a "comprehensive floodplain management program" that was highly rated by FEMA (Grimm, 1998, p. 62). However, a record storm directly over the city persuaded policy makers that the city's design rainfall might be substantially underestimated and the floodplain maps should be revised.

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 five people dead, 54 injured, 200 homes destroyed, and 1500 homes and businesses damaged. The two areas that experienced the greatest damage were not within 500-year floodplains shown on the city's floodplain map.

After the 1997 flood, concerned citizens prompted the city government to take actions to reduce the risk in future floods. The floodplain map had been developed using precipitation frequencies provided in NOAA Atlas 2, with a 100-year design value of 7.34 cm of rain in a 2-h period. The city stormwater utility initiated a study to re-evaluate the amount of rainfall associated with a 100-year storm, and a task force of scientific and technical experts, citizens, and regulatory agency personnel was formed to oversee the rainfall study (City of Fort Collins, 2004). However, viewpoints of the task force members varied, and different assumptions led to different estimates. Ultimately, the task force was unable to agree on a design rainfall estimate. The

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[2] PMF is defined as "the flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the drainage basin under study" (ICDS, 1998).

[3] PMP is defined as "theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographic location during a certain time of the year" (ICDS, 1998). The estimation procedure involves transposing historical storm data to the location of interest and maximizing the moisture in the air to simulate the extreme meteorological conditions that would cause the maximum rainfall to occur.

[4] Examples include the Fountain Creek Watershed Study (http://fountain-crk.org, accessed 27.07.04), the South Boulder Creek Flood Mapping Study (City of Boulder, 2006), a paleoflood study of Elkhead Reservoir (Jarrett and Tomlinson, 2000), and mesoscale modeling to estimate extreme rainfall (Cotton et al., 2003).

City Council was presented with the following three options for the 100-year, 2-h design rainfall value (Fort Collins City Council, 1999):

(1) adopt a design value of 9.32 cm of rain in a 2-h period, based on a regional analysis of Front Range raingage data from Fort Collins, Longmont, and Boulder, applied uniformly over the city;
(2) adopt a design value of 11.10 cm, based only on data from the raingage in Fort Collins, applied uniformly over the city;
(3) adopt design values of 11.10 cm in the eastern part of the city and 13.97 cm in the western part of the city.

City staff strongly recommended option (1) as the best estimate of the 100-year precipitation, stating, "Adoption of a higher value would be, in essence, adoption of a higher level of protection than 100-year" (Fort Collins City Council, 1999, p. 127). The staff report emphasized that none of the estimates could be considered truly correct, and that the value could be refined and changed again in the future.

A majority of task force members recommended option (1), which was also endorsed by FEMA, CWCB, and local agencies. A minority of the task force, including citizens who had been directly impacted by the 1997 flood, recommended option (3). One Council member supported option (3), expressing concern about future climatic changes including potential intensification of rainfall with global warming (Fort Collins City Council, 1999). The City Council selected option (1) in a 4 to 1 vote. Through this process, in 1999 the design rainfall value was changed from 7.34 to 9.32 cm, an increase of 27%.

The new design rainfall has had important implications for the city's floodplains and stormwater facilities: (1) regulatory floodplains became wider and deeper, causing additional properties to be within mapped floodplains and subject to regulation; (2) new stormwater facilities (detention ponds, culverts, bridges, etc.) must be designed to handle higher peak flows; and (3) many existing stormwater facilities are considered undersized and potential solutions to be found (City of Fort Collins, 2004). In Fort Collins there was pressure to "do something" after the 1997 deadly flooding, and convening the task force and changing the maps were among the designated actions.

4.2. Cherry Creek Reservoir: site-specific PMP studies

The Cherry Creek Dam is located about 20 km upstream from the confluence of Cherry Creek with the South Platte River in central Denver (Fig. 2). It was constructed in 1950 to protect the region from flooding (USACE Omaha Dist., 2003). When the dam was designed in 1944, spillway design typically was based on a historic storm of record in the region, multiplied by a safety factor. The Cherry Creek spillway design flood was based on a 1935 storm in the plains of eastern Colorado, increased by a "reliability factor" of 25% (USACE Omaha Dist., 1999b).

