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How Hurricane Katrina influenced the design of hurricane protection and risk reduction systems and national approaches to risk and resilience. Part 2: Designing the Hurricane and Storm Damage Risk Reduction System and resulting long-term engineering guidance and practice changes

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ABSTRACT

Following Hurricane Katrina, the US Army Corps of Engineers, supported in part by the risk and reliability analysis conducted by the Interagency Performance Evaluation Task Force (IPET), made a major shift from 'protection' to 'risk reduction' as the principal goal in flood mitigation. The mitigation of the flood risk in Southeast Louisiana was embodied in the design and construction of the 'Hurricane and Storm Damage Risk Reduction System', the post-Katrina initiative for New Orleans flood mitigation. It also spawned a major overhaul of many of the Corps of Engineers' technical guidance and engineering practice documents, incorporating risk as a key measure in the planning and design processes. The criteria applied for the design of the HSDRRS are discussed, with summaries of the associated major changes in Corps engineering guidance and practice relevant to flood mitigation.

Key words: Design criteria, Engineering practice, Flood risk, Hurricane Katrina, New Orleans, Risk mitigation

HIGHLIGHTS

- The losses from Hurricane Katrina and subsequent forensic and risk analyses for New Orleans resulted in substantial changes to the knowledge base and guidance for planning and designing coastal risk reduction systems.
- The new knowledge was a substantial input to the design of the Hurricane and Storm Damage Risk Reduction System that is currently in place in New Orleans.
- The processes used were considerably different from past practice and resulted in a more robust and resilient system with some capacity to deal with uncertainty and change. This paper highlights the new processes.
- The same knowledge base was the stimulus for significant changes to the US Army Corps of Engineers engineering guidance and practice documents. A major change was the incorporation of risk-based decision making in many aspects of project development and execution.

INTRODUCTION

The losses from Hurricane Katrina and subsequent forensic and risk analyses for New Orleans resulted in substantial changes to the knowledge base and guidance for planning and designing coastal flood risk reduction systems.

The new knowledge, generated by an exhaustive and comprehensive forensic study of the hurricane protection system around New Orleans subjected to Hurricane Katrina (IPET Final Report, 2009; IPET Supplemental Report, 2009), represented a landmark shift in design approaches for the Corps of Engineers. It substantially changed the way the inputs to the design of the Hurricane and Storm Damage Risk Reduction System that is currently in place in New Orleans were formulated and analyzed. The processes used were considerably different from past practices and resulted in a more robust and resilient system with some capacity to deal with uncertainty and change.

The same knowledge base was the stimulus for significant changes to the US Army Corps of Engineers (USACE) engineering guidance and practice documents. A major change was the incorporation of risk-based decision-making in many aspects of project development and execution. The documents updated with this information are highlighted. An example of these documents is Engineer Regulation ER 1105-2-101 Risk Analysis for Flood Risk Management Studies, USACE (7/17/2017).

One of the major shifts in philosophy, post-Katrina, was the change from 'Protection' to 'Risk Reduction' relevant to mitigation measures that deal with storm surges and waves. Going forward the public needed to understand that the term 'protection' was not appropriate because it implied a 'fail-safe' system and associated level of protection. Under the conditions of climate uncertainty, it is impossible to guarantee that an area is protected against all flooding – only that it is protected against an expected 'design' event of relatively uncertain frequency. For example, the US standard for floodplains is a 100-year event. Hence, an area not prescribed to be within the 100-year floodplain was not 'protected' but has a risk of flood losses that are less than those areas within the floodplain. In the case of the New Orleans Hurricane and Storm Damage Risk Reduction System, the risk reduction objective was defined by a new combination of stochastically generated hurricane storm tracks and storm surge levels in order to define a new 100-year event. Risk reduction was the more appropriate objective, focusing on reducing the likelihood of losses, with the realization that there will always be some chance of flooding and losses from potentially larger and statistically likely storm events regardless of what mitigation measures are deployed. That remaining potential loss is defined as the residual risk.

The lessons learned through the IPET forensic and risk analyses and the Corps of Engineers applications of that knowledge in the immediate repair and short-term upgrades to the Pre-Katrina era Hurricane Protection System were leveraged into the design and construction of a new risk mitigation infrastructure system termed the Hurricane and Storm Damage Risk Reduction System (HSDRRS). The HSDRRS was a first in many aspects for US flood mitigation efforts, using probabilistic quantification of the flood hazard using joint probability analysis methods, incorporating new failure mode and fragility analyses for structures, explicitly including uncertainty in consideration of structure design and adding 'structural resilience' to preclude overtopping failure of structures to name a few. Figure 1 provides a map of the HSDRRS depicting the major structural components that were constructed in addition to broad increases in flood wall and levee elevation and strength.

