The Art of Scientific Precision

River Research in the United States Army Corps of Engineers to 1945

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In river engineering, all objectives of the engineering process are subordinated to one factor: control. The aim is not to use knowledge of natural forces to develop new technological devices such as airplane wings or computer chips but to control the forces themselves.[1] But the science is inadequate. We still do not fully understand the dynamics of river flow, and complex natural systems exceed our ability to mimic them in laboratories. Consequently, engineers must fall back on art, intuition, and close empirical study. River engineering remains in many ways experimental and tentative.

The problems are daunting. Viewed holistically and over a long period of time, rivers exist in a state of equilibrium; changes occur within a limited range and tend to offset one another. The rare period of readjustment—a sudden shift in the channel, for instance—will eventually lead to a new dynamic equilibrium. One author has suggested that the process is analogous to a soldier's career: 98 percent boredom and 2 percent terror,

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1. The emphasis I put on scientific knowledge—and the specific end of control to which the knowledge is directed—departs from Walter Vincenti's analysis in his *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore, 1990), especially 13, 51, 137–69. Although one can draw a parallel between testing propellers in a wind tunnel and analyzing a scale model of a river—particularly the desire for predictability—clearly the object of the former is to develop or improve a technology, whereas the latter's objective is more commonly to discover "performance characteristics" of the river itself.

with "most of the significant work accomplished during moments of terror."[2] But from year to year a river's physical features hardly seem static. Sediment load, morphology, discharge, and even location can change. There is perpetual adjustment of the five variables that influence river flow: velocity, channel width, channel depth, gradient, and bed "roughness" (the resistance of a bed to flow). Heraclitus neatly summed up the quandary: "No one can step twice into the same river."

The technologies to control river flow have not changed fundamentally for ages. They include dams, levees and floodwalls, bank revetment, jetties, channel stabilization, and dredging. The emphasis is on the effective application of existing technologies; the innovation usually is in the details. In the last two and a half centuries engineers have applied mathematical rationalization to structural design, allowing each unique design to respond to the particular combination of variables affecting flow in a given stretch of river over time. The challenge is somewhat analogous to designing suits for a customer who is both demanding in his needs and discontented with his shape, constantly indulging in fad diets and binge eating. Even experts may wonder how to design a suit—or dam, revetment, or levee—for a constantly changing profile. The answer, of course, is to design within a range of anticipated parameters. Still, neither the tailor nor the river engineer will sanguinely predict success. In the case of river engineering, humility is especially called for when the river's discharge is known to vary widely or human activity modifies the floodplain.

This article analyzes the evolving relationship between river engineering and science by focusing on the largest river engineering organization in the world: the U.S. Army Corps of Engineers, an agency presently composed of some 37,000 civilians, 300 officers, and 200 enlisted personnel.[3]

2. Jeffrey F. Mount, *California Rivers and Streams: The Conflict Between Fluvial Process and Land Use* (Berkeley, 1995), 12. My analysis of river behavior derives principally from Mount's book, which is now the best introduction to fluvial processes for the nonspecialist.

3. For more on the engineering-science relationship, see the following articles in *Technology and Culture*: Edwin T. Layton Jr., "Science as a Form of Action: The Role of the Engineering Sciences," 29 (1988): 82–97; "Mirror-Image Twins: The Communities of Science and Technology in Nineteenth-Century America," 12 (1971): 562–80; and "American Ideologies of Science and Engineering," 17 (1976): 688–700. Also see David Channell, "The Harmony of Theory and Practice: The Engineering Science of W. J. M. Rankine," 23 (1982): 39–52, and "Engineering Science as Theory and Practice," 29 (1988): 98–103; Edward W. Constant, "Scientific Theory and Technological Testability: Science, Dynamometers, and Water Turbines in the 19th Century," 24 (1983): 183–98; Robert Friedel, "Engineering in the 20th Century," 27 (1986): 669–73; and Bruce Seely, "Research, Engineering, and Science in American Engineering Colleges: 1900–1960," 34 (1993): 344–86. For the manipulation of language by scientists and engineers in order to enhance or maintain professional reputation, see Ronald Kline, "Construing 'Technology' as 'Applied Science': Public Rhetoric of Scientists and Engineers in the United States, 1880–1945," *Isis* 86 (June 1995): 194–221. For a hydraulic engineer's defense of "engi-

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Since its permanent establishment as a small officer corps in 1802, the Corps of Engineers has contributed to science and applied scientific knowledge to practical problems. Its engineers have occasionally advanced theoretical science, but its research efforts have largely been empirical and inductive, reflecting an organizational culture and sociopolitical context that have often decisively influenced laboratory and field investigations. The major difference between nineteenth- and twentieth-century army engineers is not in their approach but in their self-confidence; today, army engineers appreciate better the challenges of unlocking the secrets of river behavior. An examination of the Corps's river research, emphasizing the agency's laboratory program at the Waterways Experiment Station during the New Deal, illuminates the limitations of scientific analysis—and the necessity of engineering art—in the complex world of fluvial hydraulics.

Empiricism, Mathematics, and Theory

Although many nineteenth-century army engineers thought of themselves as scientists as well as engineers, they subordinated their desire to discover nature's laws to the practical need for navigable and safe rivers. Following the precepts of the Common Sense philosophers of the Scottish Enlightenment, they suspected any theory not thoroughly verified empirically. Precise and repetitive measurements, not the search for universal truth, characterized their research, despite the French and Italian theory they had learned at West Point. They referred to the "science of hydraulics" but favored mechanical art over scientific zeal as they built wing dams, developed new gauges to read current velocities, and improved sounding devices.[4] Often, they simply found theory inapplicable. Scientists simplified

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neering science," see Boris A. Bakhmeteff, "Science and Engineering: Engineer's Scientific Approach Needed to Guide Man's Destiny," *Civil Engineering* 16 (March 1946): 99–100.

4. A. A. Humphreys and H. L. Abbot, *Report upon the Physics and Hydraulics of the Mississippi River; upon the Protection of the Alluvial Region Against Overflow; and upon the Deepening of the Mouths,* Professional Papers of the Corps of Topographical Engineers, United States Army, no. 4, (1861; reprint, with additions, Washington, D.C., 1876). Chapter 3 is titled "State of the Science of Hydraulics as Applied to Rivers." Arthur Woodford, *Charting the Inland Seas: A History of the U.S. Lake Survey* (Detroit, 1991), 97, 199; Arthur H. Frazier, *William Gunn Price and the Price Current Meters* (Washington, D.C., 1967); Arthur H. Frazier, "Daniel Farrand Henry's Cup Type 'Telegraphic' River Current Meters," *Technology and Culture* 5 (1964): 541–65. On Common Sense philosophers, see Eda Kranakis, *Constructing a Bridge: An Exploration of Engineering Culture, Design, and Research in Nineteenth-Century France and America* (Cambridge, Mass., 1997), 42–43. Among Army engineers, topographers Andrew A. Humphreys and Henry L. Abbot epitomized the Common Sense approach in their monumental, mid-nineteenth-century investigation of the lower Mississippi River. They avidly sought a deeper understanding of the behavior of alluvial rivers, and their antebellum research on the Mississippi River received worldwide scientific acclaim. Yet, they belittled abstract reasoning and considered

or "idealized" theory, focusing on certain forces and ignoring others, in order to gain insights into fundamental relationships. Engineers could not afford such luxury. River engineers came to recognize that idealized fluid mechanic[5] theories, many of French origin but based on Newtonian physics, did not adequately address the multitudinous forces that influence river dynamics.[6]

Consequently, army engineers relied on empirical techniques and inductive reasoning. When planning a project, they would ascertain the river's shape and geometry, the velocity and volume of water passing a particular point, regional geology, and the quantity and concentration of sus-

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the work of the eighteenth century Swiss mathematician Leonhard Euler, sometimes called the founder of fluid mechanics, of "little practical value." They complained (and perhaps unintentionally punned) that Euler assumed "a mathematical fluidity as the basis of his system." Like other army engineers, Humphreys and Abbot thought that neither abstract theory nor physical models could replace field observations. Good results depended on the technology of measurement and human judgment. Humphreys and Abbot, *Physics and Hydraulics of the Mississippi River,* 190. For more on Humphreys and Abbot, see Martin Reuss, "Andrew A. Humphreys and the Development of Hydraulic Engineering: Politics and Technology in the Army Corps of Engineers, 1850–1950," *Technology and Culture* 26 (1985): 1–33; Enzo Levi, *The Science of Water: The Foundations of Modern Hydraulics,* trans. Daniel E. Medina (New York, 1995), 171–73; Todd Shallat, *Structures in the Stream: Water, Science, and the Rise of the U.S. Army Corps of Engineers* (Austin, Tex., 1994), 194–99. On Euler as the founder of fluid mechanics, see G. A. Tokaty, *A History and Philosophy of Fluidmechanics* (Henley-on-Thames, Oxfordshire, 1971), 73–77, and Hunter Rouse and Simon Ince, *History of Hydraulics* (Iowa City, Iowa, 1957), 103–7.

5. The various terms that form the fluid mechanics vocabulary can be confusing. Fluid mechanics is the study of the laws of motion and tendencies to motion and can be divided into aeromechanics and hydromechanics. Aeromechanics is the mechanics of gas, usually air. Hydromechanics is the mechanics of liquids, usually water, and is divided into hydrodynamics, hydraulics, and hydrostatics. According to G. A. Tokaty, "The chief objective of hydrodynamics is to establish theoretical-analytical relationships between the kinematic elements of motion, or flow, and forces which cause and maintain them. Hydraulics studies the laws of motion of liquids in tubes, pipes, channels, elbows, and other engineering devices; as a general rule, its methods are based upon the basic concepts and theorems of hydrodynamics. Hydrostatics deals with the equilibrium of liquids at rest" (Tokaty, 2).

6. On the concept of idealization, see Edwin T. Layton Jr., "Scientific Technology, 1845–1900: The Hydraulic Turbine and the Origins of American Industrial Research," *Technology and Culture* 20 (1979): 64–89; "European Origins of the American Engineering Style of the Nineteenth Century," in *Scientific Colonialism: A Cross-Cultural Comparison,* ed. Nathan Reingold and Marc Rothenberg (Washington, D.C., 1987), 151–66; "Escape from the Jail of Shape: Dimensionality and Engineering Science," in *Technological Development and Science in the Industrial Age,* ed. P. Kroes and M. Bakker (Dordrecht, 1992), 35–68; "Technology and Science, or 'Vive La Petite Difference'," *PSA Today* 2 (1977): 173–84; "The Dimensional Revolution: The New Relations Between Theory and Experiment in Engineering in the Age of Michelson," in *AIP Conference Proceedings 179: The Michelson Era in American Science, 1870–1930,* ed. Stanley Goldberg and Roger H. Stuewer (New York, 1988), 23–38.

pended sediment. They often would analyze the size, movement, and composition of sediment particles, the kind of bed and bank material, vegetation, air and water temperature changes, and even the impact of human settlement.[7] Whenever possible they used historical data to supplement their own research, and then extrapolated into the future. They also carefully studied streams of like age, geology, and physical properties, seeking clues to river behavior.[8] Careful observation, data collection, and argument from analogy—that was the accepted method.