Subsequent to the construction of Cherry Creek Dam, federal agencies adopted PMP analysis for the estimation of spillway design floods (USACE Omaha Dist., 1999b). As methods of estimating PMP in the western US improved, the NWS developed successive PMP values for Cherry Creek Basin, listed in Table 2. In 1993, based on the generalized PMP analysis in HMR 55A, the USACE estimated that Cherry Creek Dam could safely control only 63% of the PMF. In 1995, based on the later NWS

Fig. 2. Aerial photograph of Cherry Creek Dam and Reservoir, looking southeast, taken on 21 May 1990. Cherry Creek flows northwest into Denver; housing subdivision in center foreground is near the base of the dam. (*Source*: USACE Omaha Dist., 2004.)

Table 2
History of PMP and storm studies for Cherry Creek Dam

Year of study	Basis for PMP and storm studies	Storm length (h)	Total rainfall (cm)	Runoff (cm)	Peak discharge ($m^3 s^{-1}$)
1944	1935 event pattern	9	29.2	20.6	5120
1970	HMR 44[a]	96	60.7	24.6	10,650
1988	HMR 55A generalized PMP	96	74.2	41.3	17,980
1995	NWS site-specific PMP	72	62.7	32.4	14,860
		24	53.6	—	—
2003	AWA site-specific PMP	72	44.2	—	—
		24	40.1	—	—

Sources: USACE Omaha Dist. (1999b); Tomlinson et al. (2003).

[a] 1970 site-specific PMP for Chatfield Dam applied to Cherry Creek basin; developed by NWS.

site-specific PMP analysis, the estimated peak discharge was reduced (Table 2) and the USACE calculated that the dam could safely control 75% of the PMF (USACE Omaha Dist., 1999b, 1999c).

During 1997–99, the USACE arranged public meetings in potentially affected Denver area communities to present alternative dam safety solutions and solicit public comments. USACE representatives informed the public that Cherry Creek Dam was unsafe, pointing out that the probability of overtopping the dam is very remote, but the consequences of such a failure would be catastrophic. Potential flood damage downstream would be in the range of $15–20 billion. Population within the potential flood area was estimated at 100,000. The inundation area would include 39 schools, three hospitals, three police stations and one fire department (USACE Omaha Dist., 1999c).

The USACE proposed several alternative improvements to the dam, reservoir, and basin, costing up to $250 million (USACE Omaha Dist., 1999a; CWCB, 2003b). There was much public outcry at the meetings, with opposition to any kind of construction at the dam. The meetings were attended by members of the scientific community and a few attendees questioned the validity of the NWS site specific PMP study (W. Miller, USACE, pers. comm., 5.11.03).

Although Cherry Creek Dam fails to meet USACE safety standards, it does meet the capacity requirements of the State of Colorado. State rules specify that high-hazard dams constructed prior to 1988 should be capable of safely routing the flood that would result from 75% of the PMP. Thus, the state considers the present spillway acceptable based on the 1995 USACE analysis (Byers, 1999).

Heated public controversy over the USACE findings and recommendations led the US Congress in 1999 to pass legislation prohibiting any further use of USACE funds for the Cherry Creek Basin study; therefore, the USACE ceased its dam safety study activities (CWCB, 2003a). The Colorado State Assembly passed a resolution requiring the CWCB to conduct an independent peer review of the NWS site-specific PMP estimates (CWCB, 2003c).

To evaluate the NWS estimates, in 2000 the CWCB selected a local consulting firm, Applied Weather Associates (AWA), to perform the independent peer review and conduct a new site-specific PMP study for Cherry Creek Basin. The study was funded by the state and several local communities (CWCB, 2003c). Site-specific PMP estimates presented by AWA in April 2003 were lower than the NWS estimates by over 30% and received criticism from NWS experts. Differences between the AWA and NWS studies included significant disagreements about orographic and barrier effects in the basin and assumptions about the spatial distribution of extreme rainfall (CWCB, 2003a; NWS, 2003; AWA, 2003). AWA agreed to amend one aspect of its calculation procedure by adding depth–area envelopment. Revised PMP estimates presented in August 2003 were still approximately 25% lower than in the NWS study (Table 2) (Tomlinson et al., 2003).