The reports, Hurricane Storm Damage Risk Reduction System Elevation Report (USACE 2012) and Hurricane Storm Damage Risk Reduction system Design Guidelines, Interim, (New Orleans District 2012), provide a detailed documentation of the coastal and hydraulic engineering analysis performed to determine the project design elevations for three legacy projects within the spatial domains of the HSDRRS: Lake Pontchartrain & Vicinity, West Bank & Vicinity, and New Orleans to Venice projects, including the portions of the Mississippi River Levees coincident with these projects.

Congress authorized the Secretary of the Army to:

- repair and restore these projects;
- accelerate the completion of unconstructed portions;
- armor critical elements; and
- in the case of the existing Lake Pontchartrain & Vicinity project and the existing West Bank & Vicinity project, raise levee and floodwall heights where necessary and otherwise enhance the existing Lake Pontchartrain &

Fig. 1 | Map of the HSDRRSS depicting the major structural components that were constructed in addition to broad increases in flood wall and levee elevation and strength, June 2013 (*Source*: Corps of Engineers).

Vicinity project and the existing West Bank & Vicinity project to provide the levels of protection necessary to achieve the certification required for participation in the National Flood Insurance Program.

For the HSDRRS coastal and hydraulic engineering analyses, new processes and procedures were supported in part based on the IPET analyses and results. A team consisting of the USACE, the Federal Emergency Management Agency (FEMA), the National Oceanographic and Atmospheric Administration (NOAA), the private sector, and academia developed a new process for estimating hurricane inundation probabilities, the Joint Probability with Optimal Sampling (JPM-OS) method. This process is documented in the IPET Final Report, Vol. VIII and in Journal Papers by Resio & Westerink (2008), Resio *et al.* (2008, 2013), Resio & Irish (2015). The results were applied to USACE work by the Interagency Performance Evaluation Team (IPET) risk analysis, the Louisiana Coastal Restoration and Restoration project, and FEMA Base Flood Elevations for the production of Digital Flood Insurance Rate Maps (DFIRM) for coastal Louisiana (LA) and Texas.

As recommended in the IPET analysis (IPET Final Report, Vol. I) three major flaws in the pre-Katrina Hurricane Protection System had to be addressed in the formulation of the HSDRRS: (1) the hurricane protection system in New Orleans did not perform as a system; (2) redundancy should be a component of the system; and (3) consideration should be given to the performance of the system if the design event or system requirements are exceeded. These became fundamental aspects of the planning for the HSDRRS.

A systems approach was used in the coastal and hydraulic engineering analyses. Surge and wave models were inclusive of the entire flood mitigation area and all related components of the mitigation effort. Analyses included the evaluation of the effects of subsidence and sea-level rise on surge elevations and waves. The construction of the hurricane protection system to the design elevations and cross-sections in this report ensures that the components (walls, levees, pumping stations, drainage systems, etc.) have a common capacity and capability based on the hazard. Redundancy was also included in the system planning and design through the presence of secondary structural measures that were located within the perimeter of the main HSDRRS. The existing levee/floodwall system in the Inner Harbor Navigation Canal/GIWW (IHNC/GIWW) and along the three outfall canals was designed to provide a useful measure of redundancy to the flood risk reduction system behind the primary line of protection at the perimeter (such as with overtopping). On the West Bank, the Harvey and Algiers Canal areas on the West Bank have levee/floodwalls along the interior drainage outlets that provide redundancy with respect to the external perimeter structures and associated pumping and water control structures. Consideration was given in the analyses to structural resiliency, the performance of the system if the design event or system requirements are exceeded. This was primarily through the consideration of armoring of the back side of levees where overtopping may occur in rare events.

Levee/structure design height

The HSDRRS design elevations are sufficient to provide protection from a hurricane event that would produce a 1% exceedance surge elevation and associated waves. The design elevations presented in this report are determined for each location of interest, using the 1% annual exceedance still water elevation, 1% annual exceedance wave height, and 1% annual exceedance wave period, assuming simultaneous occurrence of maxima of surge level and wave characteristics. These assumptions are conservative and are in line with a resilient design approach recommended by the IPET.

The design criteria for the levee and structure elevations also consider wave overtopping limits. Guidelines for establishing the overtopping rate threshold (i.e., the threshold associated with the onset of levee erosion and damage) in different types of embankments can be found in Engineering Manual (EM) 1110-2-1100 (Part VI), Table VI-5-6. These threshold values are consistent with those that are adopted by the Technical Advisory Committee on Flood Defence in the Netherlands (Technische Adviescommissie voor de Waterkeringen).

The following wave overtopping rates were established for the New Orleans HSDRRS systems:

- For the design still water, wave height, and wave period, the maximum allowable average wave overtopping of 0.1 cubic feet per second per foot (cfs/ft) at 90% level of assurance and 0.01 cfs/ft at 50% level of assurance for grass-covered levees.
- For the design still water, wave height, and wave period, the maximum allowable average wave overtopping of 0.1 cfs/ft at 90% level of assurance and 0.03 cfs/ft at 50% level of assurance for floodwalls with appropriate protection on the backside.

