Tidal Calculations in The Netherlands, 1920-1960

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This article describes the computing problems in the field of tidal calculations in the Netherlands between 1920 and 1960. These calculations were necessary to predict the changes in the water movements caused by hydraulic works like the Zuiderzee Works and the Delta Works. The growth of computing problems in this field was not only caused by the increasing technical complexity of the hydraulic works, but also by the growing importance of the tidal calculations in the decision process. Before the introduction of the digital computer, several solutions were developed and used: numerical methods, contracting young men for the calculations, analog electrical machines, and large-scale models. The required accuracy of the predictions and the number of alternative plans for which calculations had to be done were important factors in the choice between the alternative methods.

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In 1918 the Dutch government called upon the assistance of the famous physicist H.A. Lorentz for the solution of an urgent problem. The problem involved the prediction of the changes in tidal motions which, it was feared, would result from the planned enclosure of the Zuiderzee, a large bay on the North Sea. Calculations proved to be so complex that it took Lorentz eight years to complete his investigation. After the Zuiderzee Works project, such tidal predictions became regular practice in the preparation of hydraulic works in the tidal waters of the Delta Region of the Netherlands, such as dams and land reclamation projects. The demand for computing resources increased to such an extent that it began to hamper technological progress in this field. In the search for a solution, a number of parallel initiatives were taken to develop new methods to predict changes in tidal effect. A large flood in 1953 accelerated the research using these methods, and resulted in the execution of the hydraulic works known as the Delta Works.

The computing problems emerging in this field were of a type similar to those encountered by the military during the Second World War in, for example, ballistics and the Manhattan Project. Historians of computing have paid special attention to the military problems because these formed the primary stimulus for the development of digital computers. However, the success of the digital computer cannot be explained solely in terms of computational demands arising from military sources. The increase in general demand for computing aids in those days was at least as important. Such demand had always existed, but for several reasons it strongly increased during the twentieth century. One of the main reasons was the growing volume of technological research and the growing rate of application of scientific methods in this research. Scientific methods were often mathematical in nature and brought forth many computational problems. A variety of computing methods were developed as a response to these computing needs. They consisted not only of technical devices; the phenomenon of the human computer and the use of analog machines also became widespread. To understand the success of the digital computer, the growing demand and different methods of computing will have to be further investigated.

The present article focuses the investigation on one sector of technology: the field of civil engineering in the Netherlands. Within this field we chose one specific subject that created an important computing problem: the prediction of the effects of hydraulic works on water movements in tidal water. Three computing methods were developed for this purpose in this century before the introduction of the digital computer: the numerical method, with the calculations performed by hand; the electrical analog method; and the scale model. Surprisingly, the scale model was not the first but the last of these three methods, the reasons for which will emerge from a discussion of the factors determining the choice between the competing methods.