The CWCB staff, having worked closely with all parties involved, expressed satisfaction that the AWA study was "the best scientific answer that is conservative and defensible but representative of the Cherry Creek Basin and Colorado climatological and hydrological characteristics" (CWCB, 2003b, p. 3). In accord with the staff's recommendation, the CWCB members unanimously approved the AWA study.

In 2004, Congress removed the restriction that had prevented the USACE from participating in further Cherry Creek studies. The USACE agreed to cooperate in attempts to resolve "the many controversial concerns regarding the Corps Dam Safety recommendations" and to use Colorado's alternative PMP estimate in a PMF analysis (CWCB, 2003b). William Miller, Cherry Creek Dam Project Manager (pers. comm., 5.11.03), points out that it is USACE policy to use PMP estimates calculated by the NWS; therefore, the 1995 NWS site-specific PMP is the figure that the USACE currently accepts. He is hopeful that the state, the USACE, and the NWS can come to agreement on a scientifically based PMP estimate for Cherry Creek Basin.

5. Analysis and discussion of case studies

In both of the above cases, re-study of scientific information using new data and methods led to recommendations that more restrictive design values should be adopted. Scientists disagreed on the proper magnitude of the change and the dispute was carried into the political arena. However, the outcomes differed. Fort Collins succeeded in obtaining City Council approval of a change and moved quickly to implement it, but the Cherry Creek Dam case remains unresolved after more than 10 years of debate and re-study. Analysis of the two cases shows technical similarities but important differences in how scientific information and uncertainty interacted with the political aspects of the flood management process. Section 5.1 focuses on how scientific and technical uncertainty is accommodated in flood management decision making, Section 5.2 focuses on values issues related to public priorities, and Section 5.3 considers the differing perspectives of various participants and how they affect decision processes.

5.1. Scientific uncertainty and expert judgment

Risk assessment literature draws a useful distinction between natural variability and knowledge uncertainty (NRC, 2000; Cullen and Frey, 1999). Natural variability is inherent in physical processes, such as precipitation and runoff. When the outcomes of physical processes can be measured repeatedly and presented as frequency distributions, they can be estimated using statistical techniques. This paper uses the term "sampling uncertainty" to refer to the uncertainty in estimates calculated using limited data samples from naturally variable processes. Sampling uncertainty cannot be eliminated, but it can be reduced by collecting more data over time or space within a homogeneous climatic region.

"Knowledge uncertainty" (NRC, 2000) refers to limitations of scientific understanding of complex natural processes and future changes. Knowledge uncertainty can lead to inadequate representation of physical or economic processes by models, distributions, or estimated parameters (USACE, 1996). The impact of knowledge uncertainty sometimes can be roughly determined through sensitivity analysis (i.e., computing the effect of changes in assumptions or input values on model output).

The two Colorado cases show that experts working on the same problem, using reasonable assumptions and justifiable methods, can calculate quite different design values and provide conflicting recommendations to decision makers. In the Fort Collins case, the new climatological study took advantage of longer time series and data from nearby stations to reduce sampling uncertainty and improve estimates of 100-year precipitation at specific locations. However, knowledge uncertainty led to disagreement about which raingage locations to use and how to represent rainfall in different parts of the region. The latter disagreement was left unresolved by scientists and required resolution by decision makers through a vote of the City Council.

In the Cherry Creek Dam case, knowledge uncertainty was fundamental. To ensure against overtopping the dam, the PMP estimate must be an upper bound for the amount of precipitation that could possibly fall in the basin. However, to minimize construction costs, decision makers would like to use the *smallest* possible PMP estimate that would preclude overtopping. Scientists and decision makers were faced with a delicate task of reducing the PMP as much as possible without reducing it too much and risking catastrophe. In their studies on the Cherry Creek Dam, NWS and AWA experts disagreed on the influence of particular local meteorological, hydrological and topographical factors on precipitation.[5] Decision makers were divided, with USACE policy supporting the official estimate from NWS and state officials accepting the reduced PMP estimate from AWA.