To test engineering designs, engineer officers built on-site some small-scale models of Ohio River locks in the late nineteenth century. However, they lacked faith in three dimensional representations of the river itself and thus eschewed the use of physical models to study river mechanics. In the first quarter of the twentieth century, engineer officers also modeled the giant Wilson Dam on the Tennessee River and, using indigenous material, a section of the earthen Gatun Dam in the Panama Canal.[9]

As navigation projects increased in number and size in the early twentieth century, the eccentricities of river behavior became evident. Neither

7. For an early discussion, complete with sketches, about the instruments used for measuring velocity and for gathering and analyzing sediment samples, see the report of the Missouri River Commission, appendix E, "Instruments and Methods Used in Taking and Reducing Sediment and Velocity Observations on the Mississippi, Missouri, and Arkansas Rivers, 1879," *Annual Report of the Chief of Engineers,* United States Army, pt. 4 (1887), 3121–24. Margaret S. Petersen, *River Engineering* (Englewood Cliffs, N.J., 1986), 7–9. American engineers differentiate between a stream's bed and bank, but European engineers have objected that natural channels frequently constitute one natural unit in which no distinction between bed and bank can be made. To a large extent, the dispute reflects differences in stream profile between major American and European rivers. See Serge Leliavsky, *An Introduction to Fluvial Hydraulics* (New York, 1966), 142.

8. In the case of the Mississippi, army engineers applied some of the lessons learned by European engineers working on the Danube. See Reuss, "Andrew A. Humphreys," 22. A particularly ambitious study employing historical and contemporary data from Europe and India was the Report of the Board of Commissioners on the Irrigation of the San Joaquin, Tulare, and Sacramento Valleys of the State of California, 1873, the first federal irrigation survey; the report is reprinted with an introduction in W. Turrentine Jackson, Rand F. Herbert, and Stephen R. Wee, eds., *Engineers and Irrigation,* Engineer Historical Studies, no. 5 (Fort Belvoir, Va., 1990). Since before the Civil War the Corps had sent engineer officers abroad to study Europe's great rivers and to collect the latest literature on river hydraulics; see Shallat, 100. Mark Twain satirized the scientific use of historical data in *Life on the Mississippi* (paperback reprint, New York, 1981), 93. He suggested that since the lower Mississippi River had shortened itself 242 miles over the previous 176 years, "any person can see that seven hundred and forty-two years from now the Lower Mississippi will be only a mile and three quarters long, and Cairo [Illinois] and New Orleans will have joined their streets together." He goes on to say, "There is something fascinating about science. One gets such wholesome returns of conjecture out of such a trifling investment of fact."

9. House Committee on Rivers and Harbors, *National Hydraulic Laboratory: Hearings on S. 1710,* 70th Cong., 1st sess., 26–27 April 1928, 70–72 (testimony of Chief of Engineers Maj. Gen. Edgar Jadwin).

scientific knowledge nor human resources seemed equal to the challenge of understanding the motion of water. Yet the need to comprehend became even more imperative in the 1930s as the nation embarked on a massive flood control program. The 1936 Flood Control Act inaugurated the "Big Dam Era," which raised new concerns over sedimentation and other problems that could affect reservoir storage capacity or a river's flood carrying ability. Flood control magnified the engineering challenges.

River engineers faced an astounding array of questions. Why do alluvial rivers like the Mississippi weave back and forth like drunks in an alley? Do meanders result from terrain characteristics or from alluvial processes? (Eventual answer: alluvial processes.) The manner in which sediment, or bed-load material, moves along a stream bed attracted attention because of the effects on sediment deposition. Do bed-load particles leap along the bottom like ballet dancers across a stage? Do they slide along in a layer like maple syrup across a stack of pancakes or roll along like bowling balls? (Eventual answer: all three, depending on various factors.) Science desired answers; politics demanded them. Three decades into the twentieth century, engineers still knew far more about the structures they placed in streams than about the streams themselves.

If permanent solutions were to be found, thought many turn-of-the-century scientists, mathematics would provide them. In a deterministic world, nature's laws were both knowable and computable. Differential equations provided the key. Once integrated, they revealed the trajectory of substances as big as a galaxy or as small as an atom. They extended the empirical approach and heightened the researcher's predictive power. When equations proved erroneous, new ones replaced them.[10]

However, differential equations generally required a massive amount of data collection. Lorenz Straub, later a distinguished hydraulic engineer, provides an example. As a young engineer, he worked for the Kansas City district office of the Corps. Daily for nearly two years (1929–30) he and his associates measured the suspended sediment in the Missouri at Kansas City. Finally, he felt confident enough to develop an equation for average conditions. As Straub recognized, the formula ($S = 30.4 \times 10^{-11}\ Q^{2.16}$, in which S is the suspended load in tons per second and Q is the discharge) only worked for that particular river reach. Farther up or down the river, a new formula, with a different coefficient and exponent, would probably be required.[11] Much effort went into small advances. Moreover, as the size, shape, and other physical properties of river reaches changed over time, equations based on earlier measurements proved faulty, and predictions based on those measurements needed revision.

10. Ivar Ekeland, *Mathematics and the Unexpected* (Chicago, 1988), 19–25.

11. Lorenz G. Straub, "Mechanics of Rivers," in *Hydrology,* ed. Oscar E. Meinzer (New York, 1942), 627–28.

In short, mathematics based on empiricism, no matter how ingenious, could not obtain scientific certainty; but engineers studying rivers and other natural phenomena had also concluded that theory and deduction were of limited practical usefulness and often required modification or outright rejection. In his laboratory in Hannover just after the turn of the century, the German engineer Ludwig Prandtl began hammering away at this intellectual logjam, in the process establishing the modern study of fluid mechanics. He and his students, nearly all mechanical engineers, brilliantly melded theoretical mechanics to empirical techniques and engineering design to scientific theory. Through laboratory experiments, they refined and reconciled principles of fluid mechanics reaching back at least to Leonhard Euler and his compatriot Daniel Bernoulli and substantially reduced the gap between theory and practical application (hydraulics).[12]

Prandtl disliked the cumbersome coefficients attached to many equations (such as Straub's, above). He sought "systematic approximations in the general differential equation," an approach that echoed Newtonian physics and anticipated the use in the twentieth century of stochastic numbers to describe randomness.[13] Prandtl's simplified equations "expressed the essential physical relations and dropped the non-essentials," according to Theodore von Kármán, one of his students.[14] By simplifying the equations, Prandtl increased their explanatory power.

12. On Prandtl, see Karl Wieghardt, "Ludwig Prandtl (1875–1953)," in *Hydraulics and Hydraulic Research: A Historical Review*, ed. Guenther Garbrecht (Rotterdam and Boston, 1987), 297–99; Rouse and Ince, *History of Hydraulics* (n. 4 above), 229–32; Hunter Rouse, *Hydraulics in the United States, 1776–1976* (Iowa City, Iowa, 1976), 125–26; Hunter Rouse, "Hydraulics' Latest Golden Age," *Annual Review of Fluid Mechanics* 8 (1976), reprinted in *Selected Writings of Hunter Rouse,* ed. John F. Kennedy (Iowa City, Iowa, 1991), 2:100–11. Guenther Garbrecht, *Wasser: Vorrat, Bedarf und Nutzung in Geschichte und Gegenwart, Buchreihe zur Kulturgeschichte der Naturwissenschaften und der Technik* (Hamburg, 1985), 196–97. Particularly good on Prandtl's analytical approach is Paul A. Hanle, *Bringing Aerodynamics to America* (Cambridge, Mass., 1982), 42–52. Prandtl's contributions are discussed in more technical terms in various chapters of Leliavsky (n. 7 above) and Levi (n. 4 above), 423–31. On Euler's and Daniel Bernoulli's contributions, see Daniel Vischer, "Daniel Bernoulli and Leonhard Euler: The Advent of Hydromechanics," in Garbrecht, *Hydraulics and Hydraulic Research,* 145–56, and Tokaty (n. 4 above), 70–77.

13. Quoted in Levi, 424. On Newton's method, see James Gleick, *Chaos: Making a New Science* (New York, 1987), 217–20; Richard S. Westfall, *Never at Rest: A Biography of Isaac Newton* (Cambridge, 1980); and two books by I. Bernard Cohen, *Franklin and Newton: An Inquiry into Speculative Newtonian Experimental Science and Franklin's Work in Electricity as an Example Thereof* (Philadelphia, 1956), especially 91–150, and *Science and the Founding Fathers: Science in the Political Thought of Thomas Jefferson, Benjamin Franklin, John Adams and James Madison* (New York, 1995), 42–43, 56–58, 76, 99–100. On the use of stochastic numbers in hydrology and fluid mechanics, see Erich J. Plate, "Hydrology and Hydraulics: Partners in Design of Hydraulic Systems," in *Issues and Directions in Hydraulics,* ed. Tatsuaki Nakato and Robert Ettema (Rotterdam, 1996), 365–66. It is worth bearing in mind that "stochastic" comes from the Greek *stochazesthai,* meaning to aim at a target (while not necessarily hitting it dead center).

14. Theodore von Kármán, *Aerodynamics* (Ithaca, N. Y., 1954), 54.

Prandtl's work on turbulence and, more especially, his boundary layer theory excited engineers and scientists in Europe and, following World War I, the United States.[15] Practical design applications ranged from airplane wings to ship hulls to dam penstocks, from improved propellers to better spillways. In river mechanics, Prandtl's research promised to increase understanding of turbulence resistance, bed-load movement, and sediment transport, among other phenomena. His approach required and stimulated the development of river laboratories, especially in Europe. But could models of rivers ever be reliable? Many doubted that anyone could reproduce in a laboratory the natural processes of flowing rivers. In early twentieth century fluvial hydraulics this became a heated question that thoroughly embroiled the United States Army Corps of Engineers.

The Debate over River Modeling

To test models of dams or lock gates, late-nineteenth-century engineers built fixed-bed models, in which the bed and bank materials did not erode and no deposition occurred. However, the models served limited uses. Contrary to Newton's law of similitude, they rarely generated phenomena similar to the prototype. As early as the mid-eighteenth century, Jean Charles de Borda had discovered that the theory of similitude failed to explain much in the complex world of fluid mechanics.[16]

Moreover, river engineers faced formidable problems of scale. If they used the same horizontal and vertical scales to model a river 1,000 miles long with depths of 100 feet or more, the model depths would be much too small to allow testing, and the flow would be laminar rather than turbulent. If the scale were 1:2000, for instance, the channel depth would be half an inch, clearly too small to mimic the flow of water in the prototype.[17] For river models to be more than marginally useful, a different mathematical approach was needed.

That possibility emerged with the development of dimensional analysis. This method yields equations that describe the relationship among selected variables—principally force, mass, length, and time—without reference to specific units of measurement. The equations may be enormously complicated or simple, but they never fully explain phenomena. Rather, they give partial solutions and suggest promising paths for further research. They use

15. Boundary layer theory examines the characteristics of a thin film of a fluid—both air and water are fluids—on the surface of a solid body as it flows over the body.

16. The skill of the army engineers in building fixed-bed models was demonstrated at the 1893 World's Columbia Exposition, where the Corps displayed nineteen models of various river and harbor improvements. Army Corps of Engineers, *World's Columbian Exposition, War Department Exhibit* (Washington, D.C., 1893), 5–56. On similitude, see Layton, "The Dimensional Revolution" (n. 6 above), 26, and "Escape from the Jail of Shape" (n. 6 above), 40–41; Rouse and Ince, *History of Hydraulics,* 123–26.

