"Strong, Invincible Arguments"?

Tidal Models as Management Instruments in Twentieth-Century Dutch Coastal Engineering

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One of the striking achievements of twentieth-century engineering was the development and use of mathematical models as design tools. Thanks to these tools, engineers could predict the effects of different design choices before actually building expensive prototypes or making premature decisions. The proof of the pudding might thus be had without the actual eating. Such modeling proved useful wherever engineers were facing complex challenges and high stakes.¹

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1. The important role of applied mathematics in the shaping of modern engineering is well documented. See, for example, Edwin T. Layton, "Millwrights and Engineers: Science, Social Roles, and the Evolution of the Turbine in America," in *The Dynamics of Science and Technology: Social Values, Technical Norms and Scientific Criteria in the Development of Knowledge*, ed. Wolfgang Krohn, Edwin T. Layton, and Peter Weingart, vol. 2 of *Sociology of the Sciences* (Dordrecht, 1978); Eda Kranakis, *Constructing a Bridge: An Exploration of Engineering Culture, Design, and Research in Nineteenth-Century France and America* (Cambridge, Mass., 1997); Terry S. Reynolds, *Stronger than a Hundred Men: A History of the Vertical Water Wheel* (Baltimore, 1983). Walter Vincenti underscores the importance of modeling in his chapter on control-volume analysis in *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore, 1990). No hard-and-fast line can be drawn between the use of complex mathematical functions and full-fledged mathematical modeling. We are dealing with a continuum. Full-fledged mathematical modeling predicts complex system behaviors from a relatively large number of heterogeneous factors. It is the possibility of "playing" with factors in representations of systems with tightly coupled elements that most sharply characterizes mathematical modeling.

Because they are formal representations of physical structures, it can be seductive to think of mathematical models as constrained only by nature and the rules of mathematics. However, mathematical models are both representations and tools, and like all tools they are shaped as much by their uses as by the materials they are made of. For readers of this journal we need hardly belabor the point that engineering is about shaping not only matter but also the social networks in which matter is molded. As part and parcel of modern engineering practice, models are also often employed to influence participants in social networks—that is, they are used as management tools for persuading publics and forging political consensus. In this article we describe how the modeling of tidal flows in estuaries and maritime rivers was influenced by this inherent duality. We focus on the Netherlands because its sub-sea-level topography fostered the development of such models as tools for hydraulic engineering, and because the practical organization of Dutch water management cast the role of these models as hopeful instruments of political persuasion and consensus building into sharp relief.²

2. Many readers will recognize this point of departure as rooted in the social constructivist approach to the history of technology originally put forward by Wiebe Bijker and Trevor Pinch. The central point here is that artifacts are not shaped only by some set of abstract technical criteria but rather are primarily determined by interactions among “relevant social groups,” i.e., social groups that for one reason or another are stakeholders in the properties and social effects of the artifact in question. See Wiebe Bijker and Trevor Pinch, “The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other,” in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. Wiebe E. Bijker, Trevor Pinch, and Thomas P. Hughes (Cambridge, Mass., 1987), and also Wiebe Bijker, “Sociohistorical Technology Studies,” in *Handbook of Science and Technology Studies*, ed. Sheila Jasanoff (Thousand Oaks, Calif., 1995). However, for our case Bijker’s and Pinch’s notion of relevant social groups needs some revision. In the first place, the institutionalized and highly structured nature of stakeholding in Dutch hydraulic engineering suggests that we are not dealing with basically isolated groups and individuals conjoined only by their interest in this single issue but rather with a network of actors sharing a history and a future. In this sense Dutch water history deviates markedly from the history of water in the United States, where ad hoc groups and individual engineer-entrepreneurs seem to have left a much bigger mark on hydraulic policies and achievements (see also footnote 5). Moreover, power differentials among Dutch hydraulic actors are highly salient, so that from the point of view of major actors the issue is not so much a question of interacting with other “relevant groups” as it is one of managing a hydraulic network in which other “relevant actors” occupy legally and institutionally fixed positions. In this sense our approach might better be described as “societal” rather than “social” constructivism. Secondly, this article demonstrates that “societal construction” not only pertains to objects of design but to design tools themselves. In Dutch hydraulic engineering, social influences affected not only hydraulic works as artifacts but also the different models, including mathematical models, that engineers developed to design and legitimate these works. The general point that mathematical models are not only descriptions of nature but also tools to mobilize publics and politics has become plain in recent years around

The models in question did not aim to predict tidal levels at sea; that had been accomplished in the 1870s by Lord Kelvin, using Fourier analysis. What concerned Dutch civil engineers in the middle decades of the twentieth century was how to predict the propagation of tides (both regular tides and so-called storm surges) into bays and estuaries and up tidal rivers.³ Being able to predict the propagation of tides into bays and up tidal channels was necessary for estimating the magnitude of the hydraulic threat to inland locations and for predicting the effects of hydraulic “improvements” in complex waterway networks.

Surprisingly, neither the mathematics nor the calculating technologies employed were particularly novel.⁴ There was, therefore, little substantive reason why the mathematical modeling of tidal propagation could not have emerged earlier. Moreover, a motley variety of modeling approaches and calculating methods emerged, not a single best practice. The search for strong, invincible arguments was pursued along several tracks at once. We argue that to explain the timing and variety of Dutch tidal modeling we must take into account not only new engineering challenges but new social and managerial challenges as well.

Center and Periphery in Dutch Water Management

To a far greater extent than was the case in, for example, nineteenth-century France, or even the United States, Dutch water management was locally and regionally organized.⁵ This was a legacy of the Middle Ages,

issues such as global warming. See Steve Rayner and Elizabeth L. Malone, eds., *Human Choice and Climate Change* (Columbus, Ohio, 1998).

3. By “propagation” we mean the translation of high water levels at sea through estuaries and tidal rivers in a landward direction, i.e., a direction that would normally be considered upstream. The rate of the translation and the water levels and currents prevailing at specific locations depend on numerous contingent and structural factors, such as prevailing sea level, weather, and river discharges, as well as on structural factors like the shape of the river bed, the roughness of the bottom, and the morphology of possible cache basins. The structural factors can to some extent be manipulated by hydraulic engineers. Storm surges are unusually high water levels caused by the (near) coincidence of spring tides with heavy onshore gales at sea. In shallow waters like those off the Dutch west coast the wind effect can attain dramatic proportions, raising the basic astronomical high-tide level by three or four meters. In combination with heavy river discharges these storm surges time and again wreaked havoc as they propagated through the Delta system and strained dikes, in many cases ancient and often poorly maintained, past their breaking point.

4. For the history of calculating technologies, see Michael R. Williams, *A History of Computing Technology* (Englewood Cliffs, N.J., 1985); Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine* (New York, 1996); Paul E. Ceruzzi, *A History of Modern Computing* (Cambridge, Mass., 1998).

5. See the July 2002 issue of *Technology and Culture* (vol. 43, no. 3), a special issue devoted to water technology in the Netherlands. On France, see Antoine Picon, *L'invention*

when local water boards (*waterschappen*) were organized for the purpose of building and maintaining dikes and for managing drainage in the dike-enclosed areas, or polders.⁶ Though it had many virtues, the fragmented local system was weak when it came to coordinating major projects. In spite of the fact that from the thirteenth century on deteriorating conditions and frequent flooding made it clear that a more effective method of organization was needed, the *waterschappen* and provinces remained loath to share their prerogatives with any central power.

Matters took a decisive turn in 1798. A Dutch Bonapartist faction had come to power at the point of French bayonets in 1795. French statist ideology inspired the founding of a national hydraulic engineering corps. This new agency, called the Rijkswaterstaat, had to invent a political mandate for itself alongside those of the well-established local hydraulic agencies.⁷ The provinces and the *waterschappen* persistently frustrated centralist ambitions. Even the near monopoly on formally trained engineers that the Rijkswaterstaat had achieved by the mid-nineteenth century gradually evaporated as local water boards also began to employ graduates of the Delft engineering school. The Rijkswaterstaat therefore always had to maneuver within the context of a locally entrenched base of professional counterexpertise.⁸

de l'ingénieur modern: L'école des ponts et chaussées (Paris, 1992); Terry Shinn, *Savoir scientifique et pouvoir sociale: L'école polytechnique, 1794–1914* (Paris, 1980); A. Brunot and R. Coquand, *Le corps des ponts et chaussées: Histoire de l'administration Française* (Paris, 1982); Jean Claude Thoenig, *L'ère des technocrates: Le cas des ponts et chaussées* (Paris, 1987); and, from another and explicitly comparative perspective in which the centralizing ambitions of the corps are manifest, Kranakis. For the United States, again see Kranakis, but see also 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): 64–82, and "The Art of Scientific Precision: River Research in the U.S. Army Corps of Engineers to 1945," *Technology and Culture* 40 (1999): 292–323; Todd Shallat, *Structures in the Stream: Water, Science and the Rise of the U.S. Army Corps of Engineers* (Austin, Tex., 1994); John M. Barry, *Rising Tide: The Great Mississippi Flood of 1927 and How It Changed America* (New York, 1997).

6. William H. TeBrake, "Taming the Waterwolf: Hydraulic Engineering and Water Management in the Netherlands during the Middle Ages," *Technology and Culture* 43 (2002): 475–99. Petra J. E. M. van Dam, "Ecological Challenges, Technological Innovations: The Modernization of Sluice Building in Holland, 1300–1600," *Technology and Culture* 43 (2002): 500–520.

7. For a well-informed overview of the history of the Rijkswaterstaat, see Harry Lintsen, "Two Centuries of Central Water Management in the Netherlands," *Technology and Culture* 43 (2002): 549–68. See also Toon Bosch and Willem van der Ham, *Twee eeuwen Rijkswaterstaat, 1798–1998* (Zaltbommel, 1998), and Willem van de Ham, *Heersen en beheersen: Rijkswaterstaat in de twintigste eeuw* (Zaltbommel, 1999).