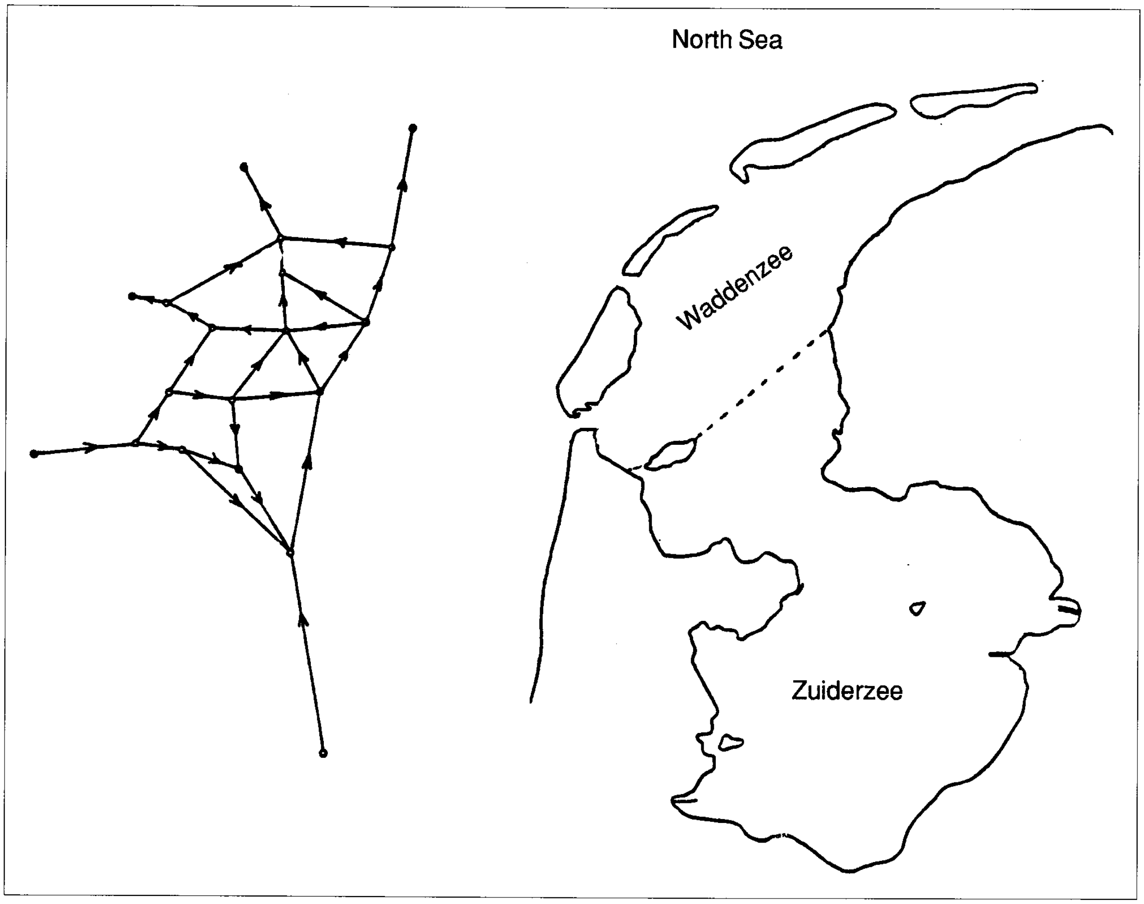

Figure 1. The Waddenzee and the Zuiderzee (on the right) and the network of channels (on the left) representing them (before enclosure). The dotted line is the projected enclosing dam.

The Zuiderzee enclosure project

At the turn of the century the enclosure of the Zuiderzee was extensively discussed by Dutch civil engineers and politicians. The plan was promoted for several reasons: the gain of new land, the creation of a reservoir of fresh water for agriculture and drinking, the increased safety from flooding in the surrounding areas, and a reduction of costs of dike maintenance.

Although the Netherlands cherished a long tradition of land reclamation, culminating in the nineteenth century in draining the largest inland lake, existing knowledge was insufficient for a project of this complexity. One of the main problems was the construction in tidal water of a large dam with a length of 30 kilometers. On the seaward side of it a shallow inner sea, the Waddenzee, was separated from the North Sea by a chain of islands. It was expected that the new dam would change the existing patterns of tides and the height of water elevations during storms in the Waddenzee, but the extent of the change remained uncertain. Knowledge of the changes was important to determine the height of the enclosing dam and the dimensions of the sluices in the dam, and to predict sand movements in the Waddenzee. Moreover, it might prove necessary to increase the height of the existing dikes joining the dam.

A method to determine the changes in the water levels was not available. Such a method had already been sought in the nineteenth century, when hydraulic works in tidal waters caused unexpected rises of water levels or changes of currents in waterways. On several occasions the government had been forced to establish a special state committee to investigate problems of this kind. The work of these committees, however, had not resulted in generally applicable methods to predict the changes in the water movements beforehand.

One of the promoters of the Zuiderzee project, the civil engineer and politician C. Lely, in one of his first proposals stated as his opinion that the increase in the existing water levels would be marginal and would occur only in the immediate environment of the dam.[1] In 1911, in an article in *De Ingenieur*, a leading journal of engineering in the Netherlands, the height of the high tides was estimated to double. The article's author, H.E. de Bruijn, argued that the actual figure could not be determined by way of computation but rather that "one has to feel it, as it were, based on experience gained elsewhere and on relevant research."[2]

In 1918, after a long period of discussion over the various plans, the Dutch parliament granted approval to proceed with the project under the condition that a committee be appointed to investigate the changes in the water elevations. The government invited Lorentz to chair the committee, since he had, as president of the Dutch Academy of Sciences, already studied the problem.

Lorentz decided to attempt calculation of the changes in water elevation by first computing the water movements. He developed several new methods to solve the problem. For a proper understanding of what follows, some explanation of two of these methods has to be given: the *harmonic method* and the *exact method*. The harmonic method made use of the so-called harmonic analysis for tidal prediction that Lord Kelvin and others had developed in the nineteenth century. The tides at specific places were calculated by extrapolation from observed cyclic patterns. This analysis was not applicable when the traditional pattern was being modified. In his harmonic method, Lorentz approximated the tide wave function by its main harmonic constituent. He furthermore modeled the Waddenzee and the Zuiderzee as a network of internally connected channels originating in the inlets connecting the Waddenzee with the North Sea (see Figure 1). He divided this network into sections within which the depth and width and the bottom resistance could be assumed constant. In total, the network of the Zuiderzee and the Waddenzee consisted of 28 sections, some of them further divided into subsections with different dimensions.

Lorentz calculated the tide pattern in this network. The water movements in shallow water were described by two differential equations (see box). In the equations, Lorentz linearized the nonlinear term representing the frictional effect between the water current and the bottom. He could subsequently solve the differential equations, obtaining two linear equations for each section. The resulting set of equations could be solved, using as boundary conditions the tidal movement at the inlets on the seaside and the fact that the currents are zero at the land side. The calculation was first performed for the existing situation. In the meantime, an extensive program of physical measurement of currents and water levels was undertaken. The computed values were compared to the factual values, thereby calibrating the model. Subsequently the dam was introduced into the model and future tidal propagations were calculated.

With this method the changes in the normal tide pattern were calculated. The method was not appropriate to compute the maximum water elevations during tidal waves, however, because of their noncyclic character. The exact method was developed for that purpose. In this method the quadratic resistance term was maintained and the equations solved by substituting power series for the unknowns. Wind effects could also be taken into account with this method.

