Research and Applications Needs in Flood Hydrology Science: A Summary of the October 15, 2008 Workshop of the Planning Committee on Hydrologic Science

ISBN
978-0-309-13248-0

34 pages
8.5 x 11
2009

William S. Logan and Laura J. Helsabeck, Planning Committee on Research Applications Needs in Flood Hydrology Science: A Workshop, National Research Council

Research and Applications Needs in Flood Hydrology Science

A Summary of the October 15, 2008 Workshop of the Planning Committee on Hydrologic Science

By William S. Logan and Laura J. Helsabeck

Planning Committee on Research Applications Needs in Flood Hydrology Science: A Workshop

Water Science and Technology Board

Board on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

Support for this project was provided by National Aeronautics and Space Administration Grant Number NNX07AB28G. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organization or agency that provided support for the project.

This summary is available on the internet from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, D.C. 20055, (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); internet <http://www.nap.edu>.

Printed in the United States of America.

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

Foreword

The Committee on Hydrologic Science (COHS) is a "standing committee" organized and overseen by the National Research Council's (NRC) Water Science and Technology Board (WSTB) that addresses research and educational opportunities in the hydrologic sciences. COHS is oriented toward the scientific activity of U.S. federal agencies with programmatic interests in hydrologic research. Its objectives are to (1) provide a venue for discussion of priority research topics in the hydrologic sciences; (2) identify opportunities for development of new National Academies studies; and (3) provide oversight of projects conducted under its auspices (COHS as presently constituted does not itself produce reports).

From time to time, COHS gathers U.S. Government agency representatives and others to outline some of the key issues in hydrologic science that confront their agencies and the nation as a whole. One such issue, which began as an unpublished discussion paper titled "Hydrology from Space," was eventually recast and funded as an *ad hoc* study that produced the NRC consensus report "Integrating Multiscale Observations of U.S. Waters" (NRC, 2008). The workshop that is the basis of this Summary began similarly, and may yet lead to a traditional study.

NRC workshops are organized by formally appointed planning committees. The members of this committee were Dennis Lettenmaier, University of Washington, Victor Baker, University of Arizona, and David Ford, David Ford Consulting Engineers, Sacramento. The other members of COHS, who contributed to drafting of the original discussion paper and played various roles in the workshop itself, are Eric Wood (Chair), Princeton University, Daniel (Pete) Loucks, Cornell University, Emily Stanley, University of Wisconsin, Charles Vörösmarty, City University of New York, and Chunmaio Zheng, University of Alabama.

This document presents the rapporteur's summary of the forum discussions and does not necessarily reflect the views of the COHS members or other participants. Furthermore, the summary does not intend to imply agreement of COHS members or attendees with summary content either in part or in entirety.

This workshop summary has been reviewed in draft form by persons chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purposes of this review are to provide candid and critical comments that will assist the institution in making the published summary as sound as possible and to ensure that the summary meets institutional standards of objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following for their participation in the review of this summary: Eric F. Wood, Princeton University; Gerald E. Galloway, Jr., University of Maryland; Jery R. Stedinger, Cornell University; and David T. Ford, Consultant Engineer.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse, nor did they see the final draft of the workshop summary before its release. The review of this summary was overseen by Kenneth W. Potter, University of Wisconsin. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this summary was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this summary rests entirely with the authors and the National Research Council.

Contents

Workshop Background and Objectives

Flood damages have increased greatly over the last century. As noted by Pielke et al. (2002; Figure 1), a number of reasons for this have been suggested, the most common being development that has encroached upon flood plains. More recently, climate change, as it might have and might in the future affect weather extremes, has been suggested as a possible cause, notwithstanding that the scientific evidence as to whether U.S. floods have increased is mixed. It is generally accepted that in a warming climate, some acceleration of the hydrologic cycle can be expected, based on the fact that the water holding capacity of the atmosphere increases with temperature. Specifics, however, are much more difficult to ascertain, given strong regional variations in the manifestation of climate change, and the interaction of mechanisms that might (or might not) lead to increased flood frequency in a warming climate.

A complication of making regionally specific predictions of the likelihood of climate change affecting flood frequency is the increasing awareness that methods of planning for hydrologic extremes have become outmoded in an era of global change. Milly et al. (2007) states that stationarity[*], an assumption that underlies essentially all water resources planning, "is dead." The question raised by the Committee on Hydrologic Science is, *what is to replace it*?

This one-day workshop was intended to foster initial discussions among the science and applications communities of the following issues related to planning for hydrologic extremes (particularly flooding)[†].

- What should be the underpinnings and motivating science and applications questions in a new science of hydrologic extremes?
- What can and should be the role of new observing methods, both *in situ* (including new sensor technologies) and remote sensing? How might approaches to the estimation of hydrologic extremes differ based on the richness of the historic observations?

---

[*] A stationary time series is one whose statistical properties such as mean, variance, etc. are all constant over time. The assumption of stationarity underlies most traditional flood forecasting methods, including those codified by laws and regulations. Estimation of the "100-year flood," for example, uses historical stream gaging data from rivers that are assumed to behave similarly over the period of record to precipitation events that are also assumed to be generated from the same random population of possible events. Changing climate or land use challenges this assumption.

[†] See Stedinger and Griffis, 2008.

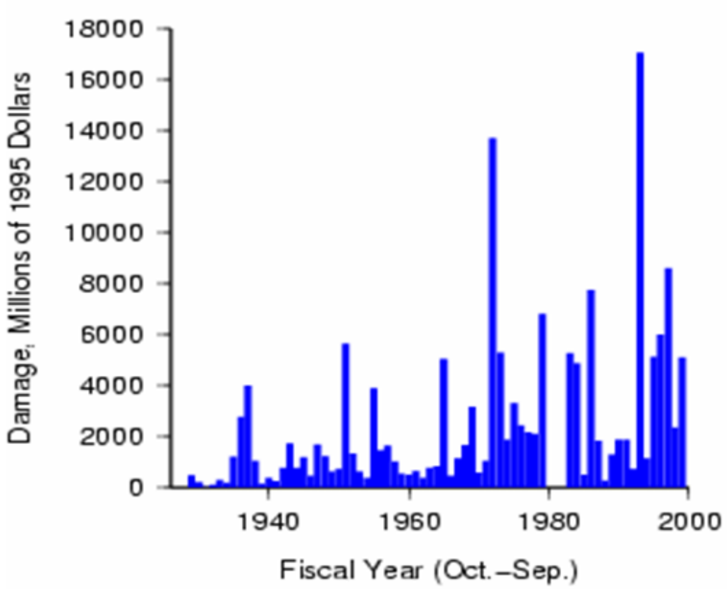

FIGURE 1 U.S. flood damages, 1926-2000, in 1995 dollars. SOURCE: Replotted, with permission, from Pielke et al., 2002.