8. The provinciale *waterstaten* became increasingly professionalized in the last quarter of the nineteenth century, followed by the local *waterschappen* in the course of the twentieth. In 1900 the national Rijkswaterstaat employed sixty-four Delft-trained civil engineers; the various provincial *waterstaten* employed sixteen, and an additional ten were in the employ of (mostly the largest) local *waterschappen*. Thus, at the turn of the

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The Rijkswaterstaat's effectiveness was also hampered by its own regionally based organization. Until the 1930s the agency possessed neither a strong central directorate nor specialist staff departments. This not only discouraged innovation, it also retarded the accumulation of new engineering knowledge within the organization. New bodies of knowledge tended to be developed in the course of specific engineering projects in the regional directorates, only to dissolve again as the participating engineers dispersed to other posts within the Rijkswaterstaat. To the extent that such locally developed knowledge diffused at all throughout the organization it did so through internal reports or in the heads of peripatetic engineers. Much of it moved through external channels, such as publications in the national engineering journal *De Ingenieur*, or lectures before the Royal Institute of Engineers. But this was not enough to turn the tide: by the early twentieth century the Rijkswaterstaat was having a hard time learning to apply the new materials and methods that were by then reshaping hydraulic engineering the world over. Its prestige, its self-confidence, and consequently its budget were at a low ebb. World War I only worsened matters by driving the price of building materials to such prohibitive heights that construction became impossible, even though Dutch neutrality kept actual war at bay.

In 1916 a storm surge caused dike failure and flooding in the province of North Holland. The floodwaters literally lapped at the sluices of Amsterdam. This stimulated the passage, two years later, of a law authorizing the closure and reclamation of the Zuider Zee, a large arm of the North Sea extending into the center of the country and the immediate source of the 1916 floodwaters (fig. 1). Although various schemes for damming up and reclaiming the inland sea had been debated since the mid-nineteenth century, the project had languished until the 1916 flood redefined the Zuider Zee as also a dangerous body of water.

The minister of public works at this juncture happened to be the politician and civil engineer Cornelis Lely. In his youth, failing to find employment elsewhere, he had been secretary and chief engineer of the Zuider Zee Association, a private, member-financed initiative to lobby for closure and reclamation of the Zuider Zee. As chief engineer, Lely had developed a master plan for the reclamation project, which he was now, half a lifetime later, in a position to see enacted into law. Lely had no faith in the Rijkswaterstaat's will or ability to see the project through and proposed a separate government agency to oversee the closure and reclamation. This new agency, the Dienst Zuiderzeewerken (Service for the Zuider Zee Works), was

century nearly 29 percent of the domestically active hydraulic engineers were employed by local and regional bodies. This percentage increased in the course of the century. *Vereeniging van Delftse Ingenieurs, Alfabetische naamlijst van ingenieurs gepromoveerd aan de Delftse Academie en van ingenieurs en technologen gepromoveerd aan de Polytechnische School* (The Hague, 1900).

FIG. 1 Present-day Netherlands showing major twentieth-century hydraulic projects. The darker areas are the reclaimed polders in the former Zuider Zee, now the IJsselmeer. The Zuider Zee Dike separating the IJsselmeer from the Waddenzee is visible near the top of the map, the Delta region in the south-west. (Toon Bosch and Willem van der Ham, *Twee eeuwen Rijkswaterstaat, 1798–1998* [Zaltbommel, 1998], 206. Reproduced with permission, Europese Bibliotheek, Zaltbommel.)

everything the Rijkswaterstaat was not: centrally organized, dynamic, charismatic, technocratic, single-minded, disposed to learn from experience, and committed to invention. The first effort at the large-scale modeling of tidal propagation was undertaken in the course of this project, without the participation of the Rijkswaterstaat.

The exclusion of the Rijkswaterstaat from the Zuider Zee works, far and away the most alluring civil engineering project of the era, was the straw

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that broke the camel's back. In 1924 a high-level Rijkswaterstaat committee charged with finding a way out of the malaise recommended a thorough reorganization. It advocated strong central leadership, embodied in a new position of director-general. To facilitate the accumulation and cultivation of knowledge it recommended the creation of a number of central research departments. The object was clearly to reconstruct the Rijkswaterstaat as an expert and innovative agency, capable of setting its own hydraulic engineering agenda and of framing the necessary projects. The Zuider Zee debacle had shown that in order to survive as a prestigious agency with a stable budget the Rijkswaterstaat had to be able to manage its own political environment; first and foremost this meant defending itself against arbitrary ministerial decisions by linking its hydraulic agenda to those of specific constituencies and their representatives in parliament. Only an agenda based on such a managed political consensus could routinely hope to carry the day in the annual struggle for budgetary allocations.

From the point of view of the Rijkswaterstaat, the Zuider Zee was, at least in the short term, a lost cause. The agency had to make do with the major remaining coastal engineering challenge in the country, the Delta region of the southwest, comprising the deltas of the Rhine, the Maas (Meuse), and the Schelde Rivers. This complex system of estuaries, tidal creeks, and tidal rivers flowing among highly fertile islands and peninsulas built up of numerous interconnected polders had been extremely flood prone in the past. It also contained the economically crucial harbors of Rotterdam and Dordrecht and their nautically vulnerable passages to the sea. Maintaining navigability in the sandy and ever shoaling seaways without at the same time compromising the safety of the contiguous land or aggravating the salinity of the tidal rivers to the detriment of agricultural irrigation was a knotty problem. Finding a way to cut that knot, which depended on the availability of efficient and precise tidal propagation models, became a major goal of the Rijkswaterstaat's new Directorate of Maritime Rivers in the 1930s.⁹

The most important feature of the Rijkswaterstaat's reorganization of 1930 was the creation of the post of director-general. Since the mid-nineteenth century the Rijkswaterstaat had lacked an authoritative and single-minded leadership capable of formulating policy and defending it at high

9. The development of tidal propagation models was not, however, initially coupled to efforts by the Rijkswaterstaat to recapture the initiative in Dutch hydraulic engineering. In fact, while the Rijkswaterstaat was busy taking stock, a committee appointed in 1918 to allay fears about secondary effects of the Zuider Zee closure (under the chairmanship of the physicist Hendrik Lorentz) was putting the final touches on its modeling of tidal flows in the future Waddenzee. Lorentz's inspired approach, the validity of which was demonstrated at the closure of the Zuider Zee in 1932, proved seminal for the development of mathematical and analog models by the Rijkswaterstaat in the two decades thereafter.

levels in the Ministry of Public Works, Trade, and Industry. The new position was exploited to the full by the new incumbent, the prominent civil engineer Johannes Aleid Ringers. Ringers had already made a name for himself as a Rijkswaterstaat engineer and an entrepreneur. He had been chief engineer in charge of construction of the North Lock at IJmuiden, then the largest lock in the world. At the time of his appointment as director general he was managing director of the consortium of contractors building the Zuider Zee dam. Ringers advocated modern “scientific” engineering methods, including mathematical and scale modeling. Accordingly, one of the first measures he took upon his appointment as director general was to increase the number of specialist staff departments. One of these was a special Study Service for the Tidal Rivers, Estuaries, and Coasts, whose mission was to collect data on currents, sand transport, tidal regimes, salinity, and so forth in the Delta’s waterways and along the Dutch coast. The aim was basically to manage channel dimensions in the interests of shipping, but the knowledge gained was soon being put to a variety of uses. The Study Service rapidly became a think tank for overall hydraulic policy in the Delta. However, in view of the delicate balance of interests in the Delta it had to tread lightly. Skeptical constituents had to be convinced that proposed measures were in their (ultimate) interests and that they were technically and economically feasible. In large part this depended on trust in the Rijkswaterstaat’s competence in design, construction, and the prediction of effects. But credibility was not easily come by. In the absence of hydraulic puddings that could actually be eaten, proof had to be mustered otherwise. It was for this reason that, very soon after its founding, the Study Service became the main site for the development and application of mathematical tidal modeling in the Netherlands—and, at that time, quite possibly in the world.¹⁰

In a dissertation published in 1937, Jannis Pieter Mazure, an engineer with the Dienst Zuiderzeewerken and a participant in Hendrik Lorentz’s Waddenzee modeling effort (see the next section) described three main uses for tidal modeling.¹¹ First, it increased the certainty and self-confi-

10. During the interwar period, Dutch tidal modeling was highly innovative. There were some parallel developments in Germany and Belgium, but these were not so advanced as to prevent us treating tidal propagation modeling in the Netherlands in this period as a national endeavor, carried out by Dutch engineers and scientists involved in the design of major hydraulic projects. Leading German and Belgian work up to the mid-1930s included J. Öltjens, “Über die Berechnung der Flutwellenlinien in einem Tideflusse,” *Zentralblatt der Bauverwaltung*, no. 27 (1919); H. Reineke, “Die Berechnung der Tidewellen in Tideflüsse,” *Jahrbuch der Gewässerkunde Norddeutschlands*, nos. 3 and 4 (1921); L. Bonnet, “Contribution à l’étude théorique des fleuves à marée et application aux rivières à marée du bassin de l’escaut maritime,” *Annales de travaux publics de Belgique* (1922, 1923); H. Krey, *Die Flutwelle in Flusssmundungen und Meeresbuchten* (Berlin, 1926); E. Schultze, “Die Bestimmung der Abflussverhältnisse im Tidegebiet,” *Die Bautechnik* (1934): 438, 493.