The cases illustrate the crucial role of expert judgment in bridging the gap between uncertain scientific knowledge and decision makers' need for information they can act on. A civil engineer observes, "Science and engineering have different jobs. The scientist's job is to explain natural phenomena. The engineer's is to deal with them whether they are adequately explained or not" (Vick, 2002, p. 17). Thus, technical estimates often must be based on professional judgment and experience. Experts may provide "error bars", representing a range of values they consider most likely, but these also include subjective judgment and are prone to biases (e.g., the overconfidence of experts demonstrated by Vick, 2002). Substantial disagreements between experts suggest a conceptual problem with treating estimated design values such as the 100-year rainfall or the PMP as absolute, physically valid quantities without the consideration of uncertainty.

5.2. Risk perception and public motivation

A disaster creates a "window of opportunity" for policy innovation, with heightened public awareness of risk and motivation to take protective action (Kingdon, 1984; Birkland, 1998). At such times, successful innovation can often be traced to the strategic actions of "policy entrepreneurs", such as citizen activists and committed bureaucrats (Meo et al., 2004). That type of entrepreneurship is evident in the Fort Collins case. The city's floodplain management staff, surprised at the scale of the flood event, moved quickly to re-evaluate the design standards used in developing the existing floodplain maps. A vocal group of citizens lobbied for increased flood protection and opposition was temporarily muted. Concerned citizens were brought into the decision process as members of the task force, where they had an opportunity to learn about the alternative calculations and the complexity of the science.

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[5] A review of procedures used to determine PMP points out that subjective elements cause significant problems and "improvements to PMP estimates are most critical for small-area basins during short events" (NRC, 1994, p. 19). The critique applies well to Cherry Creek Basin.

Local, state, and federal flood management representatives agreed on the option that appeared to best match the official policy of protection against a 100-year flood. However, a City Council member and some citizens argued for a higher design rainfall value that would, in effect, have increased protection beyond the 100-year flood. For these citizens, it appears that the issue at stake was not the value of the design rainfall (a scientific issue) but rather that they wanted a higher standard of protection against flooding (a values issue). Ultimately, innovation that enhanced flood protection and satisfied most of the participants was achieved by recalculating technical estimates, without directly questioning the standard of protection.

In contrast, citizens in the Cherry Creek Basin had no recent experience of severe flooding and apparently did not see the dam as a threat. The impetus for change did not originate locally but was proposed by a federal agency. The USACE described potentially catastrophic consequences if the dam were to be overtopped, but also pointed out the extremely low probability of such an event occurring. Citizens were more concerned about the costs and inconvenience of a major dam reconstruction project in their neighborhood. State officials, caught between public opposition and pressure from federal agencies, insisted on further study. The different PMP estimates seemed to provide technical justification for conflicting priorities and value judgments about acceptable risk. Disagreement between experts became a major barrier to further action.

The case studies illustrate how, in a political setting, uncertainty in technical information tends to become confounded with values issues (the appropriate standard of protection). In both cases, participants focused on seeking technical estimates to meet federal minimum protection criteria, treating the criteria as unalterable givens to the decision process.

5.3. Differing perspectives

The case studies highlight the tension between stakeholders with different values, priorities, and goals. Safety, damage reduction, and resource protection are the overriding goals of flood management (Wright, 2000), but a high level of protection often involves high cost and restrictions on use of property. Among the general public, priorities shift. As the Fort Collins case illustrates, safety concerns peak after a major flood, but attention gradually shifts to concerns about costs and property rights as memory of the damage recedes. Regional and local practitioners must balance flood management goals with the goals of different stakeholders in their communities.

The federal Interagency Committee on Dam Safety acknowledges the tension between conflicting goals related to safety and cost, stating “criteria used by dam designers, regulators, and owners now focus on ensuring public safety”, but “debate continues over the proper criteria and degree of conservatism warranted” (ICDS, 1998, Section IB). A National Research Council report (NRC, 1994) expresses concern that safety not be compromised in an effort to reduce costs:

> Engineering for flood survival is particularly important for high-hazard structures, such as dams above populated areas. There is usually a direct trade-off between cost and safety, with high estimates of precipitation extremes leading to high construction and retrofitting costs (p. 1).
>
> … unscrupulous practitioners could design regional PMP studies to yield lower values, saving dam owners millions of dollars, but increasing the risk that a dam spillway may be inadequate. This puts tremendous pressure on the regulatory agencies (p. 14).