- What should be the interface between the science of hydrologic extremes and applications issues, such as the need to replace standard methods, such as Bulletin 17B‡ and other methods that are based on stationary statistical methods?
- How can advances in techniques for the accurate analysis of ancient flood events (e.g., House et al., 2002) aid estimation of future flood magnitudes and frequency, and understanding of the generative processes for extreme flood phenomena?

It is emphasized that the workshop was intended to focus primarily on floods in a planning, rather than an operational forecasting, setting.

The workshop opened with welcoming remarks by Eric Wood, chair of the Committee on Hydrologic Science (COHS), to the participants (Appendix A) on behalf of the Committee on Hydrologic Science (Appendix B) and the National Research Council's Water Science and Technology Board. Workshop planning committee members Dennis Lettenmaier, Victor Baker, and David Ford then summarized the history, purpose, and agenda (Appendix C) of the workshop. Will Logan (NRC) explained that the purpose of the meeting was to highlight issues for future attention by participants and the National Research Council, but that no consensus findings or recommendations would result from the workshop. This would be left to any future follow-up consensus studies on topics highlighted by participants. Eric Wood then turned the floor over to Dennis Lettenmaier, who introduced the first speaker.

‡ The 1982 flood-frequency guidelines for federal projects in the U.S. (USGS, 1981).

Topic I

What Should Be the Underpinnings and Motivating Science and Applications Questions in a New Science of Hydrologic Extremes?

PRESENTATION

Upmanu Lall of Columbia University presented on the first, challenging task of outlining the questions scientists and practitioners need to be asking themselves in a "post-stationary" world. He noted that of all the many topics of interest in flood hydrology science, the past can be summarized as "the hydrologic engineer was in charge." That is, the focus was primarily on a small subset of topics such as the design of structures, whether standards-based or risk-based, and insurance issues. Above all, the assumption was that of static risks. But this is changing with the acknowledgement that flood risk is conditional or dynamic, depending on watershed or land use conditions, climate conditions and the changing distribution of populations and assets. Standard practice in the past, for river flooding, is examining frequency and severity of floods as if these are invariant over a long enough period of record. Given the epochal or quasi-cyclical nature of climate variability that is organized over decadal and longer time scales, and flood records that are a few decades long, it is inevitable that flood frequency and severity will look very different as a transition across epochs is observed. This could be confused with anthropogenic changes in climate. A defensible and successful approach to mapping changing flood risk in time would need to recognize both systematic natural climate variations over decadal scales and anthropogenic changes in climate. The challenge is to develop a framework to encompass assessment of conditional (given observed climate conditions, as reflected in slowly varying ocean temperature fields) or dynamic (i.e., varying over time and indexed to climatic conditions) risk. Infrastructure operation and design could then use these more precise estimates of flood risk relevant for those conditions instead of reflecting the high uncertainty associated with the static risk estimate that lumps these very different conditions into a single flood risk measure that is invariant with time.

Lall then raised some "open questions," as he termed them. The most prominent of these was whether we can do a better job of learning from major storms like Hurricane Katrina. A second was how we can generate a scientific basis for spatially explicit risk and exposure analysis, especially in the urban setting, and also over a large river basin. Finally, he wondered aloud whether we might develop ways to process information on short term vs. long term risk, incorporating uncertainty and discounting over time. This would have a bearing on decisions on infrastructure design as well as on financial risk management.

Lall had three additional concerns on the climate side. First, he said, for combined sea-level rise and wind surge we have not done a good job of developing detailed scenarios for the analysis of these risks for urban infrastructure and land use investments that are expected to last 30 to 50 years, or more. And what, he asked, are the prospects for developing scenarios at national scales for inundation/salt water intrusion and its chronic demographic and ecological impacts? Second, he noted that we have scarcely begun to develop a monitoring, prediction and risk zone mapping capability for glacial lake outburst flooding. Third, can we predict inter-annual and longer persistent wet spells (and their hydrology) that lead to persistent lake flooding?

Returning to river issues, Lall summarized what he called "dogmas"; that extreme rainfall plus antecedent land conditions equals an extreme river flood, that topography and channel network structure lead to scaling laws for flood extremes, and that various principles for regionalization of flood frequency related to area or statistical homogeneity are available. All, he said, assume stationarity, and we have done very limited causal analysis of climate mechanisms and their use in prediction of static or dynamic risk. For example, extreme floods are usually related to moisture pulled in from the oceans, not local convection. Recognizing that it is large scale moisture transport that leads to such floods could revolutionize flood hydrology, since the emphasis could shift from modeling the flood wave on the land surface to the moisture transport or flood wave as it progresses from the oceanic source to the watershed.

To begin to answer this question, Lall stated, we have to look at the intersection of these systems with the ocean-atmosphere-land system, and we have not systematically done that. We need to know how much moisture is out there and how it is being moved in the various atmospheric layers. It is important to know how the moisture is organized and how it is moving, Lall stated, because about 90 percent of the moisture transport takes place in 10 percent of the atmosphere. We need to know how much is being moved in the lower and the higher levels. Soil moisture, he said, is recognized as an important antecedent condition for flooding and also for lending persistence to the prevailing atmospheric regime. However, even the persistence in the soil moisture is induced by initial widespread rainfall which usually has an oceanic source and whose occurrence is marked by a well defined organization of ocean-land temperature fields. These lead to clustered ocean locations where strong convection (evaporation) takes place, and the resulting moisture in the atmosphere is then moved in relatively narrow bands along reproducible pathways, much like "atmospheric rivers" that then translate into landfall and heavy rainfall over a large area where conditions for the convergence of lower atmosphere flow are ideal, leading to flooding.