A problem with the exact method was its trial-and-error character, which made it very labor intensive. Solutions to the equations could only be obtained by means of repeated estimates of the value of a key function involving seaside water currents. To reduce the labor, Lorentz simplified the system of channels to a greater extent than before, into a model consisting of only two channels. In this model the high water levels during a historic storm were calculated. He had to repeat the calculations about ten times before a sufficient estimation of the currents at the inlets was found. The result of the calculation indicated an increase of the water level from a maximum of 2.4 meters above normal sea level in the old situation to a maximum elevation of about 3.5 meters after the construction of the dam.

The concluding report of the committee did not reveal much about the actual computing work. It did note that in the execution of the investigation, two calculating machines of different manufacture were used, a Burroughs and a Millionär. But it did not mention which part of the total of eight years that the commission needed to complete its task was spent on the calculations. J.T. Thijsse, the civil engineer assisting Lorentz, later remarked that the calculation of the existing tides by the harmonic method took one month for two persons who worked in duplicate to avoid errors.[3] One of the engineers who worked at the Office of the Zuiderzee Works, J.P. Mazure, later mentioned that this same task took three months of work for two calculators.[1] It has to be realized that this was only a small part of the total calculations.

The committee also considered a quite different approach to determine the tidal changes, that of hydraulic models. These were frequently used in research for the Zuiderzee Works. Very simple models were built in Hol-

Lorentz's differential equations

The equations that Lorentz applied for the water movement in a channel were

$$\delta s / \delta t = -gbq\, \delta h / \delta x \pm (gs^2) / (bq^2 C^2)$$
$$\delta s / \delta x = -b\, \delta h / \delta t$$

- s: current in a channel
- h: water level
- b, q: width, depth of the channel
- g: constant of gravity
- C: friction coefficient between water and bottom

The last term in the first equation is the quadratic resistance term. The second equation is called the continuity equation. In the report of the commission, the equations were formulated in a slightly more complicated way.

land, while more complicated questions — for example, involving the construction of small-scale sluices — were directed to the laboratory of Professor T. Rehbock in Karlsruhe, Germany. According to a footnote in the concluding report, however, the committee rejected this alternative for the tidal problem:

> The idea has been considered seriously, but it appeared that the small scale that would have to be applied, would induce difficulties of such an importance that it had to be rejected.[4]

After the dam was completed in 1931, the tide patterns corroborated the predictions of the committee completely. The error was only a few centimeters on a rise in the tidal range of up to 70 centimeters. One of the most questioned predictions of the committee was also validated, namely that the currents between the islands separating the Waddenzee from the North Sea would increase as a result of the closure. The predictions as to the heights of water elevations during storm surges proved to be less accurate. It was a long time before these errors became evident because of the low frequency of severe storms. In 1972 Thijsse concluded, on the basis of empirical data, that the predictions of Lorentz had been up to 30 centimeters too low. In the meantime, after a storm in 1953 to which we will return later, the dike was heightened by about 40 centimeters to comply with higher security standards.[5]

Lorentz had nevertheless succeeded in predicting the changes in the water levels with a convincing degree of accuracy and certainty, using numerical methods. For a long time the report of the committee formed an important handbook for hydraulic engineers.

Human computers

The tidal research carried out by Lorentz was incorporated in the investigations of a new Research Service ("Studiedienst") that was established in 1929 by the "Rijkswaterstaat," the National Public Works Administration. The "Studiedienst voor de Zeearmen, Benedenrivieren en Kusten" (Research Service for Estuaries, Maritime Rivers, and Coasts) was given responsibility for the planning of hydraulic projects on the maritime parts of the main rivers wherever they were influenced by tidal motion. These were mainly located in the southwest of the Netherlands. The aim of the projects was to improve the navigability of these rivers and to increase the safety from flooding in the adjacent areas, where more than a million people lived.

The projects again required tidal calculations. In 1934 the mathematician J.J. Dronkers was appointed to the Studiedienst to carry out the necessary studies. Dronkers could not directly use Lorentz's harmonic method, since for rivers he had to take into account an upland discharge, which was not harmonic in nature. He therefore adapted the exact method of Lorentz for use on rivers. He subsequently started using this method not only for the calculation of water elevation during storm surges, as Lorentz had done, but also to calculate the normal tide movements. The first application was the canalization project of the Hollandse IJssel river. The calculated changes in the tides proved accurate within centimeters. In 1935 Dronkers published an explanation of his method in *De Ingenieur*.[6] He began to put it into practice for different rivers and for parts of the Delta.

The trial-and-error character of the solution soon became a more serious problem than it had been in the case of the Zuiderzee. We saw that initial estimations had to be made for the currents in the seaside water inlets and at branching points in the channel system. Lorentz applied the exact method only in a two-channel network. In the Delta Region many more branching points occurred. The number of estimates that had to be made during the calculations multiplied, augmenting the number of times the calculations had to be repeated, and thereby heavily increasing the magnitude of the computing labor. Dronkers did not discuss this issue in his publications, however. In a 1938 report he just stated that to calculate the tides in a certain river in the Dutch East Indies (today Indonesia) would take four persons about five months.