Uncertainty of knowledge of variables and functions

Uncertainty may be represented by a specific probability distribution with associated parameters, or sometimes expressed simply as standard deviation. Present guidance, USACE (2012), supplements freeboard assumptions by providing upper and lower bounds of required levee performance based on specified levels of assurance of protection against the design flood using the design criteria stated above. A probabilistic approach (Monte Carlo) was used in applying these criteria by using a spectrum of potential wave overtopping situations that incorporates uncertainty in the still water elevation and wave characteristics. This resulted in the final structural elevation determinations.

The IPET identified resilience (in this case it could also be termed robustness for structures) as one of the 'Overarching Lessons Learned' from Hurricane Katrina. Engineers are working to develop guidance to define resiliency and the level of resilience needed for levees and structures. For the HSDRRS design, resiliency was defined as the ability of the levee or structure to provide protection during events greater than the design event without total failure. The minimum criterion for resilience was that levees and structures do not catastrophically breach when design criteria are exceeded. Resilience also includes designing for possible changes in conditions, with the flexibility to adapt to future design conditions. Guidance considered for the HSDRRS structures included, ensuring that the height of all barriers is sufficient to prevent free flow at the 0.2% annual exceedance event. The 0.2% annual exceedance event was selected because it represents the approximate recurrence of Hurricane Katrina and is approximately equivalent to a 1 in 500-year event. The 0.2% water (surge and wave) elevations were determined for each location of interest using the JPM-OS hazard analysis for a large number of potential hurricane events in the region.

Structures/pump stations

Pump stations throughout the New Orleans area have been constructed and are operated and maintained by local government agencies. There are no existing federal pump stations in the HSDRRS of greater New Orleans. Prior and present hurricane protection projects do not rely significantly on the ability to pump out water from rainfall and overtopping of levees and walls. In urban and urbanizing areas, the provision of a basic drainage system to collect and convey local runoff from rainfall is usually considered a non-federal responsibility. Within the New Orleans area, however, Congress authorized a federal project to improve interior drainage, the Southeast Louisiana Urban Flood Control Project.

Recognizing the damage that may result from a weakened or inoperable storm drainage system, the Corps' New Orleans District also examined alternatives to reduce the consequences of interior flooding. They include:

- Completion of the Southeast Louisiana Urban Flood Control Project, a federal project to improve interior drainage in New Orleans and surrounding communities.
- Design and construction of positive shut-off gates at pump stations to block backflow.
- Providing fronting protection at pump stations to improve resilience and survivability of pump stations through storm surge events.
- Storm proofing selected pump stations to improve discharge capabilities during storm events.

Subsidence

Planning for anticipated subsidence, both short-term and long-term, was included in the design of the HSDRRS. During the design of individual reaches, geologists and geotechnical engineers examined site-specific soil conditions and estimate long-term settlement and subsidence in the barriers. For levees over soft foundations, engineers typically recommend construction in several lifts. This allows the foundation soils to consolidate and gain in shear strength. When future lifts are constructed to higher elevations, the footprint of the levee system does not need to increase. Final construction lifts are typically constructed with added height in the anticipation of long-term settlement. This added height assures that the levee crown elevation will be at or above the design elevation.

Future conditions

Design elevations have been calculated for both existing conditions and future conditions (year 2057). Existing conditions represent conditions that exist at the completion of the HSDRRS. Future conditions include changes in still water levels (SWLs) and wave characteristics due to subsidence and sea-level rise. Historical subsidence, projections of sea-level rise, and previous studies have been used to estimate future changes in SWLs. Natural subsidence rates, including sea-level rise, have been mapped by the New Orleans District for the Louisiana Coastal Area Plan. A relative sea-level rise of 1.0 foot (ft) over 50 years has been used for the purposes of the HSDRRSS design efforts. The effect of increasing sea-level rise on surge levels has been further investigated and resulted in the 1.5–2.8 ft increase in surge level, applied as future conditions. Moreover, the wave characteristics have also been corrected for the increasing water depth.

The New Orleans District, USACE, has also planned regular reassessment of design parameters in order to assure the effectiveness of the system in future years. Changes in sea level and land loss are some of the factors that need to be periodically revisited. As the inventory of storms increases, periodic assessment of the JPM-OS method should also be undertaken. The system should also undergo a reassessment after major events or significant changes in design and analysis methodologies. The intent is to conduct such reviews no less than once every 10 years.