Our current global climate models are not very helpful at this scale. Agreement among the models is often poor, there are issues with downscaling them, and they suffer error propagation issues, Lall said. Much of the large-scale atmospheric moisture transport that corresponds to extreme floods appears to relate to lower-level jets and their intersection with upper-level troughs. These are problems that need to be worked out, he added. Even the fundamental prediction of these models that precipitation should be increasing with temperature can be called into question. Yet for all these problems, Lall is optimistic that there may be some climatic predictability of floods. He pulled together empirical evidence correlating sea surface temperature and floods in West Coast states, spoke of the potential importance of "atmospheric rivers" in concentrating precipitation in certain regions of the U.S., and finally examined some composites and event analyses of extreme floods in the U.S., Brazil, and India.

Finally, Lall closed the circle on his presentation with his view of the key questions that need attention if assumptions of stationarity are limiting our advancement. Overall, he asked, given that there is evidence of inter-annual variability in flood incidence related to organized large-scale climate, how best can we develop a capacity for dynamic risk assessment, specifically with respect to frequency, spatial extent, and duration? If—as he stated in his talk—global and regional climate models are not likely to directly inform precipitation, and statistical downscaling is suspect, are there empirical pathways to achieve the same goals? Can we focus work on global and regional climate models toward atmospheric moisture pathways and mechanisms for flood generation? And how can we restate the climate change-related flood questions so we focus on mechanisms and causal chains to avoid error propagation in our models? With respect to the latter, he asked, how will local convection and stability change affect modest localized floods? How will spatio-temporal changes in ocean thermal content change the structure of low level jets, and tropical and extra tropical cyclones that then lead to enhanced flood potential? And how will regional flood-frequency estimates—static or dynamic—be improved using climate information, and be used to inform adaptation?

PLENARY DISCUSSION

A brief discussion, led by Dennis Lettenmaier of the University of Washington, emphasized the lack of integration of climate modeling and hydrologic modeling. One participant noted that beginning perhaps 30 years ago the paradigm was that by generating a scientific understanding of the climate system, this would help us understand precipitation, which would help us understand floods and their effects. This investment appears not to have been fruitful as scientists hoped, at least from the perspective of flood hydrologists.

Three reasons for this were touched on by various participants. First, atmospheric models still have difficulty resolving crucial precipitation related phenomena, such as “atmospheric rivers” and low-level jets. Second, much of the research was oriented toward average weather conditions rather than the extremes associated with flooding. Third, hydrologists have tended not to integrate atmospheric conditions into their analysis of, for example, streamflow trends from stream gauge records, and atmospheric scientists have tended to do the reverse. Reanalysis of both kinds of data together may yet yield useful results.

Finally, several participants noted that while 30 years ago a meeting like this to consider linked atmospheric and hydrologic processes would never have occurred, hydrologists will need to improve their communication with social scientists, economists, insurers, biogeographers, and others to effectively understand and address the flood vulnerability issue.

BREAKOUT SESSION REPORT

Rapporteur Eric Wood summarized the discussion in the first breakout group. He first discussed the relationship between flood *science* and flood *engineering*. There was considerable discussion in the session of the apparent divide between “little” floods and “big” floods. He also noted that there are issues with the estimation of probable maximum precipitation and probable maximum floods, and many in the group seemed to think that the methods need to be updated. This would require updating the scientific basis of such estimates, including a comprehensive review of probable maximum precipitation methods.

Wood noted that we still lack understanding with respect to the causes and behavior of truly large flood events. However, beyond this, how would a better scientific understanding find its way into design guidance? It was not clear to many in the session how to move forward to provide a vision for doing the necessary research and obtaining the funding for that research. It seems clear that there is an interagency interest in having such research done, and there was discussion of increasing interagency efforts in such research. However, interagency groups have very little funding at present for this kind of effort.

Last, Wood summarized discussion of the *beneficial* aspects of floods—for ecosystems, for example. There is very little discussion of this in most guidance documents. How should such beneficial aspects—to the extent that they may be understood—be integrated into guidance as well as into design? Overall, he stated, there appear to be a great number of issues that the science and engineering community needs to pursue.

Topic II

What Can and Should Be the Role of New Observing Methods, Both *In Situ* (Including New Sensor Technologies) and Remote Sensing? How Might Approaches to the Estimation of Hydrologic Extremes Differ Based on the Richness of the Historic Observations?

PRESENTATION

Doug Alsdorf of The Ohio State University spoke on the topic of new observing methods for flood hydrology science, emphasizing his overall theme that *floods are two-dimensional* (2D), and one particularly useful remote sensing technique to look at floodwaters beneath inundated vegetation—interferometric synthetic aperture radar (InSAR). Flood waters move laterally across floodplains, wetlands, or urban environments and this movement is not bounded like that of typical channel flow. This two dimensional flow is obvious, but not well measured. Water flow within channels is measured by essentially one-dimensional methods. The water surface elevation is routinely gauged and combined with periodically collected velocity profile data to form a rating curve indicative of discharge. This approach, however, does not capture the complexity of floodwater flows because these are unbounded and have velocities that vary spatially as well as temporally.

According to Alsdorf, there are almost no two-dimensional height mappings of these flood water heights (e.g., essentially nothing like that of a topographic digital elevation map where elevations are mapped in a spatially continuous manner). Instead, the measurements often come from high water marks on the sides of buildings, bridges, or vegetation. High water marks fail to capture the temporal dynamics of rising and falling waters which are important for calibrating and validating two-dimensional hydrodynamic models. Occasionally, small devices are deployed before the arrival of a flood (e.g., level loggers, etc.) and are used to measure the temporal variations in flood water heights. These can be surveyed to provide a slope measurement between two or more devices. Nevertheless, these devices still represent a one-dimensional measurement, not a blanketing 2D measurement.

Hydrodynamic flood models that depend on water height measurements are only as accurate as the calibrating and validating data, Alsdorf stated. Because of the lack of 2D measurements, the models can often produce results that may be reasonable but incorrect. For example, models of Amazon floodplain flow do not match the measured height changes that occur during the passage of the annual flood wave. These models thus predict incorrect water routing and incorrect water heights. Models of smaller floodplains in the U.K. do match 2D mappings of inundated area but the degree to which they match flood water elevations is unknown.

