Investigation of the Performance of the New Orleans Flood Protection Systems in Hurricane Katrina on August 29, 2005

Volume I: Main Text and Executive Summary

by

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Final Report
July 31, 2006

This project was supported, in part, by the National Science Foundation under Grants No. CMS-0413327 and CMS-0611632. Any opinions, findings, and conclusions or recommendations expressed in this report are those of the author(s) and do not necessarily reflect the views of the Foundation.

This report contains the observations and findings of an investigation by an independent team of professional engineers and researchers with a wide array of expertise. The materials contained herein are the observations and professional opinions of these individuals, and do not necessarily reflect the opinions or endorsement of any other group or agency.

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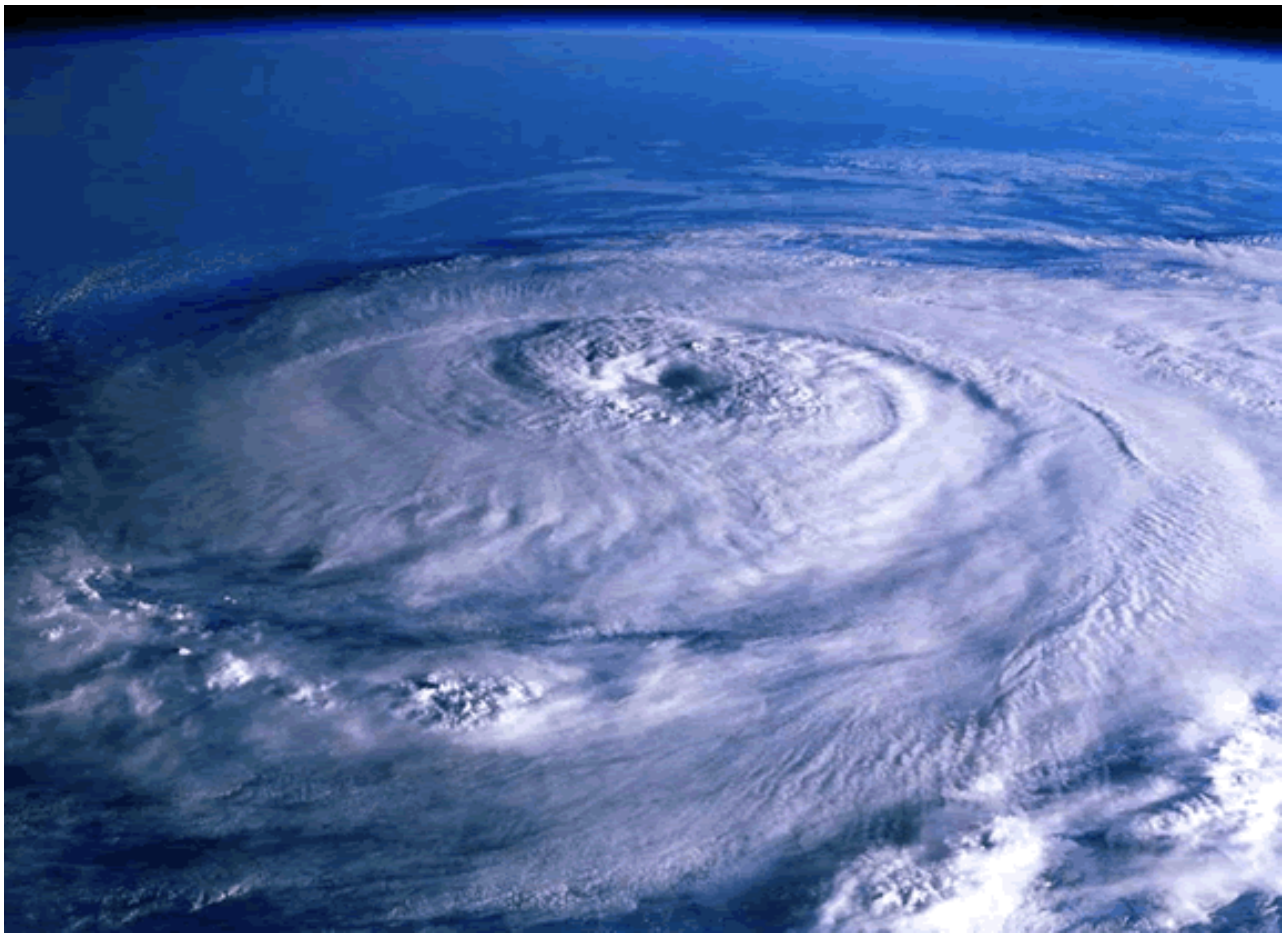

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This report is dedicated to the people of the greater New Orleans region;
to those that perished, to those that lost friends and loved ones,
and to those that lost their homes, their businesses, their place of work,
and their community.