Once initial construction was completed, the responsibility to operate, maintain, repair, replace, and rehabilitate barriers was turned over to the local sponsor in most cases. Periodic inspections and annual reviews submitted to the USACE will assure proper performance. To ensure that requirements are well understood, an operation, maintenance, repair, replacement, and rehabilitation manual is developed for each project and serves as the basis for future monitoring, inspection, and reporting. In addition, the Corps of Engineers will conduct periodic surveys of levees as part of an improved quality assurance program.

LONG-TERM CHANGES IN ENGINEERING GUIDANCE AND PRACTICE RESULTING FROM KATRINA

The USACE is the owner and regulator of 708 large dams and regulator of over 2,500 levee systems (14,000 miles) in the USA. The Corps' mission and infrastructure responsibilities also include hydropower, water supply, navigation, and environment. The characteristics of the infrastructure under USACE governance have been described by Halpin & Escuder (2015). They state that 'from a risk perspective, the infrastructure is diverse, spanning over five orders of magnitude in probability of failure, consequences of failure, and annualized risk. Approximately one-third of the portfolio is actionable for undesirable risks.' Also, 'Historically, management solely via compliance via a traditional "one-size-fits-all" engineering standards was viewed as not improving understanding or decisions, nor was it cost effective.'

The same paper described the USACE strategy of adaptive learning to implement risk governance. After a decade of effort and gradual growth and improvement, the Corps' expertise and experience in risk assessments and risk-informed decision-making is substantial. The Corps has worked strategically with other agencies, industry, and international partners to further build expertise and overall governance to include considerable development of new policies and guidance. The paper cites that 'risk-informed decisions have reshaped the very culture of the agency'.

Hurricane Katrina served as one broad stimulus for these actions and the evolution of risk management and analysis within the Corps and other federal agencies. The Corps of Engineers had accepted risk as an important measure in the 1990s, as evidenced by the development of policy and guidance documents addressing risk use for Corps analyses such as 'Guidelines for Risk and Uncertainty Analysis in Water Resources Planning, Volume I, Principles', (IWR Report 92-R-1, March 1992), Engineer Regulation ER 1110-2-1150, Engineering and Design for Civil Works Projects, August 1999, and EM 1110-2-1619, Risk-Based Analysis for Flood Damage Reduction Studies, 1996. While these became part of the Corps governance policy documents, risk-based analysis and management did not rise to prominence until after the Katrina event.

Organizational changes

A primary organizational change within the Corps was the establishment of new national technical centers for Risk Management, Modeling, Mapping, Consequence Estimation, and Infrastructure Modification. These centers have assisted in shaping and implementing risks informed decision-making and continuing to adapt through training, policy, and methodology development. They provided the capability to begin conducting routine risk assessments and providing support to decision-making. For example, USACE moved from a solely standards-based approach for its dam safety program to a dam safety portfolio risk management approach. The standards-based approach is included in the risk-informed approach to the dam safety program, and dam safety program decisions are now be risk-informed.

Method changes

The use of the more sophisticated tools for hazard analyses used in the IPET and for the design of the HSDRRS demonstrated the value of new approaches, and the risk analysis accomplished for pre-Katrina and post-Katrina situations demonstrated the value of risk as a measure of the return on investment of such information. The Corps adapted some of their primary analytical tools to integrate risk assessment and analysis into their standard methodologies. An example is the incorporation of risk into the Hydrologic Engineering Center program HEC-FDA, Flood Damage Assessment.

One of the key bases for a risk-informed decision, and prioritization of the work, is a consideration of tolerable risk. Tolerable risk is the risk remaining after risk reduction measures have been implemented. The establishment of tolerable risk standards and methods was a key enabler for using risk to inform decisions by providing a gage for determining the effectiveness of proposed or completed risk mitigation measures. This goal remains a work in progress beyond the Dam Safety Program.

Levee safety program

The USACE Levee Portfolio Report shares the current understanding of the flood risks and benefits associated with the portfolio of levee systems within the USACE Levee Safety Program. The USACE Levee Portfolio Report is organized around risk (e.g., the flood risk associated with levees) to describe the magnitude of risk, key drivers of risk, sources of uncertainty in the understanding of risk, and distinct factors of risk within the USACE levee portfolio.

USACE levee portfolio

The USACE Levee Safety Program has conducted a comprehensive inventory, inspection, and risk assessment effort for the entire USACE levee portfolio. This provides a more comprehensive understanding of the portfolio than previously known: where the levees are (inventory); their condition (inspection); and the flood risk associated with each levee (risk assessment). The USACE levee portfolio includes about 2,220 levee systems totaling approximately 14,150 miles in length. Over 1,200 levee sponsors operate and maintain roughly 2,000 of these levee systems, spanning roughly 70% of the length of the entire portfolio. The remaining almost 200 levee systems are operated and maintained by USACE.