11. Jannis P. Mazure, *De Berekening van getijden en stormvloeden op benedenriv-*

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dence of engineers by giving them insights into the effects of hydraulic engineering projects and allowing them to predict those effects quantitatively. Second, the use of models helped to prevent the kinds of catastrophes that might occur were only intuition to be relied upon. And finally, tidal modeling was important “because unforeseen consequences of a measure can cause serious damage to third parties, and the resulting protests can disturb the working atmosphere and undermine trust in the technical leaders.”¹² Mazure’s modeling credo resonated with the Rijkswaterstaat’s new project as embodied in the Study Service: creating new tools for the centralized management of a complex field populated by strong and knowledgeable local actors.¹³

We distinguish three periods in the contested emergence of mathematical tidal modeling in the Netherlands: the era of the Zuider Zee works (1918–30), the years of planning for the Delta project (1929–55), and the decade of reconstruction of the Delta (1955–65). After 1965, new digital electronic computers provided such a quantum leap in calculating power that (adaptations of) the most laborious—but also the most precise—mathematical method very rapidly became the method of choice.

The Zuider Zee Works, 1918–1930

Since the mid-nineteenth century the closure and reclamation of the Zuider Zee had been on the Dutch political and hydraulic-engineering agenda. Many plans were put forth. The strongest contender among these

ieren (Delft, 1937). Mazure’s dissertation was based on practical tidal modeling that he did for the provincial *waterstaat* of North Brabant in the early 1930s.

12. *Ibid.*, 65–66

13. Wiebe Bijker also writes of a new centralist and “technocratic” Rijkswaterstaat, although he positions it later in time, after the devastating flood of 1953 and the subsequent adoption of the “Deltaplan.” “In the Deltaplan, coastal protection previously provided by some 1,000 kilometers of dikes under decentralized control was to be taken over by less than 30 kilometers of dikes under centralized control. By the late 1950s, the faith in the Rijkswaterstaat was such that this centralization met with no resistance”; Bijker, “Sociohistorical Technology Studies” (n. 2 above), 243. More recently, Bijker has argued that the organizational framework and the managerial and engineering tools were already in place *before* the flood, although he sees them as a legacy of the successful struggle in 1945–46 to close the wartime breaches in the dikes on the inundated island of Walcheren rather than of the mathematical and electrical modeling efforts and associated hydraulic planning that took place in the 1930s; see Wiebe Bijker, “The Oosterschelde Storm Surge Barrier: A Test Case for Dutch Water Technology, Management, and Politics,” *Technology and Culture* 43 (2002): 569–84. While Bijker clearly recognizes the importance of tidal modeling for the centralizing project, his emphasis on physical scale modeling (which became relevant for the study of tidal propagation only in the very late 1940s but did play a significant role in the Walcheren closures) fails to do justice to the importance and variety of rival modeling methods available by 1940.

was the plan first submitted in 1891 by Cornelis Lely as secretary of the Zuider Zee Association, which called for the construction of a 30-kilometer-long dam across the mouth of the Zuider Zee and reclamation by stages of the resulting freshwater lake.

Although reclaiming land from the sea was no novelty in the Netherlands, nothing on the scale of the Zuider Zee project had ever been attempted. The influence of tides and tidal currents was the major complicating factor. For one thing, the effects of the closure dam on tidal levels and currents on its seaward side—that is, in the relatively shallow, island-enclosed Waddenzee—were a source of worry and speculation. Everyone expected that the new dam would change the existing patterns of tides and water levels during storms, but how and to what extent? The biggest political threat to the project came from the mundane worry that higher tides would require very costly heightening of existing dikes along the coasts of the Waddenzee.

Really trustworthy estimates of these effects could not be made. Intuition and simple calculations were the only tools available, and these had led to major embarrassments in the past.¹⁴ In an 1887 report, Lely reckoned the increase at 15 centimeters during storm surges along the coasts imme-

14. An infamous case in point was the Nieuwe Waterweg, the new seaway to Rotterdam Harbor, dug in the 1850s. This project was one of the most dramatic failures in Dutch civil engineering history. The head of the project, civil engineer Pieter Caland, had conceived the plan on the assumption that initially only a small canal would have to be constructed, which would automatically be enlarged to the appropriate size by the scouring action of tidal water movements. In 1858 he had calculated the strengths and durations of the currents and their effects on sand movements. His computations were immediately criticized. In the event, his assumptions indeed proved wrong, and the canal remained too shallow. For an assessment from the viewpoint of a proponent of tidal modeling, see Mazure, *De Berekening van getijden*, 55. Misguided intuition had been responsible for similar failures in American hydraulic engineering in the course of the nineteenth century. Todd Shallat (n. 5 above) describes how the perpetual Delaware Bay breakwater project not only failed to solve the problem of shoaling in the main shipping channel but actually caused unwanted shoaling elsewhere. John Barry (n. 5 above) provides striking descriptions of the hands-on, intuitive acquaintance that both James Eads and Andrew Humphreys had with the lower Mississippi River and how this informed their rival perspectives on flood control and navigability. Eads had acquired intimate experience of the river as a salvage captain and diver, while Humphreys' elaborate quantitative survey in the service of the Army Corps of Engineers extended to actually tasting clay dredged up from the bottom. Nonetheless, river engineering based on this mixture of science and intuition—the “levees only” policy—missed the mark and actually exacerbated the devastating effects of the flood of 1927. But the success of James Eads's equally intuitive effort to maintain navigational depth in the Mississippi River's South Pass by means of jetties belied both the effects of the levees upstream and Caland's failure at Rotterdam. The principle involved (encouraging the river current to scour its own channel by constraining it) was very similar to that invoked by Caland and by proponents of the “levees only” position on the Mississippi, but the outcome was quite different. For more detailed accounts, see Reuss, “Andrew A. Humphreys” and “The Art of Scientific Precision” (both n. 5 above).

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diately adjacent to the dam.¹⁵ We do not know whether he calculated this value or just intuited it. In any case, Lely reconfirmed the figure in 1894 as chairman of a state committee to plan the Zuider Zee closure, during his first term as cabinet minister.

At a meeting of the Royal Institute of Engineers in that same year, the civil engineer H. E. de Bruijn argued that the changes would be much larger. He even advanced the counterintuitive view that due to the closure the currents in the channels between the islands bounding the Waddenzee would increase. This claim met with general disbelief. In 1911 De Bruijn reiterated his vision of future rises in water levels, estimating that the difference between low and high tide in the Waddenzee would double (from about 0.8 to 1.6 meters).¹⁶ It appears that he based his opinions on intuition, since he argued that the actual figures could not be determined by computation but rather that "one has to sense it, as it were, based on experience gained elsewhere and on relevant research."¹⁷

The storm surge of 1916 and consequent large-scale flooding north of Amsterdam galvanized decision making on the Zuider Zee closure. Plans for closure could now count on broad popular support.¹⁸ But the possible effects on tidal patterns in the Waddenzee remained a stumbling block. A member of the provincial legislature of Groningen, one of the provinces bordering the Waddenzee, predicted that during storm surges water levels would be far higher than Lely had anticipated. Inasmuch as dike construction and maintenance were still local and provincial responsibilities, the representative had reason to be concerned. An engineer from Groningen's Provinciale Waterstaat calculated that water levels would rise by about 1.3 meters in the vicinity of the closure dam. During the 1860s provincial public works agencies, the Provinciale Waterstaten, had been established to coordinate water management at the provincial level, thus giving rise to a three-tiered system of hydraulic governance.

In 1918 Lely got his way with the Zuider Zee reclamation, but only on condition that he appoint a state committee to resolve the question of water levels in the new Waddenzee. Lely, now in his third term as minister of public works and eager for a decisive end to the debate, called on the internationally renowned physicist Hendrik Lorentz to chair the committee.

It took the committee eight years of hard work to come to a conclusion.¹⁹

15. Jannis P. Mazure, "Hydraulic Research for the Zuiderzeeworks," in *Selected Aspects of Hydraulic Engineering*, ed. Johannes Th. Thijsse (Delft, 1963).

16. H. E. de Bruijn, "Invloed van de afsluiting van de Zuiderzee op de vloedhoogte buiten den afsluitdijk," *De Ingenieur* 26 (1911): 28–30.

17. *Ibid.*, 29.

18. Jan M. Dirkzwager, *Water, van natuurgebeuren tot dienstbaarheid* (The Hague, 1977), 81.

19. Staatscommissie Zuiderzee, *Verslag Staatscommissie Zuiderzee, 1918–1926* (The Hague, 1926).

Lorentz and his collaborators developed two new modeling methods, both based on fluid dynamics: the harmonic method and the exact method. The former made use of the harmonic analysis for tidal prediction that Kelvin and others had developed in the nineteenth century. Kelvin, however, had sought only to extrapolate from the existing tidal pattern, whereas in the case of the Zuider Zee closure (and the Rotterdam Waterway) engineers were attempting to predict how the introduction of hydraulic works would change the existing pattern. Lorentz therefore modified Kelvin's approach. He approximated the tidal wave function by its main harmonic component, the diurnal moon effect. He furthermore modeled the Waddenzee and the Zuider Zee as a network of branching channels originating in the openings between the islands where the Waddenzee met the North Sea (fig. 2). He divided this network into sections in which he could assume that depth, width, and friction between seawater and seabed were constant. In total, he partitioned the network of the Zuider Zee and the Waddenzee into twenty-eight sections, some of which he further divided into subsections with different dimensions.

Lorentz then calculated the tidal pattern in this network.²⁰ He performed the calculations first for the existing situation. In the meantime, an extensive program of physical measurement of currents and water levels was undertaken. Lorentz compared the computed values to the empirical ones, thereby calibrating the model. He then introduced the dam into the

20. Two differential equations described the movement of water in shallow areas:

$$\frac{\delta s}{\delta t} = -gbq \frac{\delta h}{\delta x} \pm \frac{gs^2}{bq^2 C^2}$$

$$\frac{\delta s}{\delta x} = -b \frac{\delta h}{\delta t}$$

Where:

s = current in a channel

h = water level

b = width of the channel

q = depth of the channel

g = gravitational constant

g/C^2 = coefficient of friction between water and seabed

To simplify the calculations, Lorentz linearized the nonlinear term representing the frictional effect between the current and the seabed (the last term in the first equation). He could then solve the equations, using as boundary conditions the tidal movement at the inlets on the seaward side and the fact that the currents would be zero on the shore side. This meant that he could compute the harmonic function, which represented the water levels at different moments in time, in each section in one series of computations, and thus he did not have to repeat the procedure for different moments (as was the case with the exact method). This was, of course, only possible for a regular harmonic wave, such as the diurnal moon effect, not for occasional storm surges consisting of a single non-harmonic wave.