Different stakeholder perspectives toward these concerns underlie the conflict over PMP and construction at the Cherry Creek Dam. The remainder of this section reviews and analyzes several dominant perspectives.

5.3.1. Federal management perspective

Federal agencies responsible for managing water resources and flood hazards (notably the USACE, the NWS, the US Geological Survey, and the Soil Conservation Service) developed many of the hydrometeorological analysis tools currently in use. Uniform standards and methods were needed to provide comparable evaluations of flood control projects by different agencies, compute equitable flood insurance rates throughout the country, minimize public confusion, and discourage legal litigation (Thomas, 1985). To create consistent federal policies, numerous interagency committees were appointed to establish uniform guidelines and methods (Wright, 2000).

US federal guidelines for floodplain management and dam safety are intended to provide consistent safety standards in the face of competing interest groups and shifting public priorities. So the guidelines focus on the desired level of protection; i.e., FEMA requires flood insurance and special building standards in areas with more than a 1% annual probability of flooding (as defined by standard techniques to delineate the 100-year floodplain), and the PMF requirement for high-hazard dams sets an extremely high safety standard that aims to ensure against dam failure.

5.3.2. Technical practitioner perspective

In implementing federal guidelines regionally and locally, flood managers and engineers must grapple with the problems of scientific uncertainty not addressed by the guidelines. Technical procedures frequently compensate for uncertainty by building a margin of safety into design estimates. A common method is to calculate a best estimate of the levee height or elevation of buildings required to withstand a given flood, then augment it by a standard increment of height called “freeboard” (NRC, 2000; ASFPM, 2000). For example, the ASFPM recommends that new construction in a floodplain be required to be elevated by 1–3 feet (0.3–0.9 m) above the base flood elevation (ASFPM, 2000). Flood management professionals interviewed in our study mentioned freeboard as an important means of dealing with a multitude of uncertainties in technical calculations.

Less visible adjustments for uncertainty are embedded in hydrologic models and technical procedures, in which expert judgment plays a major role (Section 5.1). For example, hydrologic factors such as the spatial distribution, timing and intensity of extreme rainfall are highly variable and can greatly affect runoff. Modelers typically assume that the design rainfall occurs over an entire city or subbasin at the same time (as in the Fort Collins case). In Colorado this is a choice to err on the side of safety, as the thunderstorms that produce the most extreme rainfall are generally small in spatial extent.

Flood hazards differ regionally, depending on climate, geography, and human activities. Several practitioners interviewed in this study argued that the uniformity in federal guidelines and methods unduly restricts the use of methods that would better fit local conditions.

5.3.3. Policy perspective: acceptable risk versus acceptable cost

Unlike the committees that recommend federal safety guidelines, regional and local officials must negotiate directly with other stakeholders to find a balance between acceptable risk and acceptable cost. One tool for doing so is formal risk analysis, which explicitly considers the potential losses in a hazardous event and is increasingly advocated for assessing potential flood mitigation and dam safety measures (see Mileti, 1999; Heinz Center, 2000 for flood mitigation and Lave et al., 1990; Dubler and Grigg, 1996; Graham, 2000 for dam design).

In floodplain management, NFIP procedures have led communities to focus on the 100-year flood, often with little consideration of more severe floods.[6] Mileti (1999, p. 159) warns, "federal policies arguably have lessened the chances that hazard-prone development will be exposed to short-term losses (e.g., from a 100-year storm), while allowing the potential for greater losses from disasters with longer return frequencies to grow". He recommends using risk analysis to consider all potential flood levels. In dam safety, use of risk analysis to evaluate the spillway capacity of existing dams has been debated by engineers and policy makers for over 30 years (Graham, 2000). Dubler and Grigg (1996, p. 168) observe: "Spillway design flood criteria are extraordinarily conservative, resulting in what are probably many instances of unjustified expenditures." Other analysts of engineering policy agree, pointing out that dam modifications designed to meet PMF criteria often have high cost to benefit ratios and might even have serious negative consequences (Graham, 2000; Lave et al., 1990). These analysts favor a risk analysis approach that is site specific and considers costs and benefits.