New Orleans has now been flooded by hurricanes six times
over the past century; in 1915, 1940, 1947, 1965, 1969 and 2005.

It must be our goal that it not be allowed to happen again.

Table of Contents

VOLUME II: APPENDICES

APPENDIX G: LOOKING FORWARD

EXECUTIVE SUMMARY

This report presents the results of an investigation of the performance of the New Orleans regional flood protection system during and after Hurricane Katrina, which struck the New Orleans region on August 29, 2005. This event resulted in the single most costly catastrophic failure of an engineered system in history. Current damage estimates at the time of this writing are on the order of $100 to $200 billion in the greater New Orleans area, and the official death count in New Orleans and southern Louisiana at the time of this writing stands at 1,293, with an additional 306 deaths in nearby southern Mississippi. An additional approximately 300 people are currently still listed as "missing"; it is expected that some of these missing were temporarily lost in the shuffle of the regional evacuation, but some of these are expected to have been carried out into the swamps and the Gulf of Mexico by the storm's floodwaters, and some are expected to be recovered in the ongoing sifting through the debris of wrecked homes and businesses, so the current overall regional death count of 1,599 is expected to continue to rise a bit further. More than 450,000 people were initially displaced by this catastrophe, and at the time of this writing more than 200,000 residents of the greater New Orleans metropolitan area continue to be displaced from their homes by the floodwater damages from this storm event.

This investigation has targeted three main questions as follow: (1) What happened?, (2) Why?, and (3) What types of changes are necessary to prevent recurrence of a disaster of this scale again in the future?

To address these questions, this investigation has involved: (1) an initial field reconnaissance, forensic study and data gathering effort performed quickly after the arrival of Hurricanes Katrina (August 29, 2005) and Rita (September 24, 2005), (2) a review of the history of the regional flood protection system and its development, (3) a review of the challenging regional geology, (4) detailed studies of the events during Hurricanes Katrina and Rita, as well as the causes and mechanisms of the principal failures, (4) studies of the organizational and institutional issues affecting the performance of the flood protection system, (5) observations regarding the emergency repair and ongoing interim levee reconstruction efforts, and (6) development of findings and preliminary recommendations regarding changes that appear warranted in order to prevent recurrence of this type of catastrophe in the future.

In the end, it is concluded that many things went wrong with the New Orleans flood protection system during Hurricane Katrina, and that the resulting catastrophe had it roots in three main causes: (1) a major natural disaster (the Hurricane itself), (2) the poor performance of the flood protection system, due to localized engineering failures, questionable judgments, errors, etc. involved in the detailed design, construction, operation and maintenance of the system, and (3) more global "organizational" and institutional problems associated with the governmental and local organizations responsible for the design, construction, operation, maintenance and funding of the overall flood protection system.

After eight months of detailed study, a much clearer picture has now emerged regarding the causes and mechanisms of this catastrophe. Many of the findings of this study represent a different view of key elements of this event than has been publicly presented to date.

Hurricane Katrina was a large hurricane, and its arrival at New Orleans represented the root cause of a natural disaster. This disaster grew to a full blown catastrophe, however, principally due to the massive and repeated failure of the regional flood protection system and the consequent flooding of approximately 85% of the greater metropolitan area of New Orleans.

As Hurricane Katrina initially approached the coast, the resulting storm surge and waves rose over the levees protecting much of a narrow strip of land on both sides of the lower Mississippi River extending from the southern edge of New Orleans to the Gulf of Mexico. Most of this narrow protected zone, Plaquemines Parish, was massively inundated by the waters of the Gulf.

The eye of the storm next proceeded to the north, on a path that would take it just slightly to the east of New Orleans.