17. Petersen (n. 7 above), 466–67.

so-called dimensionless parameters. The trick is to ensure that dimensionless parameters for the model and prototype are of equal magnitude—or as close to equal as possible. Once understood, this concept enabled engineers to tinker with the variables and obtain reliable results from distorted models that utilized different vertical and horizontal scales.[18]

A related problem focused on movable-bed models, in which the bed and bank material were erodible and could be transported, thus mimicking actual river behavior. Replicating actual river conditions required putting some sort of material in the model to represent bars and other natural obstacles.[19] What, engineers pondered, should be used for the erodible material, and would that material correctly mimic actual bed and bank material. Moreover, could the complicated forces that govern the flow of river water ever be replicated in a model?

Louis Jerome Fargue constructed the first known movable models in 1875 and used them to examine various river improvements on the Garonne River in Bordeaux. However, the English engineer Osborne Reynolds first properly correlated time and depth scales—necessary for his study of wave motion—in 1885 on a tidal model of the Mersey River near Liverpool. His work led to the development of the Reynolds number, a dimensionless parameter that relates viscosity to inertia and describes the onset of turbulence. Through the application of physical science to traditional engineer empirical research, Reynolds' contribution greatly expanded the potential of river models. Reynolds' contemporary, Hubert Engels, established the first river laboratory at the Technical University in Dresden in the early 1890s (fig. 1). Others soon followed at technical universities in Charlottenburg (Berlin), Karlsruhe, Danzig, and Braunschweig. Italian, Czech, French, and Austrian institutes also constructed facilities.[20]

The earliest hydraulic laboratories in the United States were not designed to study river behavior. The University of California established the

18. Hunter Rouse, *Fluid Mechanics for Hydraulic Engineers* (New York, 1938), 14–15, 24–26; Henry L. Langhaar, *Dimensional Analysis and Theory of Models* (New York, 1951), 1–2; Stephen J. Kline, *Similitude and Approximation Theory* (New York, 1965), 1–9; Layton, "Escape from the Jail of Shape," 45–52. The first textbook in dimensional analysis was Percy Williams Bridgman, *Dimensional Analysis* (Cambridge, Mass., 1921). For a definition of dimensionless numbers, see Army Corps of Engineers, *River Hydraulics,* Engineering Manual 1110-2-1416 (Washington, D.C.), glossary.

19. For definitions of fixed and movable beds, see Army Corps of Engineers, *River Hydraulics,* 106, 108. The American Society of Civil Engineers has reprinted this manual and distributes it as *Technical Engineering and Design Guide No. 18* (New York, 1996). See also Petersen, 464–77 (chapter written by Emmett M. Laursen).

20. Rouse and Ince, *History of Hydraulics* (n. 4 above), 181–82, 206–11; Layton, "Escape from the Jail of Shape," 53–54, and "The Dimensional Revolution," 23–25, 27, 29–31. For a description of some early river laboratories, see Verein Deutscher Ingenieure, *Hydraulic Laboratory Practice* (in German), rev. and trans. John R. Freeman (New York, 1929).

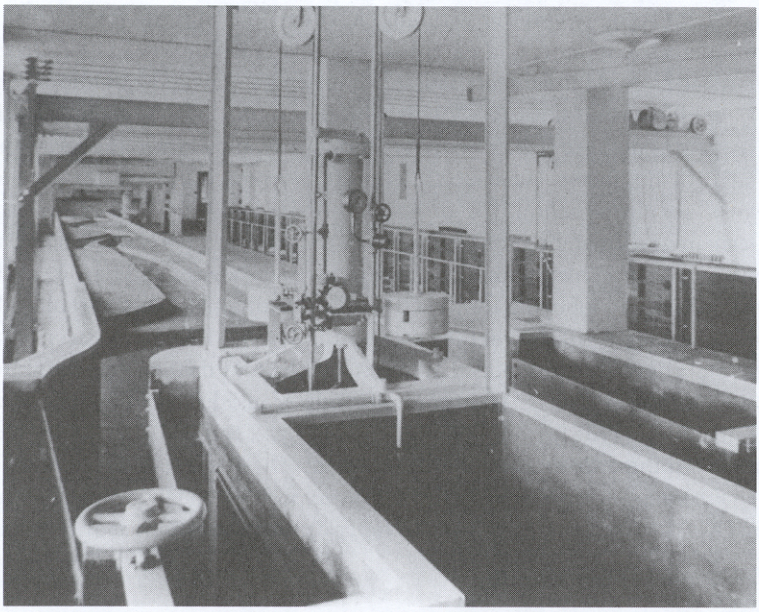

FIG. 1 Hubert Engels' river laboratory in Dresden. The photograph is undated but most likely comes from the 1920s or 1930s. (Author's collection)

first university hydraulic laboratory in the early 1880s to study Pelton waterwheels. Lehigh University, Worcester Polytechnic Institute, and Cornell University followed shortly.[21] By 1922, there were thirty-nine college hydraulic laboratories, twelve commercial, and one government (a hydraulic flume at the National Bureau of Standards [NBS] used principally to test U.S. Geological Survey river gauging meters). In many cases the facilities were minimal and met only the most generous description of "hydraulic laboratory."[22] A river engineer wishing to test new theories might

21. Rouse, *Hydraulics in the United States* (n. 12 above), 53–54, 63. Freeman, *Hydraulic Laboratory Practice,* 697–98; W. Ross Yates, *Lehigh University: A History of Education in Engineering, Business, and the Human Condition* (Bethlehem, Pa., 1992), 84. Leslie Hooper, "Representative Hydraulic Laboratories in the United States and Canada," *Journal of the Boston Society of Civil Engineers* 25, no. 1, sect. 2 (January 1938), 76. There is some disagreement about which college had the first hydraulics laboratory. Rouse makes the case for the University of California and notes that the Lehigh laboratory (1886) was removed in 1895. Hooper, however, says that the earliest hydraulic laboratory at Berkeley dates back only to 1902. It may be that the earlier laboratory did not survive, and later facilities were indeed established in 1902. Yates simply observes that Mansfield Merriman's laboratory at Lehigh was "said to be the first in the United States."

22. J. Waldo Smith and Silas H. Woodard, comp., *A Descriptive Directory of Hydraulic Laboratories in the United States of America* (New York, 1922). Senate Committee on Commerce, *To Establish a National Hydraulic Laboratory: Hearing Pursuant to S.J. Res.*

have felt like Betty Crocker without a kitchen. As late as the mid-1930s no commercial laboratory and fewer than ten college laboratories in the United States addressed fundamental questions relating to fluvial hydraulics.[23]

Beginning in the early 1920s, the distinguished engineer John R. Freeman bemoaned the lack of river laboratories and blamed the U.S. Army Corps of Engineers, "who decry laboratory research in river and harbor work," for the situation.[24] Enormously impressed by river laboratories in Germany, Freeman became convinced that the United States needed at least one outstanding hydraulic laboratory to investigate river and harbor problems. He began lobbying for the establishment of a national hydraulic laboratory in early 1922, when he visited the lower Mississippi River basin during a devastating flood.[25] Later that year he told the Senate Committee on Commerce, "I never was more intensely aroused in my life than I was then, by seeing the fearful conditions down there, and that is why I am here now with these [hydraulic laboratory] plans."[26]

Freeman was right about the Corps's opposition to laboratory research on river and harbor problems. In a letter drafted in the Office of the Chief

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209, 67th Cong., 2d sess., 21 September 1922, 9. In his polemic against the Corps, Arthur Morgan stated that this number of laboratories—about 50 altogether—proved that civilian hydraulic engineers unanimously supported the laboratory approach. While this conclusion may or may not have been warranted, Morgan did not differentiate between river modeling laboratories and those built primarily to test turbines and other hydraulic structures. Had he done so he might well have found supporters of river modeling laboratories far fewer. See Arthur Morgan, *Dams and Other Disasters: A Century of the Army Corps of Engineers in Civil Works* (Boston, 1971), 190.

23. Hooper, 54–55. In 1933, the research committee on the dynamics of streams of the newly created hydrology section of the American Geophysical Union reported that thirty-eight laboratories worldwide had the capability of studying open channel flow and river hydraulics. Of these, twenty-seven were in Europe and one in Canada. The remaining ten were in the United States. Two were federal government laboratories (National Bureau of Standards and the Waterways Experiment Station), and eight were associated with universities. *Transactions of the American Geophysical Union* (hereinafter *TAGU*) (Washington, D.C., 1933), 383–85.

24. Freeman, *Hydraulic Laboratory Practice,* 697.

25. For more on the development of early hydraulic laboratories in Europe and the United States, see Freeman, *Hydraulic Laboratory Practice*; John R. Freeman, "The Need of a National Hydraulic Laboratory for the Solution of River Problems, Etc.," *Transactions of the American Society of Civil Engineers* (hereinafter *TASCE*) 87 (1924): 1033–97; Rouse and Ince, *History of Hydraulics,* 219–28; Rouse, *Hydraulics in the United States,* 102–5; Senate Committee on Commerce, *National Hydraulic Laboratory: Hearing on S.J. Res. 42,* 68th Cong., 1st sess., 21 May 1924, 28–34. Freeman's papers at MIT contain a large collection of correspondence that detail his efforts to convince Congress to authorize a national hydraulic laboratory. See the John Ripley Freeman papers (MC 51), Institute Archives and Special Collections, Massachusetts Institute of Technology Libraries, Cambridge, Massachusetts, boxes 43–45.

26. Senate Committee on Commerce, *To Establish a National Hydraulic Laboratory: Hearing on S.J. Res. 209,* 67th Cong., 2d sess., 8 September 1922, 10.

of Engineers, Secretary of War John W. Weeks told Sen. Wesley L. Jones, chairman of the Committee on Commerce, that "the art of dam construction is so far advanced in this country that a national hydraulic laboratory is not necessary to advance that science."[27] Corps officials threw out other objections: operating a national hydraulics laboratory was not an appropriate federal function, adequate data was already available, and models were useless for analyzing floods on large sediment-bearing streams such as the Mississippi and Missouri.[28]

Freeman continued to lobby, and the Corps's opposition weakened. In April 1926, Secretary of War Dwight F. Davis admitted to Senator Jones that "the art of river regulation and control" required theory and scientific investigation; but, he continued, "Field experience in the solution of problems of this nature is undoubtedly of much greater value than laboratory experiments could possibly be. . . . If however, the proposed laboratory will assist even in small measure in solving the problems of river control and regulation it will be of sufficient value amply to repay the Federal Government its cost." Mirroring the Corps of Engineers position, Davis predictably insisted that any such laboratory should be under the supervision of the War Department.[29]

In 1921, the Philadelphia district engineer, Major L. E. Lyon (one of the relatively few non-West Point officers in the Corps), directed the construction of a model of the mouth and lower part of the Delaware River. Although a simple, concrete, fixed-bed model housed in an old barracks building at Fort Mifflin, Pennsylvania, the model was a significant advance for, like models in Europe, it enabled engineers to analyze river behavior and not just engineering design. "It is believed," boasted Lyon to the chief of engineers, "that the model of the Delaware River referred to is the first of its kind to be constructed in this country, and it is considered desirable to place the Corps of Engineers on record as among the pioneers in applying experimental methods on river models to the improvement of rivers." Built on a horizontal scale of 1:20,000—three inches across the flume represented a mile across the river—the model's dimensions precluded obtaining precise results and it enjoyed only lim-

27. Weeks to Jones, 9 August 1922, box 3008, entry 103 ("General Correspondence, 1894–1923"), Record Group (RG) 77 (Office of the Chief of Engineers), National Archives and Records Administration, College Park, Maryland (NARA); Morgan, 194. Morgan's book reflects some excellent research, but his selective use of quotes and his pronounced prejudice against the Corps significantly undermine the book's integrity.