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Figure 29.

FIG. 2 Figure from the report of the Lorentz commission showing the subdivision of the as yet open Zuider Zee into tidal compartments. The inset on the right maps the same body of water as a simplified network of channels representing tidal flows in the compartments at a specific moment in the tidal cycle. (*Staatscommissie Zuiderzee, Verslag Staatscommissie Zuiderzee, 1918–1926* [The Hague, 1926], 100.)

model and calculated future tidal propagations. The calculations were extremely laborious. Johannes Th. Thijsse, a young civil engineer assisting Lorentz, later recalled that preliminary calculation of the existing tides took two persons, working in duplicate to compensate for errors, one whole

month.²¹ The total computing labor was many times greater. Nevertheless, Lorentz managed to calculate the expected changes in the normal tidal pattern. Depending on the exact position of the dam, he predicted that the tidal range would increase by 0.60 to 0.75 meters. De Bruijn was vindicated, at least in theory. His (intuitively derived) counterintuitive prediction that the currents between the Wadden islands would increase was—to everyone's surprise—corroborated by Lorentz's calculations.

Lorentz applied the second modeling method, the so-called exact method, to compute maximum tidal levels during storm surges. This approach had already been considered by a committee investigating the effects of the 1916 storm surge on the Rotterdam Waterway.²² That committee had opted not to use the exact method because it would require a "gigantic expenditure of labor and time."²³ The exact method mathematically represented a system of channels as a set of equations derived from fluid mechanics. Variable parameters described the detailed hydraulic situation, and calculations were made on the mathematical representation. Lorentz introduced the term "exact method" to distinguish this approach from his harmonic method. He considered harmonic analysis inappropriate for computing the propagation of storm surges because of their noncyclical character.²⁴ However, the trial-and-error nature of the calculations made the exact method very time consuming.²⁵ The calculations showed that if a

21. Johannes Th. Thijssse, "De Toepassings-Mogelijkheden van verschillende getijberekeningen," *De Ingenieur* 50 (1935): B259–61 (with postscripts by Johan van Veen and Jo J. Dronkers).

22. The prevalence of physicists in the early days of Dutch tidal modeling is remarkable. The Rotterdam Waterway Committee was also chaired by a physicist, Lorentz's colleague at the University of Leiden, H. G. van de Sande Bakhuyzen. The formation of this committee marked the beginning of official concern for the condition of the Delta and in particular for the deleterious effects on salinity and on storm surge levels of the continual enlargement of Rotterdam's channel to the sea by means of steam dredges. The committee was appointed in 1916 and presented its extensive report in 1920, six years earlier than the Lorentz committee.

23. *Verslag van de staatscommissie benoemd bij K. B. 20 Maart 1916: No. 23* . . . (The Hague, 1920), 291. A more complex precursor to Lorentz's exact method had been published independently by one of the committee members, a professor of civil engineering at Delft. See Gerard H. de Vries Broekman, "Invloed van eb en vloed op benedenrivieren," *De Ingenieur* 31 (1916): 544–53, 954–55. De Vries Broekman himself was not sanguine about the practicality of his method, lamenting: "Alas, the laboriousness of the calculations corresponds to the enormity of the interests sometimes associated with them, knowing the influence of the tidal cycle in advance." *Ibid.*, 553.

24. In his exact method Lorentz did not simplify the term in the equations representing the resistance but solved them by a more complex numerical procedure (power series). He could also take wind effects into account.

25. Solutions to the equations could only be obtained by means of repeated estimates of the value of a key function involving seaward-side tidal currents. To save time and labor, Lorentz simplified the system of channels to a model that consisted of only two channels, for which he calculated high-water levels during a historic storm surge. He

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storm surge equivalent to that of 1894, with high water levels of 2.4 meters in excess of normal high tide, were to occur after the enclosure of the Zuider Zee, an additional rise of 0.95 to 1.3 meters, depending on the exact location of the closure dam, would have to be taken into account.²⁶ These were much larger figures than the 15 centimeters that Lely had estimated. On the basis of these calculations a more advantageous location for the dam was chosen, and the affected dikes were raised at government expense.

Upon completion of the dam in 1932, the new tidal patterns conformed almost exactly to Lorentz's predictions. Even the hotly contested prediction that the currents in the channels between the Wadden islands would increase was borne out.²⁷

Lorentz had succeeded in predicting changes in water levels with a remarkable degree of accuracy and reliability, using manual methods of calculation. His success increased public trust in tidal calculations. The committee's report became an important handbook for hydraulic engineers. It began to be appreciated that mathematical tidal modeling was an important tool for managing both the substance and the politics of hydraulic engineering. The challenge was to develop new methods that were accurate, fast, and cheap enough to be used in actual engineering and, no less important, that enjoyed the trust of politicians and stakeholders. This was especially pressing for modeling tidal flows on the hydraulically and politically much more complex estuaries and tidal rivers of the Delta region.

Planning the Delta, 1929–55

The Delta region in the southwest includes the seaward approaches to a number of harbors, including Rotterdam. Maintaining and modernizing these waterways was a matter of national interest and of great concern to the Rijkswaterstaat. It was clear that working in the Delta at the rapidly increasing scales demanded by modern shipping would require new coastal

had to repeat the calculations about ten times to get an accurate estimate of the currents at the inlets. He augmented his final result by 20 percent to allow a sufficient margin of error.

26. Staatscommissie Zuiderzee (n. 19 above).

27. Predictions of the increase in storm-surge levels proved less accurate. It took a long time before the inaccuracies on this point became evident because severe storms occur infrequently. In 1972, Thijsse, by then director of the Delft Hydraulics Laboratory, concluded on the basis of empirical data that Lorentz's storm-surge predictions had been too low by as much as 30 centimeters. This did not pose any immediate danger, since in order to take account of wave action the dam had been built some 7 meters above mean sea level, i.e., much higher than the highest predicted water levels. Moreover, after the "super storm" of 1953 the dam had been raised by about 40 centimeters to comply with revised standards of safety. See Johannes Th. Thijsse, *Een halve eeuw Zuiderzeewerken 1920–1970* (Groningen, 1972).

engineering techniques, including new methods of tidal modeling. The models employed for the Zuider Zee works had been a one-shot effort, developed to settle a political logjam. There, speed and efficiency of calculation were not the major criteria; accuracy and the establishment of public trust in the outcomes were the important points. But in the Delta, where the evaluation of different plans would require numerous repetitive calculations, speed and efficiency became as salient as accuracy.

The government's main aim in the Delta region in the 1920s and early 1930s was to improve and maintain the accessibility of several harbors, primarily that of Rotterdam but also those of Dordrecht and Slidrecht. However, there was a serious worry that improving accessibility—that is, increasing the cross sections of the fairways by dredging—might increase the danger of upstream flooding by making it easier for storm surges to propagate upstream.²⁸ The 1916 storm surge committee for the Rotterdam Waterway had calculated that this effect could be moderated by damming the Brielse Maas, just south of the Rotterdam Waterway, at its funnel-shaped mouth (fig. 3). However, this tidal river was also the main approach to the port of Dordrecht. This had stimulated plans for an alternative approach via a new canal south of Rotterdam (the Koedood canal). This canal could either be fitted with locks (disadvantageous for shipping) or it could become a new tidal channel, or *kill* (disadvantageous for water management). The issue could only be settled on the basis of tidal propagation models. There were also several other smaller projects relating to shipping and safety in the region. Given the interests at stake and the institutionalized power of stakeholders to articulate and defend them, the Rijkswaterstaat was under pressure to provide precise and reliable predictions about the effects of various alternatives. This was the initial motivation for the systematic pursuit of practical tidal modeling methods by the new Study Service for the Tidal Rivers, Estuaries, and Coasts.

The head of the Study Service was the talented and energetic civil engineer Johan van Veen. One of Van Veen's first projects was to calculate current flows for an open Koedood Kill under a wide range of ambient conditions. He soon found that existing mathematical methods were far too tedious to give him the many solutions he needed within a short span of time. This led him to develop a method for tidal modeling based on analogies between tidal flows and electrical currents. The idea of building mechanical or electrical equivalents to solve tidal problems was not new. Kelvin had developed a mechanical tide predictor in the 1870s, and such machines had been used at the beginning of the twentieth century to pre-

28. Increasing a channel cross section might well decrease the chance of flooding in the immediate vicinity but increase the chance of upstream flooding by lowering resistance to the upstream propagation of storm surges and hence allowing a greater volume of water to be introduced into the system.

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FIG. 3 Preliminary version of the Deltaplan, circa 1954, showing the approximate locations of the new closure dams and an overview of the Delta region. The locations of Rotterdam, Dordrecht, and the Biesbosch are emphasized. (Rijkswaterstaat, Deltacommissie.)

dict tides in several harbors. They were, however, not suitable for computing the propagation of storm surges and predicting changes in tides and in storm surge propagation caused by the construction of hydraulic works. Mechanical and electrical analog computers came into use in the United States in the interwar period.²⁹ At the end of the 1920s Vannevar Bush built his so-called differential analyzer to solve mathematical problems. At about the same time, working with others, he built an electrical network analyzer to simulate the behavior of electrical power networks.³⁰ Quite possibly Van Veen was inspired by these developments or by prior publications, but neither he nor any of his critics refer explicitly to them.³¹

It appears justified to assume that Van Veen pioneered this particular analogy between electrical networks and the behavior of water in tidal areas. Employing electrical properties like resistance, capacitance, inductance, and the difference between alternating and direct current, Van Veen defined tidal flows as analogous to flows of electrical current, and was hence able to calculate tidal flows on the basis of relatively simple equations already well accepted in the field of electrical engineering. However, Van Veen's 1932 publication describing his approach met a scathing response.³² The main critics were Jannis Mazure of the Dienst Zuiderzeewerken and two Rijkswaterstaat colleagues, one from the Directorate of Upper Rivers and one from the General Service, a rival staff department devoted to topographical and hydrological measurements. The critics sharply attacked the new method's lack of physical validity, emphasizing the fundamental differences between hydraulic and electrical currents. In the face of this acerbic criticism, Van Veen let the matter rest. In 1934 he hired a mathematician from the University of Leiden, Jo J. Dronkers, to work out new mathematical approaches.