In the same period, however, the harmonic method of Lorentz was adapted for use on rivers by L.P. Mazure of the Zuiderzee Department of the Rijkswaterstaat. It was of a lower accuracy than the exact method, but it required less computation. The head of the Studiedienst, the civil engineer J. van Veen, started doing calculations with this method.

The amount of computational work had grown to such an extent by 1938 that the Studiedienst suddenly hired nine young men as human computers, a newly created function.[7] They started to make tidal calculations on the lower rivers, using both numerical methods.

The work of the computers was rather monotonous. As a rule, their calculations were duplicated to avoid errors. When errors were detected in matching the different results, each calculator looked for them in his own calculations. When the computers executed Dronkers' exact method, each of them was assigned responsibility for a section of some specific river. Each would then transmit the results of the calculations to the colleague responsible for the adjacent section of the river. In the words of one of them, whom we interviewed, "In the end one came to know each and every peculiarity of one's own particular section of the river."[8]

The calculations were facilitated by the use of slide rules and desk calculators. For the exact method, mostly slide rules were used. The desk calculators were predominantly used for the harmonic method. This difference originated because the harmonic method required greater accuracy in the intermediate results, even though the overall results it produced were less accurate. For the application of the exact method, use of the less accurate but faster slide rules was adequate. Already in 1939, Van Veen mentioned the desk calculators when, in a publication in *De Ingenieur*, he complimented the computers on their work:

> 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.[9]

The computers were men, mostly with a high school education and high marks for mathematics. Either they had lacked the opportunity to attend a university or had discontinued their studies at a university or an engineering school. Ranking their job in the existing hierarchy presented a problem to the Rijkswaterstaat. Its organizational structure was characterized by a closed, hierarchical ranking system. The system consisted of two separate hierarchies, one administrative and the other technical, with the engineers at the topmost level. The computers could not be admitted to any level of the existing technical corps. As a consequence, until 1940, a distinct and separate rank was distinguished in the organizational structure, namely that of computer. In 1941 a second rank was added, that of assistant computer, with eight of the computers previously belonging to the single rank now becoming assistants, thus forming the second rank.

During the Second World War, from 1940 onward, the work of the computers exempted them from conscription to forced labor in Germany. Their number, some ten in all, remained virtually unchanged during this period. They started evaluating a multiplicity of plans for the Delta Region, including plans to interconnect four or five islands. For each plan the water heights during previous tidal waves were calculated. Different cases were simulated, for example, a tidal wave combined with high or low upland discharge.[10] In the course of time, the computers were divided into two distinct groups. Six of them worked for Dronkers using mainly his exact method, while the other four worked for Van Veen using the harmonic method.

The electrical method

Beside the numerical methods a totally different approach was developed by the Studiedienst. J. van Veen, the director, had worked on it in the early days of the service. Van Veen was a civil engineer with broad interests. (For instance, he published on geographic history.[11]) The method he introduced for the tidal calculations was based on the similarities between the motion of water and the flow of electricity. By comparing water currents with electrical currents, the problem could be formulated as an electrical analogy and solved on that basis. When Van Veen introduced this method in 1931, it was immediately criticized by J.P. Mazure of the Zuiderzee Department and other colleagues of the Rijkswaterstaat.[12,13] The criticism concerned the lack of physical validity of this approach, because of the difference in physical behavior of water currents and electrical currents. Van Veen then abandoned this approach and contracted Dronkers to solve the problem.

In the meantime, however, he continued his work on what he began to call the "electrical method." In 1937 he published on it and elaborated more systematically on the similarities between hydraulic and electrical phenomena.[14] He compared water currents with electrical currents. In electricity, electrical tension causes the current. In the case of water, currents are mainly caused by the slope of the 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, Van Veen made some important simplifications in his method. For example, he represented the quadratic resistance in water motions by a linear resistance

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in his electrical formulas. He justified this measure by referring to Lorentz, who had adopted the same simplification. He called his method an "engineer's way" in contrast with the more 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 its advantageous savings in calculating labor:

> The electrical method proceeds at a much faster rate than is the case with the exact method. While the first produces its results already after calculating for 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.

Van Veen proposed the combined use of two methods — his own to make a first guess, and the exact method to calculate the details more accurately. Like his presentation in 1931, his 1937 publication was received negatively, this time not only by colleagues of the Rijkswaterstaat but also by Professor J.M. Burgers of the Technical University in Delft.[15,16] The criticism again concerned the lack of physical validity of the method. It was stated that Van Veen had neglected a fundamental property of the water movements in rivers, expressed by the continuity differential equation (see box on p. 25), and, further, that phase differences in branching points were neglected. It was argued that the method would only be appropriate in specific cases, but that Van Veen had not specified in which.