Risk assessments within the Levee Safety Program provide a systematic, evidence-based approach for estimating and describing the likelihood and consequences of existing and future risk associated with levee systems. Risk assessments consider what can go wrong, how it can happen, the consequences if it happens, and how likely it is to happen. To support decisions in the management of the portfolio, a levee safety action classification (LSAC) is assigned as a final step in developing a risk characterization for each levee system. LSACs range from very high risk (immediate action recommended) to very low risk (maintain routine activities). LSAC assignments are used by USACE to prioritize resources across the portfolio and to organize widespread levee-related risk information into reasonably commensurate groupings for action (Levee Portfolio Report, 2018).

National levee database

The national levee database (NLD) includes 9,272 levee systems, 29,635 miles of levees that include 47,184 levee structures. It is maintained by the Corps of Engineers in partnership with FEMA.

The NLD is a congressionally authorized database that documents levees in the USA. The NLD is maintained and published by the USACE. It recently underwent a refresh making more tools available to data managers to keep information updated and provides an improved dashboard that makes finding and understanding levee information easier than ever. NLD information includes the location, general condition, and risks associated with the levees.

The NLD contains information about the condition and risk information for approximately 2,000 levee systems (approximately 15,000 miles/mostly levees affiliated with USACE programs. An additional 6,000 levee systems – approximately 15,000 miles – have location information, but little to no information about condition and risk. One of the goals for the NLD is to include data about levees owned and operated by all other federal agencies, tribes, states, municipalities, levee boards, and private entities. This information will be added as it becomes available.

The database includes attributes of levees and floodwalls relevant to flood fighting, design, construction, operation, maintenance, repair, and inspection. Because the location and characteristics of levee systems can be viewed on a map with real-time data from other sources, such as stream gauges and weather radar, it is a useful tool for a variety of public agencies and individuals including flood plain managers, emergency management agencies, levee system sponsors, and citizens who live or work behind a levee.

The NLD information is presented in a convenient dashboard and includes the ability to search on specific areas of interest or geographically. The database is available at https://levees.sec.usace.army.mil.

Federal dam safety program

For 30 years, the federal government has used the National Dam Safety Program (NDSP) to protect Americans from dam failure. The NDSP is a partnership of the states, federal agencies, and other stakeholders that encourages and promotes the establishment and maintenance of effective federal and state dam safety programs to reduce the risks to human life, property, and the environment from dam-related hazards. The program is administered by FEMA and provides the following:

Information needs for dam safety: Under FEMA's leadership, state assistance funds have enabled all participating states to better their programs through increased inspections, emergency action planning, and the purchase of needed equipment.

Dam safety training: FEMA has expanded existing training programs and initiated new training programs to enhance the sharing of expertise between the federal and state sectors.

Grant assistance to the states: Grant assistance provides vital support for the improvement of state dam safety programs that regulate most of the 87,000 dams in the USA.

Dam safety research: A national research program in dam safety focuses on priorities and produces products for both the layperson and the expert and develops technological tools that drive data collection and analysis toward a better understanding of risk and remediation needs.

NDSP partners: To encourage individual and community responsibility for dam safety, FEMA coordinates partnerships through two federal organizations, the National Dam Safety Review Board and the Interagency Committee on Dam Safety.

Partners include the Association of Engineering Geologists, the Association of State Dam Safety Officials, the Bureau of Reclamation, the Federal Emergency Management Agency, the Federal Energy Regulatory Commission, the Institute for Water Resources, and the US Society of Dams.

USACE dam safety program

The USACE operates and maintains approximately 700 dams nationwide and in Puerto Rico that provide significant, multiple benefits to the nation – its people, businesses, critical infrastructure, and the environment. These benefits include flood risk management, navigation, water supply, hydropower, environmental stewardship, fish and wildlife conservation, and recreation.

USACE's dams are part of our nation's landscape, integral to many communities, and critical to watershed management. Our dam safety professionals carry out a dam safety program to make sure these projects deliver their intended benefits while reducing risks to people, property, and the environment through continuous assessment, communication, and management. (By comparison, there are more than 87,000 dams in the National Inventory of Dams that are federally, state, locally, and privately operated and maintained.)

ENGINEERING GUIDANCE CHANGES

The Corps has accomplished a broad spectrum of changes to their engineering guidance and practice documents. Without this comprehensive umbrella of new and updated engineer regulations (ER), engineering circulars (EC), and EMs, governance of the processes and application of the principles of risk and resilience would be futile. This includes the modernization and continued evolution of processes that are facilitated through Engineering and Construction Bulletins (ECB) and Engineering Technical Letters (ETL). The following is a sample of the key updated or new governance documents that provide policy and guidance for the application of risk and resilience in Corps practice. This includes a few draft documents that are still in development and formalization stages.