28. Townsend to the chief of engineers, 29 September 1922, box 3008, entry 103, RG 77, NARA; Morgan (n. 22 above), 189; Senate Committee on Commerce, *To Establish a National Hydraulic Laboratory,* 47; Hoffman to Brig. Gen. Harry Taylor, assistant chief of engineers, 12 September 1922, box 3008, entry 103, RG 77, NARA; Morgan, 189–90, 202–4.

29. Davis to Jones, 23 April 1926, box 50, entry 109 ("General Correspondence Relating to Civil Works, 1923–1942"), RG 77, NARA.

ited use. Still, it contributed to the study of tidal characteristics of the lower Delaware.[30]

Although its opposition to a national hydraulic laboratory weakened, in practice the Corps continued its conservative research approach. Major Lyon's enthusiasm aside, fixed-bed models were generally used to test hydraulic structures, not to study river or tidal mechanics. In line with this tradition, in 1929 the Corps rented quarters in the University of Iowa laboratory to perform experiments on models of dams, spillways, and locks to be constructed on the upper Mississippi River.[31]

However, a conservative approach to laboratory modeling did not signal disinterest in events overseas. Possibly stimulated by Freeman's agitation, Corps officers monitored advances in European laboratories. In 1927, Freeman persuaded Maj. Gen. Edgar Jadwin, the chief of engineers, to direct three engineer officers enrolled at the Massachusetts Institute of Technology to attend the lectures of George Henry De Thierry, a visiting professor who had headed the hydraulic laboratory at Charlottenburg.[32] Again, in 1929, two engineer officers attended the lectures of Theodor Rehbock, head of the hydraulic laboratory in Karlsruhe, when Rehbock visited MIT. One engineer officer forwarded detailed lecture notes to General Jadwin.[33]

The Corps of Engineers also benefited from Freeman's largess. In the mid-1920s, Freeman established the "Freeman Fund" to enable outstanding young hydraulic engineers to visit engineering projects, including laboratories, in the United States or abroad. Freeman decided to have the American Society of Civil Engineers, the Boston Society of Civil Engineers, and the American Society of Mechanical Engineers administer the program and select the scholars. The three organizations chose the first six Freeman Fellows in 1927.[34] In the fellowship's first decade, five engineer officers and one future civilian corps employee received support. They all studied in Germany and became acquainted with European hydraulic laboratories. More than that, they met and continued to correspond with other engineers studying abroad, either on Freeman Fellowships or on university

30. Maj. L. E. Lyon, Philadelphia district engineer, to the chief of engineers (with enclosures), 7 August 1922, box 3008, entry 103, RG 77, NARA; Morgan, 197–98.

31. Enzo O. Macagno, David D. Moran, David W. McDougall, eds., *The First Half Century of Hydraulic Research at the University of Iowa* (Iowa City, Iowa, 1971), 10; Sherman M. Woodward, "Hydraulic Laboratory Research at the State University of Iowa," *Scientific Monthly,* October 1930, 7–9.

32. Freeman to Jadwin, 24 March 1927; Jadwin to John R. Freeman, 2 April 1927; Lt. Col. R. C. Moore, chief, Military Division, to the district engineer, Boston, 4 April 1927; and Freeman to Jadwin, 6 April 1927, all in box 50, entry 109, RG 77, NARA.

33. Col. S. A. Cheney, district engineer, to Jadwin, 29 April 1929, with enclosures, photocopies filed in the library of the Waterways Experiment Station (WES), Vicksburg, Mississippi.

34. Rouse, *Hydraulics in the United States* (n. 12 above) 106–7.

scholarships. From the ranks of these study-abroad scholars came many future leaders of the hydraulic engineering profession.[35]

Support for foreign travel also existed outside of the Freeman program. After World War I, the Corps commonly sent most engineer officers to a civilian engineering college for one year, and a number of them won scholarships for study abroad. In early 1928, for example, three engineer officers were Rhodes Scholars at Oxford.[36] In these ways, engineer officers studied the latest theories of river mechanics, much based on laboratory research, while Jadwin continued to express strong reservations to a United States national hydraulic laboratory.

The Establishment of the Waterways Experiment Station

In 1927, a disastrous flood devastated the lower Mississippi Valley. The following year, Congress passed a flood control act that authorized the Corps to implement the so-called Jadwin plan to control floods in the valley. Part of the plan included the construction of a vast river hydraulics laboratory somewhere along the lower Mississippi River that would be entirely under the Corps's control.[37]

General Jadwin included a laboratory in his plan in deference to the congressmen and engineers, including professional societies, who vigorously supported it, especially after the 1927 flood. If a laboratory were constructed, Jadwin strongly believed it should be under the control of the Corps and not the National Bureau of Standards, part of the Department of Commerce.[38] As he told the House Committee on Rivers and Harbors in

35. Ibid., 109. In the list of Freeman Fellows, Rouse fails to identify Clarence E. Bardsley as a civilian employee of the Corps.

36. House Committee on Rivers and Harbors, *National Hydraulic Laboratory* (n. 9 above) 72.

37. Jadwin's plan was printed in House, *Flood Control in the Mississippi Valley,* 70th Cong., 1st sess., 8 December 1927, H. Doc. 90. The plan was authorized in the *Flood Control Act of 1928* (*Statutes at Large* 45 [1929]: 534), signed into law on 15 May 1928. For more on the 1927 flood, see Pete Daniel, *Deep'n As It Come* (New York, 1977); Arthur DeWitt Frank, *The Development of the Federal Program of Flood Control on the Mississippi River* (New York, 1930); Bruce Alan Lohof, "Hoover and the Mississippi Valley Flood of 1927: A Case Study of the Political Thought of Herbert Hoover" (D.S.S. diss., Syracuse University, 1968); Martin Reuss, "The Army Corps of Engineers and Flood-Control Politics on the Lower Mississippi," *Louisiana History* 23 (spring 1982): 131–48.

38. Quotations from prominent engineers favoring a government laboratory appear in a report submitted to Congress by Herbert Hoover, secretary of commerce; see House Committee on Rivers and Harbors, *National Hydraulic Laboratory,* 40–43. This report is evidently a revised version of a report first distributed the previous September that may have been partially drafted by Freeman. See "The Need for a National Hydraulic Laboratory," 6 September 1927, box 50, entry 109, RG 77, NARA. Freeman, of course, led the lobbying for the government laboratory and lambasted the Corps for earlier opposing the laboratory. See House Committee on Rivers and Harbors, *National Hydraulic*

April 1928, the "essential thing for the staff of a successful laboratory is to have immediate personal contact with the men who are doing the field work," not, as Freeman and Secretary of Commerce Herbert Hoover thought, to isolate scientific research from work in the field or to ensure that hydraulic, aerodynamic, and structural specialists could work together.[39]

The chief of engineers also desired that the laboratory be close to the river under investigation, in this case the Mississippi, so that hydraulic tests used "the same water and the same mud" that the river contained.[40] He selected the Memphis vicinity for the laboratory site, but in November 1929 Maj. Gen. Lytle Brown, the new chief of engineers, moved the site to Vicksburg, Mississippi, where the Corps's new Lower Mississippi Valley Division office was to be situated. The new laboratory would simply be called the Waterways Experiment Station or WES, a name designed to placate Hoover (by this time president), Freeman, and supporters of a national hydraulic laboratory in the Department of Commerce. As one historian has noted, the words "hydraulic," "research," and "laboratory" purposely do not appear.[41]

More than just a bureaucratic turf war, the dispute between Hoover and Jadwin went to the heart of research engineering. Do research engineers belong in laboratories or in the field? What conditions are necessary to ensure that prototype and model share approximately the same parameters? Should government laboratories serve basic knowledge or technological application, and can the two approaches be practically separated in engineering research? Ironically, WES, a laboratory the Corps did not particularly want and had earlier opposed, became a bureaucratic petri dish in which to test these issues.

For the moment the dispute between Hoover and Jadwin ended in anticlimax. On 14 May 1930, President Hoover signed an act authorizing a National Hydraulic Laboratory at the Bureau of Standards. General Brown had removed the only significant obstacle to authorization when he announced his support of the proposal earlier that year. The reversal of the Corps's position amazed the House Committee on Rivers and Harbors. In explanation, Brown wrote to the Secretary of War: "The matter of opposing the proposed hydraulic laboratory at the Bureau of Standards rests

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Laboratory, 21–29; "Engineer Favors Study of Floods," *Providence Journal,* 24 April 1927; and John Ripley Freeman, "Needed: More Science in Flood Control," *Technology Review,* December 1927, 95–102.

39. House Committee on Rivers and Harbors, *National Hydraulic Laboratory,* 66. Again, the points Hoover made and to which Jadwin referred were also made in the earlier draft of the previous September.

40. Ibid., 64.

41. Ben H. Fatherree, "History of the Corps of Engineers Hydraulics Laboratory," manuscript, 15–16, Office of History, Headquarters, U.S. Army Corps of Engineers (OH HQUSACE), Alexandria, Virginia.

entirely with the former chief of engineers [Jadwin], and not with the Corps of Engineers. I favor such a laboratory and have some time since informed those who have approached me on the subject that I saw no objection to it whatsoever."[42] Placing all the blame on Jadwin was at best disingenuous. Other officers had agreed with Jadwin, and Brown hardly could have publicly opposed a plan embraced by his commander-in-chief.

Subsequently, a completely unanticipated paradox occurred. While WES flourished, the NBS laboratory disappointed its many advocates. Even Freeman's support diminished as he refused to tailor his plans for the laboratory to NBS budget limitations. Other problems ensued. New Deal politics over the control of research budgets hounded the Bureau of Standards, NBS hydraulic laboratory directors exerted insufficient leadership, and during World War II aerodynamics researchers temporarily utilized laboratory facilities, forcing the shelving of hydraulics projects.[43]

While still chief of engineers, General Jadwin had chosen twenty-nine-year-old 2d Lt. Herbert D. Vogel as the first director of WES. Vogel had recently returned from Europe, where he had spent the academic year 1928–29 studying under De Thierry at the Technical University in Charlottenburg. He received his Ph.D. in 1929. At General Jadwin's direction, he had also visited hydraulic laboratories in Germany, the Netherlands, Czechoslovakia, France, and Italy. In his travels, he met both European and American engineers. Upon his arrival in Vicksburg, Vogel immediately began to make use of his contacts. At the same time, his doctorate from Berlin earned him credibility and respect among civilian engineers.[44]

Vogel's first job was to construct the facilities, and he discharged the responsibility with characteristic vigor. From the beginning Vogel desired a laboratory in the monumental tradition typical of Corps projects since the early nineteenth century.[45] While at Obernach, Germany, visiting Hubert

42. Lytle Brown to the secretary of war, memorandum, "Instructions by the President as per 9 January 1930," 21 January 1930, box 51, entry 109, RG 77, NARA; Rouse, *Hydraulics in the United States* (n. 12 above), 108–10.