Hurricane Katrina has been widely reported to have overwhelmed the eastern side of the New Orleans flood protection system with storm surge and wave loading that exceeded the levels used for design of the system in that area. That is a true statement, but it is also an incomplete view. The storm surge and wave loading at the eastern flank of the New Orleans flood protection system was not vastly greater than design levels, and the carnage that resulted owed much to the inadequacies of the system as it existed at the time of Katrina's arrival. Some overtopping of levees along the eastern flank of the system (along the northeastern frontage of the St. Bernard and Ninth Ward protected basin, and at the southeast corner of the New Orleans East protected basin), and also in central areas (along the GIWW channel and the IHNC channel) was inevitable given the design levels authorized by Congress and the surge levels produced in these areas by the actual storm. It does not follow, however, that this overtopping had to result in catastrophic failures and breaching of major portions of the levees protecting these areas, nor the ensuing catastrophic flooding of these populous areas.

The northeast flank of the St. Bernard/Ninth Ward basin's protecting "ring" of levees and floodwalls was incomplete at the time of Katrina's arrival. The critical 11 mile long levee section fronting "Lake" Borgne (which is actually a Bay, connected directly to the Gulf of Mexico) was being constructed in stages, and funding appropriation for the final stage had long been requested by the U.S. Army Corps of Engineers (USACE), but this did not arrive before Katrina struck; as a result large portions of this critical levee frontage were several feet below final design grade. In addition, an unfortunate decision had been made to use local dredge spoils from the excavation of the adjacent MRGO channel for construction of major portions of the

levees along this frontage. The result was that major portions of these levees were comprised of highly erodeable sand and lightweight shell sand fill.

When the storm surge arrived, massive portions of these levees eroded catastrophically and the storm surge passed through this frontage while still on the rise, crossed an open swamp area that should have safely absorbed most of the overtopping flow from the outer levees (if they had not catastrophically eroded), and it then crossed easily over a secondary levee of lesser height that had not been intended to face a storm surge largely undiminished by the minimal interference of the too rapidly eroded outer levees fronting Lake Borgne. The resulting carnage in St. Bernard Parish was devastating, as the storm surge rapidly filled the protected basin to an elevation of approximately +12 feet above sea level; deeply inundating even neighborhoods with ground elevations well above sea level in this area.

The storm surge swelled waters of Lake Borgne also passed over and then through a length of levees at the southeast corner of the New Orleans East protected basin. Here too, the levees fronting Lake Borgne had been constructed primarily using materials dredged from the excavation of an adjacent channel (the GIWW channel), and these levees also contained major volumes of highly erodeable sands and lightweight shell sands. These levees were also massively eroded, and produced the principal source of flooding that eventually inundated the New Orleans East protected area. Here again there was an area of undeveloped swampland behind the outer levees that might have absorbed the brunt of any overtopping flow, and a secondary levee of lesser height was in place behind this swampland that might then have prevented catastrophic flooding of the populous areas of New Orleans East. This secondary levee was not able to resist the massive flows resulting from the catastrophic erosion of the highly erodeable section of the Lake Borgne frontage levee, however, and the floodwaters passed over the secondary levee and began the filling of the New Orleans East protected basin.

The catastrophic erosion of these two critical levee frontages need not have occurred. These frontages could instead have been constructed using well compacted clay fill with good resistance to erosion, and they could have been further armored in anticipation of the storm surge and wave loading from Lake Borgne. The levee at the northeast edge of St. Bernard Parish could have been completed in a more timely manner. The result would have been some overtopping, but not catastrophic erosion and uncontrolled breaching of these critical frontages. Some flooding and damage would have been expected, but it need not have been catastrophic.

The storm surge swollen waters of Lake Borgne next passed laterally along the east-west trending GIWW/MRGO channel to its intersection at a “T” with the north-south oriented IHNC channel, overtopping levees along both banks to a limited degree. This produced an additional breach of a composite earthen levee and concrete floodwall section along the southern edge of New Orleans East, adding additional uncontrolled inflow to this protected basin. This failure could have been prevented at little incremental cost if erosion protection (e.g. a concrete splash pad, or similar) had been emplaced along the back side of the concrete floodwall at the levee crest, but the USACE

felt that this was precluded by Federal rules and regulations regarding authorized levels of protection.