Dronkers saw his mission as adapting Lorentz's purely tidal methods to the hydrodynamics of tidal rivers, with their variable upstream discharges. Since these were not harmonic phenomena, Dronkers opted for the exact

29. For the history of early analog computers, see Campbell-Kelly and Aspray (n. 4 above), 60–63, and Larry Owens, "Vannevar Bush and the Differential Analyzer: The Text and Context of an Early Computer," *Technology and Culture* 27 (1986): 63–95. For the post–World War II history of analog computers, see James S. Small, "Engineering, Technology and Design: The Post–Second World War Development of Electronic Analogue Computers," *History and Technology* 11 (1994): 33–38.

30. Campbell-Kelly and Aspray, 62, and A. Michael McMahon, *The Making of a Profession: A Century of Electrical Engineering in America* (New York, 1984), 185–86.

31. As early as 1900 articles had appeared in U.S. and German mathematical journals about electrical machines and even hydraulic methods to solve mathematical equations. J. S. Frame, "Machines for Solving Algebraic Equations," *Mathematical Tables and Other Aids to Computation* 1 (1943).

32. Johan A. van Veen, "Rapport betreffende het Koedoodkanaal," in *Het Koedoodkanaal* (The Hague, 1933). Jannis P. Mazure, "De Invloed van het Koedoodkanaal op de waterbeweging," in *Critiek op de nota over het Koedoodkanaal* (The Hague, 1933).

method of calculation, which Lorentz had reserved for (also nonharmonic) storm surges.³³ He applied this method not only to the calculation of water levels during storm surges but also to the propagation of normal tides.³⁴

The trial-and-error nature of the calculations soon became a much more serious problem than it had been in the case of the Zuider Zee. Lorentz had applied the exact method to a simple network composed of only two channels. The numerous channels and branching points in the Delta caused the number of iterations to multiply dramatically. Dronkers suppressed this problem in his early publications, but it soon became evident that the amount of computing labor required would become prohibitive.³⁵

In his 1937 dissertation, Mazure reviewed existing tidal modeling techniques and proposed an adaptation of Lorentz's harmonic method to tidal rivers. Mazure's approach was less accurate than the exact method, but it required far less computation. Van Veen started using Mazure's method as a way to compute first approximations of tidal effects. Although the method was indeed approximate, it was certainly much faster than Dronkers's tedious calculations, which had already begun to irritate Van Veen.

By 1938 the Study Service was so overwhelmed by the mass of calculations that it hired nine young men as human calculators, a newly created function.³⁶ The new recruits were high-school graduates with high grades in mathematics. They performed tidal calculations using both Dronkers's and Mazure's manual methods.³⁷ The calculations were made on slide rules and desk calculators. For the exact method, slide rules were generally used. The desk calculators were predominantly used for the harmonic method. This was because the harmonic method was very sensitive to inaccuracies in intermediate calculations. Even then, in spite of this greater care, the final solutions were less accurate than those achieved with the exact method, which could tolerate use of the less accurate but faster slide rules. Van Veen praised the human computers and their symbiosis with desk calculators in

33. This method was based on linearizing the quadratic "resistance" term.

34. In 1935, Dronkers described his method in "Een Getijberekening voor beneden-rivieren," *De Ingenieur* 50 (1935): B181–187.

35. In a 1938 report, Dronkers estimated that the computation of the tides in a certain river in the Dutch East Indies (now Indonesia) would take four people about five months.

36. *Jaarboekje Personeelsdienst Rijkswaterstaat* (The Hague, 1939).

37. The actual manual calculating work was, of course, quite monotonous. As a rule, calculations were duplicated to avoid errors. In case errors were detected when matching the different results, each human calculator looked for the errors in his own calculations. When executing Dronkers's exact method, each calculator was assigned responsibility for a section of some specific river. He would then transmit the results of his calculations to the colleague responsible for the adjacent section of the river. As one member of the computing staff later confided: "In the end one came to know each and every peculiarity of one's own particular section of the river." Th. Klumpers, interview by Frida de Jong of Delft University of Technology, June 1988.

a 1939 article: “For a good many years the calculating machines have been rattling in order to process the many millions of figures, and we are compelled to express and extend our appreciation and gratitude to all the many dedicated people who have participated in the execution of this particularly unpleasant task with such great care and perseverance.”³⁸ Throughout the Second World War the computing staff were exempted from conscription to forced labor in Germany. Their number, some ten in all, remained virtually unchanged during this period.

While Dronkers was refining the manual exact methods, Van Veen again took up work on what he began to call the “electrical method.” In 1937 he elaborated his ideas in a second publication, in which he emphasized the similarities between hydraulic and electrical phenomena.³⁹ He called his method an “engineer’s way,” contrasting it to the more principled mathematical method that required “a lot of time and adequate mathematical ability.” He admitted that his method was less accurate than that of Dronkers, but pointed to the enormous savings in calculating labor: “The electrical method proceeds at a much faster rate than is the case with the exact method. While the first is already producing results after calculating for only one or two days, the other method produces its results only after several months. However, some specific details of the changes cannot easily be determined from the ‘electrical method,’ while the changes in high and low tides also cannot be accurately predicted other than in very approximate terms. The exact method, on the contrary, produces such predictions with accuracy.”⁴⁰

Van Veen also proposed a division of labor: first the electrical method in order to arrive at an approximation, then the exact method to calculate the details. But even this compromise failed to assuage the critics. As with his first publication on the electrical method, in 1932, Van Veen was taken to task, this time not only by his Rijkswaterstaat colleagues but also by Johannes M. Burgers of the Delft Polytechnic, an expert in applied mechanics and, as it happened, Mazure’s thesis advisor.⁴¹ The critics again assailed the electrical method’s purported lack of physical validity.⁴²

38. Johan A. van Veen, “De Nauwkeurigheid der tegenwoordige getijberekening,” *De Ingenieur* 54 (1939): B90–91.

39. In electricity, a potential difference causes a current to flow. In the case of water, currents are mainly caused by the slope of a river (gravity) and by tidal forces. Van Veen compared the slope of a river to a direct current and tides to an alternating current. However, he simplified his method considerably. For example, in his formulas he represented the quadratic term in the hydraulic equations describing the resistance between the water and the bottom by a linear term. He justified this by claiming that Lorentz had adopted the same strategy. Johan A. van Veen, *Nota betreffende de afdamming der Brielsche Maas* (The Hague, 1937). This is an internal Rijkswaterstaat report, published in March 1937.

40. Ibid.

41. Mazure, *De Berekening van getijden* (n. 11 above); Johannes M. Burgers, “Getijstroomberekening met behulp van wetten analoog aan die van Ohm en van Kirchhoff,” *De Ingenieur* 52 (1937): B112–13 (with a postscript by Johan A. van Veen).

42. According to them, Van Veen had neglected a fundamental property of the

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Calculations of normal harmonic tidal propagation throughout the Delta system were basically intended to show the outcome of different engineering designs before they were actually built—for example, to estimate the effect of damming up the Brielse Maas on high-tide levels at Dordrecht. It was one thing to design hydraulic works with an eye to their performance during normal tides, but from the viewpoint of safety the question was inevitable: what would happen during a storm surge? Sea dikes, for example, were never designed to withstand only routine high tides, but rather the extreme high-water levels caused by storm surges. There were basically two questions in the storm-surge issue: How high could they go offshore? And what would the effects of the highest conceivable storm surge at sea be at various points in the Delta system, particularly at vulnerable locations such as Dordrecht?⁴³ Modeling storm surges in relation to engineering goals thus required research on maximum likely storm surges, on the propagation of storm surges as deviant tidal flows, and on the effects of various engineering options for managing those flows. This program, which gained momentum in the late 1930s, strained the modeling and calculation resources of the Study Service to the utmost and was a major factor in the hiring of the human calculators referred to above.

Again, this was due not only to the complexity of the hydraulic system but also to the sharp conflicts of interest among different regions and parties in the Delta. Tidal propagation models, as Mazure had stated, were important tools in the Rijkswaterstaat's efforts to manage these conflicts and to maintain its engineering authority in the Delta. One major conflict concerned the future of the Biesbosch, a large, sparsely populated maze of islands and tidal creeks at the confluence of the Maas and Rhine Rivers just upstream of Dordrecht. The province of North Brabant had long wanted to permanently reclaim this brackish and potentially very fertile marsh but had been prevented from doing so by the Rijkswaterstaat on the grounds that reclamation would eliminate an important storm surge reservoir and hence endanger the vulnerable sea defenses at Dordrecht. To counter this *force majeure*, Brabant's Provinciale Waterstaat had retained Mazure in the early 1930s to model the effects of reclamation work in the Biesbosch on the tidal system in the vicinity. Mazure used Lorentz's harmonic, or linear, method and calculated that storm-surge levels at Dordrecht would increase by 9 centimeters, assuming a storm surge like that of 1916. The Rijkswater-

movement of water in rivers, expressed by the continuity differential equation (the second equation in footnote 20), and, further, had neglected phase differences in branching points. They argued that the method would be appropriate only in specific cases, but that Van Veen had not specified which cases these were. Burgers, "Getijstroomberekening."