In spite of the heavy criticism, Van Veen proceeded with his method. Until then he had not constructed a functional (electrical) apparatus for practical application. He worked with formulas like those for electricity which were solved mathematically, after which the results were numerically worked out for the different sections of a river. In the following years, Van Veen succeeded in constructing a small electrical network that modeled the river Lek, one of the Dutch rivers where tide currents as well as an upland discharge affected the water's motion (see Figure 2). Van Veen, a civil engineer, received the necessary aid from two electricians, one employed by a radio broadcasting organization and the other by PTT, the National Telecommunication Service. After the war, in 1946, Van Veen published the results of his experiments[17] and again admitted that his electrical method was not the most accurate, although he made mention of experiments with semiconductors (so-called cuprox-cells) that might serve to represent the quadratic term in the equations more adequately. More than before, he now emphasized the importance of the savings in "dead calculating labor":

> My purpose is to eliminate the repetitive, dead calculating labor. At the present moment it has become possible to construct what may be termed a calculating machine, capable of carrying out, by itself, the very complicated and tiring calculations, viz. the solution of intricate or complex equations with the same number of unknowns, by itself.... Of the 300,000 man-hours of labor required up till now for the implementation of any major project, only very little will be necessary.

Debate over methods

With this publication of 1946, a debate evolved between Van Veen and his coworker Dronkers about their respective methods. Dronkers countered Van Veen's claim concerning the amount of computing labor by pointing out the fact that, in the preparatory phase, the electrical method also required great quantities of computing labor.[18] He stated as his opinion that only half of the labor was saved and noted that the claims concerning the cuprox-cells had not as yet been adequately demonstrated. On the other hand, he admitted that his own method required extensive computing labor. As an example he mentioned a big tidal wave project, on which six persons worked for almost two years, an investment of labor considerably less than the 300,000 hours mentioned by Van Veen.

In a postscript to Dronkers' article, Van Veen sought to support his claim by experiments conducted at the PTT on the construction of electrical analogs "for the simulation of its telegraph cables." Again he attacked Dronkers' method for its labor requirements, as "something sufficient to raise doubt in even the most credulous." He continued:

> Only one answer fits Dr. Dronkers' writing and it seems that he agrees: "Wait and see" and "Give me the tools." I appeal to his patience just as I have been patient for the past 10 years with the numerical methods and their endless calculations to obtain results that required revision with excessive frequency and that were repeatedly inconsistent.

To what extent the criticism about errors in the results of Dronkers' method is justified, remains unclear. But it can be concluded from the debate that an impasse had been reached. Both scientists, Van Veen and Dronkers, had quite different preferences. The mathematician Dronkers chose the accurate but labor-intensive exact method. The engineer Van Veen preferred the less accurate and less labor intensive methods, the numerical harmonic method and the electrical one. Neither of them could claim to have an ultimate solution for the tidal calculations.

The causes of the problem

The question arises at this point of why the numerical methods that proved a success in the days of Lorentz did not offer a solution for the Delta Region. I have already mentioned the greater technical complexity due to the upland discharge and geographical situation in the Delta Region, with its large number of branching points. However, calculating the water movements in the Zuiderzee, a large unbroken expanse of water, was also a complex problem.

A further difference was no less significant: the place of the tidal research in the decision process. Lorentz had done his detailed investigations on the Zuiderzee after Parliament had approved the project. In the case of the Delta Region, however, such research became part of the preparatory phases of the projects. This meant that the preparatory phase in the decision process took on a more scientific character, in that it required a more detailed and precise analysis. In this phase, however, numerous alternative plans were available for which calculations had to be done. Moreover, many different parties were involved, like local authorities and shipping interests. For example, the city of Dordrecht, which was situated along waters in the Delta Region, was continually interfering in the development of projects, out of concern for the consequences of changes in the water levels along its quays. These quays were so low that in the abutting houses provisions were made to place small barriers in the doorways during high water.[10] So every rise of high water levels meant an immediate danger in this city. For shipping in the Delta Region, the magnitude of the currents was of great importance. Increases could necessitate the use of pusher tugs on certain routes. J.P. Mazure, one of the engineers concerned with tidal calculations, stated in 1937 that through the interests of third parties even the trustworthiness of the engineering profession itself became associated with the tidal research:

> ...unanticipated consequences of an action can cause major damage to third parties, and the resulting protests disturb the working atmosphere and undermine trust in the technical leadership.[15]

The tidal calculations served to determine the consequences of each plan for different interested parties. This required a sufficient degree of accuracy and certainty of the calculations. The numerical approach could meet these requirements only at the expense of a proportional increase in calculating work. The enhanced role of tidal research in the decision process thus diminished the attractiveness of this approach.