43. Rouse, *Hydraulics in the United States,* 110–11; Carroll W. Pursell Jr., "A Preface to Government Support of Research and Development: Research Legislation and the National Bureau of Standards, 1935–41," *Technology and Culture* 9 (1968): 145–64; Rexmond C. Cochrane, *Measures for Progress: A History of the National Bureau of Standards* (Washington, D.C., 1966), 400–401. For more on the origins of the NBS Hydraulic Laboratory, see *Annual Report of Director of the Bureau of Standards to the Secretary of Commerce for the Fiscal Year Ended June 30, 1930* (Washington, D.C., 1930), 2; U.S. Department of Commerce, *Technical News Bulletin of the Bureau of Standards* 158 (Washington, 1930), 53; "National Hydraulic Laboratory," *Science,* 4 July 1930, 7–8; George K. Burgess, "The National Hydraulic Laboratory at the Bureau of Standards," *Civil Engineering* 1 (1931): 911–16. Burgess's article includes floor plans of the laboratory.

44. Fatherree, 17–18; Herbert Vogel, "Conception, Birth and Development of the U.S. Waterways Experiment Station," manuscript, General Files, folder 123-6, OH HQUSACE 5–13.

45. On the Corps's monumental tradition, see Shallat (n. 4 above), esp. 127–40.

Engel's outdoor laboratory, he was reputed to have said, "In the United States we will build like at Obernach—only ten times as large."[46] Jadwin had severely constrained Vogel at Memphis by limiting his first year expenditures, salaries and construction costs together, to $50,000. However, at Vicksburg under the new chief of engineers, General Brown, no such constraints appeared. For the laboratory's site, the Corps purchased 147 acres of land four miles south of the city; WES eventually grew to nearly five times that size.[47]

Vogel completed the rough laboratory facilities in December, 1930, and the Corps began building the first models a month later. The previous July WES had already produced its first research paper. Called paper H and titled *Sediment Investigations on the Mississippi River and Its Tributaries Prior to 1930,* the study offered a detailed historical overview of the subject.[48] Once engineers completed the models, their initial tests dealt only with the hydraulics of flow in open channels; neither bed movement nor structures were considered. Among other findings, the tests proved conclusively that substantial model distortions of long lengths of a river could still produce successful results.

The first test at WES that produced immediate practical results was a preliminary investigation of Mississippi River backwater flooding on the Illinois River.[49] The 1928 flood control act obligated the federal government to fund the cost of levees along the Illinois River up to the limit of the Mississippi River's influence, and the Mississippi River Commission needed to know quickly the full extent of the government's responsibility. Fortunately for Vogel, who had hoped for more time before applying models to practical problems, he persuaded Clarence E. Bardsley, a professor of hydraulic engineering at the University of Missouri, to assist him at WES during the year 1930–31. Bardsley had been a Freeman Fellow in Berlin in 1928–29 when Vogel had first met him.

At WES Bardsley successfully applied dimensional analysis to several problems relating to distorted models. He did so with slide rule and

46. Vogel, "Conception, Birth and Development," 14–15. Writing years later, Vogel could not recall making the remark, but conceded he might very well have.

47. Ibid., 13–14; Fatherree (n. 41 above), 18–19. The history of the rather complicated real estate transactions to acquire land for WES is related in Gordon A. Cotton, *A History of the Waterways Experiment Station, 1929–1979* (St. Louis, 1979), 8–10.

48. U.S. Waterways Experiment Station, *Sediment Investigations on the Mississippi River and Its Tributaries Prior to 1930,* paper H (Vicksburg, Miss., 1930). Vogel had the idea to name the first nine papers produced by WES using the letters in the word "hydraulic" sequentially. Thus, the second paper was paper Y. After paper C was published, the laboratory returned to numerical order with paper 10. Vogel's inspiration has confused librarians around the world, who always want to put paper A as the first WES report. Bureaucrats rarely consider the poor librarian!

49. Herbert D. Vogel, "Research at Waterways Experiment Station," *The Military Engineer* 24 (July–August, 1932): 331–34.

mechanical calculator and despite challenges that might have overwhelmed others. Indeed, the story suggests the proverbial silk purse made from the sow's ear, for Bardsley ran tests in models that were positively crude. He carved out the fixed-bed Illinois River model with a grapefruit knife using a template based on closely spaced soundings of the Illinois River. Thus began the mix of art and science that characterized so much of WES's future accomplishments.[50]

The challenges and pressures left the personnel at WES undaunted. In mid-1931, Col. W. B. Gregory, a reserve officer in the Corps of Engineers and a Tulane civil engineering professor, visited WES and reported to the chief of engineers: "The methods of research as used in the laboratory seem to be excellent and full of promise." The "energy and enthusiasm" of the staff particularly impressed him.[51] Meanwhile, support for hydraulic modeling emerged in both professional and popular literature. In mid-1931, *Popular Mechanics* published a laudatory article, "Taming Ol' River," that lauded WES's potential, even though the practical application had yet to be determined.[52] The following year, Benjamin F. Groat, a distinguished private engineer (and early supporter of a national hydraulic laboratory), proclaimed: "In the present state of knowledge a properly constructed and properly tested model will answer the difficult questions of hydrodynamics much more quickly and accurately than the most profound mathematical analysis."[53]

50. Herbert D. Vogel and John Paul Dean, "Geometric versus Hydraulic Similitude: Factors to Be Considered When Using Models to Study Flows in Open Channels," *Civil Engineering* 2 (1932): 467–71; Vogel, "Conception, Birth and Development" (n. 44 above), 19–20; Rouse, *Hydraulics in the United States* (n. 12 above), 109–17. Vogel wrote that Bardsley came to WES in the summer of 1931, but Bardsley indicated in the 1941 *Who's Who in Engineering* that he served in 1930–31. This is undoubtedly correct since the study (U.S. Waterways Experiment Station, *Experiment to Determine the Limit of Backwater Influence in the Illinois River,* paper Y [St. Louis, 1931]) was published in February 1931. Bardsley later served in the Pittsburgh district office of the Corps. For a clear explanation of the ways in which WES handles questions of distortion, see Hooper (n. 21 above), 254–58. The early experiments at WES might fruitfully be compared with interwar tests of the Bureau of Public Roads (BPR). Bruce Seely has shown that the BPR's "infatuation" with science led it to conduct a series of experiments that yielded little practical information. Soil mechanics—like fluid mechanics—was simply too complex for strictly theoretical treatment. WES engineers showed more flexibility in understanding this fundamental point. Bruce Seely, "The Scientific Mystique in Engineering: Highway Research at the Bureau of Public Roads, 1918–1940," *Technology and Culture* 25 (1984): 798–831.

51. Col. W. B. Gregory to Maj. Gen. Lytle Brown, memorandum, "Report on U.S. Waterways Experiment Station at Vicksburg, Miss.," 11 July 1931 (copy), Freeman papers, box 46, MIT.

52. "Taming Ol' Man River," *Popular Mechanics,* June 1931, 899–901.

53. Benjamin F. Groat, "Theory of Similarity and Models," *TASCE* 96 (1932): 273. See also Groat's response to the discussants on 335–86. Groat's involvement with modeling was relatively long for an American engineer. Fourteen years earlier he had written another article dealing with models: "Ice Diversion, Hydraulic Models, and Hydraulic Similarity," *TASCE* 82 (1918): 1138–51.

The Staff

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Like the facility, the staff was very much Vogel's creation. The young director wished to obtain the very best talent from both the civilian and military communities. He persuaded Chief of Engineers Brown that selected officer graduates with recent B.S. or M.S. degrees in civil engineering (they all also had West Point undergraduate degrees) should come to WES to be "assistants to the Director." At WES these officers usually served only a brief internship, but the time could be extended. A number of them later became distinguished army generals and one, Lt. Paul Thompson, was a Freeman Fellow in Berlin from 1935 to 1937 and became the third director of WES in 1937.[54]

Vogel also valued more informal contacts, such as Lt. Hans Kramer. Born in Germany, but a naturalized American and West Point graduate, Kramer was the first Corps Freeman Fellow. He spent the years 1930–32 at the Technical University at Dresden, where he received a Ph.D. under the guidance of Engels. He and Engels coauthored an article showing how models help explain the manner in which running water carries bed-load material (*Geschiebe*) along a river's bottom.[55] Subsequently assigned to the Memphis district office, Kramer became Vogel's close friend, and traveled down to Vicksburg frequently in the years 1932–35. The two young officers engaged in many animated discussions, and Kramer assisted in developing some of the first tests at WES dealing with bed-load. Both Kramer and Vogel also became generals.[56]

Vogel's success with recruiting civilians rested very much on the poor employment conditions brought on by the Depression. After receiving permission to write his own travel orders—remarkable authority for a second lieutenant—Vogel went to all the major civil engineering universities. That access enabled him to meet not only young engineer officers with potential, but also promising civilian engineers. President Hoover's economy pro-

54. Thomas Sturm, "Oral History Interview with Brigadier General Paul W. Thompson (USA, ret.)," OH HQUSACE, 45–47; Fatherree (n. 41 above), 25; official biographical files, OH HQUSACE. Other young West Point lieutenants who interned at WES and later became Army generals were Kenneth D. Nichols, with a new B.S. from Cornell, and Thomas Lane and John (Jack) Person, both with B.S. degrees from MIT.

55. Hubert Engels, assisted by Hans Kramer, "Large-Scale Experiments in River Hydraulics," *Civil Engineering* 2 (1932): 670–74. The German word *Geschiebe,* literally "that which is shoved," is often used in hydraulics literature to denote bed-load.

56. Rouse, *Hydraulics in the United States* (n. 12 above), 109, 115–16; Public Works Historical Society, "Oral History Interview with General Herbert D. Vogel," transcript, OH HQUSACE, 45–48. Kramer circulated his ideas concerning bed-load in the professional literature. Hans Kramer, "Sand Mixtures and Sand Movement in Fluvial Models," *Proceedings of the American Society of Civil Engineers* 60 (1934): 443–83, and "The Practical Application of the Du Boys Tractive-Force Theory," *TAGU,* pt. 2 (1934): 463–66.

gram prohibited Vogel from making any new civil service appointments, but he hired temporary help at $100 per month. With dim employment prospects elsewhere, positions in the Corps of Engineers (or the Bureau of Reclamation) proved particularly enticing. Several "temporary" recruits stayed with WES and had long and distinguished careers.[57] Engineers with academic appointments worked at WES for relatively short periods of time.