43. The second question is directly relevant to our study of the modeling of tidal propagation, but answering it well depends on a good answer to the first question.

staat adamantly maintained that even this small increase would prove too much for Dordrecht's antiquated dikes and it continued to forbid reclamation.⁴⁴ But the controversy made it clear that in order to avoid embarrassing questions in Parliament the Rijkswaterstaat would soon have to provide detailed and convincing calculations of its own. In a scenario to which we have since become accustomed, but which was then quite unusual, the political debate about reclamation had become a technical debate about the virtues of different approaches to tidal modeling and their underlying assumptions. The Rijkswaterstaat's authority in the Delta region hung in the balance.

At this juncture Van Veen became increasingly suspicious of working assumptions about the maximum possible height of storm surges. The worst-case estimate had always been the highest recorded (and adequately documented) storm surge. Van Veen's analysis of the various factors responsible for storm surges suggested that a worst case of more than 3 meters above normal high tide at the Hook of Holland, at the entrance to the Rotterdam Waterway, was within the bounds of possibility.⁴⁵ A rough calculation of the effects of such a storm surge at Dordrecht yielded, not Mazure's mere 9-centimeter increase above mean high tide, but an increase of about 1 meter.⁴⁶ By 1939 new statistical techniques provided even more alarming news. Log-linear plotting of the frequency versus height of historical storm surges suggested that a storm-surge increase of 4 meters in excess of mean high tide at the Hook of Holland could be expected to occur once every three hundred years.⁴⁷

Galvanized by these new insights, Van Veen became something of a hydraulic Cassandra, warning anyone who would listen that a major disaster was in the offing. In a later work he confessed: "The technical planning or carrying out of a plan seldom expends our capacities to the full. It is the pre-

44. S. H. Ringma, *Verzamelrapport berekeningen benedenrivieren, 1937–1944* (The Hague, 1944). Enno de Boer, "Zestig jaar Deltawerken: Dordrecht als opening en sluitpost," in *Nederlandse ingenieurs en hun kunstwerken*, ed. Marie-Louise ten Horn-Van Nispen, Harry W. Lintsen, and A. J. Veenendaal (Zutphen, 1994).

45. Van Veen began to analyze storm-surge heights as the specific outcomes of a number of independent factors, such as wind speed and direction, upstream discharge, the astronomical tide, long-term processes of subsidence and sea-level rise, and so on. He found that none of the historically severe storm surges had seen the combination of the most extreme potential values for all factors. In theory, therefore, worse was yet to come. He arrived at his estimate of three meters by combining the most extreme historical values and doing a little extrapolation. See the unpublished first report of the 1939 storm surge committee, issued in 1940.

46. Note that this difference in results is attributable not to the different methods of calculation used but to different assumptions regarding the maximum height of a potential storm surge. Mazure used the storm surge of 1916 as his standard reference.

47. Pieter J. Wemelsfelder, "Wetmatigheden in het optreden van stormvloeden," *De Ingenieur* 54 (1939): B31–35.

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vious work, the organization and general diplomacy required, that absorbs our energy. . . . [F]ear of novelties demands clever handling. Sometimes, or perhaps often, the opposition comes from the top—the providers of money—*then strong, invincible arguments are needed.*”⁴⁸ It is in the light of this political labor of “organization and general diplomacy” that we should understand the development of mathematical tidal modeling by Van Veen and others during this period.⁴⁹ In the absence of bitter empirical proof—which would soon be provided by the unprecedented storm surge of 1 February 1953—what stronger arguments could Van Veen have made?

Nonetheless, Van Veen was bringing some very bad news on the basis of very slim evidence, and it is not surprising that the higher echelons of the Rijkswaterstaat and the government required further proof. Statistical risk was a new and subtle kind of political and administrative challenge. A massive and costly response to the mere possibility of a theretofore unanticipated calamity would have been hard to sell to taxpayers. In 1939, therefore, the minister of public works appointed a committee on storm surges to define a way forward in light of the conflicting interests prevailing in the Delta and the controversy about the height and frequency of future storm surges. Van Veen was appointed secretary to the committee and authored the reports. The committee members included senior Rijkswaterstaat engineers, the chief engineers of the provincial *waterstaten* of South Holland and North Brabant, and Dordrecht’s director of public works (also a Delft-trained civil engineer). Their mandate was, essentially, to produce an engineering consensus on the effects of future storm surges in the Delta region against the background of various interests and projects, such as maintaining the nautical accessibility of Rotterdam, fighting salinity in the tidal rivers, reclaiming the Biesbosch, and ensuring the safety of Dordrecht and other riverine towns.

The committee’s findings were never published; the three “preliminary” reports of 1940, 1942, and 1944 went no further than the minister’s desk and those of a small circle of hydraulic engineering experts. The first amounted to an unsubstantiated warning of the threat of flooding due to storm surges of unprecedented height. By the time of the committee’s second unpublished report, submitted in April 1942, results from Dronkers’s exact method calculations were available to give that warning some teeth.⁵⁰

48. Johan A. van Veen, *Dredge, Drain, Reclaim: The Art of a Nation*, 5th ed. (The Hague, 1962). Emphasis added.

49. The impulse behind the development of mathematical modeling within the Rijkswaterstaat at this point in time could be described as “technocratic,” i.e., deriving from a tendency on the part of engineers to define themselves as the only relevant authorities and to manage the political process of decision making about appropriate measures to be taken.

50. The estimate of future storm-surge heights at “coastal points” was derived from the “worst case factors” approach used by Van Veen as early as 1939, which served as

In the autumn of 1942, the chairman of the committee, D. A. van Heijst, chief engineer of the Rijkswaterstaat's directorate of tidal rivers, informed the minister of public works that the committee's membership had to be expanded. As he explained: "[I]t is better that possible criticisms be dealt with and where applicable disproved in the bosom of the committee itself than that these should come from outside and become public knowledge. This is of particular importance because the results of the research must justify heightening the dikes and the great expenditures thereby devolving on interested parties."⁵¹

Managers like Van Heijst understood that the committee's political credibility depended on avoiding a public debate over the scientific merits of the calculations. It was prudent, then, to co-opt potential expert opponents. The most prominent of these was Johannes Thijsse, who had been a young assistant to Lorentz in the early 1920s and was by this time professor of civil engineering at Delft and director of the Delft Hydraulics Laboratory, founded in 1927 to perform scale-model investigations of waterways and hydraulic structures for the Rijkswaterstaat and other clients. Thijsse was the doyen of Dutch hydraulic modeling and could well have become Van Veen's nemesis had he not been brought onto the committee. He had privately expressed skepticism about the extreme predictions the committee had issued under Van Veen's leadership. Along with other new members, Thijsse in fact challenged the validity of the Rijkswaterstaat's mathematical modeling methods. The dispute remained unresolved, as war forced the committee to suspend work in the summer of 1944.

In January 1946, Van Veen published a third article on the electrical method in *De Ingenieur*.⁵² With characteristic aplomb, he claimed that "for a study of the theory of tides, a handbook of electrical engineering is essential." He described a small electrical network that he had constructed just prior to the war with the aid of two electrical technicians. The network, effectively an analog computer for calculating tidal propagation, modeled a portion of the Lek River, one of the maritime branches of the Rhine (fig. 4). Van Veen proposed to use the network as a hydraulic engineering tool. He

grounds for the dire predictions in the first (unpublished, 1940) report of the 1939 storm surge committee. This provided a number of storm-surge heights at locations along the coast, which served as points of departure for Dronkers's section-by-section calculations of the so-called storm-surge curves upstream of the reference points. This was the first time that the exact method was deployed on a large scale to establish storm-surge heights. Johan A. van Veen, *Conceptrapport commissie inzake de stormvloed op de benedenrivieren* (The Hague, 1942), 11.

51. D. A. van Heijst to Secretary General of Department of Public Works, 3 September 1942, dossier 627, "Report Storm Surge Committee," Archive Rijkswaterstaat Directie Benedenrivieren 3.07.07, National Archives, The Hague.

52. Johan A. van Veen, "Electrische nabootsing van getijden," *De Ingenieur* 61 (1946): B17–20.

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FIG. 4 A portion of Johan Van Veen's first prototype electrical model of the Lek River. The circuitry is visible in the upper portion of the photograph, while the electronic schematic of the various river sections, indicated by names of towns along the river, can be seen below. (Johan A. van Veen, "Electrische nabootsing van getijden," *De Ingenieur* 61 [1946]: B18.)

made no bones about the fact that this tool was intended to replace, as far as possible, the tedious harmonic and exact methods, with their reliance on manual computation: "The intent . . . is to avoid the dead calculating work that has to be repeated over and over again. It is now possible to construct a machine . . . which can itself perform the extremely complicated and tedious calculations, the solution of twenty or thirty complicated or complex equations with an equal number of unknowns. . . . Of the 300,000 man-hours of labor necessary for a sizable plan, only a few will remain."⁵³ The speed of the new machine enabled many more options to be calculated rapidly enough so that the results could be used in the actual planning and design of hydraulic projects. "We can finally answer practical questions on time. Every river plan of any significance requires not one but tens of tidal calculations, and every calculation, employing ten men, easily took several months."⁵⁴

In a postscript to this article, Dronkers emphasized the precision of the exact method and tried to parry Van Veen's criticism of its extreme laboriousness. Dronkers claimed that the complex calculations for the 1939 storm surge committee, "the most difficult and laborious possible," in which the entire Delta system was modeled for seven different plans, took six men no more than two years' time—including all the preparatory work of defining the channel sections.⁵⁵ Van Veen rejoined: "For years now the