Engineer Regulations: www.publications.usace.army.mil/USACE-Publications/Engineer-Regulations/

1. ER 1110-2-1156 Safety of Dams Policy, 3/31/2014: This regulation prescribes the guiding principles, policy, organization, responsibilities, and procedures for the implementation of risk-informed dam safety program activities and a dam safety portfolio risk management process within the USACE.
2. ER 10-1-51 Roles and Responsibilities – Dam Safety Modification Mandatory Center of Expertise 9/28/2012.
3. ER 10-1-55 Organization and Functions – Roles and Responsibilities Risk Management Center, 6/30/2013.
4. ER 1100-2-8162 Incorporating Sea-level Changes in Civil Works Programs, 12/31/2013:

   This Regulation provides USACE guidance for incorporating the direct and indirect physical effects of projected future sea-level change across the project life cycle in managing, planning, engineering, designing, constructing, operating, and maintaining USACE projects and systems of projects.
5. ER 1105-2-101 Risk Analysis for Flood Risk Management Studies, 7/17/2017:

   This regulation provides guidance on risk assessment requirements for flood management studies including but not limited to feasibility studies, post-authorization changes, general reevaluation studies, dam and levee safety studies, and major rehabilitation studies. This regulation is jointly promulgated by planning and engineering. The risk framework is a decision-making process that comprises three tasks: risk assessment, risk communication, and risk management.
6. ER 1110-2-8156 Policies, Guidance, and Requirements for Geospatial Data and Systems, September 2012: General criteria for the use and development of geospatial technologies throughout the USACE. This includes, but is not limited to, geospatial system development and utilization as well as the acquisition, processing, storage, distribution, and utilization of geospatial data and systems. This ER provides a framework that promotes interoperability through the use of data standards and an open platform to move data seamlessly throughout the organization.

7. ER 1110-2-8160 Policies for Referencing Project Evaluation Grades to Nationwide Vertical Datums, March 2009: This regulation establishes USACE policies for referencing project elevation grades to nationwide vertical datums established and maintained by the US Department of Commerce. Its purpose is to ensure that controlling elevations and local datums on USACE projects are properly and accurately referenced to nationwide spatial reference systems used by other federal, state, and local agencies responsible for flood forecasting, inundation modeling, flood insurance rate maps, navigation charting, and topographic mapping.

Engineering Manuals: www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/

1. EM 1110-2-1413 Hydrologic Analysis of Interior Areas, 8/24/2018
2. EM 1110-2-1420 Engineering and Design Hydrologic Engineering Requirements for Reservoirs, 9/24/2018
3. EM 1110-2-6056 Standards and Procedures for Referencing Project Evaluation Grades to Nationwide Vertical Datums
4. EM 1110-2-3600 Management of Water Control Systems, 10/10/2017

Engineer Circulars: www.publications.usace.army.mil/USACE-Publications/Engineer-Circulars/

1. EC 1110-2-6065, Comprehensive Evaluation of Project Datums, July 2007: This document provides guidance on the proper application of vertical datums used to reference protection elevations on flood control structures or excavated depths in navigation projects – hereinafter referred to as the Comprehensive Evaluation of Project Datums (CEPD) project. It describes specific procedural actions immediately required to evaluate the accuracy and adequacy of existing flood protection elevations or controlling navigation depths relative to federal datums established by the Department of Commerce and prescribed for government-wide use by the Federal Geographic Data Committee (FGDC). This guidance implements lessons learned from the IPET study conducted after Hurricane Katrina, as identified in Volume II (Geodetic Vertical and Water Level Datums) of the Final IPET Report.
2. EC 1165-2-218, Levee Safety Policy and Procedures, DRAFT, 3/10/2018: This includes LSAC Table.
3. EC 1165-2-217, Review Policy for Civil Works, 2/20/2018: The purpose of this EC is to establish general policy and guidance for Corps of Engineers (Corps) implementation of Executive Order (EO) 11988, Floodplain Management, as amended by EO 13690, Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input1 for most Corps actions, except for those taken under the Corps Regulatory Program.
4. EC 1110-2-6067 USACE Process for the National Flood Insurance Program (NFIP) Levee System Evaluation, August 2010: The purpose is to provide a consolidated document that will guide USACE procedures for levee system evaluations in support of the NFIP as administered by the FEMA.
5. EC 1165-2-218 Policies and Procedural Guidance for Processing Requests to Alter US Army Corps of Engineers Civil Works Projects, September 2017.
6. EC 1165-XX2-XXXX, USACE Enterprise Risk Management System, Principles and Terminology (Draft): This EC begins a process to establish an Enterprise Risk Management (ERM) System within the Civil Works Program of the USACE.
7. EC 1110-2-6072 Comprehensive Guidance on Levee Safety (DRAFT), July 2015.
8. EC 1165-2-212 Sea-Level Rise Considerations for Civil Works Programs, October 2011: This circular provides USACE guidance for incorporating the direct and indirect physical effects of projected future sea-level change across the project life cycle in managing, planning, engineering, designing, constructing, operating, and maintaining USACE projects and systems of projects.