The surge next raised the water levels within the IHNC channel, and produced a number of failures on both the east and west banks. Two major failures occurred on the east side of the IHNC, at the west edge of the Ninth Ward. Overtopping occurred at both of these locations, but this was not the principal cause of either of these failures. Both failures were principally due to underseepage flows that passed beneath the sheetpile curtains supporting the concrete floodwalls at the crests of the levees. Like many sections of the flood protection system, these sheetpiles were too shallow to adequately cut off, and thus reduce, these underseepage flows. The result was two massive breaches that devastated the adjacent Ninth Ward neighborhood, and then pushed east to meet with the floodwaters already rapidly approaching from the east from St. Bernard Parish as a result of the earlier catastrophic erosion of the Lake Borgne frontage levees.

Several additional breaches also occurred farther north on the east side of the IHNC fronting the west side of New Orleans East, but these were relatively small features and they just added further to the uncontrolled flows that were now progressively filling this protected basin. These breaches occurred mainly at junctures between adjoining, dissimilar levee and floodwall sections, and represented good examples of widespread failure to adequately engineer these “transitions” between sections of the regional flood protection system.

Several breaches occurred on the west side of the IHNC, and these represented the first failures to admit uncontrolled floodwaters into the main metropolitan (downtown) protected area of New Orleans. These features did not scour and erode a path below sea level, however, so they admitted floodwaters for a number of hours and then these inflows ceased as the storm surge in the IHNC eventually subsided. Only 10% to 20% of the floodwaters that eventually inundated a majority of the main (downtown) New Orleans protected basin entered through these features.

These failures and breaches on the west side of the IHNC all appear to have been preventable. One failure was the result of overtopping of an I-wall, with the overtopping flow then eroding a trench in the earthen levee crest at the inboard side of the floodwall. This removal of lateral support unbraced the floodwall, and it was pushed over laterally by the water pressures from the storm surge on the outboard side. Here again the installation of erosional protection (e.g. concrete splash pads or similar) might have prevented the failure.

The other failures in this area occurred at “transitions” between disparate levee and floodwall sections, and/or at sections where unsuitable and highly erodible lightweight shell sand fills had been used to construct levee embankments. Here, again, these failures were as much the result of design choices and/or engineering and oversight issues as the storm surge itself.

As the eye of the hurricane next passed to the northeast of New Orleans, the counterclockwise swirl of the storm winds produced a storm surge against the southern edge of Lake Pontchartrain. This produced additional temporary overtopping of a long section of levee and floodwall at the west end of the lakefront levees of New Orleans east, behind the old airport, adding further to the flows that were progressively filling this protected basin.

The surge against the southern edge of Lake Pontchartrain also elevated the water levels within three drainage canals at the northern edge of the main metropolitan (downtown) New Orleans protected basin, and this would produce the final, and most damaging, failures and flooding of the overall event.

The three drainage canals should not have been accessible to the storm surge. The USACE had tried for many years to obtain authorization to install floodgates at the north ends of the three drainage canals that could be closed to prevent storm surges from raising the water levels within the canals. That would have been the superior technical solution. Dysfunctional interaction between the local Levee Board (who were responsible for levees and floodwalls, etc.) and the local Water and Sewerage Board (who were responsible for pumping water from the city via the drainage canals) prevented the installation of these gates, however, and as a result many miles of the sides of these three canals had instead to be lined with levees and floodwalls.

The lining of these canals with levees topped with concrete floodwalls was rendered very challenging due to (a) the difficult local geology of the foundation soils, and (b) the narrow right of way (or available "footprint") for these levees. As a result of the decision not to install the floodgates, the three canals represented potentially vulnerable "daggers" pointed at the heart of the main metropolitan New Orleans protected basin. Three major breaches would occur on these canals; two on the London Avenue Canal and one on the 17th Street Canal. All three of these breaches eroded and scoured rapidly to well below sea level, and these three major breaches were the source of approximately 80% of the floodwaters that then flowed into the main (downtown) protected basin over the next three days, finally equilibrating with the still slightly elevated waters of Lake Pontchartrain on Thursday, September 1.