Luck had something to do with selections too. Vogel hired MIT graduate Spencer Buchanan in the summer of 1933, when Buchanan arrived at WES on his way home to Texas with his family. Buchanan, who had studied under Karl Terzaghi, the founder of modern soil mechanics, had failed to find employment elsewhere. He stayed at the station until 1940, turning a small soils research laboratory into a distinct organization with work that extended far beyond support to the hydraulic engineers. Buchanan developed and maintained close ties between WES and MIT and Harvard, where Arthur Casagrande, another Terzaghi student, taught. He contributed immeasurably to WES's expertise in areas such as sediment and bed-load movement in rivers and underseepage of dams.[58]

WES's second director, Lt. Francis H. Falkner, who had interned at WES in 1933, was not as fortunate as Vogel. In 1935, Falkner asked Lorenz Straub, then an associate professor at the University of Minnesota, to become WES's first technical director, the highest civilian position at the laboratory.[59] A former Corps of Engineers employee in Kansas City with a continuing interest in Missouri River sedimentation problems, a promoter of hydraulic modeling, and chair of the committee on stream dynamics of the American Geophysical Union's Hydrology Section, Straub seemed a superb choice.[60]

57. Fatherree, 24–25. Two University of Illinois graduates, Joseph B. Tiffany and Frederick R. Brown, came to WES in the early 1930s and ended their careers as the WES technical director, the top civilian position. Tiffany was technical director from 1940 to 1968. Brown succeeded Tiffany in 1969 and remained in that position until his retirement in 1985.

58. Ben Fatherree, "History of the Geotechnical Laboratory," manuscript, OH HQUSACE, 4–13; Vogel, "Conception, Birth and Development," 22; Cotton (n. 47 above), 24–26.

59. Straub to Falkner, 6 April 1935, and Falkner to Straub, 17 May 1935, both in the Lorenz G. Straub papers, file "Positions offered LGS," St. Anthony Falls Hydraulic Laboratory (hereinafter, SAFHL), University of Minnesota, Minneapolis, Minnesota.

60. Straub's vita can be found in two files of his papers, "Positions offered LGS" and "Miscellaneous Correspondence for Lab History." SAFHL. On the origins of the Hydrology Section, see O. E. Meinzer, "Formation of the Section of Hydrology of the American Geophysical Union," *TAGU* (1931): 227–29, and unpublished notes compiled by Charles A. Whitten, "Early History of Hydrology in the IUGC and AGU," American Geophysical Union, Washington, D.C. I am grateful to Mr. Edward Todd of the AGU for providing Whitten's notes to me. On Straub's work, see his first report as chairman of the stream dynamics committee, Lorenz G. Straub, "On Dynamics of Streams," *TAGU* (1933): 379–88. The article lists all hydraulic laboratories in the world. His committee reports continued in subsequent volumes of *TAGU* into the early 1940s.

Moreover, he was in the middle of research on sediment transportation, using some of the data he had collected at Kansas City, and his work nicely complemented investigations at WES.

However, Straub's initial enthusiasm for the position declined when the University of Minnesota offered him a promotion to full professor. He realized that civil service salaries could not possibly compete with his remuneration from both academic and consulting work. Failing to obtain Straub, Falkner dropped the idea of a technical director and promoted two of his staff as "technical assistants."[61] Though unsuccessful, Falkner's invitation shows the strong interest of WES's leadership in obtaining the best available talent from the academic world.

The Corps's major rival for federal water projects was the Department of Interior's Bureau of Reclamation. One might expect, therefore, that the two agencies' hydraulic laboratories would exhibit similar characteristics, especially since numerous federal engineers worked at both laboratories during their careers. Yet important and illuminating differences existed. Under Vogel, the staff at WES grew continually despite Hoover's economy program. From just 21 employees in 1931, the staff steadily increased to 215 people in 1934, including 9 professional engineers, 66 subprofessional engineers, 7 clerks, 14 tradesmen and skilled workmen, and 119 laborers. In contrast, the Bureau's laboratory began with a staff of 12 in 1930 and climbed to only 42 in 1934, of whom 22 had temporary appointments supported by Public Works Administration funds.[62] These numbers reflect the fact that, unlike WES, physical modeling at the Bureau directly resulted from, and depended upon, the planning and construction of just one project, Boulder (Hoover) Dam. Into mid-1933, the dam remained the laboratory's focus.[63]

Aside from the disparity in personnel numbers, the Bureau and Corps laboratories also differed somewhat in their approach to research. Both agencies emphasized practical applications in their research activities, but

61. Straub to Falkner, 21 May 1935; Falkner to Straub, 27 May 1935; Straub to Falkner, 31 May 1935; Falkner to Straub, 4 June 1935, all in Straub papers, file: "Positions offered LGS," SAFHL. Fatherree, "History of the Hydraulics Laboratory" (n. 41 above), 69.

62. Fatherree, "History of the Hydraulics Laboratory," 26; "Hydraulic Research," a personnel list compiled by E. W. Lane, 30 April 1934, Record Group 115 (Bureau of Reclamation), General Correspondence, Personnel, Denver, 1906–1942, Box 16, NARA, Rocky Mountain Branch, Denver, Colorado (I thank former Bureau of Reclamation historian Robert Autobee for locating this record for me); Hunter Rouse, ed., *Hydraulics, Fluid Mechanics, and Hydrology at Colorado State University* (Fort Collins, 1980), 11.

63. For the history of the Colorado State University hydraulic laboratory, the Bureau of Reclamation's first facility, see Hunter Rouse's historical sketch in Rouse, *Hydraulics, Fluid Mechanics, and Hydrology*. Also see U.S. Department of the Interior, Bureau of Reclamation, *Hydraulic Laboratory Practice* (Denver, 1953), 1–2, and *Model Studies of Spillways,* Boulder Canyon Project Final Reports, pt. 6 (Hydraulic Investigations), bulletin 1 (Denver, 1938), 15–18. After World War II, the Reclamation laboratory was relocated to the Denver Federal Center.

the Corps's flood control responsibilities stimulated more fundamental research in actual river behavior—particularly in the Mississippi's. The Corps needed to know how the Mississippi "worked" in order to develop a comprehensive flood control scheme. In contrast, in the words of Bureau engineer Jacob Warnock, "every problem studied in the Bureau of Reclamation laboratories relates to the specific design of an actually proposed structure." In fact, most of the laboratory's work responded to specific queries from the Bureau's design engineers.[64]

Catastrophe—the 1927 Mississippi River flood—catalyzed the establishment of the Waterways Experiment Station, and another catastrophe, the Depression, provided an outstanding cadre of engineers in WES's formative years. Freeman fellowships and university scholarships enabled some of the best young engineers to study overseas and bring back the latest developments in physical modeling and fluid mechanics. Beginning in 1933, New Deal public works programs provided projects and funding that increased WES's workload and enhanced its visibility. Except for some early army support for study overseas, none of these factors emanated from within the Army Corps of Engineers, or, for the most part, even from within the engineering profession. WES resulted from external social and political influences that only tangentially dealt with research engineering.

Experiments at WES

WES helped define the possible in both theory and practical application. The number of experiments mushroomed as regional Corps offices sought specific information on planned or ongoing construction projects. Generally, these offices funded the tests, using construction or operation and maintenance monies.[65] WES personnel introduced the results into the

64. Jacob E. Warnock, *Hydraulic Laboratory Report No. 31: Hydraulic Model Testing of Structures* (Denver, 1937), 9. Bureau of Reclamation, *Hydraulic Laboratory Practice,* 1. The Bureau of Reclamation seemed to be intent on emphasizing its practical mission. Responding to an inquiry from the American Geophysical Union about the Bureau's work on flood wave phenomena, Bureau of Reclamation engineer Ivan E. Houk noted that "since the laboratory-work is conducted primarily for the purpose of developing adequate and satisfactory designs, the investigations of wave-phenomena are more or less of an incidental nature"; *TAGU* (1938): 359. It is worthwhile noting that the Bureau's design and laboratory engineers could easily communicate with one another since most lived and worked in the Denver area. This sharply contrasts with the situation of the Corps of Engineers, where the design work was done in regional district offices and the testing was done at WES.

65. The fact that science—even basic science—could be funded out of monies meant for public works projects seems to have escaped historians who have accused New Deal administrators of lack of support for the physical sciences. Carroll W. Pursell Jr. wrote that the New Deal was "no new deal for the physical sciences" in "The Farm Chemurgic Council and the United States Department of Agriculture, 1935–1939," *Isis* 60 (fall 1969):

technical literature, but the laboratory's raison d'être was practical application. By July 1933, forty-six tests were completed or in progress at WES. These included a number dealing with specific reaches of the Mississippi River and its tributaries, the Ohio River, St. Clair River, Brazos River, and Columbia River. By 1936, the number had increased to 164.[66]

One aspect of model testing that attracted much attention at WES was the appropriate bed material to use in movable models. Eventually, over sixty materials, including sand, finely ground coal, walnut shells, loess, slag, Gilsonite, and Haydite were tested.[67] In one of the more novel tests, Vogel experimented with oat grains to determine how water flowed around bends. As he later explained: "An oat grain has a natural streamlined shape. And like any such shape it would point in the direction of flow, yet move across the current by little bounces. This led us to believe that in a broad and relatively shallow river the movement of the bed particles is in the direction of decreasing water." In this way, engineering intuition preceded scientific discovery. However, Paul Thompson remembered the story a bit differently. He recalled that the idea of using oat grains came from observing Vogel's wife using them in a recipe and wondering "whether those oat

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307. Spencer R. Weart argued that New Deal support of fundamental research lagged behind most other Western nations; see "The Physics Business in America, 1919–1940: A Statistical Reconnaissance," in *The Sciences in the American Context: New Perspectives,* ed. Nathan Reingold (Washington, D.C., 1979), 312–13. A. Hunter Dupree hardly mentioned New Deal aid to the physical sciences in *Science in the Federal Government: A History of Policies and Activities,* 2d ed. (Baltimore and London, 1986), 361–67. See also Daniel Kevles, *The Physicists: The History of a Scientific Community in Modern America* (paperback reprint, with a new preface by the author, Cambridge, Mass., 1995), 252–66.

66. U.S. Department of Commerce, Bureau of Standards, *Hydraulic Laboratories in the United States* (Washington, D.C., 1933), 67–68; F. H. Falkner, *Hydraulic Laboratory Projects of the Corps of Engineers, U. S. Army* (Vicksburg, Miss., 1936), 7. Corps-sponsored experiments at other laboratories supplemented the work at WES. The St. Paul district maintained an office at the University of Iowa laboratory until 1948, and modeled numerous Upper Mississippi locks and dams there. In 1934, the Corps of Engineers built a tidal laboratory at the University of California, Berkeley. At the Carnegie Institute of Technology the Corps supported research on Lock No. 9 on the Allegheny River, Tygart Dam in West Virginia, and other projects in Pittsburgh District. Army engineers funded the construction of models of the Cape Cod Canal at MIT. By 1936, university laboratories were conducting a total of twenty-nine different investigations for the Corps. Occasionally, too, the Corps would build on-site laboratories, such as the Bonneville Hydraulic Laboratory, built to support the construction of the Corps's Bonneville Dam on the Columbia River. See Falkner, 7; Macagno, Moran, and McDougall (n. 31 above), 10, 13; Hooper, "Representative Hydraulic Laboratories," 59–62, 74–82, 101, 127–29, and 193–97.

67. Fatherree, "History of the Hydraulics Laboratory" (n. 41 above), 75. The experiments continued under the supervision of Vogel's successor, Lieutenant Falkner. The four most promising substances turned out to be a limed resin, a certain coal from Kansas, Haydite, and Gilsonite. Haydite is the trade name for a porous, granular material used to make lightweight concrete. Gilsonite, named after its discoverer S. H. Gilson, is a black bitumen found in Colorado and Utah.

grains would do anything."[68] Kitchen technique may have preceded engineering insight.