He summarized his presentation with five points. First, because we need more precise measurements of natural events on the Earth's surface, we should "get into space," in other words he suggests increasing remote sensing techniques as one of the solutions. Second, water flow across floodplains is more complex than implied by 1D, point-based measurements. Third, flow paths and water sources are not fixed in space and time, but rather vary with flood water elevations. Fourth, hydrodynamic models do show promise for improving our understanding of floodplain hydraulics. And finally, to fulfill this promise, we need much more high-resolution topography and 2D mapping of water levels, their changes through time and space, and inundated area.

PLENARY DISCUSSION

The discussion session was led by Charles Vorosmarty. He asked participants to think in terms of packages of observations—i.e., the Decadal Survey approach—including InSAR and the proposed Surface Water Ocean Topography (SWOT) satellite mission, and then to think in terms of "What are the science questions that we would be able to answer?" Alsdorf emphasized that SWOT will not be "pointable" at a given flood, but rather will catch many floods worldwide but at random. It is oriented more toward storage and discharge of large rivers on about a weekly basis. As for other kinds of questions we could answer better if we had improved 2D waterbody data, he mentioned two examples:

- What are the methane and carbon dioxide fluxes from the hydrosphere to the atmosphere? These are partly a function of water depth.
- How fast are Arctic lakes disappearing?

Several other participants emphasized the importance of *in-situ*, ground-deployed sensors. These have several advantages over satellite-based sensors, in that they are cheaper, can be quickly deployed (48 hours before a major storm event, for example), have orders-of-magnitude better spatial resolution, and can be programmed to resolve phenomena at very short time intervals. Another participant emphasized the need to coordinate other measurements with the many Lidar airborne topography missions that are being flown. Merging data at disparate scales was viewed by some as a very difficult challenge in many cases, but the National Weather Service (NWS) has done this on an ad hoc basis, for example, using radar information on rainfall to constrain a stochastic model on storms.

One participant said that the NWS has noted that climate related trends in hydrologic parameters model output are often smaller than the errors in the estimates themselves. The NWS has to prioritize its research based on its potential impact on applications, and in some cases (e.g., a project with only a 25-year life cycle) one might ask, "Is climate change in a 25-year timeframe so small that it doesn't matter?" Another participant gave an example of the opposite, namely recent increases in summer precipitation in many parts of the highly populated coastal Eastern U.S. And in the case of the truly extreme events, as one participant noted, one has to either expand one's observation in space with satellites—or in time with paleohydrology—to achieve both scientific understanding and predictive capability.

Finally, a participant noted that we might feel more comfortable with our decision-making under uncertainty if we had a better scientific framework on which to hang not only climate-related hydrologic trends but those that may be due to urbanization, regulation, levees, and floodplain alteration.

BREAKOUT SESSION REPORT

Rapporteur Geoff Bonnin (NOAA, National Weather Service) summarized the breakout session as having focused primarily on the need for more data—and better use of the data—in modeling and for decision support. He said that many participants in the session stated a strong need for many more observations both spatially and temporally and of more physical elements and of complementary elements that allow confirmation by comparison between physical elements. The need exists in the context of the necessity to establish these observations as part of a long-term and consistent observing system. The theme of new sensing technologies was secondary to the need for more observations. Additionally, observing resources are limited and so there is a need to determine how to specify observing systems in order to maximize the benefit of those resources.

Bonnin noted that an underlying theme was a recognition that many types of data and many different periods of record exist in many locations and forms. Many of those present felt there is a need to develop analyses and techniques for analysis and assimilation that extract more information out of current and future observing records and collections of records.

The group, he stated, discussed how traditionally we have observed physical elements such as rainfall, streamflow, and water surface elevation. However, these are characteristics of phenomena that create impacts on society. Society is now asking questions about the impacts themselves such as: Will/did my house get flooded? How much of the house was submerged? They are also asking questions in areal, in addition to point, terms such as: How much of New Orleans was flooded? And how much of Georgia is without sufficient water to sustain industry? If scientists wish to help answer these questions, it would seem the best answer is to improve our recording of the impacts themselves, rather than just the characteristics of the phenomena.

Bonnin said that many in the group believed that access to both the raw data and analyses of the data need to be improved. It is not enough, they said, to have collected the data, but it is essential to make investments in data analysis to develop useful information products such as precipitation frequency analyses and flood frequency analyses. Real-time access to information for decision support and rapid access for analysis would also be important, and a participant noted that the Federal Emergency Management Agency has funds for post-event data collection in presidentially declared disasters.

Finally, Bonnin repeated some closing comments that Robert Hirsch had made at the end of the session. Hirsch had summarized what he believed it would take to provide society with estimates of risk at any point as follows:

- We need to understand the potential effect of climate change, but it is important to start by analyzing the information we already have. For example, USGS state-wide analyses of flood frequency are greater than 30 years old in some cases and NOAA precipitation frequency and duration analyses are similarly out of date. Given the interest in climate change as it affects flood risks, the first thing to attend to is to make sure that our analyses consider the most recent data. Then, look at the data and see if we can identify or describe changes in precipitation or flooding that may be related to changes in climate.
- Consider the watershed. What changes have occurred (urbanization, conversion from forest to agriculture)? What changes will occur? And what differences do the watershed changes make?
- Consider the channel and floodway. What changes have occurred (bridges, culverts, buildings, changes in channel dimension or roughness, floodplain land use changes)? What about the role of land-surface subsidence (changing slopes)?
- Consider flood control structures. We should know what and where they are, what their current characteristics are and how they actually operate in addition to how they were and are supposed to operate. What

are their modes of failure and how do those failure modes affect the watershed and its people and environment? What do we actually know about how flood risk changes after these structures are put in place—risk from smaller floods versus risk from great floods.

Topic III

What Should Be the Interface Between the Science of Hydrologic Extremes and Applications Issues, Such As the Need to Replace Standard Methods, Such As Those Laid Out In Bulletin 17B and Other Methods That Are Based on Stationary Statistical Methods?

PRESENTATION

Tim Cohn of the U.S. Geological Survey summarized the apparent and paradoxical disconnect between the practice and the science of flood frequency analysis. In essence, he stated that neither partner in this marriage is entirely knowledgeable about, confident in, or respectful of the other. On the one hand, Bulletin 17B in fact does address nonstationarity, and it expresses considerable concern specifically about climate change. So the recent "scientific finding" of nonstationarity as a central component of flood frequency analysis does not come as news. On the other hand, operational activities seldom if ever consider the very substantial nonstationarities associated with development and other land-use change that we know exist from both science and theory, with the result that flood risk is often greatly underestimated.