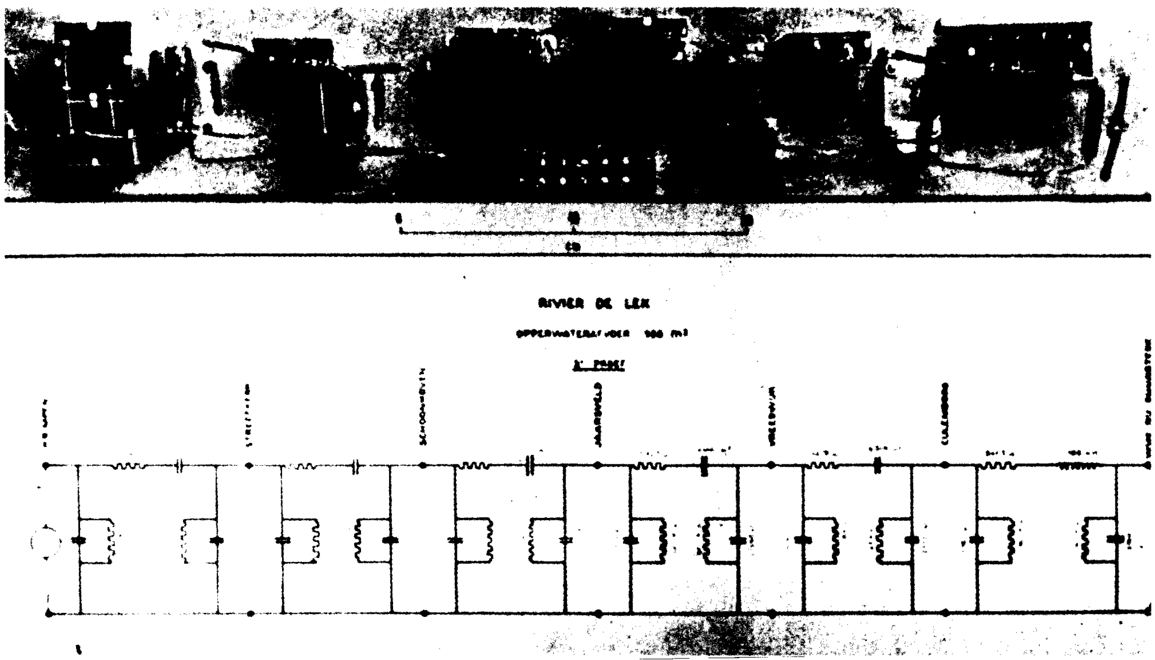

Figure 2. The electrical network representing the river Lek. In the middle are the names of the towns along the river (photo: Van Veen's 1946 article in *De Ingenieur*[17]).

The scale model

The problems of the Studiedienst paved the way for the National Hydraulic Laboratory, the "Waterloopkundig Laboratorium," to take an important initiative. The head of the laboratory, J.T. Thijsse, had as a young engineer assisted Lorentz in the calculations of the tides in the Zuiderzee. In the 1930s he had dedicated his efforts to the construction of scale models. In 1935 he participated in the short discussion that followed the publication of Dronkers' method and some years later he again expressed himself several times on the subject of tidal calculations, though he was not actively involved in research on the topic. In 1938 he took up a professorship at the Technical University in Delft and in this capacity he served as a member of the "Stormvloed-commissie," a committee that advised on hydraulic projects in the Delta Region.

In 1940 Thijsse started some exploratory experiments on the construction of scale models for the investigation of tidal motion. In 1947 he continued this research with the construction of a large hydraulic model of the northern part of the Delta Region. Such a model posed two problems. On the one hand, the degree of reduction had to be sufficiently large to incorporate a large geographic area in a model of moderate extension. On the other hand, the reduction had to be sufficiently small to maintain a turbulent current in the model, and to guarantee sufficient accuracy of the measurements of the water elevations, at the reduced scale. To meet both requirements, Thijsse reduced the horizontal dimensions in the model to a higher degree than the vertical ones. The moderate vertical reduction maintained the turbulent character of the flows and the accuracy of the measurements of the (vertical) water levels; the greater horizontal reduction compressed the size of the model. Even so, the model was 50 meters long (see Figure 3) and therefore was constructed outside the laboratory in large army tents.[19] In the course of the years, the model was extended to cover a larger geographic region, a process which was hindered by the adjacent buildings. Part of the solution to this obstacle was found in distorting the topography of the river system in the model.

An important characteristic of the scale model was the possibility to evaluate alternative damming plans quickly and the immediate visibility of the results. With the scale model it proved possible to determine the water elevations with high accuracy (on the order of centimeters at full scale). But it did have its limitations. The application was of course restricted to one geographic area, the northern part of the Delta Region. Changes in the topography of the river system, particularly in the depth of the rivers, could only be made with major difficulty. Furthermore the currents could not accurately be determined; there might be errors of up to 10 percent. And wind effects could not be modeled.

Coexisting methods

With the scale model a third method had entered the field of tidal calculations. It did not replace the existing methods, but the three methods entered a long phase of coexistence (which continued until all were replaced by digital computers). The other two research groups read-

Figure 3. The construction of the scale model, about 1948 (photo: Waterloopkundig Laboratorium, Delft).

justed their activities in this period. Dronkers got his own research unit within the Rijkswaterstaat. He continued working with the exact method, which he applied mainly to regions outside the Delta Region that were not part of the scale model, and to projects outside the Netherlands, where his fame was growing. In these cases only a limited number of alternatives had to be evaluated, which did not justify building a scale model. He attempted to accelerate the computing process by designing graphic aids and standard computing forms. Until the introduction of the digital computer, the most important computing aid used by his group remained the slide rule. In this period women were occasionally appointed to the position of calculator. However, they generally did not stay for long.