Vogel's vigorous advocacy of model investigations set the tone at WES. In various professional journals, Vogel informed the engineering profession of WES research contributions. At the same time he warned that "a complacent attitude" toward scale models was "far from justified."[69] He described how WES constructed and operated movable models in an April 1933 paper, but his most complete explanation of laboratory modeling appeared the following November. In the *Proceedings of the American Society for Civil Engineers,* he discussed the history of three-dimensional modeling, geometric versus dynamic relationship (undistorted linear relationship versus one where various factors or physical properties must be constant), bed movement and turbulence in open-channel models, and movable versus fixed beds.[70] Mainly through Vogel's efforts, WES's fame rapidly spread. By the time Vogel left Vicksburg, in mid-1934, model testing there had already clarified the ways water moves through river bends on large rivers such as the Mississippi and bed-load material moves at a stream's fork.[71] In a short time, WES had made significant contributions to the study of fluvial hydraulics.

A look at one set of experiments illustrates WES's empirical procedures. In 1932, the chief of engineers directed WES to study the bed-load of the Mississippi River. There were two objectives. The first was "to discover and evaluate laws to the end that the river hydraulician might be able to calculate the action of a given bed material under given conditions." The second and more immediate was to discover basic laws relating to bed-load movement.[72]

Over the next two and a half years ten series of experiments were conducted in a tilting flume that held a sand bed. For bed-load material, researchers went right to the source, using various kinds of natural mixtures

68. Public Works Historical Society, "Oral History Interview with General Herbert D. Vogel" (n. 56 above), 41; Vogel, "Conception, Birth and Development," 21; Sturm, "Oral History Interview with Brigadier General Paul W. Thompson (USA, ret.)" (n. 54 above), 54.

69. Vogel and Dean, "Geometric versus Hydraulic Similitude" (n. 50 above).

70. Herbert D. Vogel, "Movable Bed-Models," *TAGU* (1933): 509–12, and "Practical River Laboratory Hydraulics," *Proceedings of the American Society of Civil Engineers* 59 (1933): 1413–39. The latter paper, along with the discussion it generated, was reprinted in the *TASCE* 100 (1935): 118–44.

71. Herbert D. Vogel and Paul W. Thompson, "Flow in River Bends: Recent Experiments on a Mississippi River Model Discredit Helicoidal Theory of Flow," *Civil Engineering* 3 (1933): 266–68; Herbert D. Vogel, "Movement of Bed Load in a Forked Flume: Conclusions Drawn from Tests at the U.S. Waterways Experiment Station," *Civil Engineering* 4 (1934): 73–77; Gerard H. Matthes, "Diversion of Sediment at Branching Channels," *TAGU* (1933): 506–9. Fatherree, "History of the Hydraulics Laboratory," 54–55.

72. U.S. Waterways Experiment Station, *Studies of River Bed Materials and their Movement, With Special Reference to the Mississippi River,* paper 17 (St. Louis, 1935), 1.

taken from the Mississippi River close to Vicksburg. The other test variables were the slope of the flume and the depth of the water. The engineers developed a special automatic sandfeed to ensure that equal amounts of mixture entered and left the flume. Definitions dealing with size and description of bed-load came from Lieutenant Kramer's dissertation, "Modellgeschiebe und Schleppkraft" (Bed-load in models and tractive force).

Two time-consuming problems dealt with the value of the "critical tractive force" that brings about movement of the bed-load material and the rate of movement of a given material at various values of the tractive force. Evidently the work took a toll on the researchers' eyesight, for it was difficult to determine when the bed-load first moved. The problem became "especially serious" when tests called for the use of turbid water.[73]

Nevertheless, the staff succeeded in developing an equation for finding the rate of bed-load movement "for a given sand mixture resulting from a given set of hydraulic conditions." The equation, said the final report, was not intended as the "final solution to the problem of bed-load movement" and was to be used with caution. It could be applied only to sand mixtures and gradients within certain size ranges. The researchers reminded readers that the results were obtained in a straight flume with a uniform flow. Their application to rivers with curved channels and varying cross sections—which includes practically all rivers—"has not yet been established."[74]

In fact, engineers criticized both the equation and the term "critical tractive force." Hans Albert Einstein, perhaps the foremost theoretician in the field of bed-load movement, argued that "a distinct condition for the beginning of transportation does not seem to exist. It is just as impossible to determine the limit of initial movement as to determine the maximum possible flood of a river."[75] Neither Einstein nor any other engineer suggested that the WES experiments were unproductive; they extended work on bed-load movement reaching back to Grove Karl Gilbert's *Transportation of Debris by Running Water*.[76] Also, they provided valuable information about riffle development, roughness coefficients, velocities, and

73. Ibid., 30.

74. Ibid., 30, 46.

75. Hans Albert Einstein, "Formulas for the Transportation of Bed Load," *TASCE* 107 (1942): 562.

76. Grove Karl Gilbert, *The Transportation of Debris by Running Water* (Washington, D.C., 1914); Stephen J. Pyne, *Grove Karl Gilbert: A Great Engine of Research* (Austin, Tex., 1980), 238–44; Rouse, *Hydraulics in the United States* (n. 12 above), 80–81; Freeman, *Hydraulic Laboratory Practice,* 27–28. One significant parallel between Gilbert's work and WES's was that both resulted from concerns over practical river problems. Whereas problems with the Mississippi River stimulated much of the research in Vicksburg, Gilbert sought to find a safe procedure to resume hydraulic mining in California. In this regard, Gilbert's work was a signal failure. N. C. Grover, chief hydraulic engineer of the U.S. Geological Survey, noted that Gilbert's experimental work "was quite inadequate to the problem involved," although, he continued, it was "the best that has been done in this

turbulence criteria. On the other hand, the report's claim that "many of the basic laws underlying the subject of bed-load movement" had been discovered certainly exaggerated the report's significance.[77]

One undeniable success of the experiments was the data collection. By the summer of 1934, engineers had collected over six hundred samples of bed material from the lower Mississippi River and its major tributaries. At WES, Buchanan and a small staff of soil mechanics engineers studied each sample to determine physical properties and the factors that influenced the rate of movement. WES sent some samples to Louisiana State University, where geologists used them to develop a comprehensive petrographic analysis of the Mississippi River system.[78] More samples would be collected in the future, but this early work proved extremely valuable in advancing knowledge of bed-load material in the lower Mississippi system.

The experiments on bed-load showed both WES's strengths and weaknesses. Based on an impressive number of bed-load samples and numerous runs in the test flume, the experiments resulted from procedures at once comprehensive and conscientious. Both the raw data and the analyses contributed to the study of fluvial hydraulics. Yet the effort required little in the way of theory, nor did researchers seek to understand the mechanics involved. They sought to identify mathematical relationships among numerous properties that would help them anticipate problems on the Mississippi. Exactly why things worked the way they did awaited further research—and theory.

Similitude, Rationalism, and WES's Response

While progress at WES was largely empirical, some engineers—generally from the academic community—desired greater theoretical understanding and a more rational approach. They wished to comprehend the forces and mechanical factors that caused a particle to stay in suspension or to sink to the river bottom.[79] They also believed that this knowledge would lead to more accurate river models and tests. These engineers generally encouraged the use of dimensionless numbers, such as the Reynolds number, discussed above, and the Froude number, which expresses the ratio between the influences of inertia and gravity in a fluid. Engineers eagerly sought to test the usefulness of these numbers in transferring parameters between prototype and model.

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country and probably elsewhere in the study of transporting power of water." Senate Committee on Commerce, *National Hydraulic Laboratory* (n. 25 above), 11.

77. Waterways Experiment Station, *Studies of River Bed Materials,* 1.

78. Ibid., 116–19. See also Vogel's progress report on these experiments, "Sediment-Studies at the United States Waterways Experiment Station," *TAGU,* pt. 2 (1934): 466–68.

79. Leliavsky, (n. 7 above), 1–2.

Soon after he left WES, Vogel summarized WES's position on the use of dimensionless numbers in response to a letter from Hunter Rouse, who was destined to become one of the century's premier hydraulic engineers. The gist of his remarks, written on the margins and bottom of Rouse's letter, was that model-building remained primarily an empirical art. He observed: "Reproduction of observed natural phenomena is best assurance of proper design. Original design is based upon theory founded upon experience, but modifications in design are made as required."[80]

Vogel also noted the importance of carefully monitoring the model during an experiment. He claimed that "no general rule can be laid down" to determine the criterion for flow characteristics in a model; for movable-bed models "similarity of bed movement is necessary," and for a fixed model, such as for a dam spillway, the Froude number must be used. Vogel also maintained that surface tension was a negligible factor, but as temperature rose during the day—a particular problem on a hot summer day in Vicksburg—reliable viscosity measurements became difficult. To counter this problem, engineers quickly made test runs one after another. Finally, Vogel told Rouse, "Full regard is paid to all theory when the model is designed; after that performance is the criterion." He added, "I have tried to be very conservative in my statements."[81]

"Theory founded upon experience" underpinned the professional culture at WES. Certainly WES engineers used dimensionless numbers in their research and design. However, if modifications were required they would seek additional data and employ their own professional intuition, embracing a fundamental empirical approach familiar to their predecessors in the Corps of Engineers a century before.

At WES, the research engineers continued to work to improve their models, but models are at best imperfect. Even with the most accurate scaling available, models using patches of wire screen to represent vegetation and various substances to represent sediment are approximations, just like topographic maps of the earth's surface. Their limitations are both spatial and temporal, for the prototype itself constantly changes, especially if the river is geologically young and subject to alluvial processes. At best the model is a fuzzy snapshot of the real thing and requires the experienced engineer to clarify the details.

80. Rouse to Vogel, 2 January 1935, Hunter Rouse papers, box 1, folder 1, Special Collections, University of Iowa Library, Iowa City, Iowa.

81. Ibid. While Rouse remained convinced that the methods of the hydraulic engineers "might be bettered by subordinating empirical formulas to more rational methods of attack," he conceded in 1938 that strict similitude in models was "illogical" and that "only through extreme care" can an investigator hope for dependable results. Indeed, in the case of movable beds, the "present methods of approach are at best empirical." Hunter Rouse, *Fluid Mechanics for Hydraulic Engineers* (New York, 1938), iv, 29–30.

Engineers, then, did not search so much for precision as for the degree of acceptable error, and that depended not only on test objectives but upon engineering intuition, time limitations (often the result of political exigencies), and fiscal constraints. Both in building and using the model engineering and science, rationalism and empiricism, were intertwined. Definitions of success varied. Design engineers sought safe, economical, durable, and politically acceptable technological solutions. Other engineers sought theoretical modifications or, failing that, data that they could incorporate into their own experiments. Often, but not always, WES could satisfy both groups.

The Priority of Empirical Investigations

The most ambitious movable model built at WES in the 1930s was of the Mississippi River from Helena, Arkansas, to Donaldsonville, Louisiana, a distance of about 600 river miles. Constructed in just four months in 1935, the model was 1,100 feet long with a horizontal scale of 1:2400 and a vertical scale of 1:120. It used 210 gauges and 17 flow inlets. During a test run, several junior engineers would scurry around, each one reading about 25 gauges at regular intervals. The model required 42 people to operate it correctly.[82] Engineers used it extensively to test proposed channel improvements on the lower Mississippi River.