53. Ibid., B20

54. Ibid.

55. Jo J. Dronkers, postscript to Van Veen, "Electrische nabootsing," B72.

fact has been that the methods of calculating are too complicated. Dr. Dronkers may pretend that the amount of calculating work is not so bad, but it gives me the shivers. Only one answer fits Dr. Dronkers's rejoinder and I believe he agrees: 'Wait and see.' And 'Give me the tools.' I therefore ask him to be patient, as I have been patient for ten years with mathematical methods whose calculations just never get done and which all too often give revised and deviant outcomes."⁵⁶

The Scale Model

In June 1946, with this internecine rivalry simmering in the background, the storm surge committee reconvened. A number of those present, including Johannes Thijsse, again expressed reservations about Van Veen's grim predictions. In the closing months of the war Thijsse had become something of a national hero, thanks to his scale-model simulations of the use of caissons to close the breaches in the dikes of Walcheren.⁵⁷ Riding the wave of his popular success, he now proposed to build a large scale model (fig. 5) of the northern portion of the Delta as a means of resolving the controversy. H. Versteeg, Dordrecht's director of public works and a member of the committee, reported enthusiastically to his city council: "The model would be built at a scale of 1:2800 as far as the length and breadth is concerned and at 1:64 in regard to the height; it will be 50 meters long, according to rough estimates cost 50,000 guilders, and be ready in 8–12 months. The experiments can be done at the rate of one per half day. One can let different high water levels occur at important places . . . and see what happens at other points, for example Dordrecht. One can place dams in the rivers and investigate their influence. One can also take account of the influence of the wind, etc."⁵⁸

Thijsse's proposal to venture into the scale modeling of tidal systems drew on the growing international practice of building large-scale hydraulic models (albeit mostly of free-flowing river systems) as well as some trials he himself had conducted in 1940. Having been forced by scarcities of funds and materials to wait out the war, and subsequently occupied by the Walcheren reclamation, he now used the storm surge committee's mandate to make a bid for a large-scale model of the Delta region. Scale models were good at showing changes in the hydrodynamics of a tidal area caused by the

56. Johan van Veen, reply to Dronkers, *De Ingenieur* 61 (1946): B73.

57. The dikes had been bombed in three places by British planes in October 1944 in an effort to flood out the Germans who were using Walcheren as a fort to deny the Allies access to the strategic harbor of Antwerp. For a dramatized rendering of Thijsse's contributions to closing the breaches in the Walcheren dikes, see Wiebe Bijker, "Sociohistorical Technology Studies" (n. 2 above), 234.

58. H. Versteeg to City Council of Dordrecht, 12 June 1946, Dossier A 1960-1597, Archive 8, Stadsarchief 1900–1985, Municipal Archives, Dordrecht.

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FIG. 5 The construction of the scale model of the northern Delta area, in Delft, circa 1948. (Delft Hydraulics Laboratory.)

introduction of specific elements such as dams and river sluices. These could be placed at will in the model and repositioned with little effort. However, reconfiguring a model for different projects was costly, and such major changes as increasing the depth of estuaries were almost impossible to implement. A scale model of the Delta promised to be very useful for evaluating large numbers of alternatives within a similar overall structure, but developing such a comprehensive model posed something of a dilemma. On the one hand, the downscaling had to be sufficient to incorporate a large geographic area in a model of feasible size. On the other hand, the downscaling had to be sufficiently modest to maintain turbulent flow in the model and to permit accurate water-level measurements at the reduced scale. To satisfy both requirements, as Versteeg's report indicates, Thijsse reduced the horizontal dimensions in the model more than the vertical ones. Such asymmetrical scaling was not new; Osborne Reynolds had initiated the practice toward the end of the nineteenth century.⁵⁹ And despite the horizontal downscaling, the model was so big that it had to be built in the sizable garden adjacent to the laboratory proper, protected from the weather by large army tents.⁶⁰ Over the years the model was extended to

59. Georg H. de Thierry and Conrad Matschoss, eds., *Die Wasserbaulaboratorien Europas* (Berlin, 1926).

60. Dirkzwager (n. 18 above).

cover a larger geographic region, a process frustrated by the presence of adjacent buildings. The problem was solved in part by distorting the topology of the river system in the model.

Reconstructing the Delta: The Storm Surge of 1953 and Its Aftermath

In the end, Thijsse's model failed to resolve the debates within the storm surge committee, which remained undecided on what maximum tidal level to adopt as the benchmark for dikes and other flood defenses. The impasse might well have persisted had it not been for the 1953 storm surge, which significantly exceeded all previously measured levels and caused the flooding of a large part of the Delta region and the deaths of 1,835 people. Van Veen was thoroughly vindicated, though at a terrible cost. In the meantime, the four modeling methods that had emerged in the preceding decades entered a period of uneasy coexistence, and the various research groups readjusted their activities. Dronkers got his own research unit within the General Service of the Rijkswaterstaat. He concentrated on domestic projects beyond the geographical scope of Thijsse's scale model, and extended his field of operation to foreign hydraulic projects. Thijsse's model became the workhorse of hydraulic research for the reconstruction of the Delta, in some part because its intuitively accessible mode of representation seemed more convincing to politicians and the general public than either the impenetrable mathematics employed by Dronkers or Van Veen's electrical mysteries. Van Veen's group performed calculations using the harmonic method to check the results of the scale model and to determine aspects of plans not amenable to physical modeling. Van Veen also initiated construction of an analog computer in an electrical laboratory established for that purpose in the Research Service of the Rijkswaterstaat's Directorate of Maritime Rivers.

The 1953 flood disaster quickly convinced all parties of the urgent need for an integrated large-scale project to tame the Delta in its entirety. Within three weeks of the flood the government had set up the so-called Delta Committee, with Van Veen acting once again as secretary (and later as member as well), to coordinate research in connection with dike closure and reclamation—a recapitulation of Walcheren on a large scale—and to plan future hydraulic projects.⁶¹

Thenceforth the work of the different research groups became more closely coordinated. The specific advantages of each computing method were exploited to the greatest possible degree. The scale model was further extended to cover a larger part of the Delta region after Delft municipal authorities agreed to expedite the removal of a few small adjoining build-

61. Deltacommissie, *Rapport Deltacommissie*, 6 vols. (The Hague, 1960).

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FIG. 6 Johan Van Veen's first analog computer, 1954. (Rijkswaterstaat Zeeland, Delta-documentatie 00.09.00.12.)

ings.⁶² Various devices were introduced into the model to improve its validity: rods were placed in the currents to augment the friction of the bottom, and revolving rotors were introduced to simulate the effect of the rotation of the earth on the movement of water (the Coriolis effect), a phenomenon that had in the meantime also been incorporated into Dronkers's mathematical method.

In 1954 Van Veen's electrical laboratory completed a totally electronic analog computer (fig. 6). Its performance is difficult to assess, because it is hardly mentioned in the publications of the Delta Committee. Presumably it did not quite live up to expectations. It must certainly have been fast enough, in any case many times faster than the other available methods, but in terms of reliability and accuracy—and perhaps setup time—it apparently left much to be desired. In any event, work started on the construction of a second analog computer, the Deltar, in 1955.⁶³ This device

62. Johannes Th. Thijsse, "Het Deltamodel in het Waterloopkundig Laboratorium te Delft," in *Rapport Deltacommissie*, vol. 5. Dirkzwager, 138–40.

63. A crucial problem in the design of the Deltar was the simulation of the resistance phenomenon between the water and the bottom (a quadratic term in the equations). A solution was found in the application of thermocouples, devices for measuring temperature whose output voltage was related quadratically to the input. Johan C. Schönfeld and Henk J. Strobant, "Getijonderzoek door middel van de hydraulisch-electrische analogie," in *Rapport Deltacommissie*, vol. 4.

was not finished until 1961, a year after the final report of the Delta Committee.

The Deltar consisted of a number of electromechanical units, each representing one section of the river system.⁶⁴ It took a lot of time and effort to set the machine up to model a specific river system but, just as in the scale models, different alternatives could subsequently be evaluated at an almost industrial pace. The new device, unlike its predecessor, could also incorporate wind influences into the model.⁶⁵ In spite of its speed and sophistication, by 1970 the new digital mainframe computers had rendered the Deltar obsolete as a design aid for novel hydraulic engineering projects. However, the extremely expensive machine acquired a new lease on life simulating water movements for the operational control of the huge Haringvliet discharge sluices.

Linear and exact manual calculations continued to supplement scale modeling experiments in this period, being used to check the results of the scale model for accuracy. In 1954, Dronkers and Johan C. Schönfeld proposed straightforward numerical methods of calculating tidal flows; they argued that calculations using these methods, although they required more computing work than the trial-and-error numerical methods in use until that time, could be carried out by inexperienced staff.⁶⁶

Until the 1960s it was possible to meet practical computational requirements only by the application of all four methods: the linear (harmonic) method, the exact method, the scale model, and the electrical method. During the 1960s, digital computers, which required straightforward numerical methods, increasingly came to be used for the mathematical models. The digital computer offered both the accuracy of the mathematical approach and the ability to evaluate large numbers of plans. It clearly held out the prospect of finally being able to resolve the tradeoff between speed and accuracy that had limited the technical and political utility of tidal calculations to that point. Initial experiments were performed in 1956 using a digital computer built at the Mathematisch Centrum at the University of Amsterdam. To accommodate more intensive use by Rijkswaterstaat, and particularly by the engineers of the Delta Directorate responsible for implementing the Delta Plan, the government had increased the center's funding,

64. Each unit contained a shaft whose radial position represented the mean water level in that section. Each shaft bore a circular disk whose contour represented the width of the water surface as a function of the water level in a specific section. The units were connected electromechanically in accordance with the topography of a specific river system. The water levels at sea, the downstream discharge, and the wind force and direction were entered into the machine on punched tape.

65. J. B. Schijf, "Getijberekeningen, hydraulisch en elektrisch modelonderzoek in algemeen verband gezien," in *Rapport Deltacommissie*, vol. 4.