In addition, he said, if we believe that rational policies for dealing with flood risk is based on a rational (i.e. scientific) understanding of flood frequency, then it is surprising that Bulletin 17B has not been updated in over a generation. Right now, we employ approaches that reflect an antiquated understanding of the science, at least in some cases.

Third, Cohn noted that there seems to be another disconnect between data and models. The global climate models seem to suggest that we ought to be seeing—at some time and some places—substantial changes in stream discharge statistics. However, flood data from the U.S. Geological Survey's Hydro-Climatic Data Network (HCDN) exhibit essentially no trends at all. (The HCDN consists of about 1,500 gauge sites in areas generally unaffected by development.) For example, two-thirds of the HCDN sites show less than one percent change per year in maximum annual peak discharge.

Why is this true? There are two possibilities. First, if one examines peak flows, they are much more variable than average flows. The variability at the extremes is already high. A 20 percent change in mean annual flows would be detected almost immediately, but a similar change in the 100-year flood is hard to detect statistically (and yet could have very large economic effects). Second, the statistics are such that a 10 percent increase in mean annual precipitation correlates to a mean annual flow of about 10 percent, but this has a much smaller impact on the outer edges of the distribution (e.g., the 100-year flood). Thus, if there are, indeed, trends in this "noisy" data, they would be extremely difficult to discern with statistical methods.

In closing, he noted that future changes in runoff generated by global climate models suggest dramatic shifts, if you believe the models. But there is much we do not know about floods and flood patterns. It is not easy to identify the right questions to ask, or even to define the practical problems.

PLENARY DISCUSSION

The discussion, led by David Ford of David Ford Consulting, raised a number of related points. Several participants noted that discerning regional trends in precipitation is also a challenge. One in particular mentioned that his research group had examined trends in the means of annual maximum of 24 hour rainfall, and found that only about 15 percent of them had a statistically significant change, and of those, about half were up and half were down. Even when trying to reduce noise-to-signal ratio by grouping nearby gages, this participant was not seeing many significant trends and the few trends seen did not show a lot of spatial coherence. Another participant had found the same in India—a lack of spatial coherence in regional precipitation trends. Trends in 90th percentile values are downward over time, whereas those in 99th percentile values are upward. A third participant mentioned that while one commonly hears reference to the "acceleration of the hydrologic cycle" he had not seen much evidence for this.

A second topic related to what science might be able to contribute in the post-stationarity era to help practitioners construct a flood frequency curve. One participant said that progress has been made with deterministic modeling of land-use change. This participant continued saying, with respect to climate change effects, from an operational perspective we can at least admit a greater uncertainty. This would lead to an operational decision to either build structures with greater safety factors, or to accept greater risks. Another said that at the very least we should be poring over all our hydrologic records to mine that voluminous data on a large scale. He also suggested paying at least as much attention to watersheds undergoing land-use change as on the climate change issue; he believed that is at least as great a driver for streamflow change as climate.

Another participant noted that climate changes might be observed in ways other than as trends. For example, one can sometimes see *periodicities* in precipitation. Another mentioned a case where changes in discharge were found not in the mean but in the standard deviation of the data.

Finally, several participants mentioned that non-stationarity matters much more for long-term than for short-term projects. One stated that in designing something with a life cycle of less than 50 years, it is probably not important. If greater than 50 years, it may be, but we aren't sure how. Another noted that insurance companies typically only look at 10 or 20 years of data for their risk assessment.

BREAKOUT SESSION REPORT

Rapporteur John England, U.S. Bureau of Reclamation, summarized the discussion in the breakout session. He emphasized the overall theme of change—the more things change, the more they stay the same. This is especially illustrated by the fact that there is still tension between flood science on one hand and engineering estimates and operations on the other.

He stated that within the theme of hydrologic change there are three main components that various participants in the breakout session had emphasized: changes in climate, changes in land cover and land use, and changes in water management (such as regulation). While all of these factors illustrate issues with the use of stationarity as a governing principle, there seems to be very little consensus on what the hydrologic community might use to replace it.

One of the issues, he noted, is that operationally we still have troubles defining extremes, for example, 100-year or 500-year flood. This has impacts on the quality of our flood operational estimates. Some session participants thought there has been inadequate flood research over recent decades to improve current techniques. One breakout session participant reinforced this point by making an analogy to the area of regulation of toxics relative to human health where no one study seems to have procured changes in regulations. Rather, it is a "preponderance of the evidence" issue with many investigators taking many approaches. Some attendees continued by articulating that a considerable effort in hydrologic research with pertinent and timely results needs to be resumed before significant progress can be made in its application to operations.

Finally, England stated that many participants had noted a "disconnect" between the fields of climate modeling and hydrology—a theme raised earlier in the workshop in Upmanu Lall's presentation. For flooding, we usually do a single frequency analysis of the data, but climate models have shown that there are often alternating epochs of greater and lesser precipitation. Further, the source of moisture for the largest floods may be different from that of less extreme events. Work with data sets, retrospective analysis, and projections may be needed to unify the climate and hydrologic sciences for operational benefits, according to England and some other participants.

Topic IV

How Can Advances in Techniques for the Accurate Analysis of Ancient Flood Events Aid Estimation of Future Flood Magnitudes and Frequency, and Understanding of the Generative Processes for Extreme Flood Phenomena?

PRESENTATION

Lisa Ely of Central Washington University then spoke on applications of paleoflood hydrology, types of paleoflood records, and recent advances in paleoflood hydrology. She began by defining "paleofloods" as past floods that were neither recorded by direct hydrological measurement nor in the written historical record. She noted that this definition could include modern floods in ungaged basins that were later interpreted, using paleoflood techniques, after the fact. Her take-home message was that e*vidence of past floods is present in many if not most watersheds*. Paleoflood records may not be the ultimate answer but why not use it?

Ely then gave a summary of major applications of paleoflood hydrology. These include flood magnitude and frequency to extend the record over long time scales (i.e., 100s to 1,000s of years); flood stationarity; evaluating design flood values for engineering design, flood risk assessment and river management; response of extreme floods to climatic changes; geomorphic impacts of extreme floods (i.e., what role do they play in the changing geometry of the river), which has applications for wetlands management; and communicating flood hazards to public.