The central canal of the three, the Orleans Canal, did not suffer breaching, but a section of floodwall topping the earthen levee approximately 300 feet in length near the south end of the canal had been left incomplete, again as a result of dysfunctional interaction between the local levee board and the water and sewerage board. This effectively reduced the level of protection for this canal from about +12 to +13 feet above sea level (the height of the tops of the floodwalls lining the many miles of the canal) to an elevation of about +6 to +7 feet above sea level (the height of the earthen levee crest along the 300 foot length where the floodwall that should have topped this levee was omitted). As a result of the missing floodwall section, flow passed through this "hole" and began filling the heart of the main New Orleans protected basin. This flow eventually ceased as the storm surge subsided, and so was locally damaging but not catastrophic.

The three breaches on the 17th Street and London Avenue canals were catastrophic. None of these failures were the result of overtopping; surge levels in all three drainage canals were well below the design levels, and well below the tops of the floodwalls. Two of these breaches were the result of stability failures of the foundation soils underlying the earthen levees and their floodwalls, and the third was the result of underseepage passing beneath the sheetpile curtain and resultant catastrophic erosion near the inboard toe of the levee that eventually undermined the levee and floodwall.

A large number of engineering errors and poor judgements contributed to these three catastrophic design failures, as detailed in Chapter 8. In addition, a number of these same problems appear to be somewhat pervasive, and call into question the integrity and reliability of other sections of the flood protection system that did not fail during this event. Indeed, additional levee and floodwall sections appear to have been potentially heading towards failure when they were "saved" by the occurrence of the three large breaches (which rapidly drew down the canal water levels and thus reduced the loading on nearby levee and floodwall sections.)

The New Orleans regional flood protection system failed at many locations during Hurricane Katrina, and by many different modes and mechanisms. This unacceptable performance was to a large degree the result of more global underlying "organizational" and institutional problems associated with the governmental and local organizations jointly responsible for the design, construction, operation, and maintenance of the flood protection system, including provision of timely funding and other critical resources.

Our findings to date indicate that no one group or organization had a monopoly on responsibility for the catastrophic failure of this regional flood protection system. Many groups, organizations and even individuals had a hand in the numerous failures and shortcomings that proved so catastrophic on August 29th. It is a complex situation, without simple answers.

It is not without answers and potential solutions, however, just not simple ones. There is a need to change the process by which these types of large and critical protective systems are created and maintained. It will not be feasible to provide an assured level of protection for this large metropolitan region without first making significant changes in the organizational structure and interactions of the national and more local governmental bodies and agencies jointly responsible for this effort. Significant changes are also needed in the engineering approaches and procedures used for many aspects of this work, and there is a need for interactive and independent expert technical oversight and review as well. In numerous cases, it appears that such review would have likely caught and challenged errors and poor judgements (both in engineering, and in policy and funding) that led to failures during Hurricane Katrina.

Simply updating engineering procedures and design manuals will not provide the needed level of assurance of safety of the population and properties of this major metropolitan region. Design procedures and standards employed for many elements of

the flood protection system can be traced back to initial development and use for design and construction of levees intended for protection of largely unpopulated agrarian land, not a major urban region. Design levels of safety and reliability were nowhere near those generally used for major dams; largely because dams are considered to pose a potential risk to large populations. There are few U.S. dams that pose risk to populations as large as the greater New Orleans region, however, and it is one of the recommendations of this study that standards and policies much like those used for "dams" should be adopted for levee systems protecting such regions.

Simply addressing engineering design standards and procedures is unlikely to be sufficient to provide a suitably reliable level of protection. There is also a need to resolve dysfunctional relationships between federal and more local government, and the federal and local agencies responsible for the actual design, construction and maintenance of such flood protection systems. Some of these groups need to enhance their technical capabilities; a long-term expense that would clearly represent a prudent investment at both the national and local level, given the stakes as demonstrated by the losses in this recent event. Steady commitment and reliable funding, shorter design and construction timeframes, clear lines of authority and responsibility, and improved overall coordination of disparate system elements and functions are all needed as well.

And there is some urgency to all of this. The greater New Orleans regional flood protection system was significantly upgraded in response to flooding produced by Hurricane Betsy in 1965. The improved flood protection system was intended to be completed in 2017, fully 52 years after Betsy's calamitous passage. The system was incomplete when Katrina arrived. As a nation, we must manage to dedicate the resources necessary to complete projects with such clear and obvious ramifications for public safety in a more timely manner.