Van Veen's group performed calculations by the harmonic method, to check the results of the scale model and to calculate aspects of plans that could not be studied in the hydraulic model. Van Veen also started the construction of a large electrical analog machine. For this purpose, an electrical laboratory was established within the Studiedienst.

The pace of research in all methods was greatly accelerated as a consequence of a violent storm that occurred in 1953, causing the flooding of a large part of the Delta Region and the death of 1,800 people. Up to that time only small projects had been executed in the Delta Region. The storm convinced all interested parties of the urgency to execute projects on a larger scale. Within three weeks the government inaugurated a commission, the Delta Committee, to coordinate research for the repair activities and for the planning of future waterworks.[20] Thenceforth, the work of the different research groups was 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 local authorities agreed to have the adjoining buildings removed). Artificial aids were introduced in the model to improve its veracity. Rods were placed in the currents to augment the friction of the bottom, and revolving rotors were placed in them to model the effect of the rotation of the earth on the water movements, a phenomenon that had in the meantime also been incorporated in Dronkers' numerical method.

In 1954 the electrical laboratory of Van Veen completed an electrical analog machine (see Figure 4). It was used for the simulation of projects in the same geographic area as the scale model, but that were difficult to execute in that model. The actual performance of the electrical analog machine is difficult to assess, because the machine is hardly mentioned

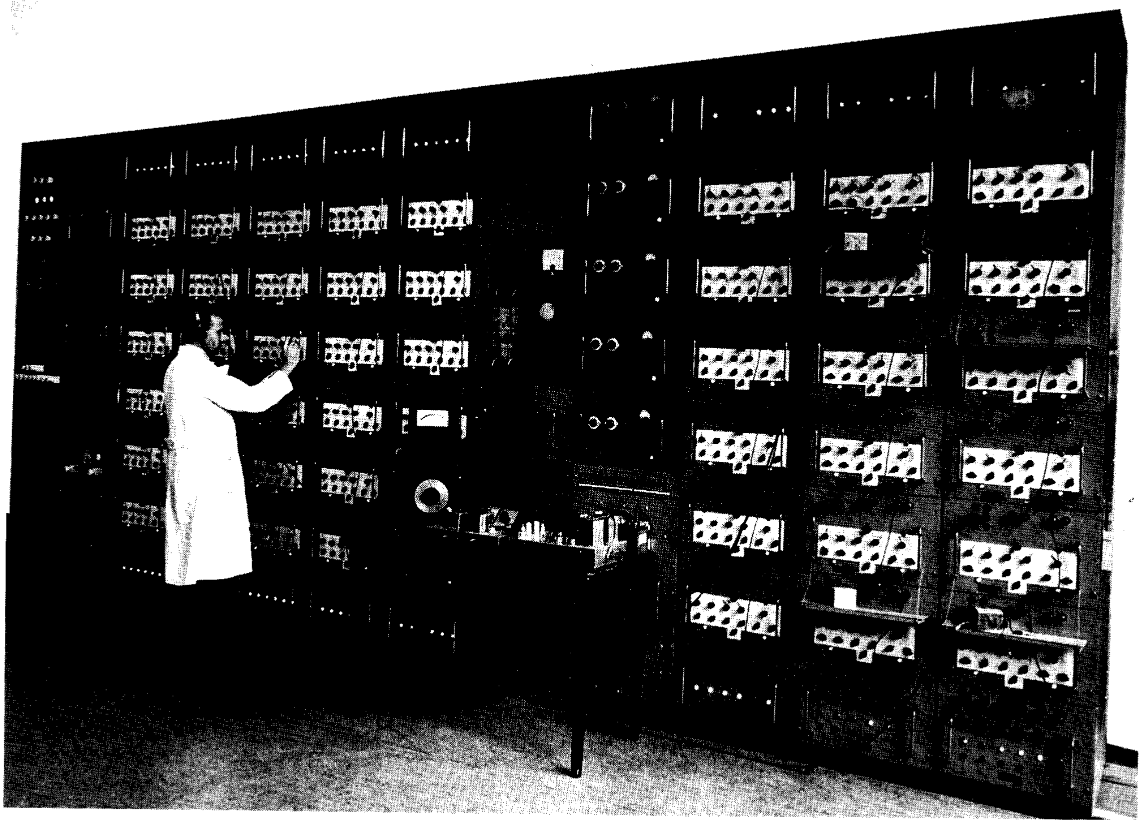

Figure 4. The electrical analog machine (1954) (photo: Rijkswaterstaat).

in the publications of the Delta Committee. Presumably its performance was not fully adequate.

In any event, work started on the construction of a second analog machine in 1955. This machine, referred to as the Deltar, was not built by Van Veen's research group, but by the Technical University in Delft. A crucial issue was the simulation of the quadratic resistance term mentioned above. A solution was found in the application of thermocouples, electrical elements of which the output tension was related quadratically to the input. The machine was not finished until 1961, a year after the final report of the Delta Committee. The Deltar consisted of units, each of which represented one section of the river system. It was partly mechanical, each unit containing a mechanical axis, the position of which represented the mean water elevation in that section. On each axis a circular disk was affixed, the contour of which represented the width of the water surface as a function of the water elevation in a specific section. The units were connected electrically in accordance with the topography of a specific river system. The water levels at sea, the upland discharge, and the wind force and direction were put into the machine on punched tape. It required a large initial effort to model a specific river system on the machine, but, just as in the scale models, different alternatives could subsequently be quickly evaluated. The electrical machine had the advantage that wind influences could be modeled. After some of the Delta gates were closed, it was used to simulate the water movements for the operational control of the discharge sluices.