The above arguments advocate risk analysis for opposite reasons, highlighting the tension between acceptable risk and acceptable cost. In floodplain management, the concern is that low-probability, high-risk events are given too little attention. In dam design, the concern is that PMF-based policies that strive to assure zero probability of failure are overly precautionary, leading to excessive costs.

Use of risk analysis is problematic, however, because high standards bring with them high uncertainties. Risk analysis methods require calculating exceedance probabilities for extreme discharges, ranging from 100- to 500-year floods for floodplain maps to 10,000-year and greater floods for high-hazard dams. Scientific uncertainties increase as event probabilities decrease, becoming very large for very rare events. Thus, balancing acceptable risk with acceptable cost becomes more difficult when one considers the effects of uncertainty.

The USACE has developed "risk-based analysis" methods that explicitly include estimates of uncertainty in the evaluation of proposed flood damage reduction strategies (USACE, 1996). For example, historically, the USACE used a standard 3 feet (0.9 m) of freeboard in designing levees, but it found that a standard freeboard allowance failed to achieve the desired level of protection in some cases and overcompensated, with unnecessary expense, in others. Under the new risk-based analysis methods, the calculation of flood discharge includes allowances for confidence bands on hydrologic variables. Thus, the method attempts to fine-tune the margin of safety included in discharge estimates to compensate for recognized uncertainties. An evaluation of the USACE methods (NRC, 2000) endorses the risk-based approach as "a significant step forward" but argues that current techniques do not adequately address many important physical and economic uncertainties.

Risk-based analysis can produce fixed estimates that allow for uncertainty; however, the effect of uncertainty tends to be hidden from decision makers. Some decision makers, from individual homeowners to local officials, may prefer information that clearly shows the range of uncertainty and allows them to weigh various alternatives based on their own goals and perspectives on acceptable risk versus acceptable cost. For example, Fort Collins citizens impacted by the 1997 flood tended to prefer the most conservative floodplain option. Maps that display a band of uncertainty along the floodplain boundary, or show the area inundated by a regional record flood, would help decision makers apply their own risk criteria.

6. Conclusions

The case studies presented in this paper show the practical significance of scientific uncertainty for flood management, demonstrating that uncertainty has substantial

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[6] Gilbert White, a leading expert instrumental in the establishment of NFIP, recalls that the 100-year flood criterion was taken from the concept of an "intermediate regional flood", whereas the term "catastrophic flood" is generally used for events of much greater magnitude and lesser frequency (NRC, 2000, p. 142). White argues that communities should be sensitive to the possibility of a 500- or 1000-year flood.

impacts on regulatory process, public safety, and costs. With FEMA's current national effort to modernize flood maps and recent debates over modification of existing dams, uncertainty has implications far beyond the two cases described here. Scientific uncertainty is unavoidable in flood management because (1) hydrological and meteorological estimates are inherently uncertain, (2) the natural and human environment is continually changing, (3) scientific understanding changes, and (4) experts and models sometimes disagree. Stakeholders need to consider the sources and implications of uncertainty in order to realistically weigh the risks and benefits of proposed strategies.

The case studies highlight an important distinction between regulatory design values and the scientific estimates on which they are based. A design value used for regulation must be clear and unambiguous in order to be enforced fairly; therefore, customary practices treat design values (e.g., the 100-year flood discharge) as absolute, certain quantities. Yet, this study reveals conceptual problems with ignoring the large uncertainty in estimates of low-probability events and with treating estimated design values as absolute, physically valid quantities without the consideration of uncertainty. Technical experts chuckle at the idea of asking the Fort Collins City Council to select the most accurate scientific estimate; yet, the estimate might better be considered the first step of a decision process. The City Council might well have an appropriate role in weighing multiple scientific and societal factors to select a design value that contains an allowance for uncertainty acceptable to the community.