Engineering and Construction Bulletins: http://www.wbdg.org/ffc/dod/engineering-and-construction-bulletins-ecb

1. ECB 2018-14 Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects 09-10-2018: This ECB reissues and updates the policy in ECB 2016-25, Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects. This policy requires consideration of climate change in all current and future studies to reduce vulnerabilities and enhance the resilience of communities.
2. ECB 2018-2 Implementation of Resilience Principles in the Engineering & Construction Community of Practice, January 2018: This ECB provides the policy and guidance for applying the USACE principles of resilience – Prepare, Absorb, Recover and Adapt (PARA) – to Engineering & Construction (E&C) Community of Practice (CoP) efforts.
3. ECB 2017-15 Managed Overtopping of Levee Systems, 7/14/2017: The USACE will use this directive and guidance for commands responsible for planning, design, construction, and operation and maintenance of civil work projects. The level of detail in the overtopping analysis will depend on the study phase. This document is applicable for all USACE riverine levee and floodwall systems. This ECB provides an interim update to expired technical guidance Engineer Technical Letter (ETL) 1110-2-299 and provides a methodology for configuring the engineered capacity exceedance related to flood overtopping at a specific location or locations along the levee system.
4. ECB 2017-3 Design and Evaluation of I-Walls Including Sheet Pile Walls, 1/27/2017: This bulletin transmits specific guidance to be used for the design and evaluation of I-Walls and Sheet Pile Walls with links to the supporting documentation located on the USACE Official Publications site and/or the Technical Excellence Network (TEN) site.
5. ECB 2016-08 Interim Risk Reduction Measures (IRRMs) for Levee Safety, 2/22/2016: The USACE will use this directive and guidance for all levee systems in the USACE Levee Safety Program, which includes those (1) USACE operated and/or maintained; (2) federally authorized, typically USACE constructed, and locally operated and maintained; and (3) locally constructed and locally operated and maintained, but have been accepted into the USACE Rehabilitation and Inspection Program (RIP). Content of this ECB will be incorporated into the future Levee Safety Program EC.
6. ECB 2018-3 Using Non-NOAA Tide Gauges for Computing Relative Sea Level, February 2018.
7. ECB 2018-7 Advanced Modeling Requirements on USACE Projects, 6/6/2018: This directive renews and updates the requirements set forth in ECB 2016-3, 'Advanced Modeling Requirements on USACE Projects' (ref b). The use of advanced modeling processes and related technologies for design and construction is required as described herein.
8. ECB No. 20-xxx, Draft, Interim Approach for Risk-Informed Designs for Dam and Levee Projects.

Engineer Technical Letters: www.publications.usace.army.mil/USACE-Publications/Engineer-Technical-Letters

1. ETL 1100-2-1 Procedures to Evaluate Sea Level Change: Impacts, Responses, and Adaptation, June 2014: This technical letter provides guidance for understanding the direct and indirect physical and ecological effects of projected future sea-level change on USACE projects and systems of projects and considerations for adapting to those effects.
2. ETL 1100-2-2 Appropriate Application of Paleo-Flood Information for Hydrology and Hydraulics Decisions, October 2014: This Engineer Technical Letter establishes guidance for the appropriate use of paleo-flood analyses and information to support USACE Hydrology and Hydraulics (H&H) decision-making.

INTERAGENCY DOCUMENTS

1. FEMA P-1025, January 2015, Federal Guidelines on Dam Safety Risk Management: This addresses common understanding of risk management processes, commonly recognized standards for safety and tolerable risk, consistency in standards within the dam safety community, and technical tools and approaches related to risk analysis that can be mutually shared and jointly developed.
2. Best Practices in Dam and Levee Safety Risk Analysis (joint with USACE, USBR, and FERC), July 2005: This training manual attempts to help fill the need for practical reference material detailing risk analysis methodology for dam and levee safety applications. It contains what is considered the 'Best Practices' currently in use for estimating dam and levee safety risks at the Bureau of Reclamation and the USACE.

CONCLUDING REMARKS: WHAT NOW?

This discussion has highlighted what has been an all-to-often path to a major change in addressing national water management issues and particularly flooding. It takes a disaster or two to stimulate change and when change is achieved, it takes an excruciatingly long time to spread that change from the realm of policy to practice and an even longer period of time to implement the change on the ground nationwide. While change is relatively easy to accomplish in terms of new construction and unfortunately, for reconstruction after a disaster, it is a virtual conundrum for those areas that are living with unacceptable (intolerable) risks but have done nothing to mitigate that risk. It seems that as a nation we continue to fix the problem one disaster at a time. Breaking this cycle is one of the most difficult yet high payoff challenges we face.