She followed this with an outline of types of paleoflood evidence that we look for in the geologic record, and are, in fact, derived from physical effects on natural indicators. She began with three indicators of estimated peak stage:

- Slackwater flood deposits, which are fine sand and silt deposited in areas of low velocity along stable, confined channels;
- Erosional scour lines or silt lines; and
- Flood scars on trees.

She then summarized three other, less direct techniques, namely:

- Alluvial floodplain stratigraphy;
- Changes in the channel geometry over time; and

- Changes in the stream's competence (i.e., the maximum particle size that a stream can transport), as inferred from the presence of boulders in the stream sediments.

She then gave one or two examples of each.

Ely proceeded to describe some of the recent advances in paleoflood hydrology. The first of these is improved resolution of standard types of dating methods and development of new ones. Second, there have been many advances in hydraulic modeling of paleodischarge, from the models themselves to topographic databases and rendering. A third is probability-based flood-frequency methods that incorporate isolated peak flow events. A fourth is the development of applications in a greater variety of geomorphic settings and geographic locations. A final advance has been the development of global paleoflood datasets for recognizing climatic patterns.

But there is no "standardized treatment" for every watershed, Ely cautioned. One has to be careful, for example, with channels that are not stable over time. More needs to be done to understand the relation between paleostage indicators and peak water-surface elevations. Finally, she noted that non-meteorological floods also occur—referring to those caused by landslides, catastrophic failure of moraines or landslide debris, etc.—that need to be considered.

Ely gave four examples of the use of paleoflood data, and then concluded by suggesting some potential future directions for research and applications. These included implications of future climate changes on floods; regional comparisons of global paleoflood records; targeting climatically sensitive or hazard-prone areas; questions related to stationarity, including non-meteorological floods, flood frequency and risk assessment using updated techniques; new methodologies in geochronology and geomorphology; and techniques for communicating flood hazards to the public.

PLENARY DISCUSSION

Victor Baker of the University of Arizona led the subsequent discussion, which began with the question "How can one incorporate urbanization in paleoflood studies?" Ely noted that in some watersheds one could compare pre-urbanization floods with post-urbanization floods, incorporating paleoflood data, and Baker stated that for extreme floods, the urban effect is usually overridden anyway. Difficulties in finding paleoflood data in more populated regions such as the eastern U.S. were noted, and Ely stated that there has been work on floodplain stratigraphy that examines grain size changes that may not even be detectable visibly. Baker noted that caves can sometimes preserve paleoflood deposits in the Appalachians.

Several participants mentioned that countries such as China, India, and Egypt have long written records of floods—up to 5,000 years in some cases. While the quality of the description varies, the dates tend to be very accurate. Ely said this can be used to put the modern record into context, and that we should be careful not to reject paleoinformation solely because it is not consistent with the present system.

Finally, there was discussion of the potential value of a major survey of paleofloods around the country. Given the scarcity of paleoflood data in a single basin, should scientists be doing more "trading off of space for time" to get a big picture of prehistoric behavior?

BREAKOUT SESSION REPORT

According to session rapporteur James O'Connor, the discussion ranged widely but could be distilled to two main issues—the primary benefits of paleoflood studies, and limits to their applicability.

The primary benefits of paleoflood analyses are often seen as an extension of the observed record of extreme events with information of actual prehistoric occurrences of large floods. Such observations, in addition to leading to improved magnitude-frequency relationships for specific locations (especially important for critical structures), can provide physical evidence supporting understanding of watershed flood-generation mechanisms and perhaps improve the poor spatial resolution of probable maximum flood estimates. Paleoflood studies also offer opportunities to investigate relations between climate conditions and flood generation—a factor affecting stationarity assumptions in flood frequency analysis.

O'Connor said that two main issues requiring research, and which may be factors limiting the applicability of paleoflood information, were raised at the breakout session. These were (1) investigation of the discrepancy between maximum floods observed from paleoflood analyses and those predicted from probable maximum precipitation studies (a topic also mentioned in the breakout session following Topic I). It was noted that for most rivers analyzed so far the maximum floods determined by paleohydrologic techniques (from physical evidence of actual floods) are much smaller than the Probable Maximum Floods (PMF) determined by probable maximum precipitation studies. Does this discrepancy owe to shortcomings in the methods of paleohydrology and/or PMP analyses? Or does it reflect some sort of bias in where paleoflood studies have been conducted? And (2) developing a better understanding of the uncertainties involved with paleoflood techniques.

The group also discussed the viability of some sort of a national paleoflood research program aimed at extending flood records for many rivers. Many of the group, however, concluded that some systematic targeted studies aimed at some of the issues noted above would be the most efficient approach to making progress at the two questions noted above.

Concluding Session

The workshop wrapped up with a summary session to identify next steps for COHS and others to pursue issues regarding flood extremes and their estimation as well as themes for future committee activities. The participants discussed the recent escalation of flood damages and an increasing awareness of the potential effects of climate change on the hydrologic cycle as they were the sounding call for this workshop. An underlying concern among the participants is whether the historical record remains the correct basis for determining current flood risk estimation—i.e., is stationarity 'dead'? There was discussion on the efforts by the National Weather Service to update rainfall design curves and general discussion on how probable maximum precipitation estimates and flood frequency curves could be updated.

Topics for future activities articulated by participants included (A) **Research to operations in hydrology.** Can the current state of practice be used to help determine how to update current operational methods that might reflect changes in precipitation or flood characteristics? What new science is ready to apply to the estimation of extreme floods and their risks—such as operations research, optimization, hydrologic modeling, two-dimensional models, etc.? **(B) Improved assessment of hydrologic data.** In discussing the role of hydrologic data as it relates to flood estimation, there were a number of suggestions on how data can be better utilized, which included (i) reanalysis of existing hydrologic datasets and determining societal implications of the flood risks, (ii) exploring new programs to collect national paleoflood data that would allow improved estimation of very large floods, and (iii) the deployment rapid-response flood teams for data collection. It was suggested that these would lead to possible improvements in collecting and utilizing flood data. **(C) The water-energy nexus.** It was expressed that the linkage between water and energy was under appreciated and a number of important issues lay at the intersection between the energy and water sectors. This led to the following issues: What are the potential impacts of climate change on energy production such as the sitting of nuclear power plants that results in issues such as the supply of cooling water and corresponding regulatory issues? What are the implications of renewable energy subsidies on water demand? How are the feasibilities of various water treatment processes affected by energy availability and cost? Are there hydrologic controls that are not being considered in some of these new proposed projects (e.g., biofuels, nuclear reactors, clean coal, and oil shales) that may constrain their development? How will probable maximum precipitation updates affect FERC relicensing? **(D) Water resources decision-making and planning under uncertainty**. It was expressed that this topic (water resources decision-making and planning under uncertainty) needs to include uncertainty related to climate change and natural variability, as well as sampling uncertainty related to network design. **(E) Hydrologic aspects of climate services**. There was a final discussion around the concept of a national climate service, with thoughts about its potential scope and design. A national climate service was viewed as being analogous to the National Weather Service, but it was unclear to the participants what products it would produce (e.g. weekly or seasonal forecasts?) or whether it would contain a private sector component?