6.1. Communicating uncertainty

The above discussion of the case studies highlights the interplay between uncertainties due to technical issues and societal values. Traditionally, technical experts have dealt with uncertainty on an ad hoc basis depending on their professional role and personal inclination. Practitioners' expert judgments are influenced to an unknown extent by personal and professional values, suggesting a need for better communication about uncertainties in flood management. Moreover, because participants in the decision-making process have different information needs and responses to risk and uncertainty, it is not possible to provide a single "optimal" estimate that meets the decision needs of all stakeholders.

This suggests that flood management decisions might benefit if scientific estimates provided to decision makers were accompanied by a clear statement about (1) the level of confidence in the estimates and (2) how uncertainty has been handled in developing strategy alternatives. Sometimes, as in the case of freeboard, allowances for uncertainty are stated openly, but often such allowances are hidden within design calculations and not clearly evident to decision makers. In Colorado, many older estimates have been challenged by recent, more detailed, analyses of local climatology and new scientific tools (such as paleoflood analysis, radar rainfall data, and recent uses of mesoscale weather models). For example in Boulder, CO, at the time of this writing, a study is underway to revise the floodplain map for South Boulder Creek. Technical consultants are using radar rainfall data and GIS technology to analyze the spatial characteristics of storms in much more detail than previously possible. New estimates of the base flood discharge are substantially lower than in prior studies, reducing the extent of the estimated 100-year floodplain (City of Boulder, 2004). However, FEMA's review of the new climatology and hydrology study raises questions on some of the assumptions used and suggests that the results underestimate the base flood discharge (FEMA, 2005b). The city plans to carry out hydraulic analyses using old and new estimates of the base flood discharge to allow direct comparison of the resulting floodplain delineations (City of Boulder, 2006). Currently, policy makers are aware of the inherent uncertainty as they make values-related decisions using the new estimates.

6.2. Reframing the decision problem

In both case studies, the decision was framed as a scientific question, asking which estimate best meets the federal criterion. Framed in that way, the discussion tends to restrict the opportunity of stakeholders to express their individual preferences (e.g., for greater safety or greater development potential). In the Fort Collins case, that narrow perspective appears to have facilitated the decision process. However, in the polarized Cherry Creek Dam controversy, it may become necessary to reframe the discussion to consider the values issues inherent in the flood management process that are highlighted by the battle over scientific uncertainty.

Older high-hazard dams create a special conundrum for policy makers because of the revision of PMP estimates by the NWS (an externality to state and local decision makers). Dam modifications required to meet the recalculated design criteria involve costs that many consider prohibitive. In the Cherry Creek Dam case, decision makers were unwilling to accept the costs and inconvenience necessary to meet the very conservative design standard based on federal criteria and NWS calculations. At the time of this writing, the USACE has not yet developed a PMF estimate based on the AWA study, and choice of a "best" PMP estimate is still unresolved. Risk analysis methods would be unlikely to resolve the stalemate, because they require use of exceedance probabilities that are also highly uncertain. No one method can be expected to give a definitive answer.

Unfortunately, USACE dam safety procedures that require exclusive use of one method have impeded the consideration of uncertainty that is needed to help decision makers evaluate policy alternatives. Perhaps it is time to consider multiple approaches, acknowledging the uncertainty in each, to determine bounds for the risk. Ultimately, decision makers will have to balance consideration of costs, benefits, acceptable risk, and uncertainties, as interpreted by multiple stakeholders, to reach a politically acceptable decision.

Uncertainty interacts with public risk management decisions in arenas beyond the specific flood management cases discussed here, including broader hazard management and climate change. The devastation of the US city of New Orleans resulting from Hurricane Katrina in August 2005 vividly demonstrates that events of low probability do happen with immense and lasting tragic consequences. In decision processes, hazard management competes with other interests (such as economic development, energy, agriculture, and environment), with social and political pressures changing over time. To achieve desired safety levels while negotiating difficult trade-offs between diverse interests, decision makers need to know how reliable their information is and scientists must acknowledge the interplay between scientific uncertainty and values. The findings from this paper can help scientists and decision makers work better together, opening a dialog so each can appreciate the complex and sometimes conflicting needs of the scientific and decision making communities.

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