Numerical methods continued to serve as an important supplement in this period. They were used to check the results of the scale model for accuracy. A general advantage of the numerical methods was the insight they provided into the physical mechanisms of the water motions. Dronkers remained interested in reducing the amount of calculating work that these numerical methods entailed. In a publication in 1954 he made a distinction between trial-and-error numerical methods, which required fewer but more experienced computers, and straightforward methods, which required more computing work, but which could be executed by inexperienced computers.[21]

Until the 1960s, it was possible to meet the computational requirements only by the application of all three methods: the numerical, the electrical, and the use of scale models. During the 1960s numerical methods started to be carried out on electronic computers. The initial experiments were made in 1956 using a digital computer built at the Mathematical Centre in Amsterdam. The use of digital computers stressed the importance of straightforward numerical methods. In the course of time, the digital computer replaced all the other methods in the problem of the tidal predictions. This, however, was a very gradual process that did not end before the beginning of the 1980s. The analog Deltar machine remained in use until 1983.

It is clear that tidal predictions constituted an important computing problem in the field of hydraulic engineering in the Netherlands. The computational demands were increased by the growing technical complexity of the hydraulic works and by the enhanced role of tidal research in the decision-making process. The results were an increase in the number of alternative plans for which calculations had to be done and a demand for greater accuracy in the results.

The growing number of alternatives favored the use of the scale model, which required a large initial investment, but in which alternative plans could often easily be simulated. The scale model alone, however, was not sufficient to meet all requirements. This was only possible by combining this method with the application of numerical and electrical methods. The important advantage of the digital computer was its capability to meet all the requirements on its own. Thus, it can be concluded that the growing technical complexity of hydraulic works and the increasing role of tidal research in the decision process laid the foundations for the success of the digital computer in this field. Kranakis also cites technical complexity as a stimulus for the development of digital computers in her study[22] about the history of early Dutch computers. In her words, "The development of computers was thus a response to...increasing social and technical complexity." With "social complexity" she indicates the use of the digital computers for business purposes.

On top of these factors, the disciplines of the engineers and scientists involved played a part in the choice of methods. The civil engineers in general had a preference for "feeling" the phenomena, and thus they tended to prefer scale models or, secondarily, analog models like the Deltar. It was the physicist Lorentz and the mathematician Dronkers who applied the numerical approach.

A question that remains is why — despite its relative advantage — the digital computer initially played such a minor part in the search for a solution of the computing problem. The first digital electronic machines that were developed in the 1940s in England and the United States were used for similar types of calculations. In the Netherlands digital electronic machines did not become available until the mid-1950s, but research on them started in the late 1940s.[22] The engineers and scientists involved in tidal research did not participate in this research, however. Rather, as we have seen, they focused on the construction of scale models and of analog machines.

An analogous question can be posed concerning the reasons why earlier mechanical tabulating machines were not used. In the 1930s and 1940s tabulating machines were used outside the Netherlands for scientific calculations. The numerical process was executed iteratively by putting the starting values on punched cards and performing consecutive operations on the cards. Thus the cost of computing work was reduced and the results could be provided within a shorter time. Tabulating machines were available in the Netherlands from the 1920s at prices that did not preclude their application to the field of tidal research. However, in the publications in this field, no mention is made of this possibility.

There are several possible reasons for the lack of attention to the digital approach. It was not a natural choice in the field of civil engineering, where most engineers had a preference for civil engineering methods. Also, the Rijkswaterstaat, as a civil engineering organization, had no great affinity for machinery involving precision mechanics and electricity. A second reason might be that this organization did not consider the development of general-purpose computing machines to be one of its tasks. These explanations, however, cannot be considered conclusive, since the Rijkswaterstaat did invest considerable amounts of money in the numerical and electrical approaches, neither of which was a strictly civil engineering method, and both of which required considerable knowledge of other fields of science and technology.

There must therefore be another reason why the digital approach got little attention. It would be worth investigating whether the social organization of calculating work was of influence. In the history of computing, we find several examples of a Tayloristic organization of calculating work, whereby the work was divided as far as possible into elementary tasks, which could be as simple as addition, subtraction, multiplication, or division. Such an organizational structure could easily give rise to the concept of constructing machines capable of executing the entire process. Occasionally, pioneers in the field of digital computers indeed pointed to a similarity between procedures for manual calculating work and programs on digital calculating machines. The organizational structure of computing work in the Rijkswaterstaat was far from Tayloristic, however. There, such work was organized more like a craft, which tended to inhibit attempts to mechanize the calculations. This situation may well help to explain the lack of attention to the digital approach. It suggests that organizational factors were influential in the choice of digital computers. ■

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