Most of the models at WES in the late 1930s were of stretches of either the Ohio River or the Mississippi River and were used to test proposed channel improvements. The first movable model of a dam project was of Conchas Dam in eastern New Mexico. WES also built models of spillways at Sardis Dam (Mississippi) and Great Salt Plains Dam (Oklahoma). A model of the Delaware River end of the Chesapeake and Delaware Canal enabled an analysis of methods to prevent shoaling. An East River, New York, model aided an investigation of possible channel improvements. A model of the Fort Peck Dam (Montana) power tunnel permitted engineers to check on water hammer and surge problems. Additionally, models facilitated analyses of generic problems, such as the permeability of certain types of rock jetties, seepage in Mississippi River levees, wave force against breakwaters, and the impact of cavitation on a baffle pier (a horizonal structure that looks somewhat like a huge concrete waffle iron and is used to dissipate energy below large spillways).[83]

82. National Bureau of Standards, *Current Hydraulic Laboratory Research in the United States* (Washington, D.C., 1939), 86; U.S. Army Corps of Engineers, Office of History, *Water Resources—Hydraulics and Hydrology: Interview with Jacob H. Douma,* conducted by John T. Greenwood (Alexandria, Va., 1997), 14; Fatherree, "History of the Hydraulics Laboratory" (n. 41, above), 85.

83. National Bureau of Standards, *Current Hydraulic Laboratory Research in the United States,* 86–95; Army Corps of Engineers, Office of History, *Interview with Jacob H. Douma,* 55–58. For an overview of WES's research in support of large dams, see

Not all movable models were successful. Those that performed worst were of coastal areas. A model of St. Andrews Bay, Florida, predicted that an old channel would shoal up, but no such thing occurred. Tests on models of the Head of Passes at the mouths of the Mississippi led to the construction of dikes to deepen the navigation channel, but the dikes failed. Problems dealing with saltwater, tides, littoral movement, and other characteristics of coastal waters continued to hamper the development of reliable coastal models.[84]

Notwithstanding the failures, within a decade WES had profoundly affected hydraulic engineering in the Corps and in the country. Its impact was all the more remarkable considering the Corps's initial opposition to the laboratory and the earlier skepticism of many engineers about river modeling. In 1940, Herbert Vogel noted how "the Missourians" had become convinced that distorted models could work and that the swing had shifted too much in the other direction. Some recent distorted models at unnamed research centers exceeded "logical limits." "In the last few years," Vogel wrote, "models have become so fashionable that, in many cases, engineers have attempted to substitute testing for thinking."[85] Paul Thompson, then director of WES, had more faith in his engineering colleagues. "By and large," he wrote, "designing engineers have come to recognize the model for what it is: a valuable tool in some cases, a worse than useless one in others."[86]

In 1945, WES completed a study on the meandering of alluvial rivers that climaxed much of its earlier river investigations (fig. 2). Capt. Haywood G. Dewey Jr., who had earlier worked in the Bureau of Reclamation's laboratory and had just returned from a year as a Freeman Fellow in Europe, supervised the study from 1942 to 1943. From mid-1943 to the end of 1944, Capt. Joseph F. Friedkin supervised the work and authored the final report. Tests were conducted in specially built flumes. To replicate erodible material, researchers used Haydite, granulated coal, a mixture of loess and coal, and

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Waterways Experiment Station, *Laboratory Research Applied to the Hydraulic Design of Large Dams* (Vicksburg, Miss., 1948). Joseph B. Tiffany Jr., "Recent Developments in Hydraulic Laboratory Technique," in *Proceedings of the Second Hydraulics Conference,* ed. J. W. Howe and Hunter Rouse (Iowa City, Iowa, 1943): 31–50.

84. Fatherree, "History of the Hydraulics Laboratory," 78. The problems of using models to investigate saltwater and coastal phenomena led the chief of engineers to establish a Committee on Tidal Hydraulics (CTH) at WES. Committee members included WES personnel and academics such as Boris Bakhmeteff, Lorenz Straub, Hans Albert Einstein, and Arthur Ippen. See ibid., 215–17, and John B. Lockett, *History of the Corps of Engineers Committee on Tidal Hydraulics (January 1949 to June 1971)* (Vicksburg, Miss., 1972).

85. Herbert D. Vogel, "Hydraulic Models—Geometrical or Distorted," in *Proceedings of the Hydraulics Conference,* ed. J. W. Howe (Iowa City, Iowa, 1949): 173–74.

86. Paul Thompson, "Hydraulic Model Testing in the Spotlight," in *Proceedings of the Hydraulics Conference,* ed. J. W. Howe (Iowa City, Iowa, 1949): 22.

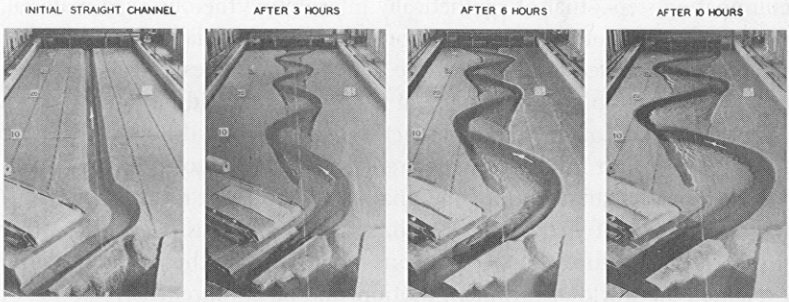

FIG. 2 The development of a river meander as shown in WES research (early 1940s). (Waterways Experiment Station.)

coarse sand. The study used hardly any theoretical works in river mechanics. Rather, the references are almost exclusively to earlier empirical studies.[87]

The investigation showed, in Friedkin's words, that "meandering results primarily from local bank erosion and consequent local overloading and deposition by the river of the heavier sediments which move along the bed."[88] As a practical matter, the study suggested where and how to stabilize banks to prevent meandering. However, its fame rests on its scientific contribution; it answered many questions dating back scores of years about the way in which meanders form. Hydraulic engineer Serge Leliavsky later called the study "one of the classical contributions to the science of river engineering."[89]

By 1945, river models had proven their worth to both research and design engineers, who used them to modify some theories, reject others, develop new equations, and gather huge amounts of data (later considerably enhanced by computer modeling). However, river models had not provided the key to supposed universal laws governing water movement. Vogel observed: "In no field of scientific or engineering endeavor does the theoretical touch so closely upon the practical as in the realm of hydraulics. In spite of this, so little is understood of the properties and propensities of water that it is all but impossible to state any explicit law controlling its action."[90] Some academic engineers nevertheless remained hopeful. Boris Bakhmeteff, the renowned hydraulic engineer and Columbia University professor, observed in 1943 that, while government laboratories primarily served "the specific needs arising from practical construction. . . . There still remains the final

87. U.S. Waterways Experiment Station, *A Laboratory Study of the Meandering of Alluvial Rivers* (Vicksburg, Miss., 1945), 27–40. An earlier WES report that anticipated some of the findings in the 1945 study was Joseph B. Tiffany Jr. and George A. Nelson, "Studies of Meandering of Model-Streams," *TAGU* (1939): 644–49.

88. U.S Waterways Experiment Station, *Meandering of Alluvial Rivers,* 3.

89. Leliavsky, (n. 7 above), 142.

90. Vogel, "Hydraulic Models—Geometrical or Distorted," 176.

culminating step—that of synthetically interpreting the observed material, with the purpose of discerning and formulating general laws."[91]

Bakhmeteff died in 1951. Had he lived a few decades longer, he might have been disappointed. The general laws he sought did not appear, even after much data collection and deductive work. Mainly through stochastic methods, modern fluid mechanics rationalized laboratory data and provided principles subject to further analysis. Yet its track record in explaining the motion of river water tantalized but rarely satisfied the scientific mind. Neither differential equations nor abstract theory sufficiently explained the world of turbulent motion, and no comprehensive model of turbulence has gained universal acceptance. Hans Albert Einstein is reported to have said that his more famous father, Albert, was interested in river mechanics, but after careful consideration opted for the simpler aspects of physics.[92] Hydraulic engineers would surely have sympathized. As we approach the twenty-first century, engineers still seek the overall resolution of problems in both turbulence and sediment transport.[93]

The Corps, too, obtained a greater respect for the mysteries of nature. Reflecting on his experiences on the Mississippi River in the 1970s, one engineer general proclaimed, "You can't sit down with a bunch of mathematics and formulas and predict in advance how a hydraulic structure is going to act and how water will act in different conditions of flow." The only thing to do, he advised, was to gather the best data possible over the years and base the design on it. "You make corrections, thereafter, from experience. It is very similar to the practice of medicine."[94] While WES researchers may not have been quite so pessimistic, they certainly would have accepted the basic point; their work showed that the world of flowing water was even more complicated than had been imagined.

WES emerged from a shotgun marriage between technology and bureaucracy; few engineer officers would have thought such an organization possible thirty years earlier. Most likely, fewer still would have been

91. Boris A. Bakhmeteff, "The Significance of Fluid Mechanics to the Hydraulic Engineer," in *Proceedings of the Second Hydraulics Conference* (n. 83 above), 4.

92. Arved J. Raudkivi, "Fundamentals of Sediment Transport," in Nakato and Ettema (n. 13 above), 29.

93. On turbulence models, see Levi (n. 4 above), 529–32, 544–47. I surveyed participants at a hydraulics and hydrology conference sponsored by the Iowa Institute of Hydraulic Research (IIHR) in Iowa City, Iowa, in May, 1995. The majority of respondents listed sediment transport and turbulence problems among the top five theoretical challenges facing the hydraulics community. John Fisher Kennedy, head of the IIHR from 1966 to 1991, called attention to the slow progress in river engineering, attributing the problem to the conservatism of engineers and to the nature of geological investigation, which is "not predisposed to dramatic developments." Fisher is quoted in Donald W. Knight, "Closure of Sessions 2, 3, and 5," in Nakato and Ettema, 453.

94. Maj. Gen. Charles C. Noble, U.S. Army, Retired, interview by author, transcript, 22–23 September 1981, 128–29, OH HQUSACE.

confident of its success. Without the leadership of Vogel, without the compelling need for a laboratory brought on by New Deal public works projects, WES might not have survived. Yet external needs and outstanding leadership do not by themselves explain WES's success. Rather, the laboratory's accomplishments also resulted from a steadfast adherence to the empirical principles and inductive approach that had guided the Corps of Engineers from the agency's inception. In the same way that ever larger particle accelerators opened new areas in subatomic physics, the large models at WES substantially improved the collection of data and testing of theory.

WES enlarged federal research responsibilities and helped lower the boundary between science and engineering. In a disciplined, bureaucratic setting, WES engineers both defined the problems and established the criteria for success. Their technique suggests that the basic distinction between scientist and research engineer may be temperament: the inability to answer fundamental questions bothers scientists, but WES engineers saw nothing unworthy in aiming for lesser, and more immediate, objectives in the "real" world of political and economic imperatives. Their results may have been approximate, provisional, and confined within a historical framework, but in the absence of better explanatory approaches these constraints hardly rendered the methodology less valuable.[95] Rather they illuminated the crucial contribution of engineering art to the world of science.

95. In this connection, it is interesting to note that currently the Corps advises its hydraulic engineers that "the best guide. . . is experience" when selecting the coefficient of boundary roughness (Manning's *n* value, which shows the energy loss due to the friction between the bed and the water). U.S. Army Corps of Engineers, *River Hydraulics* (n. 18 above), 135.