Katrina provides one of the more recent examples of this cycle, especially when you consider the more recent disastrous flood events in New York/New Jersey (Superstorm Sandy), Houston (Hurricane Ike, Harvey), Puerto Rico (Hurricane Maria), and Florida (Hurricane Joaquin, Irma, Michael). Part of this enigma results from the fact that as a nation we spend 90% of our flood-related investments on recovery and only 10% on mitigation to reduce the need for recovery. Another component is the seemingly impossible task of reversing over a century of poor land-use and management decisions, both in where we develop and how we develop the land. A risk analysis for many coastal or inland areas vulnerable to flooding is too often viewed as sophisticated bad news that reveals the obvious. While it can significantly assist in prioritizing how to incrementally reduce risk, there is always the challenge of resources (unless, of course, you have a disaster).

This is not to diminish the highly important progress that is being made in the development and application of risk tools and risk-informed decision-making. These advances are essential and provide a much more productive path forward to systematically reduce the magnitude and extent of losses suffered from flooding. Examples of such progress in developing an impressive package of policy, guidance, and practice leading to a significant culture change in a large organization in a relatively short time frame are few and far between. This is an essential step forward and provides a viable platform to prepare for the next big step, dealing head-on with non-stationarity.

All of the demonstrated increased sophistication in the application of probabilistic risk analysis and systems approach to optimizing flood risk reduction does little to deal with the climate non-stationarity that is pervasive in hydrologic analysis. Non-stationarity has often been associated with the large uncertainties represented by climate change (Milly *et al.*, 2008), yet nationally we have been dealing with other forms of it indirectly and insufficiently with our traditional tools and concepts that depend on the assumptions of stationarity for their application. Most prominent of these with respect to risk are land use, population, and property value changes. By using relatively short time spans, we can 'adjust' runoff, vulnerability, and consequence estimates to make a data set 'uniform'. This, however, precludes effective use of the wealth of information available from the paleo record that can dramatically extend our 'modern data sets' to provide a richer understanding of the occurrence of major hazard events.

The larger issue is the difficulty in estimating the recurrence interval for a large event. The IPET uncertainty analyses showed that by far (71%) the greatest source of uncertainty in flooding estimates comes from the uncertainty in estimating the storm surge and wave conditions. Add to that the fact that we have so few actual records of major surge events at any one location (surge is very dependent on local physical geometry) from which to estimate recurrence intervals of such events. Now add the issue of likely climate non-stationarity in the processes themselves, which will alter the frequency and severity of individual events. The quantification of this total uncertainty paints a picture that makes the application of probabilistic risk analysis less attractive.

The current best practice to deal with this dilemma is the application of scenario analysis. Defining scenarios that represent a broad spectrum of possible change, not just with respect to natural processes, but also the socio-economics of the area of interest, provides the background within which one can begin to understand the sensitivity of existing water management capabilities and societal capabilities to cope with different types and degrees of change (without having to forecast when those changes might occur, or how often). This provides a platform for developing incremental adaptive strategies to deal with escalating change. The benefits of this approach are substantial. In addition to avoiding the minefield of uncertainty in estimating the recurrence of major events and having to decide whether to protect against the worst-case or accept less, it is possible to develop plans for incremental risk reduction as the changes unfold with time. This is both much more affordable and practical since you avoid over-investing for conditions that may not happen. Perhaps even more important, you can adapt as you learn more both with respect to what changes are most likely and how you will choose to deal with those changes.

The most recent comprehensive example of taking this approach is the Netherland's Delta Programme. The Delta Programme is an adaptive scenario-based approach to deal with the implications of climate change on water management in the Netherlands. It started with the Delta Model effort, an initiative to assemble a set of analytical models that would easily work together to understand not only change in the water regime, but also the effects of the water regime changes on the major functions of the nation (water supply, agriculture, commerce, environment, and, of course, flood safety).

The Delta Model package was used to examine a range of scenarios representing changes in water regime (e.g., sea-level rise and flow conditions on inland rivers) and changes in the socio-economics of the nation (e.g., land-use change and population shifts). The results provided knowledge of the sensitivity of current water management capabilities to those changes and their ability to meet the nation's needs. This knowledge became the basis for a planning exercise, again using the model package as a tool, to examine alternative approaches to deal with the water regime changes when they exceeded the current water management capabilities. The underlying concept was to develop strategies that allow incremental steps to adapt. This effort led to the Delta Plan which is now their long-term strategy for dealing with climate change in concert with possible socio-economic change.

The wisdom of this approach is hard to miss. Adaptation in steps, flexibility to adjust as change unfolds, the avoidance of massive resource expenditures based on highly uncertain analyses, and the opportunity to reevaluate as knowledge and analytical tools improve. Not the perfect world, but closer.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information (https://biotech.law.lsu.edu/katrina/ipet/Volume%20I%20FINAL%2023Jun09%20mh.pdf).

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