66. Jo J. Dronkers and Johan C. Schönfeld, *Tidal Computations in Shallow Water* (The Hague, 1958). Jo J. Dronkers, "Methoden van getijberekening," in *Rapport Deltacommissie*, vol. 4.

though it seems that Rijkswaterstaat engineers and scientists in fact made little use of the opportunity.⁶⁷

In 1963 the Rijkswaterstaat acquired its own digital computer, an Elliott 503, for tidal calculations.⁶⁸ Thereafter, routine calculations for the Delta region (for instance, simulation of water flows for management of discharge sluices) were performed on the Deltar, while the Elliott handled special problems and calculations for areas outside the region, as well as other types of technical-scientific calculations.⁶⁹ In time the digital computer completely replaced the other methods of calculating tidal flows, including physical scale modeling. However, this was a very gradual process, not completed until the retirement of the Deltar in 1983.

Making Models, Producing Trust

We have argued that technical motives and considerations have not been the only shaping forces in the history of tidal modeling in the Netherlands, in contrast to what one might expect in such a specialized field of engineering. To understand when tidal modeling emerged, why such a spectrum of modeling techniques was developed, and what choices were made among them, we also have to mobilize social explanations. The basic argument has been that the position and status of hydraulic engineers, and of their main institution, the Rijkswaterstaat, were increasingly put at risk by the growing complexity of their technological ambition. Engineers not only had to solve specific design problems, they also, and perhaps more importantly, had to manage the various stakeholders involved in the future of hydraulic projects. They had to convince these stakeholders of the benefits of specific hydraulic plans and of the acceptability of the risks those plans entailed. In the shift from the Zuider Zee project to the Delta, the growing number and increased competence of stakeholders also affected choices among the alternatives. The models developed for the Zuider Zee only had to provide a degree of certainty about the effects of an already established plan. In the planning of hydraulic works for the Delta region, rapidity, flexibility, and accuracy all became important. The management potential of the models became their most salient feature.

Tidal modeling became a core element of Dutch hydraulic engineering practice in response to a political crisis touched off by the plan to separate the Zuider Zee from the North Sea. Expectations of higher tidal levels on the seacoasts adjacent to the closure dam caused the threatened provinces and

67. Gerard. F. Alberts, Frederik van der Blij and Jan Nuis, eds., *Zij mogen uiteraard daarbij de zuivere wiskunde niet verwaarlozen* (Amsterdam, 1987).

68. S. M. Argelo and H. Rietveld, "De Computertoepassingen bij Rijkswaterstaat," in *Automatisering en overheid*, ed. H. Reinoud et al. (Utrecht, 1966).

69. *Ibid.*, 167.

water boards to withdraw support for the project, seriously threatening its political viability. Reassurances based on intuition and informed guesswork failed to pacify the dissidents. Given the unprecedented nature of this closure project, more compelling proof was demanded than the mere opinions of experts. Scale model experiments, despite the fact that a number of hydraulic laboratories in Germany had proven their usefulness in investigating hydraulic phenomena, had not yet been applied to cases as large and complex as that of the Zuider Zee. In this impasse, more constraining yet for lack of a hydraulic laboratory in the Netherlands itself, the Dutch government mobilized a prestigious intellectual resource, the renowned physicist Hendrik Lorentz. New insights into fluid dynamics suggested that tidal propagation in the new Waddenzee might be mathematically modeled, and the hope was that Lorentz could work out a practical method to do this—a method rooted in the uncontested authority of physics itself.

Lorentz's values for the increase of tidal levels, which were neither as optimistic as the government's nor quite as worrisome as those of the critics, were presented some six years before the closure dam was completed. Notwithstanding their being based only on Lorentz's reputation and some postulates from fluid dynamics, they proved strong enough to deflate political opposition and ensure the continuity of the project. When actual post-closure tidal levels confirmed the accuracy of Lorentz's predictions to within a small margin of error, it was clear that hydraulic engineering had acquired a new tool—a tool that not only enabled more-or-less accurate predictions of the effects of hydraulic engineering works in tidal areas but also facilitated the management of the sociopolitical environment in which these works had to be proposed, defined, and funded. The civil engineer Jannis Mazure recognized this dual nature of tidal propagation models in his 1937 thesis. He asserted that "scientific-mathematical methods" bolstered the self-confidence of the engineers, prevented costly mistakes, and avoided spurious damage to third parties, thus conserving trust in the "technical leadership." In short, Mazure contended that thanks to these methods engineers could know what they were doing, could be in control of the situation, and could earn the confidence and cooperation of other parties.

The Rijkswaterstaat, excluded from the Zuider Zee works and anxious not to lose the initiative a second time, turned to the southwestern Delta as the major remaining coastal engineering challenge in the country. After Lorentz's overwhelming success it was clear that mastering the mathematical modeling of tidal propagation would be a key to the technical and political mastery of the Delta. Given the region's staggering physical complexity, the development and application of mathematical models of tidal propagation offered the only possibility for establishing the effects of proposed engineering works a priori. Reliance on intuition here was out of the question, and an experimental, scale-model approach was not feasible—nor was there any precedent for what the Rijkswaterstaat was facing. Hence,

mathematical models would have to be mobilized to demonstrate the desirability of constructing particular engineering works and to convince politically vocal stakeholders that their interests were being served—or at least were not being ignored. Mathematical models were thus, in the most literal sense, “management instruments” for the Rijkswaterstaat vis à vis its social environment.

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Of course, the efficacy of tidal propagation models depended on the degree of trust that politicians and the general public placed in the validity of predictions generated by the models. Speaking of the government’s hesitancy in approving hydraulic engineering works in the Delta in the period before World War II—despite vigorous tidal modeling—a prominent Rijkswaterstaat engineer noted: “The crux of the matter was really how much trust outsiders could place in the complicated and, for laymen, practically impenetrable tidal calculations on which the plans were based. These mathematical models were, after all, based on approximations of the reactions of reality to the realization of the plans, and their suitability could only be practically demonstrated upon completion of the projects.”⁷⁰

Creating and maintaining trust was a project in itself, one in which reputations and cultural repertoires played an important role, but in which ultimately the demonstrated correspondence between modeling predictions and perceived outcomes was absolutely crucial. Moreover, in order to be relevant to the political process of balancing interests and searching out compromises, the models had to be able to simulate many different design variations—rapidly, flexibly, and accurately.

Where models could not be corroborated by outcomes because of severe time lags between modeling and the completion of actual engineering works, it was at least crucial to demonstrate that different modeling approaches came to pretty much the same conclusions. The use of mathematical models as sociopolitical management tools thus generated its own particular design requirements for the models themselves. They had to be fast and flexible enough to provide parameters for a number of alternative plans within a reasonable span of time, so as to increase the likelihood that a plan might be realized and corroborate the models’ predictions. It was desirable that a number of different modeling approaches be developed, for purposes of mutual corroboration and correction where the actual realization of plans took much time. And, finally, other things being equal, more realistic modeling approaches, especially physical scale models, were preferable, inasmuch as they seemed more transparent to laymen in spite of their complex mathematical underpinnings.

70. H. A. Ferguson, *Dialog met de Noordzee: 2000 jaar Deltawerken* (Hippolytus-hoef, 1991), 106. Ferguson led part of the Walcheren reclamation and was a major figure in the reclamations after the 1953 flood. He was head of the Rijkswaterstaat’s Delta Service between 1969 and 1975.

These design requirements galvanized a search during the 1930s for modeling approaches that were fast, flexible, accurate, and intuitively accessible. Physical models of large hydraulic systems on the scale of the Delta were not yet considered feasible. This left various mathematical approaches, including Van Veen's analogy with electrical networks. The search for one best way was, however, plagued by a stubborn correlation between the precision of the method and the amount of calculating time it required. This dilemma was largely responsible for the variety of modeling methods that were developed and for the sometimes bitter rivalry among their advocates.

The modeling standoff was superficially resolved by the storm surge of 1953, which created a climate in which the Rijkswaterstaat was granted greater budgets and immense latitude for operation simply because all the conflicting parties were now convinced that the storm-surge threat was more serious than the threats to their interests posed by any coastal engineering measures that might be taken. Speed of design became more important than absolute certainty and precision. The way was cleared for less stringently valid, more approximate, but faster and more flexible styles of modeling, such as Van Veen's electromechanical analog computer and Thijssse's scale models.

This may partly explain why the digital computer set up at the Mathematisch Centrum met with such an unenthusiastic reception and why the Rijkswaterstaat continued to use the analog Deltar for major tidal calculations in the Delta region in preference to the digital computer it acquired in 1963. It may well have been the environmentalist-inspired protests against the closure of the Oosterschelde Estuary in the early 1970s that finally forced the Rijkswaterstaat to take the immense modeling power of digital machines seriously.⁷¹ Forced by the government to come up with an environmentally benign design, the Rijkswaterstaat turned to the Rand Corporation for the necessary ecological modeling expertise. Rand designed a simplified bioenergetic ecosystem model of the Oosterschelde and ran the extensive series of calculations for different closure options on the Rijkswaterstaat's digital mainframe. This proved a decisive demonstration of the immense calculating power of the digital computer and helped to launch a new era of cheap, "industrialized" modeling in all domains of hydraulic engineering in the Netherlands. This "democratization of modeling" has ironically weakened the managerial monopoly that the Rijkswaterstaat maintained over the field of hydraulic engineering thanks to its monopoly on mathematical modeling. Because mathematical modeling of tidal and other hydraulic phenomena is now cheaply available to all, local and regional hydraulic agencies have been able to reassert their own traditional authority over drainage, flood defenses, and the management of water quality.

71. Cornelis Disco, "Remaking 'Nature': The Ecological Turn in Dutch Water Management," *Science, Technology, and Human Values* 27 (2002): 206–35. Bijker, "The Oosterschelde Storm Surge Barrier" (n. 13 above).