New Orleans has now been flooded by hurricanes six times over the past century; in 1915, 1940, 1947, 1965, 1969 and 2005. It should not be allowed to happen again.

THE INVESTIGATION TEAM

The University of California at Berkeley led Independent Levee Investigation Team (ILIT) grew through the course of this investigation, and eventually numbered 35 very dedicated and accomplished individuals.

The team included a large number of leading experts across a diverse range of fields. Team members came from six states, and they came from universities, private engineering firms, and state and federal agencies.

As a group, the investigation team had very impressive prior experience with forensic studies of major disasters and catastrophes. For example, the team members had previously investigated 12 major earthquakes and 8 major hurricanes (both domestic and foreign), 14 dam failures, more than a dozen levee failures, numerous landslides, one tsunami, the pivotal Kettleman Hills waste landfill failure, the Challenger and Columbia space shuttle disasters, the Exxon Valdez tanker disaster, and a number of major offshore pipeline and oil platform failures. They are well experienced with the carnage and disarray of disasters, and with the unforgettable smell of death. They are also well experienced at the delicate and deliberate art and science of piecing their way through the devastation, carefully and professionally, and figuring out what had happened, and why; the art and science of engineering forensics.

The calibre of these assembled experts is such that we could never possibly have afforded to hire them. Instead, excepting a handful of graduate research students who worked for very low wages, these world class experts all volunteered, and they worked pro bono (for free.) They did this for the intellectual challenge, for the camaraderie of a very special group of accomplished colleagues, for the chance to make a positive difference, because it was important, and most importantly because it was the right and necessary thing to do.

The pages that follow list the names and affiliations of the members of the Independent Levee Investigation Team. I have had the opportunity to work on a number of investigations of major catastrophes and disasters, but I have never worked with a finer group. They are all heroes in my book.

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ACKNOWLEDGEMENTS

This report would not have been possible without the generous help of many individuals and organizations.

This project was supported, in part, by the National Science Foundation (NSF) under Grants No. CMS-0413327 and CMS-0611632, and additional support was provided by the Center for Information Technology Research in the service of Society (CITRIS) at the University of California at Berkeley. This support is gratefully acknowledged.

The authors also wish to express their gratitude to the U.S. Army Corps of Engineers (USACE) for their considerable assistance with numerous elements of this work. Their field investigation team from the Engineer Research Development Center (ERDC) in Vicksburg hosted and assisted our own field investigation team in the critical early days of late September and early October. The USACE has also posted massive amounts of background documents on their website, and this has been an invaluable resource. The USACE, and the Interagency Performance Evaluation Team (IPET) have graciously shared much of their field and laboratory data, and we have done the same. This positive sharing and collaboration helps everyone by providing the best possible basis for study and analysis of this event.

We are also deeply grateful to the honorable men and women of the USACE who have taken extra measures to help to provide additional documents, data and insight. Many of these prefer not to be named, but their dedication to service of the greater public good in this difficult situation has been admirable.

We are deeply grateful to the members of the State of Louisiana's independent investigation team, Team Louisiana, for their tremendous efforts and dogged persistence under very difficult circumstances, and for their generous mutual sharing of data and insights throughout this investigation. This team consists of Dr. Ivor Van Heerden, Dr. Paul Kemp and Dr. Hassan Mashriqui (all from the Louisiana State University Hurricane Research Center), Billy Prochaska and Dr. Lou Cappozzoli (both local geotechnical consultants), and Art Theis (retired head of the Louisiana Department of Public Works.) The people of Louisiana, and the nation, owe these gentlemen a great debt as their persistent efforts have, time and again, produced critical data and insights that would not otherwise have been available.

We are also grateful to the members of the field investigation team of the American Society of Civil Engineers, who jointly formed a combined team with ours in the urgent initial post-event field studies when it was of vital importance to gather all possible data and observations while (fully necessary) emergency repair operations were already damaging and burying critical evidence. This was a very strong field forensics team, and their collaboration both in the field and in the subsequent preparation of an initial Preliminary Report which was issued in early November of 2005, was of great value.

Finally we are deeply grateful to the many others who will remain anonymous, but who have assisted by providing information, data, background history and other information that might otherwise not have been available.

A great many people gave generously of themselves, their time, and their expertise to assist these studies. It was important, and we are profoundly grateful.