Overall, the participants' discussion provided insights to the workshop theme on flood research, and expanded the discussion to include general hydrologic issues that may lead to future workshops. Many participants appeared to leave the workshop not only stimulated by the event, but also eager to explore answers in the context of their own professional responsibilities.

References

House, P. K, R. H. Webb, V. R. Baker, and D. Levish (Editors). 2002. Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology. Washington, D.C.: American Geophysical Union Water Science and Application 5. 385p.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. Stationarity is dead: Whither water management. Science 319: 573-574.

Pielke, R. A. Jr., M. W. Downton, and J. Z. B. Miller. 2002. Flood Damage in the United States, 1926–2000: A Reanalysis of National Weather Service Estimates. Report to NOAA Office of Global Programs. Boulder, CO: University Corporation for Atmospheric Research.

National Research Council. 2008. Integrating Multiscale Observations of U.S. Waters. Washington, D.C.: National Academies Press.

Stedinger, J. R., V. W. Griffis. 2008. Flood frequency analysis in the United States: Time to update (editorial). Journal of Hydrologic Engineering 13(4): 199-204.

United States Geological Survey (USGS). 1981. Guidelines for Determining Flood Flow Frequency. Bulletin #17B of the Hydrologic Subcommittee. Interagency Advisory Committee on Water Data. Reston, VA: U.S. Geological Survey.

Appendix A

List of Participants

Doug Alsdorf, Ohio State University
Geoff Bonnin, National Weather Service
Shyang-Chin Lin, Federal Energy Regulatory Commission
Jerry Coffey, Mathematical Statistician, public
Tim Cohn, U.S. Geological Survey
Lisa Ely, Central Washington University
John England, U.S. Bureau of Reclamation
Jared Entin, National Aeronautics and Space Administration
Beth Faber, U.S. Army of Corps of Engineers
Robert Hirsch, U.S. Geological Survey
Claudia Hoeft, U.S. Department of Agriculture
Richard Hooper, CUAHSI
Julie Kiang, U.S. Geological Survey
Joe Krolak, Federal Highway Administration
Upmanu Lall, Columbia University
David Levinson, National Oceanic and Atmospheric Administration
Robert Mason, U.S. Geological Survey
S.K. Nanda, U.S. Army Corps of Engineers
Tom Nicholson, Nuclear Regulatory Commission
Jim O'Connor, U.S. Geological Survey
Hsien Pao, The Catholic University of America
Sanja Perica, National Oceanic and Atmospheric Administration
Quan Quan, U.S. Department of Agriculture
John Randall, Rutgers
Engene Stallings, National Hydrologic Warning Council
Nancy Steinberger, Federal Emergency Management Agency

Appendix B

Committee Biographical Information

Workshop Planning Committee

Victor R. Baker is regents professor in the Department of Hydrology and Water Resources at the University of Arizona. He is also professor of geosciences and professor of planetary sciences at the University of Arizona. His research interests include geomorphology, flood geomorphology, paleohydrology and paleoclimatology, Quaternary geology, natural hazards, history and philosophy of the Earth Sciences, and the interface of environmental science with public policy. Dr. Baker is a Fellow of the American Association for the Advancement of Science and a past Chair of its Geology and Geography Division. He is also a Fellow of the Geological Society of America, and a past President of the Society. He has served on numerous panels and committees of the National Research Council including the Chair of the U. S. National Committee for the International Union for Quaternary Research (INQUA). He currently is Vice-President of INQUA's Commission on Global Continental Paleohydrology.

David Ford is the chief executive officer of David Ford Consulting Engineers in Sacramento, California. Dr. Ford's areas of expertise include hydrologic engineering, water resource systems analysis, decision support systems, hydropower operations and economics, and natural resource policy analysis. He has been a consultant to the U.S. federal and foreign governments and was a Fulbright scholarship recipient. He is a lecturer at California State University, Sacramento and the University of California, Davis. Dr. Ford served on the WSTB Committee on Grand Canyon Monitoring and Research and the Committee on Missouri River Ecosystem Science.

Dennis P. Lettenmaier joined the University of Washington faculty in 1976 and directs the Surface Water Hydrology Research Group. Dr. Lettenmaier's interests cover hydroclimatology, surface water hydrology, and GIS and remote sensing. He spent a year as visiting scientist at the U.S. Geological Survey in Reston, VA (1985-86) and was the Program Manager of the Land Surface Hydrology Program at NASA Headquarters in 1997-1998. He was a recipient of ASCE's Huber Research Prize in 1990, is a Fellow of the American Geophysical Union and American Meteorological Society, and is the author of over 100 journal articles. He was Chief Editor of the American Meteorological Society Journal of Hydrometeorology, and recently served on the NRC Committee on the National Ecological Observatory Network (2003-2004). He was chair on the panel of Water Resources and the Global Hydrologic Cycle for the NRC study on Earth Science and Applications from Space.

Other Members of the Committee on Hydrologic Science

Eric F. Wood, *chair*, is a professor in the Department of Civil and Environmental Engineering at Princeton University. His areas of interest include hydroclimatology with an emphasis on land–atmosphere interaction, hydrologic impact of climate change, stochastic hydrology, hydrologic forecasting, and rainfall–runoff modeling. Dr. Wood is an associate editor for Reviews in Geophysics, Applied Mathematics and Computation: Modeling the Environment, and Journal of Forecasting. He was the 2001 Robert E. Horton lecturer in Hydrology for the American Meteorological Society (AMS) and is a fellow of the American Meteorological Society and the American Geophysical Union. He was a member of the National Research Council Climate Research Committee, and the Panel on Climate Change Feedbacks. He is a former member of the Water Science and Technology Board and BASC's GEWEX panel.

Daniel P. Loucks (NAE) teaches and directs research in the application of economic theory, environmental engineering and systems analysis methods to the solution of environmental and regional water resources problems. He is author of the book "Water Resources Systems Planning and Management." He has been a Research Fellow at Harvard University, an economist at the Development Research Center of the World Bank, a Research Scholar at the International Institute for Applied Systems Analysis in Austria, and as a Visiting Professor at the Massachusetts Institute of Technology, the University of Colorado in Boulder, the University of Adelaide in South Australia, Aachen University of Technology in Germany, the Technical University of Delft and the International Institute for Hydraulic and Environmental Engineering in Delft in The Netherlands, and the University of Texas in Austin. He has served as a consultant to private and government agencies and various organizations of the United Nations, the World Bank, and NATO involved in regional water resources development planning in Asia, Australia, Eastern and Western Europe, the Middle East, Africa, and Latin America. In the past three years he has had appointments at Delft Hydraulics in The Netherlands, the Institute for Water Resources of the US Army Corps of Engineers, and the South Florida Water Management District, all involving water resources and ecosystem planning and management projects. In addition to his membership in the NAE, he has served on seven NRC committees and boards.

Emily Stanley is an Associate Professor at the Center for Limnology and Department of Zoology at the University of Wisconsin. Her research interests are carbon cycling and wetland stream dynamics, stream/floodplain ecology, and effects of dam removal. She is currently an Associate Editor for Ecological applications and has participated on numerous National Science Foundation panels. She was Aquatic Section Secretary for the Ecological Society of America and is presently a steering committee member for the CUAHSI interdisciplinary working group on floodplain science.

Charles Vörösmarty is Director of the Global Environmental Sensing and Water Sciences Initiative, Professor in Civil Engineering Department, and NOAA-CREST Distinguished Scientist at The City University of New York. He was formerly Professor at the Institute for the Study of Earth, Oceans, and Space at the University of New Hampshire as well as founder and Director of its Water Systems Analysis Group. His research interests focus on the development of computer models, remote sensing application and geospatial data sets used in synthesis studies of the interactions among the water cycle, climate, biogeochemistry, and anthropogenic activities. His studies are built around local, regional, and continental to global-scale modeling of water balance, discharge, constituent fluxes in river systems, and the analysis of the impacts of large-scale water engineering on the terrestrial water cycle. He is a founding member of the Global Water System Project representing the inputs of more than 200 international scientists under ICSU's Global Environmental Change Programs. In this capacity he is spearheading efforts to develop global-scale indicators of water stress, to develop and apply databases of reservoir construction worldwide, and to analyze coastal zone risks associated with water diversion. Dr. Vörösmarty also serves on the US Arctic Research Commission, the NSF-ARCSS Committee (AC), and the Arctic HYDRA International Polar Year (IPY) Planning Team. He has served on NRC panels to review NASA's polar geophysical data sets and the decadal study on earth observations, and is co-Chair of the NSF-Arctic CHAMP hydrology initiative. For the United Nations he served as consultant to the 24-agency UN World Water Assessment Program and represented the International Council of Scientific Unions at recent UN Commission on Sustainable Development meeting

Chunmiao Zheng is professor of Hydrogeology and SSPA Faculty Fellow in the Department of Geological Sciences at the University of Alabama. Dr. Zheng's research involves contaminant transport modeling, groundwater resources and groundwater quality management, and coupling of physical transport processes with biological and geochemical reactions. Dr. Zheng has received several honors and awards and participated in many professional organizations and activities. He is president-elect of International Commission on Groundwater, International Association of Hydrologic Sciences, a member of the editorial board for the *Journal of Hydrology*, and currently treasurer of CUAHSI and software editor and associate editor for *Journal on Ground Water*.

National Research Council Staff

WILLIAM S. LOGAN, Project Director *(until September 2008)*
LAURA J. HELSABECK, Project Director
ANITA A. HALL, Project Assistant

Appendix C

Agenda

Workshop on
Research and Applications Needs in Flood Hydrology Science

Wednesday, October 15, 2008
The National Academies Keck Center, Room 109
500 5th Street, N.W. Washington, DC 20001

Sponsored by the National Research Council's **Committee on Hydrologic Science**

8:30 Welcomes and Introductions — Eric Wood, Chair, COHS
8:35 Orientation — David Ford, Dennis Lettenmaier, Vic Baker

8:45 **What should be the underpinnings and motivating science and applications questions in a new science of hydrologic extremes?**
Speaker: Upmanu Lall, Columbia University
Discussion leader: Dennis Lettenmaier, University of Washington

9:30 **What can and should be the role of new observing methods, both in situ (including new sensor technologies) and remote sensing? How might approaches to the estimation of hydrologic extremes differ based on the richness of the historic observations?**
Speaker: Doug Alsdorf, Ohio State University
Discussion leader: Charles Vorosmarty, City University of New York
10-15 Break
10:30 Breakout sessions – Room 110
Rapporteurs: Eric Wood, Princeton University
Geoff Bonnin, NOAA National Weather Service
11:30 Rapporteurs report back; discussion
12:15 Lunch – Meeting Room

1:15 **What should be the interface between the science of hydrologic extremes and applications issues, such as the need to replace standard methods,**

such as Bulletin 17B and other methods that are based on stationary statistical methods?

Speaker: Tim Cohn, U.S. Geological Survey
Discussion leader: David Ford, David Ford Consulting

2:00 **How can advances in techniques for the accurate analysis of ancient flood events aid estimation of future flood magnitudes and frequency, and understanding of the generative processes for extreme flood phenomena?**

Speaker: Lisa Ely, Central Washington University
Discussion leader: Vic Baker, University of Arizona

2:45 Break
3:00 Breakout sessions – Room 110
Rapporteurs: John England, U.S. Bureau of Reclamation
Jim O'Connor, U.S. Geological Survey
4:00 Rapporteurs report back; Discussion
4:45 Summary and wrap-up
5:00 p.m. Adjourn